Energy Conversion and Management: X 25 (2025) 100864

Contents lists available at ScienceDirect

Energy Conversion and Management: X

journal homepage: www.sciencedirect.com/journal/energy-conversion-and-management-x

A comprehensive review of vehicle-to-grid integration in electric vehicles: Powering the future

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ARTICLE INFO

Keywords:
Vehicle-to-Grid (V2G)
Electric Vehicles (EVs)
Grid resilience
Energy management
Sustainable Urban Transit

ABSTRACT

The studies have focused on a bibliometric review of electric vehicle (EV) integration with the grid. It follows a methodical procedure using a pre-established search strategy to examine and analyze previous work on vehicle-to-grid (V2G). There were 21,535 articles found initially focusing on green urban transit. Following the last cleaning, editing, and refining round, 16,457 articles remained for evaluation. The literature written in English is one of the constraints that has been acknowledged. The review looks at data from 1970 to 2023, revealing that the number of research articles about V2G has increased significantly, especially after 2000. The collaborative landscape is shown by a network that includes the top ten organizations in the world. Citation analysis of nations indicates that the United States and China are the leading countries in research on V2G technology. Notable publications and organizations are highlighted in the evaluations of institutions and journals. China showcases its numerous connections through country collaboration networks. Research subjects have evolved, shifting from older ones like "secondary batteries" and "electric vehicles" to newer ones like "charging (batteries)," "smart grid," and "greenhouse gases." This shift is evident when one looks at the keyword data thematically. The comprehensive overview of V2G research trends and collaborations, identification of gaps, suggestion of future paths, and overall value as a resource will be an indispensable tool for EV integration researchers, legislators, and industry stakeholders and its contribution to infrastructure.

Introduction

Transportation electrification plays a crucial role in mitigating greenhouse gas (GHG) emissions and enabling the decarbonization of power systems. However, current research on electric vehicles (EVs) only provides a fragmented examination of their impact on power system planning and operation, lacking a comprehensive overview across transmission and distribution levels. This limits the effectiveness and efficiency of power system solutions for greater EV adoption [1]. Vehicle-to-grid (V2G) integration, a revolutionary paradigm that puts EVs as active participants in the energy landscape, is leading this transformation [2]. V2G allows bidirectional energy transfer between EVs and the electric grid, converting them into mobile energy storage units. EVs can draw power from the grid when needed and, crucially, return excess energy to the system when their batteries are off [3]. A 121-bus synthetic transmission network for New York State power systems is used to validate the future transportation electrification in New York State from 2025 to 2035. Results show that the large-scale

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https://doi.org/10.1016/j.ecmx.2024.100864
Received 1 November 2024; Received in revised form 27 December 2024; Accepted 27 December 2024
Available online 28 December 2024
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transportation electrification in New York State will account for approximately 13.33 % to 16.79 % of the total load demand by 2035. The transmission capacity is the major bottleneck in supporting New York State to achieve its transportation electrification [4].

V2G integration is a revolutionary concept in energy and transportation as EVs and the power grid merge [5]. This paradigm offers a new view of vehicular energy usage in which EVs smoothly integrate with the power grid, transcending their nature as vehicles [6]. The urgency to prevent climate change and reduce carbon footprints has made V2G integration a key player in transitioning to sustainable energy solutions. V2G integration began in the early days of EV research when battery economy and range were significant concerns [7]. As the worldwide focus switched to renewable energy and grid modernization, EVs' potential as mobile energy assets gained significance [8]. V2G integration is a conceptual shift that challenges the unidirectional flow of energy, ushering in an era where EVs actively contribute to power grid stability and resilience [9]. The schematic diagram illustrates the Vehicle-to-Grid (V2G) ecosystem, highlighting key components: EVs, bidirectional chargers, the power grid, renewable energy sources (solar panels, wind turbines), and battery storage. EVs act as mobile energy storage units, exchanging energy with the grid via bidirectional chargers, as shown in Fig. 1. Integrating renewable energy, the grid facilitates load balancing, peak shaving, and frequency regulation. Renewable sources feed the grid or store excess energy in batteries. Arrows depict bidirectional energy flows, supporting grid stability and renewable energy optimization. The design features clear labels, color-coded elements, and a minimalistic layout for clarity and simplicity.

The history of V2G integration mirrors the rapid development of EV technology and smart grid infrastructure. Milestones from early trials to advanced pilot programs help comprehend V2G dynamics' technological, economic, and regulatory aspects. V2G integration research is a dynamic interaction between academia, industry, and policymakers [10]. Pioneering research has exposed bidirectional energy flow and how to best use EV batteries for grid services. Meanwhile, a growing corpus of scholarship examines the economic viability and legal frameworks needed for extensive V2G deployment. Despite the plethora of knowledge, gaps and obstacles remain, requiring a nuanced evaluation of the impediments to V2G's seamless incorporation into mainstream energy discourse [11].

A massive corpus of literature is analyzed in this bibliometric evaluation using rigorous methods to find trends, patterns, and insights. The bibliometric analysis selection criteria ensure a sample from varied sources representing V2G research worldwide. The complex data gathering and analysis web uses cutting-edge bibliometric tools and methodologies to explore V2G integration publication trends, geographic distribution, authorship patterns, and theme concentrations [12].

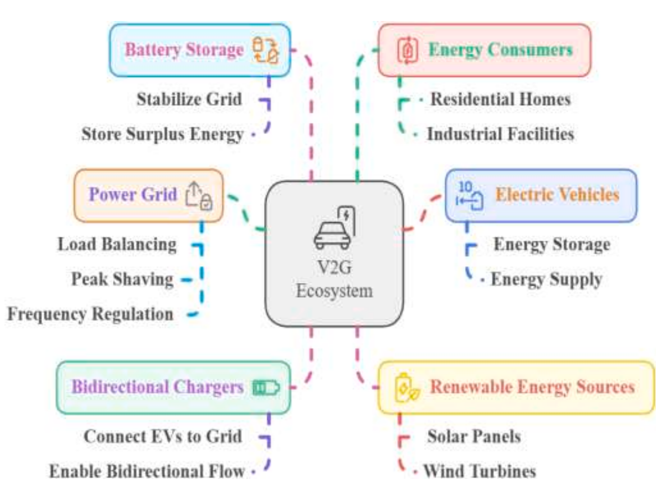

Fig. 1. V2G Ecosystem.

