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Developmental Trajectories of Electric Vehicle Research in a Circular Economy: Main Path Analysis

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Abstract: This study explored the development history and future trends of academic research on electric vehicles (EVs) in a circular economy. We collected 4127 articles on circular economy and EVs from the Web of Science database, and main path analysis indicated that academic research in the field of EVs in a circular economy has covered the following topics in chronological order: EVs as a power resource; vehicle-to-grid (V2G) technology; renewable energy and energy storage grids; smart grid and charging station optimization; and sustainable development of energy, water, and environmental systems. Through cluster analysis and data mining, we identified the following main research topics in the aforementioned field: recycling and reuse of EV batteries, charging stations and energy management, V2G systems and renewable energy, power frequency control systems, dynamic economic emissions, and energy management. Finally, data mining and statistical analysis revealed the following emerging research topics in this field from 2020 to 2023: microgrids, deep learning, loop supply chain, blockchain, and automatic generation control. Various achievements have been attained in research on EVs in a circular economy; however, challenges related to aspects such as sustainable battery recycling charging infrastructure and renewable energy integration remain.

Keywords: electric vehicles; circular economy; main path analysis; sustainable development; emerging research

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1. Introduction

According to preliminary research statistics from major institutions that track automotive sales, such as LMC Automotive and EV-Volumes, in 2022, worldwide sales of battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs) were 10.5 million, which represented a 55% increase compared to the corresponding number for 2021. The aforementioned data indicate that the entire electric vehicle (EV) industry is developing at an astonishing pace. The rapid transition of the entire automotive industry toward EVs has resulted in certain problems and challenges, such as those related to greenhouse gas emissions during battery manufacturing; power supply and charging infrastructure; battery lifespan, manufacturing costs, and performance; energy sources; environmental protection; circular economy; and sustainable development [1]. This study investigated (1) the benefits of replacing traditional gasoline-powered vehicles with EVs from the perspective of a circular economy and (2) how the development of EVs can align with a circular economy and sustainable development.

The traditional economic model is a linear economy, which typically follows the "take → make → use → dispose" sequence. In a linear economy, raw materials are collected and then transformed into products that are used and subsequently discarded as waste. This model often leads to excessive resource consumption and waste. By contrast, the concept of a circular economy emphasizes continuous cyclical use, increased efficiency, waste reduction, synergistic effects, ecological design, and shared use, thereby reducing environmental damage and impact [2]. EVs align with the idea of a circular economy, because they can

achieve efficient energy utilization and reduce carbon emissions. Therefore, the correlation between EVs and a circular economy is noteworthy. The rapid development of EVs has resulted in problems related to battery disposal. Without proper measures for reuse or recycling, the stock of discarded batteries would increase dramatically. Cyclical resource usage and waste reduction, which can be achieved by recycling and reusing batteries, align with the requirements of a circular economy [3]. In addition, the manufacturing and use of EVs generate certain levels of carbon emissions, and the energy sources of EV charging stations might be thermal power, natural gas, or coal [4]. Therefore, under rapid EV development, ensuring the cyclical use and sustainable development of the entire ecosystem is crucial.

In this study, we employed a main path analysis (MPA) for quantitatively analyzing studies related to EVs in the context of a circular economy. MPA enables researchers to understand the developmental prospects, technological evolution, and future trends of an industry or academic field for predicting the pathways of knowledge diffusion. This method has been successfully applied to analyze various fields, including Internet of Vehicle technology [5], blockchain development [6], radio frequency identification development trajectories [7], the application of artificial intelligence in the construction industry [8], and forensic science knowledge development [9]. The SCOPUS database consists of more than 1500 articles related to MPA, and we applied the MPA to analyze and review the large number of articles concerning EVs in the context of a circular economy.

In addition to MPA, topic modeling is another citation analysis technique. Topic modeling is a machine learning-based text analysis method that is used to automatically extract and identify latent topics from large-scale literature data. This method aids researchers in identifying hidden themes within a large amount of literature, which facilitates the summarization of the primary content and topics of the literature. The method involves the analysis of term co-occurrence patterns within the literature to group related literature into thematic clusters, which is highly beneficial for further literature analysis and research. This study traced the trajectory of mainstream ideas within the field of EVs in a circular economy by examining citation relationships, thereby understanding the development trends in the field, identifying crucial literature, and confirming crucial research topics and domains. To analyze the development trajectories, development trends, and potential issues in the relevant field simultaneously, MPA and cluster analysis were employed. The similarities and differences between MPA and topic modeling are summarized in Table 1.

The rapid development of the EV industry, particularly within the framework of a circular economy, has attracted widespread research attention. To date, more than 6000 studies about EVs and the circular economy have been published, with the publishing period being 1998 to 2024. However, these studies have primarily focused on specific singular topics and have not conducted a systematic and comprehensive analysis; thus, the studies have failed to fully reveal the overall development trajectory of EVs within a circular economy. To fill the aforementioned research gap, this study conducted a comprehensive and systematic analysis to explore the development history of EVs in a circular economy. This study analyzed in depth the evolution of research topics, the pathways of knowledge transmission, and the latest research focuses, including the technologies and specialized fields involved.

Table 1. Functional analysis of topic modeling and main path analysis.

Description	Comparison Item	Topic Modeling	Main Path Analysis
Similarities	Literature Analysis	Identifies and analyzes important information from large-scale literature data	Identifies and analyzes important information from large-scale literature data
	Data-Driven	Relies on large datasets, using algorithms to reveal data structure and patterns	Relies on large datasets, using algorithms to reveal data structure and patterns

Table 1. *Cont.*

Description	Comparison Item	Topic Modeling	Main Path Analysis
Differences	Visualization	Generates visualizations like topic distribution maps	Generates visualizations like main path diagrams
	Purpose and Application	Extracts latent topics to understand the underlying structure and content distribution of literature	Analyzes citation networks to identify important research directions and evolution paths in academic or technical fields
	Object of Analysis	Literature data, identifying topics through word co-occurrence or topic distribution	Citation networks, tracing knowledge flow and development paths through citation relationships
	Methods	LDA, LSA, etc., relying on probabilistic models and matrix decomposition techniques	Global main path method, key-route main path method, relying on network analysis techniques
	Output Results	Topic distribution and characteristic words for each topic	Knowledge development path diagrams showing important research work and their citation relationships

1.1. Circular Economy

1.1.1. Definition of a Circular Economy

The concept of a circular economy has gained increasing global attention. A circular economy aims to promote the cyclical use of resources while protecting the environment. Boulding (1966) stated "Our little spaceship is clearly a finite system, and as such, it has no unlimited reservoirs of anything, either for extraction or for pollution, and particularly not for reservoirs of inert matter." [10]. This description is often cited as the origin of the term "circular economy". Pearce and Turner (1990) further developed the concept of a circular economy and explained the change from a traditional open-ended economic system to a circular economic system by using the laws of thermodynamics [11]. Stahel (2008) introduced the concept of a closed-loop economy and suggested that products and resources should be designed to be infinitely recyclable. Later, he emphasized the cyclical use of resources and products throughout the production and consumption processes and offered new insights for achieving sustainability [12]. Navigator and environmentalist Ellen MacArthur established the Ellen MacArthur Foundation, which advocates for a circular economy. She emphasized that products, components, and materials should be designed to be recyclable and renewable to ensure the maximum use of resources and energy [13]. Designer William McDonough and chemist Michael Braungart developed the "cradle-to-cradle" model for product design. They advocated for the design of environmentally friendly products that can be recycled and reused so that a truly green economy can be achieved [14]. Environmental scientists Graedel and Allenby (2010) proposed the concept of a circular economy and elaborated on the importance of industrial ecology and cyclical resource usage [15]. Hawken et al. (2010) presented the concept of natural capitalism and emphasized that nature and the ecosystem should be regarded as valuable and crucial resources [16].

The European Union introduced the Circular Economy Package in 2015, putting forward specific circular economy action plans for waste management, plastics, and critical raw materials. A circular economy is an economic system in which material disposal is replaced by material reuse, recycling, and recovery in the production, distribution, and consumption processes [14].

Kirchherr et al. (2017) proposed 114 definitions of a circular economy, which collectively embody its core idea: achieving sustainable economic development by minimizing resource wastage and environmental impact [17].

By integrating the propositions of the aforementioned scholars, we defined a circular economy as an economic system that emphasized the realization of economic growth and sustainable development while maintaining the ecosystem integrity. In a circular economy,

aspects such as product design, resource management, and ecology are integrated to maximize resource utilization and retain maximum product value. The characteristics of a circular economy are as follows:

1. Respect for and utilization of natural capital: A circular economy emphasizes the finite nature of resources (Boulding's perspective) and assigns economic value to nature and the ecosystem (Pearce and Turner's perspective).
2. Cyclical resource use and prolonging product lifespan: A circular economy aims for products to be completely reused or recycled into new products or safely returned to the natural environment at the end of their life cycle (Braungart and McDonough's perspective). It also emphasizes the extension of product lifespan and the retention of product value (Stahel's perspective).
3. Consideration of the life cycle in product design: A circular economy advocates for considering the entire product life cycle during the product design phase (Ellen MacArthur's perspective) and emphasizes a systemic approach to problem-solving (Michael Pawlyn's perspective).
4. Emphasis on innovation: In a circular economy, innovation plays a crucial role in the achievement of resource efficiency and environmentally friendly solutions (Michael Pawlyn and Paul Hawken's perspectives).
5. Sustainable development: A circular economy requires an economic model that achieves balanced and sustainable development across the social, economic, and environmental dimensions.

1.1.2. Principles of a Circular Economy

The principles of a circular economy are often adhered to through a series of "R" actions, where "R" represents a strategy or method for achieving a circular economy. Different scholars have proposed different principles of a circular economy. Some common "R" actions are described in the following text. In the 1990s, the Japanese government enacted the Act for Establishing a Sound Material-Cycle Society on the basis of the reduce, reuse, and recycle (3R) initiative. This law prioritizes waste reduction, followed by item reuse and recycling, as the means for achieving a sustainable society. The policy was formally adopted at the third G8 Environmental Minister Meeting in 2004 for lowering resource consumption and maximizing resource reuse and recycling [18]. Some researchers added "repair" to the 3R initiative to develop the 4R initiative. "Repair" refers to restoring damaged items instead of discarding them, thereby extending their lifespan [12,14]. Other researchers added "refuse" to the 4R initiative to develop the 5R initiative. "Refuse" refers to avoiding the usage of unnecessary or harmful items and resources for reducing waste generation and environmental burden. People are encouraged to reject single-use items, excessive packaging, and nonrecyclable materials for reducing the generation of waste at its source [19,20]. In addition, some researchers added "rethink" and "recover" to the 5R initiative to develop the 7R initiative. "Rethink" refers to reflections on consumption patterns and lifestyles to achieve eco-friendly living, and "recover" refers to extracting valuable resources from waste [21]. "Redesign", "remanufacture", and "repurpose" were added to the existing 7R initiative to develop the 10R initiative. In particular, "redesign" refers to the consideration of a product's life cycle in the product's design phase to make it easier to repair, recycle, and reuse the product [17].

The aforementioned principles provide a framework for understanding and implementing a circular economy. Reike et al. (2018) investigated and analyzed 69 articles related to the "R" principles of a circular economy. They found that the 5R initiative, which has a clear and well-defined hierarchical structure, is the most commonly used among the aforementioned initiatives. The 4R and 6R initiatives are also frequently used, and the implementation of the 6R initiative has become feasible. The 7R–10R initiatives are new initiatives that are used less frequently than the 4R–6R initiatives [22].

1.2. Electric Vehicles

1.2.1. Definition and Types of EVs

EVs are powered by electricity generated from batteries or fuel cells. These vehicles can be distinguished into the following types according to their power source and driving mechanism: BEVs, PHEVs, full hybrid EVs (HEVs), fuel cell EVs (FCEVs), and micro hybrid EVs (MHEVs) [23–25], as shown in Table 2.

Table 2. Classification of EVs.

Abbreviation	Full Name	Power Source	External Charging Requirement
BEV	Battery Electric Vehicle	Battery	Required
HEV	Full Hybrid Electric Vehicle	Fuel and battery	Not required
MHEV	Micro Hybrid Electric Vehicle	Fuel and battery	Not required
PHEV	Plug in Hybrid Electric Vehicle	Fuel and battery	Required
FCEV	Fuel Cell Electric Vehicle	Hydrogen and battery	Not required

BEVs: BEVs rely entirely on batteries for power and do not have an internal combustion engine. These vehicles must be charged before the battery is depleted, and the charging duration usually ranges from dozens of minutes to several hours. BEVs generally have high energy efficiency and low maintenance costs; however, their range/mileage is limited by the battery capacity, which often leads to range anxiety [26,27].

PHEVs: PHEVs are driven by batteries and an internal combustion engine. These vehicles can be charged through plug-in chargers or by using the internal combustion engine as a generator. When the battery is depleted, the internal combustion engine powers the vehicle. Compared to BEVs, PHEVs usually have longer range/mileage and more flexible usage patterns but higher maintenance costs [28–30].

HEVs: HEVs are driven by an internal combustion engine and electric motor. The internal combustion engine often functions as a generator to produce electricity for the electric motor. HEVs generally have higher energy efficiency and range/mileage than traditional fossil fuel vehicles do but are inferior to BEVs and PHEVs [31,32].

FCEVs: FCEVs use a fuel cell to convert hydrogen into electricity for their electric motor. The hydrogen fuel required by FCEVs is primarily produced through the steam reforming of natural gas and other fossil primary sources, with only a small fraction of this fuel produced from renewable sources. During their use, FCEVs produce only water vapor and heat, which are not harmful to the environment. However, the infrastructure for hydrogen refueling is limited, and FCEVs are currently more costly than other types of EVs. FCEVs have been introduced for commercial use in Europe, Japan, and South Korea [33].

MHEVs: MHEVs are not fully electric. Instead, they use start–stop technology, in which the engine shuts off when the vehicle is idling (such as at a traffic light) and restarts when the accelerator is pressed. This technology improves fuel efficiency. Although MHEVs do not run in a purely electric mode, they are still partially propelled by batteries. In general, HEVs are more expensive than gasoline vehicles but have lower fuel consumption than them. By purchasing MHEVs instead, consumers are provided with a simple hybrid solution for effectively reducing greenhouse gas emissions and aligning with strict government regulations worldwide. Thus, automotive manufacturers have begun to design efficient MHEVs [34].

1.2.2. Development Trends and Economics of EVs

1. Development trends of EVs

Increased driving range/mileage: With advances in battery technology, the driving range/mileage of new EVs has surpassed that of many traditional vehicles with internal

combustion engines. In the future, further improvements in battery efficiency will result in a longer driving range/mileage for EVs [35,36].

Fast charging: Although the charging duration of EVs has been considerably reduced, EV charging still requires more time than gasoline refueling. Therefore, the development of faster charging technologies is a crucial development trend in the field of EVs [36,37].

Expansion of charging infrastructure: As EVs become increasingly prevalent, additional EV charging stations will need to be constructed in not only urban areas but also suburban and rural regions [38,39].

Development of autonomous driving technology: The integration of EV technology with autonomous driving technology is a major future development trend for EVs. Many EV manufacturers, such as Tesla and Mercedes-Benz, are developing and implementing autonomous driving, the development of which is progressing rapidly [40,41].

2. Economics of EVs

The economics of EVs refers to the economic costs and benefits of using EVs as a means of transportation instead of traditional gasoline vehicles. The crucial factors for analyzing the economics of EVs are as follows:

Total cost of ownership: Although the initial purchase price of EVs might be higher than that of gasoline vehicles, the operating costs of EVs are typically lower. The electricity costs of EVs are generally lower than the fuel costs of gasoline vehicles. EVs have low maintenance costs because of their simple structure [42,43].

Impact of EV policies: Many governments provide tax incentives and subsidies to encourage consumers to purchase EVs. Factors influencing such decisions include carbon emission reduction, energy efficiency, market development, industrial innovation, charging infrastructure, and green city image. Government policies are expected to reduce the total cost of EVs [44,45].

Drop in battery price: Battery costs are decreasing rapidly; thus, in the future, the initial cost of EVs might be similar to or even lower than that of gasoline vehicles. Extended warranty periods or mileage and reduced unit prices may contribute to a gradual decrease in the cost of battery purchase and maintenance [46,47].

Potential source of income: In some grid systems, EVs may be used for energy storage. Vehicle-to-grid (V2G) technology enables owners to charge their EVs when electricity prices are low and then transfer electricity from their EVs to the power grid when electricity prices are high. Thus, EVs might become a source of income for their owners [48–50].

Resale value: With the development of the EV market and advances in battery technology, the resale value of EVs might increase. Factors influencing the resale value of EVs include battery health, government subsidies, market demands, maintenance records, vehicle age, and mileage [51,52].

In advancing the integration of electric vehicles (EVs) within a circular economy, several challenges and opportunities have been identified. According to Sopha et al. (2022), the implementation of a circular economy for managing EV batteries involves various complexities, including technical limitations, policy barriers, and market demand fluctuations. Their study, through a systematic literature review and conceptual framework, highlights that, while these are significant challenges, policy support and technological innovation can act as crucial enablers [53]. Meanwhile, Remme and Jackson (2023) discussed the issue of "green mission creep" associated with circular economy strategies. They argue that an overemphasis on resource circularity could lead to unintended consequences, such as increased resource consumption and shifting environmental burdens, potentially undermining long-term sustainability goals [54]. Additionally, Bonsu (2020) emphasized that the transition to EVs and the move towards a net-zero economy offer substantial potential for reducing carbon footprints within a circular economy framework. However, effective policy measures are essential to manage the complexities and challenges of this transition, particularly in balancing economic development with environmental protection [55]. These studies suggest that, while circular economy strategies can support sustainable devel-

opment, a comprehensive approach is needed to avoid potential negative impacts and maximize environmental benefits.

2. Materials and Methods

2.1. Data Source

This study primarily focused on analyzing data obtained from the WoS. The WoS, which was established by Thomson Reuters (based in the United States) in 1997, is a global citation database that covers various disciplines, including science, engineering, medicine, agriculture, humanities, and social sciences. All the journals included in the WoS undergo a rigorous review process to ensure their academic quality. Thus, the literature available on the WoS is reliable and trustworthy. This study extracted and thoroughly analyzed the literature on EVs in the context of a circular economy from the WoS database.

2.2. Main Path Analysis (MPA)

MPA, which was introduced by Hummon and Doreian (1989), is a scientific analytical method that combines bibliometrics and social network analysis. This method allows researchers to identify the primary paths within extensive citation networks. By analyzing citation data, researchers can identify emerging research trends, major research topics, and influential works in specific fields. In academic citation networks, academic papers serve as nodes, and the mutual citations between papers are links. A citation network is directional; thus, knowledge flows from the cited articles to the citing articles. Links are directed from the cited articles to the citing articles, as illustrated in Figure 1. A citation network is formed by the connections between articles through citations. Subsequently, many path weight algorithms and path searching methods can be used to investigate the flow direction, weight, and path of knowledge transfer [56].

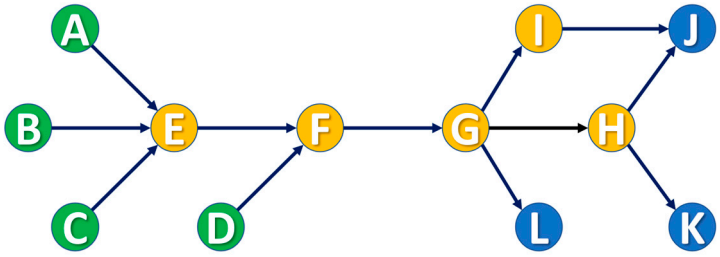


Figure 1. Example of a literature citation network.

The present study used the citation network analysis method of Hummon and Doreian (1989), which comprises two stages. The first stage involves confirming the weighting algorithm and calculating the weight of each path, thereby effectively transforming the citation network into a weighted network. The second stage involves selecting the path tracking search algorithm and extracting the finalized main paths [53].

2.2.1. Weight Assignment Algorithms for a Citation Network

MPA involves establishing traversal counts for each link during knowledge transfer. These traversal counts are then converted into weights. Three algorithms are commonly used in the literature for weight assignment: the search path count (SPC), search path link count (SPLC), and search path node pair (SPNP) algorithms. Liu et al. (2019) described these three algorithms as follows: In the SPC algorithm, the number of times a link is traversed through all possible paths from all sources to all sinks is determined. In the SPLC algorithm, the number of times a link is traversed through all possible paths from all ancestors of the tail node (including itself) to all sinks is determined. Finally, in the SPNP algorithm, the number of times a link is traversed through all possible paths from all ancestors of the tail node (including itself) to all descendants of the head node (including itself) is determined [57].

Liu and Lu (2017) empirically verified that, compared to the SPC and SPNP algorithms, the SPLC algorithm exhibits superior performance in MPA and allows for a more comprehensive exploration of knowledge diffusion phenomena. A higher SPLC value indicates a higher traversal count for the link, which indicates that the link has a stronger effect on the overall technological development in the relevant field [57]. The SPLC is calculated as follows [58]:

$$w_{0\to d}(\mu, v) = \Sigma_{\text{traversal}}^{\text{all traversales}} S_i(u, v) \quad (1)$$

$$w_{SPLC}(\mu, v) = \Sigma_{\text{all combinations of ancestors and sinks}} w_{0\to d}(u, v). \quad (2)$$

$$w_{SPLC}(\mu, v) = N^{-}_{\text{ancestors as origins}}(u) \cdot N^{+}_{\text{sinks as destinations}}(v), \quad (3)$$

$$N^{-}_{\text{ancestors as origins}}(u) = \begin{cases} 1, \text{ if u is an ancestor} \\ \sum_{\text{all ancestors}} \text{number of paths leading from an ancestor to u, otherwise.} \end{cases} \quad (4)$$

$$N^{+}_{\text{sinks as destinations}}(v) = \begin{cases} 1, \text{ if v is a sink} \\ \sum_{\text{all sinks}} \text{number of paths leaving from v to a sink, otherwise.} \end{cases} \quad (5)$$

$N^{-}_{\text{ancestors as origins}}$ *represents the number of paths from the source to node u;*
$N^{+}_{\text{sinks as destinations}}$ *represents the total number of paths from node v to a sink.*

Figure 1 illustrates the calculation of weights in the SPLC algorithm. Consider link FG in the citation network as an example. For this link, all ancestors of the tail node F (A, B, C, D, E, and F) are connected to F, which results in six potential paths (A–E–F, B–E–F, C–E–F, D–F, E–F, and F–F). The head node G of link FG is connected to all sink nodes, namely J, K, and L; thus, four potential paths exist (G–I–J, G–H–J, G–H–K, and G–L). The multiplication of these two numbers of paths yields 24 (6 × 4), which represents the SPLC value of link FG. The aforementioned logic is applied to calculate the traversal count for each link. Figure 2 displays the SPLC values of all links [59].

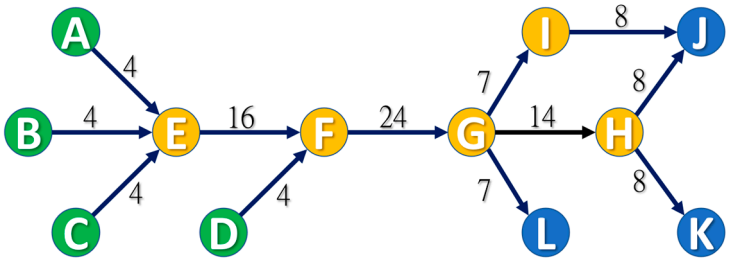


Figure 2. Example of the SPLC algorithm.

2.2.2. Path Tracking Search Algorithm

After the citation network is converted into a weighted network, one path tracking method is selected to determine the final main path graph. Since the introduction of the priority-first search algorithm by Hummon and Doreian (1989) [56], the following methods have been commonly employed for main path search:

1. Local main path method: In this method, the search process starts from the source. At each new target, the next target's link with the highest weight is selected as the main path. The nearest and highest weighted link is selected, and the most important articles in the development history of the subject domain are identified. However, important paths with high weights might be overlooked.
2. Global main path method: This method involves calculating the weights of all paths in the network from the source to the sink and then ranking them. Top-ranked paths can be determined for different requirements. In particular, the path with the highest weight is referred to as the global main path. The global main path method emphasizes the overall profile of knowledge diffusion.

3. Key route main path method: In this method, the weights of all links in the network are calculated; following which, the top links with the highest weights are identified. From the start and end points of these links, simultaneous forward and backward searches are performed from key routes to find the path with the highest weight [57].

This study used the SPLC algorithm and the search algorithm for the global main path under the considerations of the overall importance of knowledge flow and various crucial connections in the network. The mathematical model adopted for summing the weights is expressed as follows [58]:

$$w_{SPLC}(\mu, v) = \Sigma_{\text{all combinations of ancestors and sinks}}\, w_{0\to d}(u, v). \quad (6)$$

In Figure 2, 16 potential paths exist from the source to the sink. The traversal counts of all paths are tallied, and six paths (A–E–F–G–H–J, AE–F–G–H–K, B–E–F–G–H–I, B–E–F–G–H–K, C–E–F–G–H–J, and C–E–F–G–H–K) have the highest total traversal count of 66. The union of these six paths represents the global main path of the SPLC algorithm (Figure 3) [59].

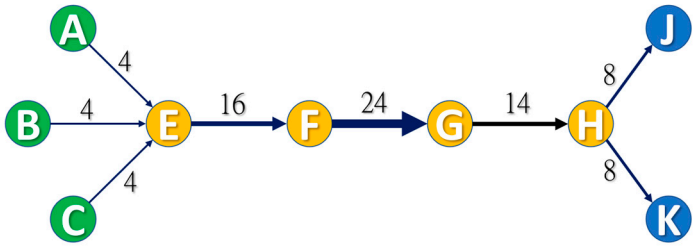


Figure 3. Global main path in the SPLC algorithm.

To calculate the citation weight and perform a path search, the MainPath 465 software (version 456) program developed by the Da Vinci Lab of the National Taiwan University of Science and Technology was used for determining the main path and performing clustering. The Pajek software program (version 5.19) was used to visualize the citation data in the form of graphs to make it easier to understand the connection characteristics of the citation network. The paths in the graphs varied in thickness; the thicker a path, the more important the article. The direction of an arrow in a graph represented the path's knowledge dissemination direction.

2.3. Edge–Betweenness Clustering

Newman and Girvan (2004) argued that the primary objective of cluster analysis is to categorize homogeneous articles within a citation network. When two papers use the same references and are both cited by other studies, the two papers have a high probability of covering related topics. The aforementioned authors proposed identifying important intercommunity edges that link different clusters and then removing these edges to identify the corresponding clusters. They used betweenness centrality to identify connections between different clusters. The concept of modularity, which was introduced by Newman and Girvan (2004), is represented by the following equation [60]:

$$Q = \frac{1}{2m}\sum_{ij}(A_{ij} - P_{ij})\delta(C_i, C_j) \quad (7)$$

where Q denotes the modularity, A is the adjacency matrix, m represents the total number of edges, and P_{ij} is the expected number of edges between nodes i and j in the null model. When nodes i and j belong to the same group, the δ-function equals 1; otherwise, the δ-function is 0. The value of Q is, at most, 1 and can be negative. When the entire network of nodes belongs to the same group, Q equals 0. If no subgraph exists in the entire graph where Q is greater than 0, no group exists [60]. The algorithm is expressed as follows:

S1: Calculate the betweenness for all edges in the network.

S2: Remove the edge with the highest betweenness.
S3: Recalculate the betweenness for all edges affected by the removal.
S4: Repeat from steps S2 and S3 until no edge remains.

After edge–betweenness clustering is performed, a sequence of removed links is obtained, where each stage is considered a potential clustering result. The result of edge–betweenness clustering is finalized by selecting the result with the largest clustering coefficient.

2.4. Research Framework

This study integrates theoretical frameworks and software tools, and the research process is composed of five steps, as illustrated in Figure 4.