Patterns in V2G research show the field's evolution across time, reflecting the technological zeitgeist. Geographic dispersion reveals regional variations and discrepancies in research efforts, enriching the understanding of V2G's contextual importance. Key journals, influential authors, and developing issues guide intellectual navigation, while keyword analysis illuminates V2G discourse's semantic dimensions [13].

Exploring the thematic analysis of V2G integration research themes becomes the innovation and exploration hubs of the present review. These areas demonstrate the complexity of V2G research, from understanding bidirectional energy flow to studying sustainable energy and smart grids. Emerging technology and interdisciplinary perspectives add layers to the story, showing a field that adapts to technological advances and changing social objectives. Citation study reveals V2G integration's intellectual pedigree, including highly cited papers, significant authors, and complex scholarly networks. The conceptual roots of V2G research are founded on this panoramic perspective of citations, which reveals the field's evolution. The evaluation identifies research gaps and future directions as we navigate this vast ecosystem. Identifying these gaps guides future study, not just academically. Future research recommendations based on gaps go beyond academia into policy and industry. Policy and business can use these findings to implement V2G solutions in real life. V2G Integration presents problems and opportunities throughout this complete examination. Collaboration is needed to address technical issues like interoperability and battery deterioration. Socioeconomic and policy issues highlight the complex relationship between regulatory frameworks, public acceptance, and market factors that affect V2G adoption. Opportunities for advancement invite stakeholders to work on cross-disciplinary and institutional solutions to these challenges.

Amer, Masri [14] discussed developments in EV battery technology, charging standards, and AI's role in enhancing EVs' performance. Lithium-ion batteries were the most prevalent due to their energy density, lifespan, and cost-effectiveness, though they are sensitive to temperature. Solid-state batteries were found to be the future solution for higher energy density and faster charging, though there are many challenges. The research suggested that policies and technological innovation should address battery recycling, material scarcity, and charging infrastructure. Sagaria, van der Kam [15] analyzed how V2G technology would be beneficial to support Spain's 2030 and 2050 energy objectives through EV battery-based energy storage. Utilizing a validated Simulink model showed that in 2030, the 122 GW new storage can be substituted by EVs and 2.7 TW in 2050 to support a high penetration of renewables. 800 GW of PV and wind or 220 GW with 18 TWh imports for 2030 could result in 42 % renewables, while for 2050, 1300 GW or 600 GW with 50 TWh imports could reach 97 %. The results show that V2G can reduce the need for new storage infrastructure and support the grid's stability.

Any review study needs a background to set the stage, and V2G integration in EVs and its historical evolution, contextual importance, and driving forces are essential aspects of a full bibliometric review. EVs are revolutionizing sustainable transportation worldwide [16,17]. The increasing popularity of EVs as a cleaner alternative to internal combustion engine vehicles is driven by environmental concerns and the need to cut carbon emissions. As this transformation continues, attention is shifting from transport electrification to energy ecosystem integration of EVs [18]. The visionary V2G technology transcends the usual function of automobiles as power users and sows the seeds of this integration [19]. This research dates back to early EV development. The initial focus was improving EV battery efficiency and range to address concerns about limited driving distances and charging infrastructure. Still, a paradigm shift occurred as the world sought comprehensive energy and environmental solutions. Innovative V2G Integration made EVs dynamic components in a two-way energy exchange framework with the power grid.

Gabbar and Siddique [20] discussed that FCS is necessary for reducing the time electric vehicles take to charge. Still, they added that FCS needs massive power, which strains the grid and increases GHG emissions. To overcome this problem, they proposed an N-R HES to support RESs and reduce emissions. Comparisons between N-R HES, diesel-based, and small nuclear systems were done to address GHG emissions, energy costs, net present cost, and return on investment. Sensitivity analysis revealed that N-R HES was a reliable, sustainable decarbonization and energy-efficient solution. Bianco, Delfino [21] presented an optimisation-based bi-level management approach for temperature control and electrical vehicle scheduling in smart buildings. The approach incorporates automatic decisions toward operational management with real-time control while keeping the associated costs down and fulfilling charging and demand response satisfaction requirements. It also presents a distributed model for the optimal optimization of temperature control in which an EV charging model considers traditional vehicle-to-grid models. The system was tested at the Savona Campus and could reduce daily costs by 20 % compared to a heuristic, with potential savings of up to 35 % when incorporating demand response. Dall-Orsoletta, Ferreira [22] studied the effects of low-carbon technologies on energy justice, of which EVs are one variant, based on lifecycle stages and varying countries. The authors suggest that EV production, use, and disposal of injustices could be flexible, cosmopolitan, and restorative. The study highlighted the need to address distributional, procedural, and recognition injustices, especially in the North-South divide, due to mining activities and the exclusion of poor and rural communities from EV adoption. Recommendations for future research include looking into battery composition, recycling, and social innovations that would ensure an inclusive energy transition and achievement of the Sustainable Development Goals. Oldenbroek, Wijtzes [23] explored the role of grid-connected hydrogen-fueled Fuel Cell Electric Vehicles (FCEVs) in balancing 100 % renewable energy systems for electricity, heating, cooling, and transport in five countries: Denmark, Germany, Great Britain, France, and Spain. They modeled national systems for 2050, assuming 50 % of passenger cars would be grid-connected FCEVs. It was observed that these vehicles, with low usage (2.1–5.5 % load factor), could effectively balance energy systems, especially during peak demand periods. In countries with high solar energy shares, such as Spain, FCEVs mainly support the grid at night, which coincides with their driving patterns.

V2G dynamics research has grown alongside EV and smart grid technologies. Early research concentrated on establishing the technological viability of bidirectional energy transfer between EVs and the grid. Realizing that EVs could consume and contribute to grid electricity amid grid stress changed energy management theory. Furthermore, this work is deeply connected to the global transition to sustainable energy alternatives. V2G Integration is important because of the need to reduce greenhouse gas emissions, improve energy efficiency, and integrate renewable energy into the grid. The study fits under the UN Sustainable Development Goals (SDGs) for affordable and clean energy, climate action, and sustainable cities and communities. This study is also influenced by technical advances and governmental measures that support the decarbonization of the global transport sector. Governments, businesses, and research institutions collaborate to make V2G Integration a key driver of smart, resilient, and sustainable cities. Technology, regulations, and consumer attitudes towards electric mobility are interconnected.

The rationale for doing this bibliometric review on integrating V2G in EVs arises from a convergence of crucial imperatives. The study is motivated by an urgent environmental necessity, as the shift to EVs in the transportation sector plays a pivotal role in reducing greenhouse gas emissions. Furthermore, the purpose stems from acknowledging the capacity of V2G integration to augment energy resilience and efficiency inside the power grid. The study seeks to analyze the two-way exchange of energy between EVs and the grid. Its objective is to provide valuable information on optimizing energy use and ensuring grid stability, especially considering the increasing dependence on intermittent renewable energy sources. Finally, the motivation is driven by a strong interest in technological progress. Electric car technology and smart grid infrastructure breakthroughs present exceptional prospects for shaping a more environmentally friendly, intelligent, and enduring energy future. So, the following objectives of this bibliometric review on V2G integration in EVs are laid.

- The study examines V2G integration literature to complete the research landscape. The review employs bibliometrics to identify publication patterns, topics, influential authors, and knowledge gaps.
- The review informs scholars, policymakers, and industry practitioners by synthesizing field knowledge. Analysis of trends and patterns informs research, technology, policy, and implementation.
- The bibliometric analysis gives stakeholders a thorough overview of V2G Integration research in electric automobiles and smart grid technologies.
- V2G technology can improve energy resilience, resource allocation, and sustainability, and the paper examines its possible uses, benefits, and problems.

The bibliometric review's scope is defined by its concentration on V2G integration within the context of EVs. The study includes literature published within a specific period, guaranteeing its relevancy and up-to-date. The system considers various sources, such as academic publications and conference papers, to offer a comprehensive perspective on the study field. Nevertheless, it is crucial to recognize specific constraints. The review may not encompass all the subtle aspects within the extensive domain of V2G integration, and the conclusions are dependent on the accessibility and reliability of the data. Furthermore, despite attempts to achieve a sample that accurately represents the population, the outcomes may be influenced by intrinsic biases in the literature or databases. Notwithstanding these constraints, the review aims to provide a comprehensive and perceptive examination of the present status of research on V2G integration in EVs and its future impact on infrastructure.

Architecture for V2G integration

V2G integration entails a complex framework specifically developed to facilitate the two-way transfer of electricity between electric cars (EVs) and the power grid. The system primarily consists of the EV, which is a portable energy storage unit [24]. It is fitted with a battery management system (BMS) that monitors and controls the charging and discharging operations [25]. The Electric Vehicle Supply Equipment (EVSE) is connected to the EV and includes a bidirectional charger, allowing electricity to flow in both directions. It also has a communication interface that enables data interchange between the EV, grid, and user. The process of connecting to the grid entails the utilization of a transformer to regulate voltage levels, a smart metre for precise monitoring of energy transfer, and the local distribution network for the delivery of electricity [26]. The aggregator platform oversees the coordination of the combined energy resources of many EVs. It communicates with the grid operator to enhance the efficiency of the power grid by providing services such as reducing peak energy demand and regulating the grid's frequency [27].

A strong communication network is necessary to provide safe and real-time data sharing, following standards such as ISO 15118 and IEEE 2030.5. The grid management system, consisting of an Energy Management System (EMS) and Distribution Management System (DMS), consistently monitors and regulates the energy flow to uphold grid stability [28]. Moreover, advanced metering infrastructure (AMI) offers a comprehensive analysis of energy patterns. Cybersecurity measures such as encryption, authentication, and intrusion detection systems are implemented to protect the system. These components work together to create a system that not only helps the grid by offering additional services and managing high-demand periods but also promotes the use of renewable energy [29]. However, there are still obstacles to overcome, such as battery degradation and regulatory problems [30]. Fig. 2 shows the basic architecture of V2G integration.

Strategies for V2G charging and discharging

V2G systems utilize several methods of charging and discharging to optimize the interaction between EVs and the grid. These initiatives aim to optimize grid stability, enhance energy efficiency, and promote the durability of EV batteries [31]. The following are the essential strategies:

a) Unidirectional charging

Unidirectional charging, or Grid-to-Vehicle (G2V) charging, is the traditional form of EV charging where energy flows only in one direction — from the power grid to the electric vehicle. This type of charging is more straightforward, involves less complex infrastructure, and is widely used in standard EV charging setups. In V2G systems, EVs use grid electricity without returning it. Essential EV charging and peak shaving can be achieved using this straightforward approach. Connecting the EV to an EVSE enables one-way electricity flow from the grid to the vehicle [32]. Unidirectional charging simplifies infrastructure and decreases EV battery stress but has less grid support than bidirectional solutions [33].