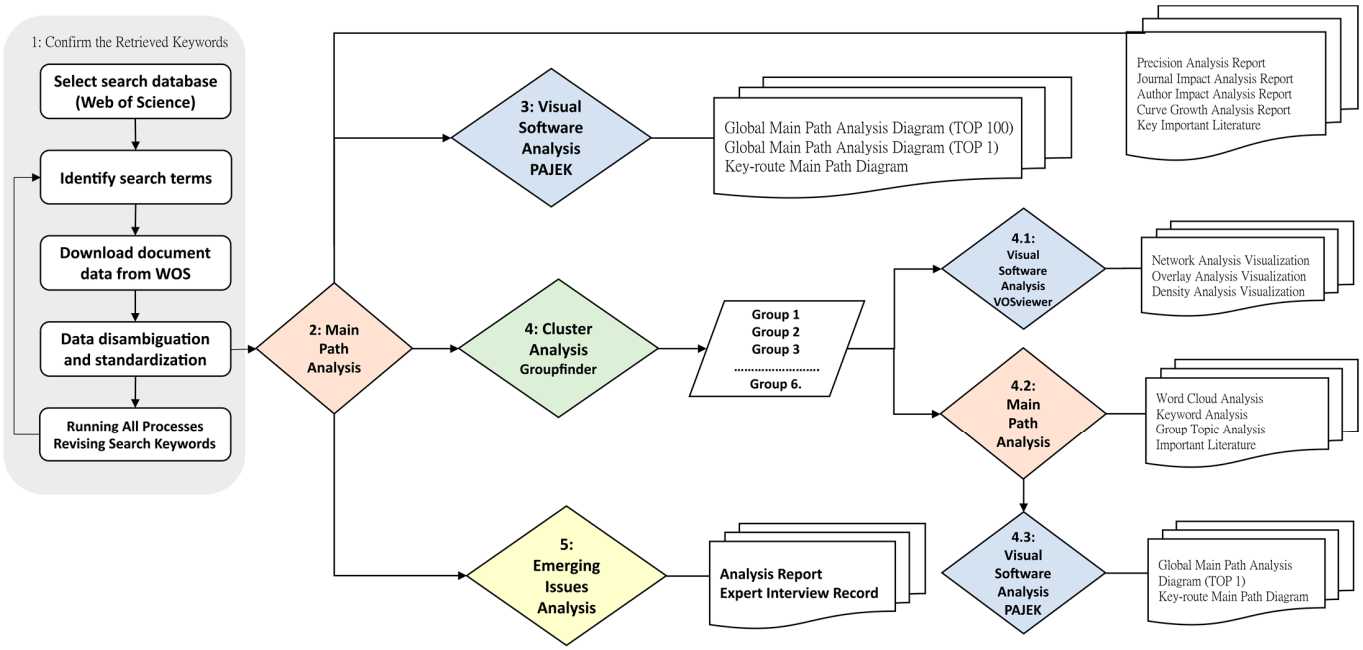


Figure 4. Research framework diagram.

Identification of Search Keywords: This initial step involves conducting a preliminary collection and review of the literature on the subject, including reading review articles on similar topics to extract potential keywords. A systematic analysis is then performed, which includes determining the appropriate databases, keywords, search syntax, and the number of articles to be reviewed. The key literature is thoroughly examined. The data are downloaded, and a preliminary main path analysis is conducted to ensure data completeness, relevance, and to verify whether the initial data and precision rates are satisfactory. This process is iteratively refined by adjusting search keywords and conducting trial analyses until the results of the precision rates, main path analysis, key route main path analysis, and clustering analysis are deemed suitable for manuscript preparation. Finally, the search keywords and search syntax are finalized. The collected literature is also subjected to disambiguation and normalization to eliminate noise factors, such as missing citation information, loops, isolated points, and duplicates in the dataset.

Main Path Analysis: Utilizing the mainpath465 software (version 456), main path analysis generates five types of files, including those for subsequent visual software analysis; log files for various analyses (such as precision analysis, journal citation analysis, and author citation analysis); related literature log files; and citation analysis files (for subsequent clustering analysis). Upon completion of this phase, various analytical reports are generated, including growth curve analysis, journal impact analysis, author influence analysis, and other related reports.

Visualization Software: The .PAK files generated from the main path analysis are used to create global main path diagrams and key extension main path diagrams through the visualization software Pajek (version 5.19). The diagrams include information on significant publications, authors, and path weights. Various main path diagrams and knowledge mobility trajectories at different stages are created by reading key publications and tracing the top 100 paths using data mining software.

Cluster Analysis: Following the main path analysis, related literature lists and citation analysis files are used for cluster analysis. This process results in corresponding cluster analysis files and citation relationship files. Subsequently, three steps are followed: (1) conducting three types of analyses—Network Analysis Visualization, Overlay Analysis Visualization, and Density Analysis Visualization—using VOSviewer software (version 1.6.20) to identify the main discussion topics within each cluster; (2) performing a main path analysis for each cluster; and (3) using Pajek to identify the global main path diagrams for each cluster. The objective is to analyze the knowledge evolution process and key publications and research topics within each cluster.

Emerging Topic Analysis: Based on the files obtained from the main path analysis (which contain lists of related cited literature), emerging topics are analyzed by comparing and matching the fields of literature themes, abstracts, and keywords. The preliminary results are validated through expert interviews to confirm emerging topics.

3. Results

3.1. Data Statistics

This study analyzed the literature extracted from the WoS regarding EVs in a circular economy. The keywords "circular economy" and "electric vehicle" were used in the search process. The search also included key topics regarding a circular economy that are discussed in Section 1 (e.g., resource recovery and recycling), as well as key topics related to EVs in the context of a circular economy, such as renewable energy. The final search syntax was as follows: TS = (("Electric Vehicle" or "Electric Vehicles" or "Electric Bus" or "electrical vehicle" or "electrical vehicles") and ("Circular Economy" or "Resource Recovery" or "Recycling" or "Renewable Energy")). The initial search yielded 5730 articles, and after applying search filters "article" as the type of literature and "English" as the language, 4127 articles remained. The final search syntax was as follows: TS = (("Electric Vehicle" or "Electric Vehicles" or "Electric Bus" or "electrical vehicle" or "electrical vehicles") and ("Circular Economy" or "Resource Recovery" or "Recycling" or "Renewable Energy")). Following an analysis conducted with MainPath 465 software (version 456), 3379 interrelated articles were obtained. As illustrated in Figure 5, the precision rate is equal to the ratio of the number of correct results to the number of all retrieved results [59]; thus, the precision rate in this study was 82% (3379/4127 = 0.82).

$$\text{precision} = \frac{|\{\text{relevant documents}\} \cap \{\text{retrieved documents}\}|}{|\{\text{retrieve documents}\}|} \quad (8)$$

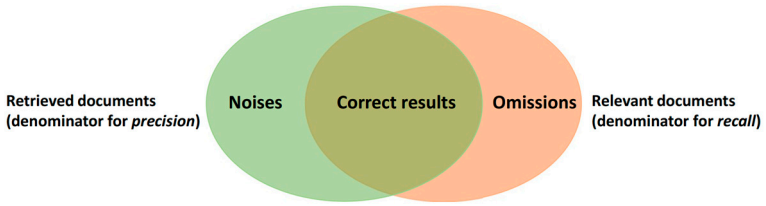


Figure 5. Data precision [59].

The annual distribution of the 4127 articles extracted from the WoS is shown in Figure 6. The number of relevant studies increased over time, which indicates that a growing community of researchers are conducting investigations related to EVs in the context of a circular economy, verifying that this topic merits in-depth investigation.

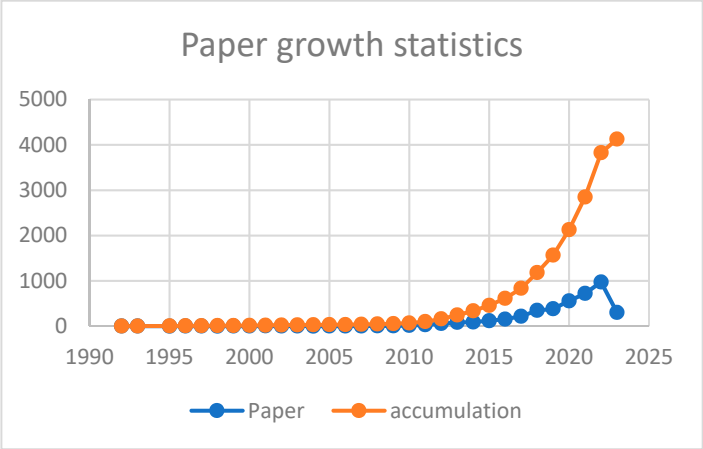


Figure 6. Statistical chart of the number of articles published with respect to EVs in the field of economic management (WoS search results).

3.1.1. Journal Influence Analysis

The g-index was used as an indicator to determine the ranking of influential journals in the field of EVs in the context of a circular economy. When the g-index values were the same, the ranking was determined using the h-index (Table 3). The top-ranking journal was Applied Energy, which exhibited a g-index of 87 and had 211 relevant published articles, which is the highest number of relevant published articles among the ranked journals. This journal is published by ELSEVIER SCI LTD, had a journal impact factor of 11.2 in 2022, and currently holds a Q1 ranking in the Science Citation Index Expanded classification. The number of citations of articles from Applied Energy is as high as 9604, which is in agreement with the journal's g-index ranking; thus, this journal has profound influence on the field of EVs in a circular economy. The second-ranked journal was IEEE Transactions on Smart Grid, which had a g-index of 75 and contained 81 relevant articles with 5689 citations. The journals ranked third to fifth were Energy, Journal of Cleaner Production, and Energy Policy, respectively. The aforementioned five journals are Q1 journals, which are the highest-ranking journals, and have a profound influence on the examined research field.

Table 3. Top ten most influential journals in the investigated research field.

g-Index Ranking	Name	g-Index	h-Index	Total Papers	Active Years
1	*Applied Energy*	87	55	211	2011~2023
2	*IEEE Transactions on Smart Grid*	75	41	81	2010~2022
3	*Energy*	73	50	210	1996~2023
4	*Journal of Cleaner Production*	58	35	148	2005~2023
5	*Energy Policy*	55	28	62	2000~2023
6	*Energy Conversion and Management*	50	31	58	1997~2023
7	*IEEE Access*	49	27	159	2016~2023
8	*Journal of Power Sources*	48	28	48	1992~2023
9	*Resources Conservation and Recycling*	44	26	65	2012~2023
10	*International Journal of Hydrogen Energy*	43	24	49	2009~2023

3.1.2. Author Influence Analysis

This study used the g-index as an indicator to determine the top 20 authors who have had a profound influence on the examined academic field. If the g-index was equal, the h-index was used for comparison. Table 4 presents the top 10 most influential authors in descending order. Because the ranking was only based on the articles included in the WoS database, many influential authors whose articles were not included in said database, including experts and editors who reviewed the relevant papers, might have been overlooked.

Table 4. Top 10 most influential authors in the examined research field.

g-Index Ranking	Name	G-Index	H-Index	Total Papers	Active Years
1	Yi Wang	30	12	30	2013~2023
2	J.P.S. Catalão	29	15	29	2015~2022
3	Yu Zhang	25	11	25	2015~2023
4	Miadreza Shafie-khah	24	13	24	2016~2022
5	Yue Li	22	12	22	2014~2023
6	Ling Zhang	20	11	20	2014~2023
7	Zheng Chen	19	10	20	2013~2023
8	Qian Zhang	18	10	18	2010~2022
9	M. Shahidehpour	17	13	17	2012~2023
10	Jin Wang	16	8	16	2011~2023

3.2. Global Main Path Analysis

Figure 7 displays the citation network diagram obtained using MainPath 465 software (version 456). Figure 8 depicts the global main path diagram, in which the green nodes represent the sources of the research field, and the blue nodes represent the sinks. Each node represents an article, and the nodes are connected by lines with directional arrows. The direction of an arrow indicates the direction of knowledge flow, and the thickness of a link indicates the weight and influence. The text codes on the nodes represent the first author's surname, the other authors' surnames, and the publication year in sequence. In the case of GmWY2023, Gm represents the first author's surname, W is the initial letter of the second author's surname, Y is the initial letter of the third author's surname, and 2023 is the article publication year.

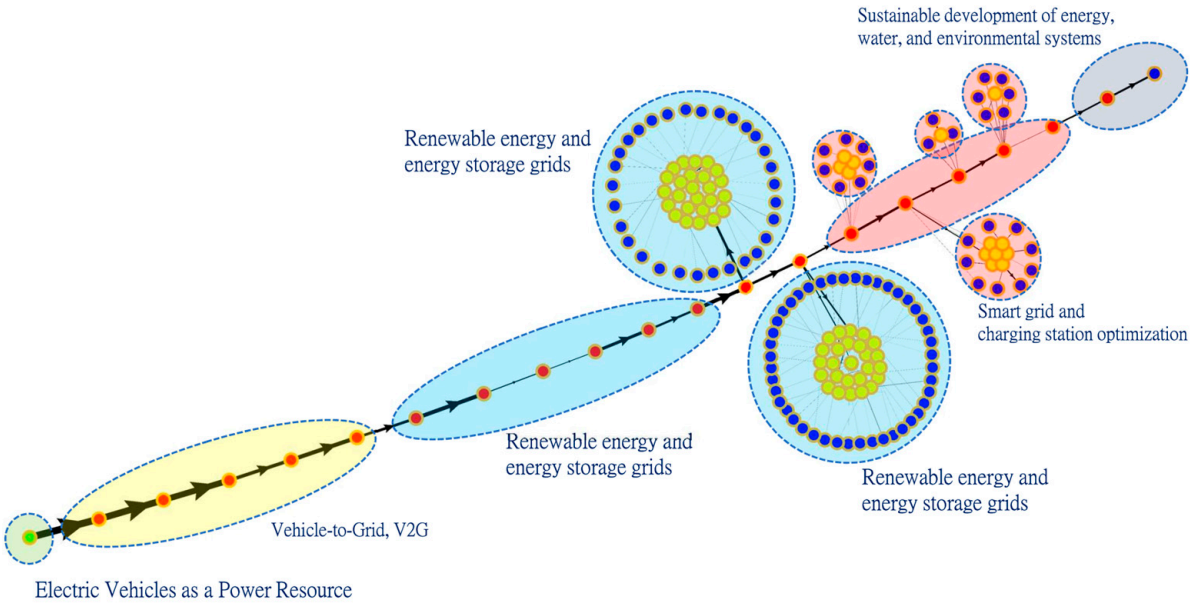


Figure 7. Global main path (top route 200) in the original citation network diagram.