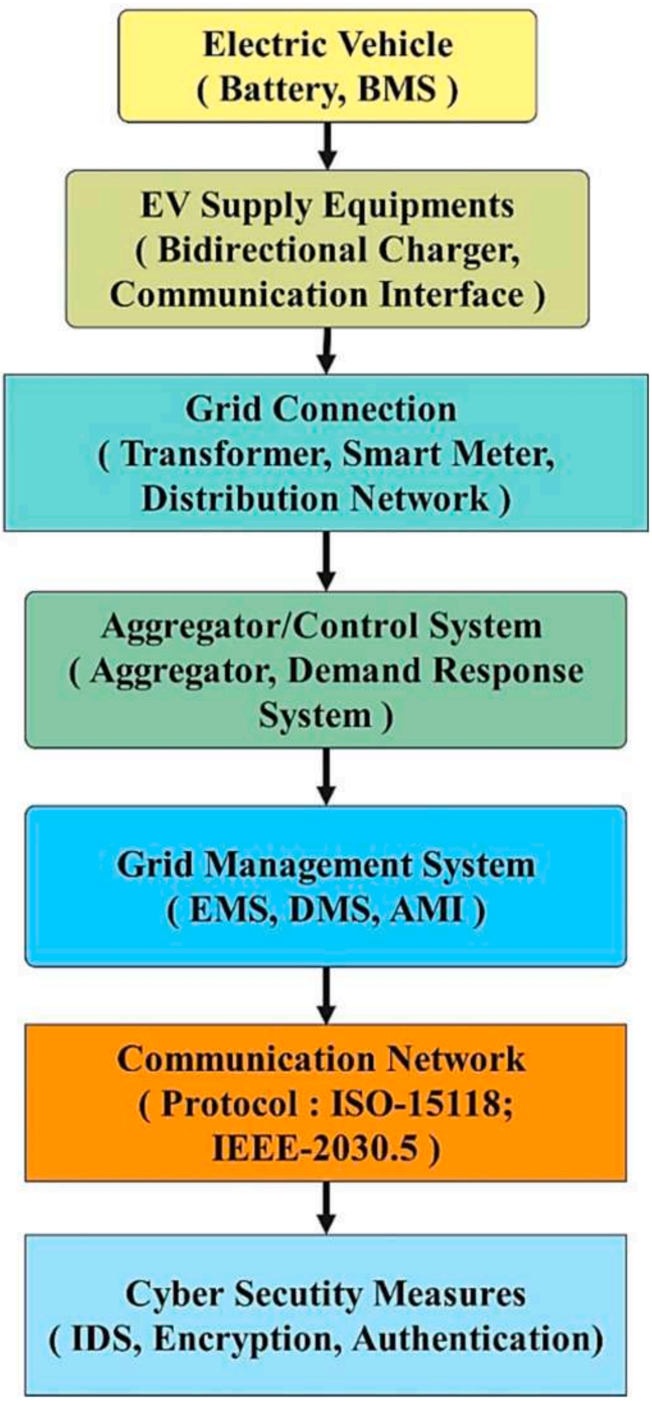

Fig. 2. The architecture of V2G Integration.

b) Bidirectional charging

Bidirectional charging allows EVs to draw electricity from the grid and return stored energy in V2G systems. This innovative technique lets EVs store energy and send power to the grid when needed. EVs are connected to Bidirectional EVSEs to allow electricity to flow both ways. Bidirectional charging boosts EV battery efficiency and supports grid tasks like load leveling and frequency regulation [34]. Avoiding battery degradation demands sophisticated infrastructure and careful control [35]. Fig. 3 shows the charging and discharging strategies of V2G.

Unidirectional charging (G2V) involves a one-way energy flow from the grid to the EV, providing essential charging with lower infrastructure costs. In contrast, bidirectional charging (V2G) enables energy flow in both directions, allowing EVs to support grid stability by providing ancillary services such as frequency regulation and peak shaving. While G2V minimizes battery wear, V2G can lead to potential degradation due to frequent charge–discharge cycles. Still, it offers more significant consumer incentives through revenue from selling stored energy, as discussed in Table 1.

Impacts of V2G strategies

The implementation of V2G strategies, including unidirectional (Grid-to-Vehicle or G2V) and bidirectional (Vehicle-to-Grid or V2G) charging, has significant implications for grid stability, renewable energy integration and economic benefits:

- *Grid Stability:* Bidirectional charging enhances grid reliability by providing ancillary services like frequency regulation and voltage control. EVs can discharge energy during peak demand, reducing the risk of blackouts. Unidirectional charging supports basic grid demand management but lacks the flexibility of discharging energy back to the grid.
- *Renewable Energy Integration:* V2G systems enable surplus renewable energy storage in EV batteries during periods of high generation (e.g., daytime for solar). Stored energy can then be supplied to the grid during low renewable output periods (e.g., at night). This minimizes the intermittency challenges of renewable energy sources, facilitating higher penetration of renewables into the energy mix.
- *Cost Savings:* For utilities, V2G systems reduce the need for expensive peak power plants, lowering operational costs. EV owners can

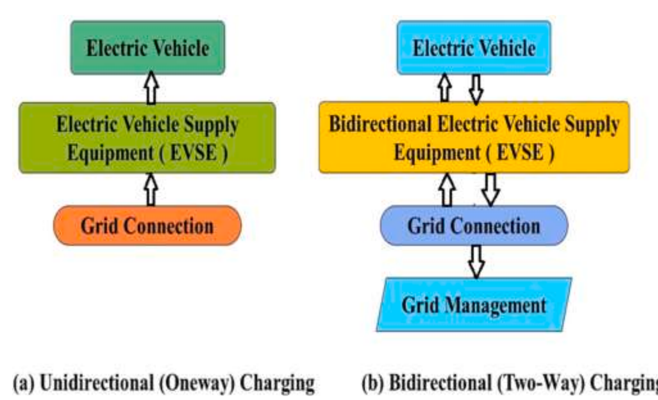

Fig. 3. Charging and Discharging strategies in V2G.

Table 1
Comparing Unidirectional vs. Bidirectional Charging.