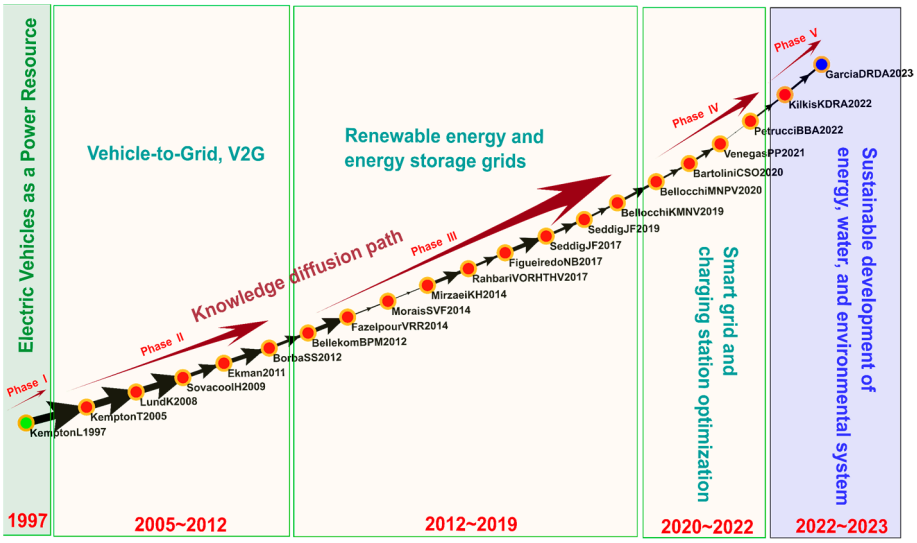


Figure 8. Global main path of the knowledge expansion system.

We used the SPLC and global main path search algorithms to analyze the crucial article paths in the evolution of the global main path of the knowledge system. This analysis involved 21 key academic papers, which are depicted in Figure 7 and described as follows:

3.2.1. Phase I: 1997 Electric Vehicles as a Power Resource

The key literature in Phase I was published in 1997. Kempton and Letendre (1997) mainly explored the potential value of EVs as an electric resource. Existing vehicles with internal combustion engines have a high energy capacity but limited efficiency. EVs that run on batteries, fuel cells, and hybrid power can become resources for power generation and energy storage [61]. Kempton and Letendre (1997) discussed how existing vehicles with internal combustion engines can be converted into novel power generation and energy storage systems and how different technologies can be used to make EVs a source of energy [61]. HEVs combine the advantages of an internal combustion engine and electric motor and optimize energy utilization under different driving conditions through an intelligent control system; thus, HEVs can become energy resources that effectively reduce fuel consumption and carbon emissions, lower dependence on fossil energy, and promote the development of a circular economy in the processes of energy production and consumption [62,63].

3.2.2. Phase II: 2005~2012 Vehicle-to-Grid, V2G: Management and Application of V2G Technology in a Circular Economy

The key literature in Phase II mainly focused on V2G technology, which involves two-way energy interaction between an EV and the electrical grid. This technology allows EVs to supply power to the grid when necessary and to charge from the grid when the load on the grid is low. Such a two-way interaction helps balance the grid supply and demand and improve grid stability and energy efficiency. The scope of V2G technology includes (1) meeting the energy demand, (2) regulating grid frequency, (3) participating in the electricity market, and (4) integrating renewable energy. First, V2G technology enables EVs to supply power to the grid during peak hours of power usage and charge from the grid during non-peak hours of power usage; thus, this technology helps reduce the grid load and peak power demand. Second, V2G technology can help the grid maintain a stable power supply frequency, because it allows EVs to charge quickly from the grid or provide power to the grid rapidly. Third, EV owners can participate in the electricity market through V2G technology and sell the electricity stored in the vehicle battery for profit. Fourth, V2G technology helps integrate renewable energy, such as solar and wind energy, in charging stations or energy storage applications [64].

Many articles from Phase II focused on the incorporation of renewable energy, smart grid technology, and V2G technology into the energy grid system. Lund and Kempton (2008) used an EV as a flexible energy storage device to balance supply and demand in the grid, reduce the dependence on fossil fuels, and improve the sustainability of the overall energy system [65].

Kempton and Tomić (2005) discussed the systems and processes required to implement V2G technology; they also proposed strategies and business models that involve using V2G technology, as well as specific steps for implementing this technology [64]. In addition, Kempton and Tomić (2005) indicated that V2G technology can help stabilize large-scale wind energy systems and identified the regions that were most likely to be the first to adopt this technology. Lund and Kempton (2008) used the Energy PLAN model to analyze EVs with different degrees of wind power penetration in two national energy systems (in Denmark and another country without combined heat and power systems). Their results indicated that the addition of EVs and V2G technology to the aforementioned energy systems could increase wind power generation without generating excess electricity and considerably reduce CO_2 emissions [65].

Sovacool and Hirsh (2009) explored the potential of, and possible difficulties involved in, integrating V2G technology into PHEVs. According to the aforementioned authors, the main barriers facing the integration of V2G systems into PHEVs are related to technology, social and cultural values, business practices, and political interests [66]. Borba et al. (2012) used an optimization tool to model the expansion of the electric power system in Northeastern Brazil to achieve the most efficient dispatch of the variable output of wind farms in the region over the next 20 years. The expanded use of wind energy in conventional power generation facilities poses risks of supply–demand imbalances in Northeastern Brazil. The aforementioned authors evaluated the possibility of using a fleet of PHEVs to resolve possible energy imbalances [67]. According to Borba et al. (2012), PHEVs (such as the 500,000 and 1.5 million new PHEVs in 2015 and 2030, respectively) can be charged at night to utilize the excess energy generated by wind farms [67].

One of the core ideas of a circular economy involves consumers effectively using circular resources in the consumption process to prolong product life, reduce waste generation and carbon emissions, and achieve sustainable economic and environmental development. The combination of V2G technology with renewable energy and intelligent control systems can meet the needs of a circular economy [64,65].

3.2.3. Phase III: 2012~2019 Renewable Energy and Energy Storage Grids

The literature in Phase III explored the integration of EVs with renewable energy systems, such as wind and solar energy systems, as well as the role of energy storage and smart grid technologies in achieving sustainable energy development. Renewable energy utilization and effective energy storage in EVs can promote the development of a circular economy. The use of renewable energy decreases the reliance on fossil fuels, and energy storage technologies enhance the energy utilization efficiency; thus, the use of renewable energy and energy storage technologies contribute to economic and environmental sustainability, which aligns with the principles of a circular economy.

Bellekom et al. (2012) performed a case study on the Netherlands, which aimed to reduce its carbon dioxide emissions to adhere to the standards in global and European initiatives. The Netherlands hoped to achieve 10 GW of wind power generation and have one million EVs on its roads by 2020 [68]. Bellekom et al. (2012) explored the possible effect of introducing large numbers of EVs and increasing wind power generation on the electricity system in the Netherlands. They simulated the Netherlands' situation in 2020 and found that the power system in the Netherlands could accommodate one million EVs and 10 GW of wind power if the EVs used a load management system to balance the electricity demand at night [68].

Jakus et al. (2023) analyzed energy management and optimization in smart parking lots for EVs to meet the needs of vehicle owners and parking lot operators and achieve

economic benefits [69]. Morais et al. (2014) examined the effect of EVs on power distribution grids and distributed energy resources and proposed effective methods for managing EV charging and discharging to reduce system operation costs and achieve a power demand balance [70]. Figueiredo et al. (2017) investigated the feasibility of solar-powered parking lots for EV charging and analyzed the economic benefits of such parking lots under various technical solutions and market conditions [71]. Seddig et al. (2017) studied the use of intelligent charging strategies for charging EV fleets with renewable energy to reduce carbon emissions and costs [72]. Rahbari et al. (2017) proposed an adaptive intelligent controller for addressing the challenges involved in integrating renewable energy and EVs into the power grid and achieved superior grid operation [73]. Bellocchi et al. (2019) compared the roles of EVs in low-carbon energy systems in Italy and Germany and analyzed the effects of carbon emission reduction under different scenarios of renewable energy generation and EV prevalence [74].

The literature in Phase III focused on the development of EVs, renewable energy systems, and energy storage technologies, thereby facilitating the connection between sustainable energy development and a circular economy.

3.2.4. Phase IV: 2019~2022 Smart Grid and Charging Station Optimization

The literature in Phase IV focused on topics related to smart grids and charging station optimization, particularly the integration of EVs with renewable energy systems (e.g., solar and wind power systems). The relevant studies explored various methods and technologies, including stochastic optimization, self-consumption systems, multi-energy systems, demand forecasting, and energy management control, to address the challenges posed by the volatility of renewable energy and EV charging demands, thereby achieving more efficient, flexible, and environmentally friendly energy systems.

Under uncertain conditions, Seddig et al. (2017) applied optimization methods to schedule the charging of different types of EV fleets, thereby lowering charging costs and maximizing the utilization of renewable energy (e.g., solar power) [72]. Rahbari et al. (2017) analyzed the prevalence of smart EVs in urban areas and the influences of these EVs on the self-sufficiency of renewable energy systems and the reduction of carbon dioxide emissions [73]. Bellocchi et al. (2019) assessed the effect of the electrification of transportation and residential heating systems on the Italian energy system [74]. Gonzalez et al. (2021) analyzed the opportunities and challenges involved in charging and discharging from EVs to the grid, and they addressed technical, economic, supervision, and user-related problems in providing flexible energy services [75]. Petrucci et al. (2022) used recurrent neural networks to predict and optimize energy demand in smart communities, thereby achieving a supply–demand balance in distribution grids by ensuring individual- and community-level energy flexibility [76].

The aforementioned studies offer valuable insights into the optimization of smart grids and charging stations, which play a pivotal role in a circular economy. By using advanced technologies and data analyses, these studies ensured that a balance was achieved between power supply and demand, thereby optimizing energy distribution, maximizing resource utilization, and attaining sustainable development.

3.2.5. Phase V: 2022~2023 Sustainable Development of Energy, Water, and Environmental Systems

The literature in Phase V was related to EVs being a vital element for achieving climate change mitigation and sustainable development goals. According to Garcia et al. (2023), EVs play a crucial role in the sustainable development of energy systems, water resources, and environmental systems, particularly in reducing carbon emissions and promoting energy transition. The reduction in carbon emissions through the use of EVs can be enhanced by sourcing the electricity required by these vehicles from renewable energy sources [77]. To facilitate energy transition, EVs are incorporated into extensive energy transformation strategies, such as those that involve using smart grids and distributed

energy resources. These innovative technologies can be used to charge EVs more efficiently, thereby simultaneously balancing grid loads and enhancing the utilization efficiency of renewable energy. Energy supply and demand can be balanced to a certain extent, and the operating efficiency of the energy system can be improved. Because of their potential roles in climate change mitigation and sustainable development, EVs are regarded as a solution for achieving energy transition and a part of the field of renewable energy technologies. Innovative technologies such as smart energy systems and EVs can help address climate change, lower greenhouse gas emissions, and promote sustainability [77].

In summary, the two studies cited in the aforementioned text regarded EVs as a crucial element of climate change mitigation and sustainable development and explored innovative technologies and research related to EVs.

3.3. Key Route Main Paths with Review Articles

Obtaining the complete technological development trend by solely using the global main path is challenging. Therefore, we performed key route MPA to expand the knowledge diagram with the key route main path (Figure 9) to ensure that no influential articles were excluded. A total of 22 node articles were obtained from the key route main path; 21 of these articles were also found on the global main path, whereas 1 article was not. This new article mainly focused on the utilization and integration of EVs with electrical grids. The results obtained using the two MPA methods were almost consistent, which indicated that the analysis results were accurate.

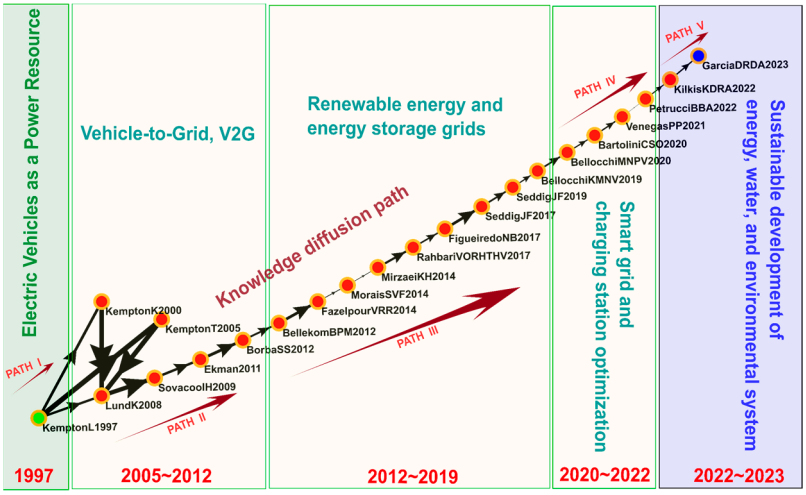
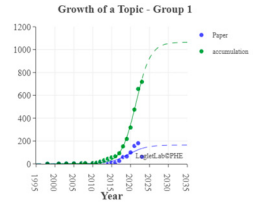
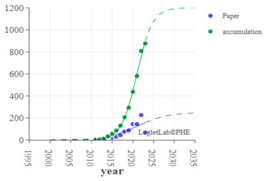
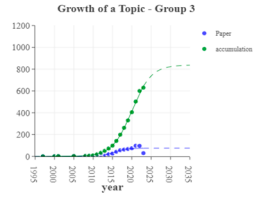
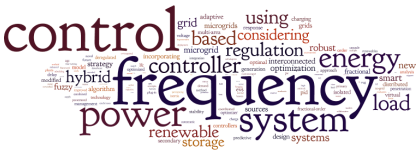
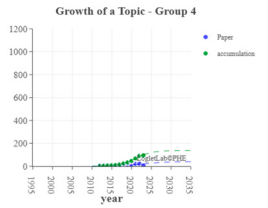
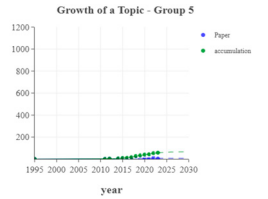
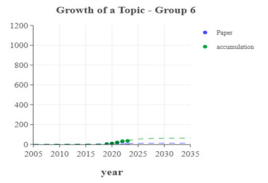


Figure 9. Extended knowledge diagram with topics from the key route main path.

3.4. Cluster Analysis

For further exploring the research topics in the field of EVs in a circular economy, we used the group finder function of the MainPath 465 software program (version 456) and adopted edge–betweenness clustering for the cluster analysis of 3379 interrelated articles. After cluster analysis was performed, 20 clusters were obtained, and the top 6 clusters were extracted for a detailed analysis. These six clusters contained 718, 876, 630, 96, 58, and 34 articles. We conducted data mining on the titles and abstracts of all the articles in each cluster using the Wordle software program (version 2.0) and obtained the research themes and main keywords of the six clusters. After reading the key literature in each cluster, we named the six knowledge clusters as recycling and reuse of electric vehicle batteries, charging station and energy management, V2G and renewable energy technologies, power frequency control systems, dynamic economic emission, and energy management and optimization. Table 5 presents information on these six clusters, including the corresponding publication periods, keywords, word clouds, and literature growth trends.

Table 5. Themes, number of papers, keywords, word cloud, and growth curve of each group.

Research Topic	Keywords	Word Cloud	Article Growth Trend
Cluster 1 The recycling and reuse of electric vehicle batteries (1998~2023)	Batteries (0.343) Battery (0.283) recycling (0.263) lithium-ion (0.209) energy (0.164) assessment (0.12)		
Cluster 2 Charging station and energy management (2011~2023)	Energy (0.480) Charging (0.384) Management (0.1967) Renewable (0.189) Optimal (0.184) Considering (0.134)		
Cluster 3 V2G/Renewable Energy (1997~2023)	Vehicle-to-grid (0.209) Charging (0.177) Renewable (0.160) Smart (0.109) Storage (0.084) Analysis (0.079)		
Cluster 4 Power frequency control system (2012~2023)	Frequency (0.614) Control (0.572) Power (0.385) System (0.375) Energy (0.281) Controller (0.218)		
Cluster 5 Dynamic Economic Emission (1995~2023)	Renewable (0.258) Dispatch (0.241) Considering (0.22483) Smart (0.224) Scheduling (0.206) Economic (0.293)		
Cluster 6 Energy Management (2019~2023)	Energy (0.852) Management (0.352) System (0.294) Distribution (0.294) Considering (0.264) Storage (0.264)		

3.4.1. Cluster 1: The Recycling and Reuse of Electric Vehicle Batteries (Period: 1998–2023)

Cluster 1: The recycling and reuse of electric vehicle batteries. The recycling, processing, and reutilization of EV batteries are closely related to the concept of a circular economy. Such practices include minimizing waste generation and reusing battery materials. The achievement of the maximum performance and value can be ensured for battery products, components, and materials through their reuse, repair, refurbishment, and recycling.

A total of 718 articles, including 19 key articles from the global main path, were obtained in Cluster 1. Figure 10 displays the knowledge flow in the global main path for Cluster 1. The common topics in this cluster were use, recycling, and reuse of EV batteries; limitations of metal resources such as lithium; supply chain problems; recycling technologies; and impact on sustainable development and the EV industry. The publication

years of the studies in Cluster 1 ranged from 1998 to 2023, and these studies could be divided into the following six phases: Phase I: Life cycle assessment/sustainability/overview, Phase II: Metal resource constraints for EV batteries, Phase III: Recycling of EV batteries, Phase IV: Nonrenewable energy, Phase V: Life cycle assessment and circular economy, and Phase VI: Sustainability of EV batteries.

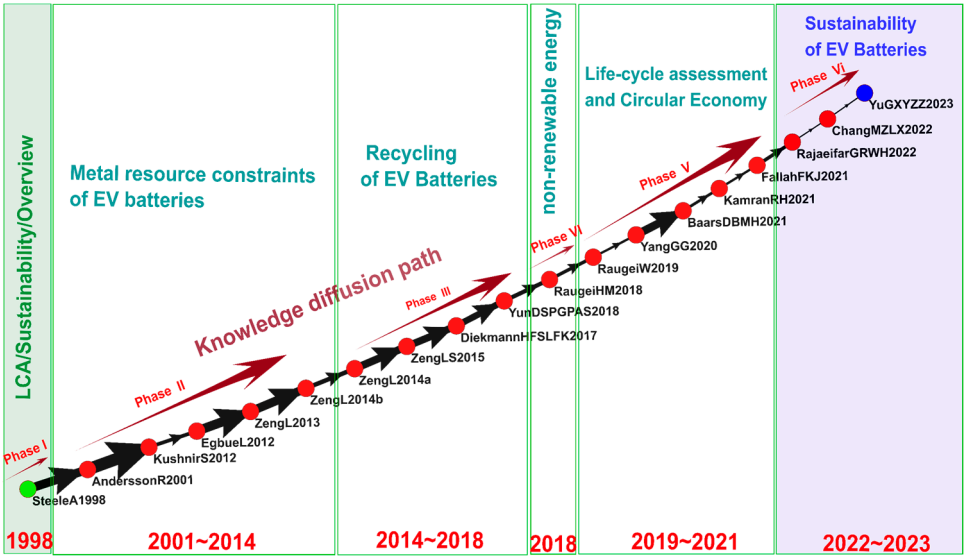


Figure 10. Global main path of the topics in Cluster 1, which are related to EV batteries.

Phase I: Life cycle assessment/sustainability/overview

The article in Phase I was published in 1998. Steele and Alle (1998) discussed the life cycle assessment of EV batteries and explored their environmental impact and sustainability. The aforementioned authors analyzed the environmental impact and sustainability of four types of batteries that they expected to be used between 1998 and 2008: lead–acid, nickel–metal hydride, nickel–cadmium, and sodium–sulfur batteries. The results indicated that, among the aforementioned batteries, nickel–metal hydride batteries had the lowest environmental impact; however, no recycling infrastructure currently exists for such batteries [78].

Phase II: Metal resource constraints for EV batteries

Andersson and Råde (2001) assessed the metal demand and availability for nine types of batteries, including those that use rare metals such as lithium, nickel, cobalt, vanadium, cadmium, lead, and rare-earth elements to determine a suitable type of battery for EVs [79]. Kushnir and Sandén (2012) examined the availability of lithium resources for a transition to EVs and noted that the flow rate of resources into society might be a considerably more difficult constraint. Lithium risks must be considered comprehensively, and appropriate policy support is required to prevent or minimize such risks [80]. Through an integrated literature review, Egbue and Long (2012) assessed the global raw material supply chain for EV batteries to examine lithium availability and lithium supply problems for lithium-ion battery production. They proposed a model for investigating the technical, geopolitical, and economic factors affecting lithium supply [81]. Zeng and Li (2014) studied the Chinese market and believed that, because of the continuous growth in the demand for consumer electronics and EVs in China, China's lithium demand will increase considerably, thereby shortening the duration of lithium storage. To maintain the sustainable development of the lithium industry, collection systems and recycling technologies for lithium-containing waste should be developed [82].

Phase III: Recycling of EV batteries

Zeng et al. (2015) analyzed the physical components and chemical composition of different types of depleted lithium batteries to obtain basic information on lithium battery recycling. Their results indicated that the separators, anodes, and cathodes of lithium batteries accounted for over 60% of their total weight [83]. To prevent raw material shortage, Diekmann et al. (2016) recycled lithium-ion batteries with a focus on energy efficiency and environmental friendliness. They stated that high temperatures should be avoided during the recycling process and found that a safe and ecological recycling process can achieve a material recovery rate of at least 75% [84]. Yun et al. (2018) examined the literature on the mechanical and chemical processes involved in battery pack recycling and identified the following crucial research topics in such literature: smart recycling systems; efficient and safe battery pack disassembly; recycling market demand adjustment; slag, electrolyte, and anode recycling; industrial-scale application; and the development of methods for recycling new batteries containing components with different performances. Moreover, they proposed a framework to transform the recycling process from concept to practice; this framework includes government incentives and effective recycling technologies [85].

Phase IV: Nonrenewable energy

Raugei et al. (2018) investigated the potential of EVs in improving transportation sustainability, particularly their ability to reduce dependence on nonrenewable energy. The aforementioned authors examined the effect of EVs on the demand for nonrenewable energy. They analyzed the nonrenewable energy demand of a typical EV throughout its entire life cycle, as well as the possibilities of charging the EV from various types of power supplies during vehicle use [86].

Phase V: Life cycle assessment and circular economy

Life cycle assessment allows a better understanding to be obtained regarding the environmental impact of EVs throughout their entire life cycle. The principles of a circular economy enable this impact to be mitigated for making EVs a more sustainable transportation choice. For EVs, a circular economy involves all stages from raw material extraction to vehicle disposal and processing (including component manufacturing, vehicle assembly, and vehicle usage).

Phase VI: Sustainability of EV batteries

The articles from Phase VI focused on the sustainability, recycling, and reuse of lithium-ion batteries of EVs. Rajaeifar et al. (2022) discussed the sustainability challenges within the supply chain and value chain of lithium-ion batteries of EVs. They described the challenges involved in various stages, from raw material supply and demand to final disposal (including battery manufacturing and battery use). The aforementioned authors also proposed market instruments, such as innovative business models, and government interventions, such as subsidies and regulations, for the aforementioned batteries [87]. Chang et al. (2022) explored the reuse of recycled lithium-ion batteries of EVs. They experimentally evaluated the discharge characteristics of different types of spent lithium-ion batteries with a parallel configuration to obtain screening and recombination criteria for improving energy utilization efficiency [88]. Yu et al. (2023) investigated the integrated recycling of lithium-ion batteries, including their reuse and the material recovery from them; provided an in-depth discussion of the challenges involved in the pretreatment process, such as rapid classification, electrolyte separation, and automated disassembly; summarized the basic knowledge on existing technologies, operational strategies for different applications, and relevant technical and environmental problems; and specified future research directions to overcome these problems [89].

3.4.2. Cluster 2: Charging Station and Energy Storage System (Period: 2011–2023)

EV charging stations and energy storage systems are crucial for achieving the goals of a circular economy. These stations and systems promote the reuse of resources, the

reduction of waste generation, and the use of green energy, all of which not only contribute to environmental protection but also ensure the sustainable use of resources.

A total of 876 articles, 16 of which were key articles, were obtained in Cluster 2. Figure 11 displays the path diagram of knowledge dissemination derived from the global main path for Cluster 2. The topics in this cluster included energy storage systems and optimization, charging–discharging and energy management schemes, the use of renewable energy in charging stations, SDG7, and EV energy management.

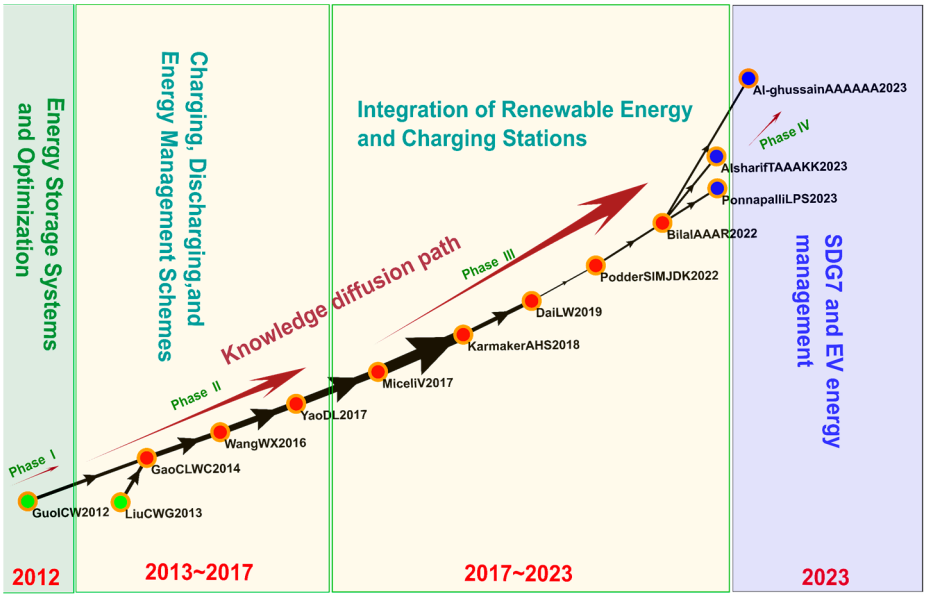


Figure 11. Cluster 2, which are related to charging stations and energy storage systems.

The one article from Phase I was published in 2012 and primarily discussed the optimal strategy for controlling solar-assisted charging facilities for PHEVs. Guo et al. (2012) integrated a local energy storage system and optimized the facility parameters to develop a detailed circuit model for charging facilities that combined solar energy systems with PHEVs. They introduced a novel theoretical and practical approach for optimizing and controlling PHEV charging facilities [90].

The studies from Phase II primarily explored the interaction between EVs and the electrical grid, including aspects related to energy storage systems, energy management, charging and discharging scheduling, and renewable energy applications. The main objective of these articles was to provide technical and strategic support for the further development of EVs, thereby enabling the better utilization of renewable energy and enhancing the overall system efficiency and reliability. Specifically, Liu et al. (2013) and Gao et al. (2014) discussed the interaction between EVs and the electrical grid and proposed control strategies for optimizing energy management [91,92]. Finally, Yao et al. (2017) introduced an optimized solution that involved utilizing renewable energy, energy storage systems, and EV charging and discharging scheduling at charging stations to enhance the overall performance and system efficiency of EVs, thereby promoting their sustainable development [93].