Feature	Unidirectional Charging (G2V)	Bidirectional Charging (V2G)
Energy Flow	Grid → EV	Grid ↔ EV
Grid Support	Minimal	Provides ancillary services (e.g., frequency regulation).
Cost	Lower infrastructure costs	Higher due to advanced chargers and communication systems.
Battery Impact	Minimal wear and tear	Potential degradation with frequent charge–discharge cycles.
Applications	Standard EV charging	Renewable integration, peak shaving, grid balancing.
Consumer Incentives	Limited	Revenue opportunities from selling stored energy.

benefit from financial incentives by participating in V2G programs and selling stored energy during peak pricing. In contrast, unidirectional charging offers limited financial benefits to EV owners, as it does not support energy discharge back to the grid.

Studies estimate that bidirectional V2G systems can reduce peak grid demand by up to 20 % and provide utilities with 10–15 % cost savings. Research highlights that integrating V2G with renewables can improve renewable energy utilization rates by 30 %, reducing curtailment. By effectively leveraging these strategies, V2G can transform EVs from passive energy consumers to active participants in a sustainable energy ecosystem.

Technological and scientific discussions

Khaligh et al., 2019 thoroughly examined and evaluated the current and upcoming developments in high-power conductive on-board chargers for EVs. To give a worldwide perspective, an overview of global charging standards and trends in EVs was presented, which shows a growing preference for on-board chargers with higher power ratings. The V2G technology is a cost-effective and efficient way to integrate EVs into power grids [36]. Zheng et al., 2019 provided a complete review of the power interaction mode between EVs and power grids and the scheduling approach for deploying V2G technology. The aim is to describe the current advancements in these sectors. EVs are increasingly dominating the market previously held by traditional internal combustion engine automobiles [37]. The study conducted by Das et al. 2020 examined the impact of future EV developments, including connected vehicles, autonomous driving, and shared mobility, on EV grid integration and the advancement of the power grid towards the future energy Internet. The study explores how EVs can influence and contribute to the development of the future energy Internet [38]. Ali et al., 2020 extensively examined the cutting-edge artificial intelligence methods used to assist different applications in a distributed smart grid. They examined the application of artificial approaches in facilitating and incorporating renewable energy resources, energy storage system integration, demand response, grid and home energy management, and security. Integrating EVs into the smart grid system will substantially increase the number of EVs and industrial machinery in the future [39].

Alsharif et al., 2021 conducted a comprehensive analysis of the effectiveness of Energy Management Systems in the EV system in lowering fuel consumption and carbon dioxide emissions. The primary objective was to bridge the gap between the study and previous research by thoroughly reviewing and updating the current state-of-the-art smart grid communication technologies, specifically focusing on integrating V2G technology through contactless charging methods. This publication was anticipated to be a valuable resource for engineers and researchers investigating smart grid communication technologies and contactless charging for electric automobiles [40]. Patil et al., 2020 comprehensively analyzed the economic advantages of integrating electric vehicles into the power grid. Recent studies concerning the incorporation of EVs with electric power systems (EPS) are categorized according to their pertinence to various stakeholders in the energy market. The authors thoroughly examined the technological obstacles to integrating EVs into the power grid. They proposed a method that involves optimal scheduling and controlled charging procedures. The rapid advancement of EVs presents substantial prospects for the enhanced utilization of clean energies in the automotive industry [41]. Yuan et al.,2021 thoroughly examined and analyzed the most advanced solutions for bidirectional optical burst converters [42]. Bibak et al. 2021 conducted a thorough literature analysis to explore the various elements of deploying EVs, focusing on their supportive functions for the grid in the V2G system. They assessed the benefits and drawbacks of integrating the V2G system into the electricity grid. They categorized them according to their suggested approach for future research [43]. Due to the escalating costs of fossil fuels and the consequential environmental concerns, EVs have emerged as a viable alternative to traditional fossil-fueled automobiles. The objectives that can be achieved by effective management of the charging and discharging of EVs are categorized into three groups (network activity, economic, and environmental objectives) and thoroughly examined by Aghajan-Eshkevari et al. 2022. Limited research studies have been specifically dedicated to EV discharge scheduling, also known as V2G technology. This is because the idea of EVs returning electricity to the power grid is relatively new and still developing. An assessment of current EV charging and discharging research is necessary to identify areas for further investigation and to enhance future studies [44]. Chen et al., 2022 categorized them into forecasting, scheduling, and pricing procedures. Due to the widespread commercialization and increasing market dominance of EVs, numerous studies have focused on the design and advancement of battery systems [45]. Ghalkhani et al., 2022 thoroughly examined recent advancements and innovations in battery design, temperature regulation, and the use of artificial intelligence in Battery Management Systems for EVs [46]. Pradhan et al. 2023 thoroughly examined the difficulties associated with transitioning on-board chargers to higher voltages compared to current technology. The study also considered the effects of newly introduced DC fast charging standards such as Megawatt Charging Systems (MCS) and ChaoJi/ CHAdeMO 3.0 on this transition. In conclusion, the difference between the most advanced technology currently available and the anticipated future needs are identified to determine the obstacles and the focus of future research endeavors. Integrating wireless power transfer (WPT) into unmanned aerial vehicles (UAVs) not only facilitates the recharging of UAV batteries but also allows UAVs to recharge other devices [47].

Mou et al., 2023 thoroughly analyzed the latest advancements in near-field wireless power transfer (WPT) technologies for charging unmanned aerial vehicles (UAVs). This study covers the characteristics of these technologies' design challenges and includes several case studies [48]. The study conducted by Chen et al., 2023 offers an extensive analysis of how smart meters can effectively manage and optimize power grids, facilitating a seamless transition to a renewable energy-based future. The complexity of smart grids increases due to the inclusion of small-scale low-inertia generators and the integration of EVs, which primarily rely on intermittent and variable renewable energy sources. The electric V2G technology is a significant advancement that allows an electric car's battery to serve as an energy reservoir, capable of storing or releasing energy when the vehicle is idle or parked [49]. Panchanathan et al., 2023 investigated several configurations of bidirectional converters that enable the exchange of active power between the grid and the vehicle in both directions [50]. The study by Mukhtar et al., 2023 examined the contrasting issues of energy poverty in Sub-Saharan Africa and the possibilities for renewable energy sources in the region. The research offered focuses on the years 2030 and 2040 as the designated periods for implementation. Prioritizing the existing infrastructure is the most cost-effective and straightforward approach for integrating renewable energy technologies with the current fossil-fueled power systems in the planned central grid [51]. Zarate-Perez et al., 2023 examined the significance of Virtual Power Plants and battery energy storage systems in mitigating grid intermittency problems and delivering supplementary market services. The report also highlighted the importance of effectively managing demand by integrating EVs and Building Energy Management Systems in Virtual Power Plants. In modern technology's fast-evolving field, power electronics are crucial in several applications, including renewable energy systems, EVs, and consumer electronics [52]. Bahrami et al., 2023 provided a thorough and all-encompassing examination of the machine learning methods used in power electronics control and optimization. The research emphasis has switched towards fuel cell-powered electric cars, which provide minimal emissions and greater efficiency compared to EV alternatives [53]. Shekhawat et al., 2023 conducted a comprehensive study on EV variations, their challenges, a detailed comparison of the most recent configurations for fuel cell electric vehicles, and the optimal arrangement of hybrid energy storage systems (HESS). The HESS was designed by integrating fuel cells, batteries, and ultracapacitors to address the varying power requirements and create an efficient transportation model [54].

Scope and differentiation from existing reviews

Many researchers, through reviews, pointed out that V2G systems could improve grid stability by integrating more renewable energy into the electricity supply and offer some economic merits. [55] stressed the need to consider behavioral and psychological factors in V2G adoption, and some of the significant barriers mentioned were battery degradation and privacy. [56] explored how AI and ML might optimize V2G operations, improving efficiency, battery health, and grid reliability. These results highlighted both the technological and user-centric needs for V2G adoption. Technical and infrastructural challenges were another common theme. [57] reviewed the effects of EV charging on distribution networks and presented strategies to mitigate hosting capacity limitations. [58] and [59] focused on designing and controlling bidirectional converters and charging technologies, respectively, which will find innovative solutions for efficient power flow and fast charging infrastructure. Ghorpade and Sharma [60] presented demand-side management strategies to balance load schedules, improve cost efficiency, and integrate renewable resources, where the potential of EVs to participate in grid operations actively was discussed. These studies, together, emphasized the need for robust charging infrastructure and advanced power management systems. Further research also considered the broader implications of EV and V2G technologies. Lehtola [61] was concerned with the impact of V2G operations on battery life and economic viability, while Fang, von Jouanne [62] compared traditional battery EVs with fuel cell EVs for V2G applications. The papers by Micari and Napoli [63] and Yang, Wang [64] discussed the regulatory, technical, and security issues and called for policy coordination and advanced cybersecurity measures. Li, Chew [65] and Goncearuc, De Cauwer [66] looked into charging infrastructure planning and strategies to address the obstacles toward V2G integration with solutions for incorporating EVs into coupled grid and traffic networks. These studies provided a comprehensive understanding of the technological, behavioral, and systemic factors that contribute to the successful adoption of EV and V2G technologies.

Unlike prior reviews, this study provides a detailed geographical analysis of V2G research trends, highlighting regional strengths and contribution gaps. For instance, it identifies that while China leads in publication volume, research from the United States focuses heavily on battery optimization and renewable energy integration. These insights allow stakeholders to understand regional priorities and collaboration opportunities. This review uniquely tracks the evolution of research themes using bibliometric keyword analysis from 1970 to 2023. Thematic shifts, such as the transition from "secondary batteries" to "smart grids" and "greenhouse gases," highlight how research focus has evolved in response to technological advancements and global energy challenges. Existing reviews primarily summarize current research without emphasizing gaps or proposing actionable recommendations. This study goes beyond by identifying critical gaps, such as the need for standardized communication protocols, robust cybersecurity measures, and consumer behavior studies, and providing specific future research directions. While earlier reviews often concentrate on foundational technologies, this study explores emerging applications like AI-based V2G optimization, rural pilot programs, and the integration of renewable energy in developing regions. This forward-looking approach aligns with sustainable development goals and ongoing global electrification efforts. This review aims to provide a more holistic and actionable roadmap for advancing V2G research and its real-world applications by addressing these unique dimensions.

Evolution of V2G

The integration of V2G has seen substantial development since its inception. Kempton and Letendre formally announced the theory in 1997. Their proposal introduced a straightforward yet groundbreaking idea: utilizing an EV's battery to store electricity for the grid. This concept heralded the commencement of a novel epoch in energy administration, whereby cars could assume a pivotal function in harmonizing the grid's workload [67]. Fig. 4 shows the evolution of V2G.

In 2007, the University of Delaware established the "Mid-Atlantic Grid-Interactive Car Consortium" (MAGICC) in partnership with the electric, automotive, and communications industries. The partnership successfully created a V2G-competent electric vehicle, specifically the AC Propulsion eBOX, which represents the initial trial of V2G technology in real-world conditions. This achievement was a notable turning point in which the idea of V2G transitioned from a theoretical concept to actual implementation.

2010 the Nissan LEAF was released, marking a significant milestone in automotive advancements. This signaled the commencement of widespread, commercially accessible electric automobiles. As the number of EVs increases, research on V2G technology has transitioned from being entirely theoretical to having actual implementations. The introduction of EVs has created new opportunities for V2G technology, enabling EVs to function as portable energy storage devices capable of supplying electricity to the grid during high demand. The Tōhoku earthquake and the subsequent Fukushima nuclear crisis in Japan in 2011 sparked a renewed fascination with V2G technology. The calamity underscored the necessity for dependable auxiliary power sources, and V2G technology was perceived as a prospective remedy. EVs' capacity to deliver electricity during blackouts rendered them a compelling choice for emergency power provision [68].