The studies from Phase III primarily analyzed the technical, economic, and environmental impacts of EV charging stations that utilized renewable energy. These studies primarily focused on addressing the energy demand and environmental issues resulting from the prevalence of EVs and proposed solutions such as hybrid energy systems based on solar and wind energy. Miceli and Viola (2017) designed a sustainable EV charging area for universities and assessed two potential solutions for managing peak loads. They evaluated the advantages and disadvantages of the two systems by using the levelized cost of electricity [94]. Dai et al. (2019) proposed an optimization model for a grid-connected system

containing a photovoltaic system, battery energy storage system, and EV charging station; they used the multiagent particle swarm optimization algorithm to resolve system design problems [95]. Podder et al. (2022) presented a hybrid charging station that employed solar and biogas energy generators, analyzed the cost and efficiency of different solar energy systems by using the HOMER software program (version 1.8.4), and assessed the technical and economic feasibility of the proposed charging station [96]. Bilal et al. (2022) used artificial intelligence-based optimization algorithms to assess the technical, economic, and environmental feasibility of establishing grid-connected EV charging stations in the northwest region of Delhi, India; they compared the advantages and disadvantages of different hybrid energy systems [97].

In Phase IV, Ponnapalli et al. (2023) and Alsharif et al. (2023) examined the microgrid system in the context of integrating EVs with the electrical grid. One of the main methods of mitigating global climate change involves adopting sustainable transportation options. The integration of EVs with renewable energy supply systems is essential for achieving Sustainable Development Goals 7 and 13 of the United Nations. EVs can be integrated with utility grids and other renewable energy supply systems by using V2G technology to create a hybrid system for achieving the aforementioned goals [98,99].

3.4.3. Cluster 3: V2G and Renewable Energy (Period: 2004–2022)

V2G technology and renewable energy can enable sustainable development in a circular economy. This technology allows EVs to be connected to the grid and facilitates the transfer of electrical energy between them. If the transferred energy is obtained from renewable sources, carbon emissions can be reduced considerably.

Cluster 3 comprised 630 articles, of which 17 articles were key articles from the global main path of knowledge diffusion. The global main path for Cluster 3 is shown in Figure 12. This cluster included topics such as battery energy storage systems, V2G technology, EVs and renewable energy, and vehicle-to-building technology.

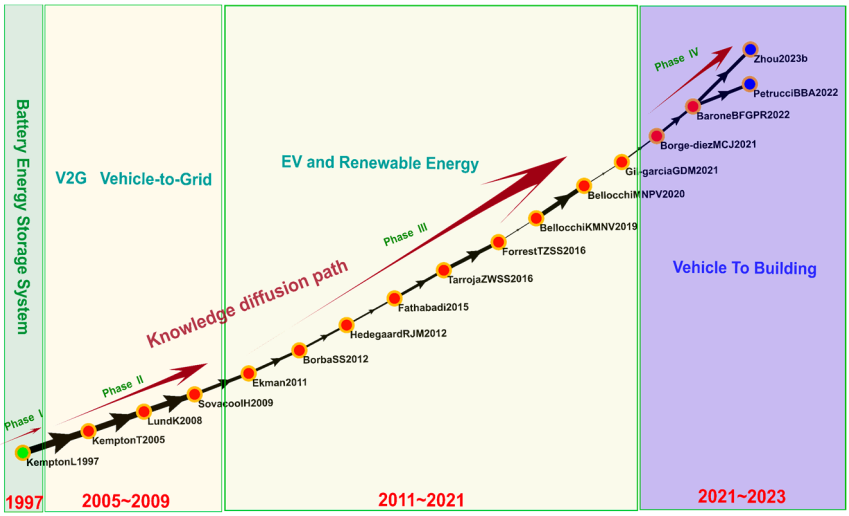


Figure 12. Cluster 3, which is related to V2G technology and renewable energy.

The study from Phase I was published in 1997 and investigated the battery energy storage system. In the United States, the mechanical power of vehicle fleets is over 10 times that of all existing power plants; however, EVs remain idle for over 95% of the day. Power companies can use battery-powered vehicles for energy storage or employ fuel cells and hybrid vehicles for power generation. EVs with an energy storage ability can reduce power generation costs and facilitate the large-scale integration of intermittent renewable energy sources [61].

The studies from Phase II primarily focused on V2G systems, which allow EVs to charge from the grid and discharge energy back to the grid. EVs can function as mobile

power banks that store energy and discharge excess battery energy to the grid when they are idle. Such discharges can enable peak loads to be managed and the grid instability caused by the use of renewable energy to be reduced. V2G technology enables the development of smart and green power systems and aligns with the principles of a circular economy [64,65].

The studies from Phase III focused on EVs and renewable energy, primarily examining the integration of EVs with renewable energy supply systems. These studies explored how EVs and renewable energy supply systems can complement each other to enhance energy utilization efficiency and reduce the reliance on traditional energy sources. The aforementioned studies examined the applications of V2G technology, smart charging strategies, green transportation, and energy transition. They emphasized the importance of EVs in promoting green transportation and energy transition, reducing carbon emissions, decreasing reliance on oil, and increasing the proportion of renewable energy in the overall energy supply [67,100–102].

The four studies from Phase IV focused on vehicle-to-building technology. These studies explored the energy interaction between EVs and buildings in the context of a circular economy and sustainable development. Borge-Diez et al. (2021) quantified the effects of eco-routing, eco-driving, and eco-charging on the energy conversion from vehicles to buildings. They used the Here mobile application and neural networks to obtain EV usage data. Their results revealed that the current charging policies are not applicable to all social groups and fail to consider the contribution of renewable energy to the overall power demand [103]. Barone et al. (2022) investigated the feasibility of implementing the "Building to Vehicle to Building" scheme in European countries. They assessed the influences of weather conditions and local energy market prices on the energy and economic performance of this scheme. In the aforementioned scheme, EVs are used as energy intermediaries between buildings, with the EVs sharing the renewable electricity generated by the solar panels of the buildings. The scheme aims to promote energy flexibility and efficiency while reducing interactions with the grid. Barone et al. used energy and economic indicators to compare the results obtained with and without the aforementioned scheme in various simulation scenarios [104]. Petrucci et al. (2022) proposed an innovative control algorithm for community energy management; this algorithm uses clients' potential energy flexibility to involve them in energy transactions. It controls the network's energy supply according to the energy flexibility of individual and community energy pools and performs real-time predictions of buildings' energy demands [76].

3.4.4. Cluster 4: Power Frequency Control System (Period: 2006–2022)

The studies in Cluster 4 primarily focused on the stable control of the power system frequency. After the proportion of renewable energy sources, such as wind and solar power, in the grid is increased, grid instability might occur because of the intermittent nature of these energy sources. The power frequency control system of EV charging stations can serve as a load regulator to help balance the supply and demand of the grid. Thus, charging stations not only consume energy but also act as flexible assets for the grid that can enable the proportion of renewable energy usage to be increased.

Cluster 4 contains 96 articles, and the global main path of this cluster is depicted in Figure 13. A total of 12 articles from the global main path included subtopics such as V2G technology and frequency regulation, power system frequency control technology, and power system frequency control algorithms.

The study from Phase I was published in 2012 and focused on V2G technology and frequency regulation. In the large-scale integration of renewable energy into the electrical grid, battery energy storage plays a crucial role in addressing the intermittent nature of renewable energy and ensuring the stability of the overall grid frequency. The integration solution developed in the aforementioned study was evaluated in terms of its effects on user convenience and load frequency control by performing simulations with models of a typical two-area interconnected grid and an automotive lithium-ion battery [105].

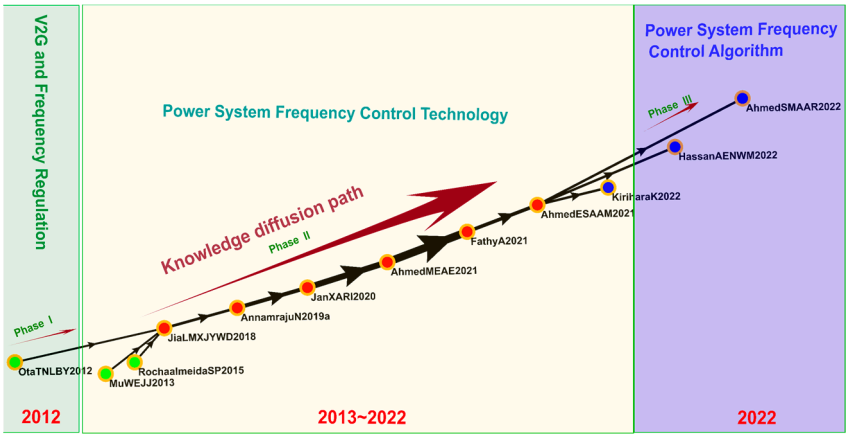


Figure 13. Cluster 4, which is related to power frequency control systems.

The literature from Phase II discussed power system frequency control technology, which is a critical technology for ensuring the stable operation of power systems. When an imbalance exists between power supply and demand, the system frequency changes. If such changes exceed the permissible limits, the power system can become unstable or even collapse. To prevent such situations, frequency control techniques must be adopted to adjust the power production or consumption in the power system so that the frequency of the power system remains within the specified range [106]. EVs and V2G technology have considerable potential in controlling the frequency of power systems. EVs are equipped with high-capacity batteries for energy storage and release. In the V2G mode, EVs can discharge surplus battery energy to the electrical grid when the grid requires more power. Moreover, they can recharge from the grid and store excess energy when the grid has excess power. The V2G mode allows EVs to become dispatchable power resources, thereby contributing to the stabilization of the power system frequency [107]. Through suitable scheduling and management, EVs and V2G technology can be used to provide frequency control services and other power system services, such as load balancing, peak power reduction, and grid backup. Thus, EVs and V2G technology can enhance the power system's stability and reliability, thereby facilitating the better integration of renewable energy (e.g., wind and solar power) into the electrical grid.

The literature from Phase III discussed power system frequency control algorithms. Kirihara et al. (2022) proposed a power system frequency control framework that uses the Open Charge Point Protocol, which is an emerging open-source protocol used to control the charging rate of EVs [108]. In contrast to studies that focused on developing highly efficient frequency controllers, Kirihara et al. (2022) focused on developing an easy-to-deploy frequency control framework with the fundamental functions of the Open Charge Point Protocol and achieved high frequency control performance even without the use of meticulously fine-tuned professional protocols [108].

3.4.5. Cluster 5: Dynamic Economic Emission (Period: 2006–2022)

The studies in Cluster 5 primarily discussed the topic of dynamic economic emission, which pertains to the dynamic management of economics and emission reduction in the operation of EV charging stations. Such a strategy emphasizes the effective adjustment of the charging speed or volume at different times on the basis of factors such as electricity prices, renewable energy supply, and grid load conditions; such charging is relevant in a circular economy.

Cluster 5 consists of 58 papers, including 6 key articles. Figure 14 displays the global main path diagram for Cluster 5. The research topics in this cluster included economic emission dispatch (EED), EED models, and EED solutions.

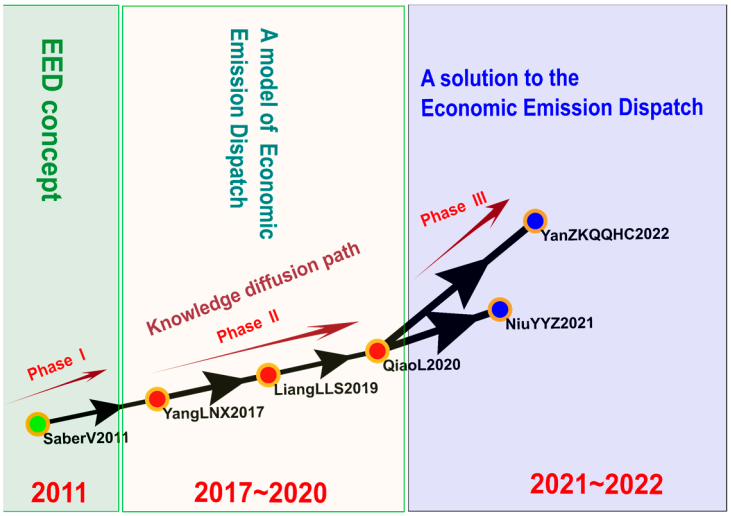


Figure 14. Global main path of the topics in Cluster 5, which are related to dynamic economic emission.

The study from Phase I was published in 1997 and discussed the concept of EED, which refers to the optimization of the operation of power generation units in an electricity system on the basis of economic and environmental factors. In the field of EVs, EED can be adopted in various applications, such as charging infrastructure and vehicle batteries for storing energy. EED can be used to balance the energy supply and demand from the electrical grid and to optimize the power dispatch. For example, when wind or solar energy supply is abundant, the batteries of EVs can store excess electricity and release it during times of peak demand or insufficient renewable energy supply [109].

The literature from Phase II discussed EED models. Three studies addressed the integration of plug-in EVs (PEVs) into the power dispatch system by considering EED. Liang et al. (2019) proposed a dynamic EED problem by considering the use of PEVs for peak shaving and valley filling. This problem is attributable to the randomness in PEV charging behavior, which substantially increases the difference between peak and valley values [110]. Qiao and Liu (2020) presented an integrated framework of EVs and wind power generation systems; this framework is called WEV and utilizes the charging and discharging of EVs to compensate for the uncertainty of wind power generation, thereby reducing the cost of wind power. Qiao and Liu (2020) proposed a multi-objective dynamic EED model (WE_DEED) based on the WEV system for simultaneously considering the emissions and total cost when solving the dynamic EED problem [111].

The literature from Phase III discussed EED solutions. Two studies focused on EED, which enables power costs to be minimized while reducing greenhouse gas emissions. The widespread use of renewable energy results in increased instability and uncertainty in the operation of the power grid. The two aforementioned studies adopted different approaches to solve this problem. Niu et al. (2021) developed a multi-objective optimization method known as the modified multi-objective cross-entropy algorithm, which enhances solution diversity and adaptability in large-scale systems. They validated the efficiency of this algorithm by testing it on grid systems with varying proportions of renewable energy [112]. Yan et al. (2022) investigated the interaction between EVs and wind power generation systems. Because the uncertainty of wind power generation introduces additional costs and affects dispatch system stability, Yan et al. (2022) utilized the energy storage characteristics of EVs to diminish the uncertainty of wind power generation and its effect on the power system [113].