Since 2016, Cenex has actively pioneered the research and development of V2G technologies and business models. The primary objective of V2G is to delineate the mechanisms via which EVscan interfaces with smart grids and to emphasize the crucial importance of establishing a mutually beneficial connection to enhance power distribution efficiency [69]. V2G technology harnesses the stored energy in the battery to provide power to the grid. Conversely, it allows the grid to recharge the battery of an EV when needed [67]. Technology is constantly advancing and is anticipated to substantially impact future grid management and the integration of renewable energy. As we go towards a future characterized by increased utilization of renewable energy sources, integrating V2G technology will be crucial in guaranteeing consistent and dependable power provision. The progression of V2G integration exemplifies the capacity of technology to revolutionize our energy systems and facilitate a more environmentally friendly future. The evolution of V2G from a theoretical concept to a practical energy management solution is a captivating narrative of invention and advancement. The narrative is ongoing as scientists and pioneers worldwide investigate novel methods to utilize the potential of EVs to enhance our energy systems and save our planet [70].

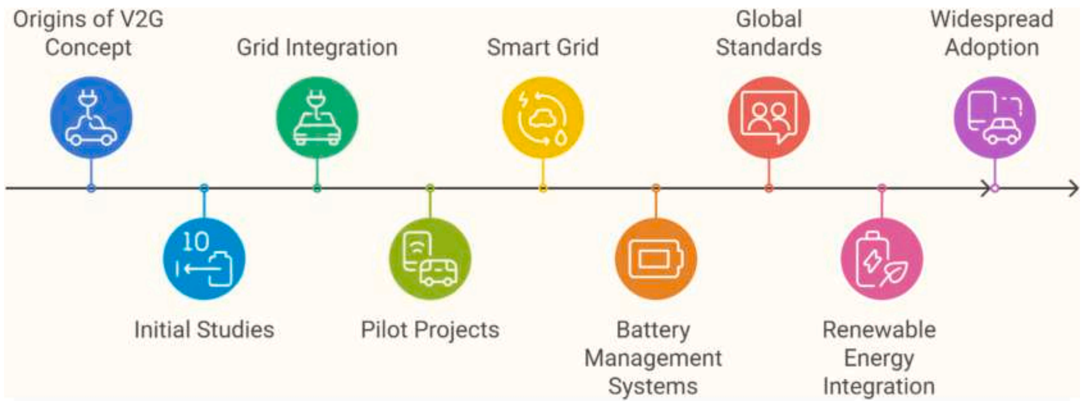

Fig. 4. Evolution of V2G.

Current state of research in V2G integration

Fig. 5 illustrates the literature analysis and depicts the study's current status in V2G. Sample data has been generated to represent this. The pie chart illustrates the primary research topics in V2G technology, with Grid Management and Services dominating at 45 %. This highlights the importance of efficiently controlling the two-way energy transfer between EVs and the power grid [71]. The research in this field concentrates on enhancing the efficiency of charging schedules, overseeing high-demand periods, and delivering grid support services such as frequency regulation and voltage management. Renewable energy integration accounts for 25 % of the share, making it the second-largest. This highlights the significance of effectively incorporating variable renewable energy sources such as solar and wind power into the grid using V2G technology. The research conducted here focuses on developing forecasting models, managing grid stability in the presence of fluctuating renewable energy inputs, and using electric vehicles as distributed energy storage resources [72,73]. The EV Market and Economics closely track a growth rate of 15 %. Comprehending market dynamics, customer behavior, and cost-effectiveness is essential for the broad adoption of V2G technology. The research in this field concentrates on examining the requirements for charging infrastructure, formulating business models for V2G services, and evaluating the financial advantages for both utility companies and EV owners, as shown in Table 2 [74].

Technology and Infrastructure account for 10 % of the total

Table 2
Current Research Trends in V2G.

Research Trend	Key Focus	Example Technologies
Renewable Energy Integration	Optimizing storage and grid feed-in from renewables	Solar and wind integration with V2G systems
Ancillary Grid Services	Frequency regulation, voltage control	Bidirectional chargers, smart inverters
Battery Management	Minimizing degradation during charge–discharge cycles	AI-driven BMS, solid-state batteries
Cybersecurity	Securing V2G networks against cyber threats	Blockchain protocols, real-time monitoring
Policy and Regulation	Encouraging adoption through incentives	Subsidies for V2G-compatible chargers