3.4.6. Cluster 6: Energy Management and Optimization (Period: 2010–2022)

The studies in Cluster 6 were related to the integration of EVs and energy storage systems, as well as methods for the more effective and efficient management and scheduling of the receipt, storage, and distribution of energy by charging stations following a continuous

increase in the proportion of renewable energy sources. The effective integration of EVs into the power system can be achieved through various control techniques and optimization algorithms. Such an integration ensures sufficient energy supply during times of peak energy demand and energy savings during times of low energy demand. It also enables a reduction in waste generation, which aligns with the goals of a circular economy, and the maximization of resource utilization efficiency.

Cluster 6 contained 34 articles, including 6 key articles from the global main path. Figure 15 depicts the global main path diagram for Cluster 6. The six key articles were published in three phases: Phase I, Phase II, and Phase III. The main topics in these phases were coordinated energy management models, solutions for energy storage and the optimization of energy storage systems, and independent renewable hybrid systems, respectively.

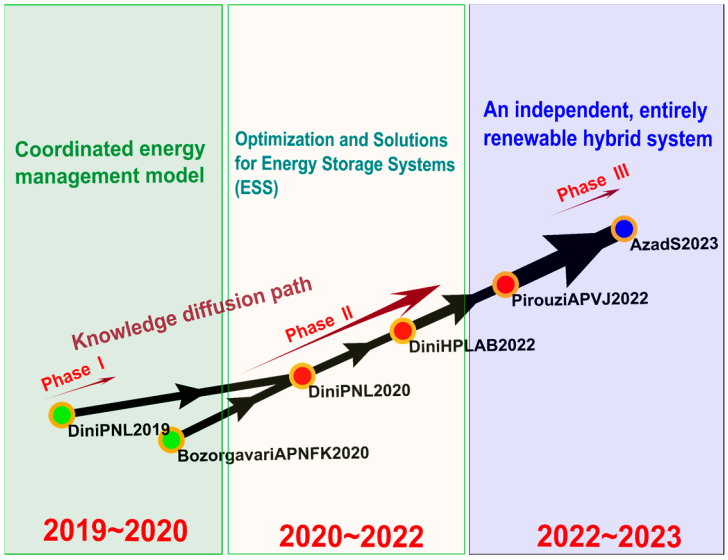


Figure 15. Cluster 6, which is related to energy management and optimization.

The studies from Phase I mainly discussed coordinated energy management; these studies optimized energy storage and distribution systems, addressed the operational uncertainties of these systems, and established models for effective and profitable energy resource management. Dini et al. (2019) proposed an energy hub management model based on day-ahead markets. This model considers different types of energy inputs (electricity and natural gas) and outputs (electricity and district heating), as well as the operation of combined heat and power systems, energy storage systems, boilers, EV parking lots, and renewable energy systems in the energy hub. Dini et al. addressed the uncertainty arising in the energy system from various factors, such as different loads, energy prices in the day-ahead market, renewable energy output, and EV parameters [114]. Bozorgavari et al. (2020) focused on the configuration planning of distributed battery energy storage systems to enhance electrical grid flexibility for exploring the optimal storage and distribution of energy in these systems. They explored the planning of distributed battery energy storage systems to increase grid flexibility and identified the system uncertainties arising from load forecasts, energy prices, and variable renewable energy outputs [115].

The studies from Phase II focused on the energy storage solutions and the optimization of energy storage systems, particularly in scenarios involving uncertainties such as variations in renewable energy production and changes in the load demand. From a microgrid perspective, Dini et al. (2020) explored a hybrid stochastic–robust coordinated power management strategy for enhancing flexibility, reliability, and safety in the connection of microgrids to EVs, energy storage systems, distributed generation systems, and demand response programs [116].

The studies from Phase III investigated the integration of renewable energy and EVs into the energy grid, as well as the flexibility and optimization potential in such an integration. These studies considered uncertainties in various factors, such as load demand, EV parameters, and renewable energy output. Moreover, they explored strategies for optimizing energy resource management, including renewable power generation and energy storage. Pirouzi et al. (2022) studied the energy storage flexibility provided by EVs in a smart distribution network; in particular, they focused on the battery storage potential of parked EVs to enhance the flexibility of the smart distribution network [117]. Azad and Shateri (2023) designed and optimized a comprehensive hybrid renewable energy system and presented an optimization method that minimized energy costs while meeting energy demands. This system included wind turbines, solar photovoltaic systems, biowaste units, energy storage equipment, and EV parking lots. The aforementioned authors demonstrated the system's economic efficiency and reliability in effectively meeting energy demands [118].

The six clusters focus on different aspects of electric vehicles (EVs) within a circular economy. Below is a table that outlines how the analysis results from each cluster can be applied to practical policymaking and industry practices, as shown in Table 6.

Table 6. Research outcomes of each cluster, with applications in policymaking and industry practice.

Cluster	Research Topic	Application in PolicyMaking	Application in Industry Practices
Cluster 1: Recycling and Reuse of EV Batteries	Recycling processes and reuse of EV batteries	Develop policies to promote battery recycling and reuse, enhancing material circularity. Provide subsidies and incentives for recycling technology and infrastructure.	Establish efficient battery recycling systems and optimize repair and reuse processes. Invest in advanced recycling technologies to improve material recovery rates.
Cluster 2: Charging Stations and Energy Storage Systems	Optimization of charging stations and energy storage systems using renewable energy	Set standards for charging station deployment, encouraging the use of renewable energy. Promote the integration of charging stations with energy storage systems for enhanced efficiency and sustainability.	Build renewable energy-based charging stations and optimize energy management systems. Develop smart charging technologies to increase energy utilization efficiency.
Cluster 3: V2G Technology and Renewable Energy	Integration of Vehicle-to-Grid (V2G) technology with renewable energy	Promote the adoption of V2G technology through supportive regulations to enhance interaction between EVs and the grid. Provide incentives and tax benefits for the implementation of V2G technology.	Develop V2G technology to use EVs as mobile energy storage units. Invest in V2G infrastructure to enable dynamic energy management and optimization.
Cluster 4: Power Frequency Control System	Role of EV charging stations in power system frequency control	Establish grid stability policies requiring charging stations to participate in frequency control and load management. Develop standards for seamless integration between charging stations and the grid.	Implement smart frequency control systems to enhance grid stability. Use EV batteries for load balancing to mitigate the impact of renewable energy variability on the grid.

Table 6. *Cont.*

Cluster	Research Topic	Application in PolicyMaking	Application in Industry Practices
Cluster 5: Dynamic Economic Emission	Application of dynamic economic emission models	Promote the integration of renewable energy with EVs to reduce carbon emissions. Develop emission management policies for charging stations, encouraging the adoption of low-carbon technologies.	Adopt dynamic economic emission management systems to optimize charging station operations. Utilize renewable energy for power dispatch to lower operational costs and environmental impact.
Cluster 6: Energy Management and Optimization	Integration and optimization of EVs with energy storage systems	Develop energy management policies to promote synergy between EVs and renewable energy sources. Establish technical standards for optimizing energy storage and distribution systems.	Develop smart energy management technologies to ensure efficient energy storage and distribution. Build flexible energy management systems to increase the share of renewable energy in the EV sector.

3.5. Analysis of the Growth in the Academic Research on EVs in a Circular Economy

On the basis of the suggestion of Ernst (1997), we created a two-dimensional framework in which the cumulative number of academic papers served as the vertical axis and time served as the horizontal axis. This framework was based on the logistic growth model and was used to depict the academic trends in the investigated field, including the growth period, growth limit, and turning point [119]. We employed the Loglet Lab 4 software program (version 4) to generate a growth curve of the academic research on EVs in the context of a circular economy. In this curve, the dashed line represents the estimated cumulative number of papers, whereas the solid line and circles denote the actual cumulative number of papers. The algorithm was used to estimate the growth period, growth limit, and turning point, as illustrated in Figure 16.

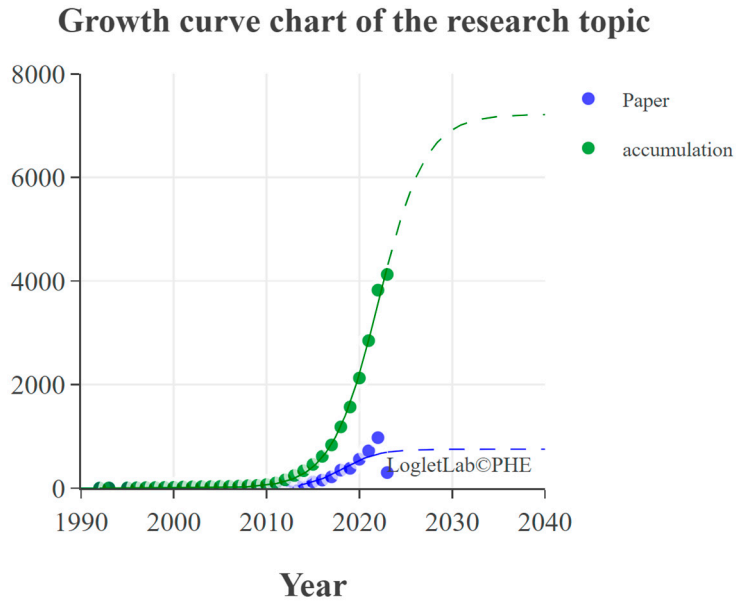


Figure 16. Growth curve of the literature on EVs in the context of a circular economy.

Academic research in the field of EVs in the context of a circular economy has been steadily increasing, with considerable growth being observed in recent years. Since 2017, more than 100 papers have been published each year on EVs in a circular economy. According to the analysis results obtained from Loglet Lab 4, the turning point of the literature

growth curve is likely to occur in 2023. Currently, the research is in a phase of rapid growth and is likely to transition to a stable phase after 2033. The cumulative number of studies is expected to reach 7000 in 2040.

4. Recent Academic Developments and Emerging Topics in the Field of EVs in a Circular Economy

Through text mining and keyword pivot analysis, we identified emerging research topics in the past 3 years (2020–2023) in the field of EVs in a circular economy. First, we collected 3379 relevant articles from the WoS database and divided them into two groups: articles published in 1993–2019 and articles published in 2020–2023. By employing text mining and pivot analysis to cross-reference keywords, we identified meaningful keywords with large differences in frequency between the two groups. Furthermore, we conducted text mining on the titles and abstracts of the extracted papers to identify the top 200 keywords. Finally, by conducting a comparative analysis between the aforementioned two groups of articles, we identified emerging research topics in the investigated academic field in the past 3 years. These topics are related to the integration of EVs with emerging technologies, such as microgrid, deep learning, loop supply chain, blockchain, and automatic generation control systems (Table 7).

Table 7. Recent emerging research topics in the field of EVs in the past three years.

No.	Literature Keywords	Group 1 1993~2019	Group 2 2020~2023	Emerging Topics
1	microgrids	36	307	◎
2	lithium-ion batteries	61	207	
3	deep learning	1	61	◎
4	loop supply chain	1	52	◎
5	load modeling	0	32	
6	real time systems	0	23	
7	machine learning	2	22	
8	blockchain	4	64	◎
9	automatic generation control	4	56	◎

Note 1. Analysis of keyword differences between articles published in 2013–2019 and 2020–2022. Note 2. ◎ indicates relevance to emerging topics, where Group 1 < 50 and Group 2 less Group 1 > 50. Note 3. Using expert interviews to confirm the final conclusion.

4.1. Emerging Research Topics—Microgrids

A microgrid refers to a local electrical grid with different distributed generation, loads, energy storage facilities, and controllable equipment. A microgrid system can be connected to or disconnected (in the island mode) from the main grid during normal or emergency situations. When this system is connected to the main grid, it can draw electricity from, or supply electricity to, the main grid. In the island mode, a microgrid can operate independently to provide power. Microgrids are primarily used to enhance the reliability and resilience of the power system, and renewable energy and energy conservation technologies can be integrated with microgrids to lower carbon emissions [120–122].

Emerging topics on microgrids in the context of a circular economy are microgrid energy management, EVs in microgrids, energy storage in microgrids, uncertainty and risk management in microgrids, renewable energy integration in microgrids, demand response in microgrids, optimization and control in microgrids, microgrid resilience and stability, microgrid design and planning, and advanced technologies in microgrids. Studies on microgrid energy management have investigated topics such as efficient energy dispatch and the effective integration of renewable energy systems and energy storage systems [123,124]. Studies related to EVs in microgrids [125,126] have explored the roles and potential applications of EVs in microgrids, including the use of EV batteries for energy storage and V2G technology. Research on energy storage in microgrids has primarily explored the utilization of energy storage systems in microgrids. For example, Alkhafaji and Trabelsi

(2022) discussed battery energy storage systems, superconducting magnetic energy storage systems, and the optimization of the size and dispatch of energy storage systems. Studies on uncertainty and risk management in microgrids have examined the uncertainty and risks associated with microgrid management [127]. For example, Muqeet et al. (2022) discussed the uncertainty arising from the use of renewable energy sources and EVs. Research on renewable energy integration in microgrids has explored the effective integration of wind energy, solar energy, and other renewable energy with microgrids [122,128,129]. Studies on the demand response in microgrids have focused on implementing demand response strategies in microgrids; such strategies are useful for adjusting the electricity demand to match the electricity supply [130]. Research on optimization and control in microgrids have investigated strategies for optimizing and controlling microgrids. For example, Hai et al. (2023) described a method for the effective dispatch and control of various resources in microgrids. Papers related to microgrid resilience and stability have explored methods for enhancing microgrid resilience and stability to address potential emergencies or imbalanced conditions [131]. For studies on microgrid design and planning, Saki et al. (2022) and Asaad et al. (2022) focused on aspects such as the optimization of the microgrid structure and resource allocation. Finally, research on advanced technologies in microgrids has investigated the use of advanced technologies (e.g., multiagent systems, the Internet of Things, and machine learning) in microgrids and energy management and control [128,132,133].

As new energy vehicles, EVs can be paired with microgrids to achieve energy storage and sharing. This pairing also enables distributed energy supply, thereby enhancing energy utilization efficiency. The distributed supply and utilization of energy can be integrated with a circular economy and EVs, achieving more flexible and efficient energy management and usage, which can promote low-carbon and energy-efficient production and lifestyles.

4.2. Emerging Research Topics—Deep Learning

Deep learning is a subfield of artificial intelligence that focuses on simulating human brain operation to identify patterns and structures within data. In the context of a circular economy, the research topics regarding the application of deep learning to EVs are as follows:

1. Predicting EV maintenance and lifespan: Deep learning can be employed to analyze battery performance data to predict maintenance or replacement times, which contributes to the extension of battery lifespans and the reduction of waste generation, thereby aligning with the principles of a circular economy.
2. Predicting energy management and optimization: Deep learning can be used to develop efficient energy management systems that can forecast energy requirements for EVs and determine the optimal charging and discharging times. Such predictions enhance energy utilization efficiency and minimize waste generation.
3. Autonomous driving: Deep learning is a core technology for autonomous driving systems. EVs with autonomous driving technology can enhance road safety, reduce traffic congestion, and decrease energy consumption, thereby promoting the realization of a circular economy.
4. Battery recycling and reuse: Deep learning can be applied to battery recycling processes to identify and categorize different battery materials, optimize the battery recycling process, and ensure the efficient recycling and reuse of battery materials.
5. Sales forecasting and supply chain optimization: Deep learning can be used to predict the market demand for EVs and optimize supply chains, thereby reducing production waste and aligning with the principles of a circular economy [134–140].

4.3. Emerging Research Topics—Loop Supply Chain

A loop supply chain is an innovative supply chain management strategy that emphasizes redirecting resources back into the production system after the end of a product's life cycle to maximize resource reuse.

In the EV industry, a loop supply chain can manifest in several areas. The research topics related to a loop supply chain are described as follows:

1. Battery recycling and reuse: Battery recycling is a crucial part of a loop supply chain. When EV batteries reach the end of their life cycle, they can be recycled and reused; this process involves extracting and reusing valuable metals from the batteries or repurposing old batteries for energy storage systems [141–143].
2. Optimization of the production process: A loop supply chain is relevant not only to the end of a product's lifespan but also to the production process. Manufacturers can seek to minimize waste generation during the production process and maximize the reuse of materials and resources [144,145].
3. Reselling and remanufacturing: Some EV manufacturers have begun to refurbish and resell used EVs. Remanufacturing can extend an EV's lifespan and prevent resources from turning into waste by keeping them in use [144,145].
4. Product design: The principles of a loop supply chain can influence product design. For example, manufacturers can consider the product's structure during the design phase to facilitate easy disassembly and recycling after the product reaches the end of its life cycle. Such a practice not only contributes to the achievement of the goals of a circular economy but also provides manufacturers opportunities to reduce costs and increase efficiency [144,145].

4.4. Emerging Research Topics—Application of Blockchain to EVs in a Circular Economy

Blockchain is a distributed ledger technology that ensures data transparency and immutability. In the EV industry, blockchain technology has various applications. The research topics related to these applications are as follows:

1. Supply chain tracking and management: Blockchain can be used to record and verify every step in the supply chain, from raw material extraction to component manufacturing and product assembly. Blockchain can enhance supply chain transparency, enable the achievement of material sustainability, and aid companies in adhering to the principles of a circular economy [146,147].
2. Battery life cycle management: Blockchain can be used to track the entire life cycle of EV batteries, including their manufacturing, usage, recycling, and reuse. Such "digital identity" can provide vital information regarding battery performance and usage history and help determine the optimal recycling and reuse strategies [146].
3. Energy trading and sharing: Blockchain can support decentralized energy trading at EV charging stations, thereby allowing EV owners to sell unused power from their vehicles. Such V2G technology enhances energy efficiency and supports a more sustainable and flexible electrical grid [148].
4. Data security and privacy: The encryption feature of blockchain can safeguard the data and privacy of EV owners. This feature is especially important for EV applications such as self-driving and vehicle-to-everything services, which require large quantities of data [149].

The aforementioned text describes some of the potential applications of blockchain in the field of EVs in the context of a circular economy. With future advances in EV and blockchain technologies, numerous innovative applications involving their integration will be developed.

5. Conclusions and Discussion

5.1. Research Results and Contributions

This study employed topic evolution analysis and technology evolution analysis to comprehensively explore the current development status and future development trends of EVs within the context of the circular economy. It also analyzed the challenges faced by the EV industry and possible solutions. By comprehensively analyzing the application of EV technology within the circular economy framework, this study obtained valuable findings related to the deep integration of EVs and the circular economy for policymakers,

businesses, and researchers; these findings can be used as a guide to realize a sustainable transportation system.

First, this study conducted a systematic review and analysis. It systematically and comprehensively reviewed the extensive literature on EVs and the circular economy without bias. By using precise computation methods, this study investigated in depth the development trajectory of EVs within the circular economy while identifying development trends and emerging issues. The study clearly delineated several key stages in EV research, namely early discussions on EVs as a power resource; the management and application of V2G technology; the integration of renewable energy and energy storage grids; the optimization of smart grids and charging stations; and the exploration of sustainable development in energy, water, and environmental systems. In addition to technical problems, this study found that sustainable battery recycling, charging infrastructure, and renewable energy integration are critical factors for the successful promotion of EVs within the circular economy. The conducted analyses revealed that promoting EV adoption is not solely a technical issue but also requires attention to social ethics, stakeholder rights, and legal governance.

Second, we identified key areas and emerging issues in the domain of EVs in the circular economy. Through cluster analysis, this study identified the main hotspots and themes in research on EVs and the circular economy. These research hotspots and themes included the recycling and reuse of EV batteries, charging stations and energy management, V2G systems and renewable energy technologies, dynamic economic emissions, and energy management. The identification of the aforementioned research hotspots and themes not only enriched the theoretical foundation of EVs and the circular economy but also provided new directions for practical application. Finally, through data mining and statistical analysis, this study recognized the following emerging research topics in EV studies over the past 3 years: microgrids, deep learning, closed-loop supply chains, blockchain, and automatic generation control.

Third, possible future research trends and directions were determined. This study not only thoroughly reviewed the development trajectory of EVs within the circular economy but also formulated directions for future research in this field. The findings of this study can help the academic and industrial communities to better understand the evolving development trends of EVs and the circular economy, thereby enabling them to direct resources appropriately for achieving continued development and innovation in this field.

Fourth, data-driven decision support tools were used in this study. Through MPA and cluster analysis, this study demonstrated how extensive citation data and analysis techniques can be used to determine the pathways of knowledge diffusion and the main research areas in a particular field. Future researchers can use this methodology to investigate crucial research trends and topics in different fields, including the field considered in this study.

5.2. Limitations and Future Research

Although this study conducted an in-depth exploration of EV technology and its application within the circular economy, it has certain limitations. First, limited data sources were used in the present study. This study analyzed literature solely from the WOoS database. Although the WoS database is extensive, it does not encompass all rel-evant research outcomes. Other databases, such as Scopus, IEEE Xplore, and PubMed, also contain many crucial research publications. Because of the lack of uniformity across different databases, future research can benefit from integrating multiple databases, which would enhance the comprehensiveness and representativeness of the study, thereby providing more universal and in-depth research conclusions.

Second, this study only investigated English language literature, which might have resulted in the exclusion of crucial contributions published in other languages. Many non-English-speaking countries, particularly those leading in the development of EV technology and the circular economy, such as Germany, China, and Japan, might have produced a

substantial quantity of high-quality research that was not included in this analysis. To fully cover global research trends and outcomes, future studies should consider including multilingual literature to avoid biases introduced by language bar-riers.

Third, this study primarily relied on MPA and cluster analysis. Although these methods are effective, the use of only two analysis techniques might have limited the diversity and depth of the research. Future studies should consider integrating other analytical methods, such as topic modeling, network analysis, and machine learning, to obtain more diverse and in-depth research perspectives. Such an approach would reveal hidden patterns and more complex research relationships.

Fourth, this study did not sufficiently explore the differences in and adaptability of EV technology applications across different regions and economies. Considerable differences in economic development levels, policy environments, and sociocultural contexts across regions might considerably affect the promotion and application of EV technologies. Future research should place greater emphasis on these regional differences and validate the generalizability of conclusions through empirical studies in more diverse regions.

Fifth, as EV technology rapidly evolves, further exploration could focus on how to improve battery recycling efficiency and battery reuse technologies, particularly under resource-scarce conditions. Investigating how the concept of a circular economy can be more effectively applied to maximize resource utilization would also be valuable. Furthermore, as renewable energy and V2G technology continue to develop, future studies should explore how these technologies can be more effectively integrated with existing power infrastructures and how innovative business models and policy support can facilitate the commercialization of these technologies.

Finally, this study did not comprehensively investigate the effect of varying global regulatory and policy environments on the development of EV technology, which is another area that future research can explore. Policies and regulations across different countries and regions may drive or hinder technological development in different ways. Therefore, future studies should explore how such differences affect the promotion and application of EV technology. Moreover, considering the increasing global focus on carbon emissions, future research should analyze and quantify the specific contributions of EVs and related technologies in reducing the carbon footprint.

Research on the aforementioned crucial aspects can increase our knowledge and un-derstanding in the field of EVs in the circular economy and advance the practical ap-plication of EV technology.

5.3. Recommendations for the Development of the Electric Vehicle Industry

Based on the analysis and conclusions of this paper, we find that the development of the electric vehicle industry can align with the circular economy. Through the analysis of academic literature, one can understand the development trends of the physical industries. We recommend that the overall automotive industry pay attention to the following trends and issues in future development.

5.3.1. Sustainable Development and Resource Recycling

Development and recycling of batteries: Battery development, which is currently one of the most important trends in EV development, involves the use of various materials and processes and is a crucial aspect of a circular economy. Following an increase in the prevalence of EVs, used EV batteries can be recycled and reused by using them in energy storage systems or recovering valuable metals from them. Lithium-ion batteries can be recycled and reused after their operational lifespan; specifically, valuable materials, such as lithium, cobalt, and nickel, can be extracted from used lithium-ion batteries for the production of new batteries. Such recycling and reuse can reduce the demand for new resources and minimize waste generation.

Integration of renewable energy supply systems with EVs: EVs are likely to become mainstream in the future; however, a considerable number of charging stations must be

established to ensure the widespread prevalence of EVs. Solar panels, wind power systems, geothermal power systems, and hydroelectric power systems can be integrated into smart charging stations to enable the monitoring and adjustment of the charging demand of EVs for ensuring a sufficient renewable energy supply, thereby reducing the environmental impact of EVs and achieving the goals of a circular economy. Such integration enhances energy efficiency and promotes sustainable environmental development and is thus a future development trend.

Product design and loop supply chain: The design of EVs can be optimized on the basis of the principles of a circular economy. Such optimization involves using recyclable materials, simplifying components to reduce maintenance costs, designing products for easy disassembly and recycling, and utilizing lighter and stronger materials for manufacturing EVs to enhance energy efficiency and driving range/mileage. An increasing number of manufacturers are attempting to develop environmentally friendly processes and sustainable supply chains to minimize waste generation and environmental impact during EV production.

Integration of V2G technology with a circular economy: V2G technology allows EVs to not only consume energy from the electrical grid but also discharge their excess stored energy back into the grid. During periods of high and low electricity demand, EVs can supply stored energy to the grid and recharge from the grid, respectively. Such bidirectional energy flow ensures efficient energy utilization and provides a new solution for energy storage and balance.

Integration of emerging technologies and EV systems: In a circular economy, emerging technologies can be integrated with EVs. The decentralized power supply of microgrids enables the green charging of EVs, and deep learning enables the optimization of the energy conservation strategies and autonomous driving of EVs. In addition, a loop supply chain ensures the maximum utilization and recycling of resources, and blockchain technology provides EV owners with transparency and privacy. The aforementioned emerging technologies can enhance the environmental friendliness of EVs and enable them to align with the principles of a circular economy.

5.3.2. Economics Issues Related to the Electric Vehicle Industry

Cost of ownership and long-term economic benefits: From the perspective of a circular economy, EVs offer greater economic advantages than traditional fuel vehicles. Although EVs require a higher initial investment than fuel vehicles, the long-term operational and maintenance costs, environmental benefits, and policy incentives associated with EVs render them a more economically appealing choice. The purchase prices of EVs are typically higher than those of fuel vehicles, mainly because of limitations in the battery technology and production scale of EVs. However, advances in battery technology and increases in production volumes have resulted in the narrowing of the gap between the prices of EVs and fuel vehicles. The battery lifespan and performance of EVs are continually improving, and EV batteries can be recycled and reused after the end of their life cycle. EVs do not require fuel, and the cost of electricity is usually lower than that of gasoline or diesel. Moreover, the mechanical structure of EVs is relatively simple, which results in them having lower maintenance requirements and a lower likelihood of mechanical failures compared to fuel vehicles.

Policy and tax incentives: Serious concerns exist worldwide regarding climate change and environmental issues, and many countries are exploring strategies to decrease carbon emissions. Because vehicles are the main source of carbon emissions, reducing vehicle emissions is crucial for emission control. Therefore, the use of EVs, which are an environmentally friendly alternative to traditional fuel vehicles, is being gradually promoted by national policies. Many governments have formulated preferential tax policies, such as tax reductions and exemptions, for EV purchases and investments in EV charging infrastructures. These incentives are designed to reduce EV purchase and usage costs, thereby stimulating the market demand for EVs.

Sharing economy and EVs: The rise of the sharing economy, especially shared car services, has positively influenced the demand for EVs. EV sharing can not only reduce resource wastage but also enhance resource utilization efficiency. EVs can be integrated with the sharing economy and comprehensive transportation systems, such as shared mobility services, autonomous driving systems, and public transportation systems, to improve the resource and energy utilization efficiency of the transportation system. Cross-system sharing of EV charging is expected to become a development trend in the field of EVs.

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