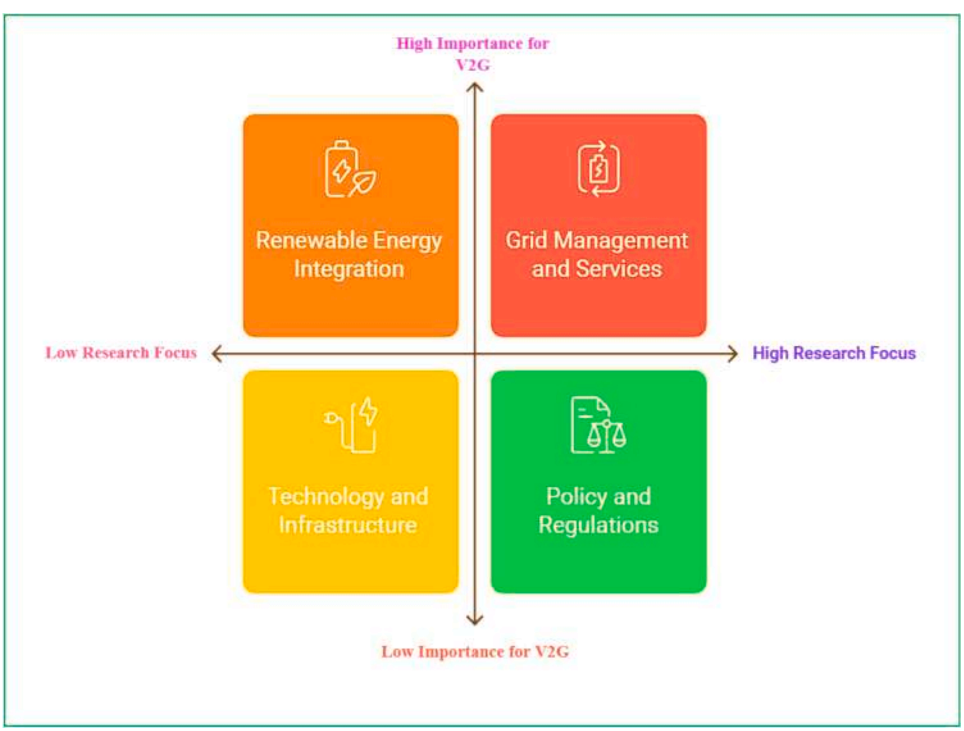

Fig. 5. Current State of Research in V2G.

allocation. This emphasizes the continuous research and development endeavors to enhance V2G technologies and infrastructure. This encompasses the creation of effective two-way chargers, communication protocols for V2G communication, and intelligent grid technologies to allow the integration of V2G systems. Policy and regulations account for the remaining 5 % [75]. Supportive laws and regulations are crucial for establishing a favorable environment for the deployment of V2G technology. The research in this field is on identifying regulatory obstacles, formulating supportive policies, and establishing standards for V2G technology and operation [76]. California policies, such as the Low Carbon Fuel Standard (LCFS), have incentivized V2G adoption by offering credits for energy fed back to the grid [77]. Similarly, EU initiatives like the Clean Energy Package have mandated interoperability standards, fostering research into standardized protocols like ISO 15118 [78]. These policies drive technological advancements and promote large-scale V2G pilot programs.

Battery Degradation: One of the significant difficulties with V2G systems is related to battery degradation, wherein frequent charge–discharge cycles needed for grid services contribute to a reduction in their lifespan. To overcome such challenges, researchers have been inclined toward developing advanced BMSs that use predictive models and machine learning algorithms to optimize charge–discharge cycles by adjusting their charging rates and depths based on the real-time health of a battery. The research has demonstrated that adaptive charging algorithms can reduce capacity fade by up to 15 % over 5 years of V2G usage, showing promise for extending the battery's lifespan [79]. Continuous monitoring of the battery's state of health (SOH) has also been effective in minimizing degradation. Monitoring SOH allows V2G systems to proactively limit the depth of discharge (DoD) during grid operations. Studies have shown that keeping DoD within 20–30 % per V2G session reduces long-term degradation while still maintaining the ability to provide grid services. This balance ensures that V2G operations do not excessively strain the battery. Advances in battery chemistries have also played an essential role in mitigating degradation issues. Lithium iron phosphate (LFP) batteries are gaining popularity in V2G-compatible EVs because of their better cycle life and thermal stability. LFP batteries can support more than 5,000 cycles with minimal performance loss, which makes them better suited for the heavy cycling that V2G is associated with [80].

Cybersecurity Protocols: Cybersecurity is a serious issue for V2G systems because of data and energy flow between electric vehicles and the grid. Being interconnected, these systems become vulnerable to cyber-attacks in the form of unauthorized access, data breaches, or even a complete power grid collapse. Researchers and industry players are creating robust cybersecurity protocols for such systems to address these issues [81]. One promising approach is to use blockchain technology to improve the security of V2G communication networks. Blockchain enables secure, decentralized, and tamper-proof transactions between EVs, charging stations, and grid operators. For example, smart contracts within a blockchain framework can automatically verify and authorize energy transactions, ensuring that only legitimate interactions occur [82]. This eliminates single points of failure and significantly reduces the risk of data tampering or malicious attacks. Multi-layered authentication mechanisms will also be developed to prevent unauthorized users and devices from accessing the V2G networks. The techniques will combine device-based authentication, encrypted key exchange, and biometric verification to guarantee that only the intended individuals and devices can access the networks. Data integrity while in transit is guaranteed using advanced encryption standards like AES-256. Such measures protect against eavesdropping or interception by malicious parties [83].

Gaps and challenges in existing literature

Identifying and tackling any deficiencies and obstacles in the power transfer process between vehicles and the power grid, known as V2G, is crucial to effectively incorporating electric vehicles into the grid. A notable deficiency exists in the absence of standardized communication protocols and interoperability standards, impeding smooth interaction between car manufacturers and grid operators, as discussed in Table 3 [84]. The regulatory framework for integrating V2G systems is inadequate and lacks consistency across different locations. This necessitates the development of comprehensive and standardized laws that address technological, economic, and legal aspects. The low availability of V2G-enabled charging stations and grid connection points is a hurdle for infrastructure development. This requires more investment to facilitate the wider deployment of V2G systems [85]. The current absence of efficient bidirectional power flow management techniques and technologies necessitates the creation of sophisticated control systems to optimize power flow, considering grid limitations. Continued investigation is necessary to comprehend and alleviate the enduring consequences of frequent charge–discharge cycles on EV batteries due to concerns regarding battery degradation and lifespan [86]. The security of V2G systems is a significant concern, requiring strong measures to safeguard infrastructure against possible cyber assaults. The level of consumer understanding and acceptance of the benefits of V2G technology is still limited, underscoring the necessity for educational initiatives. The economic feasibility of V2G technology and the establishment of sustainable business models are similarly indeterminate, necessitating inventive strategies to motivate both EV owners and grid operators. Frequent charge–discharge cycles in V2G can accelerate battery degradation. Advances in BMS now employ predictive algorithms to minimize degradation by optimizing charging schedules and depth of discharge. For cybersecurity, blockchain-based protocols are emerging as solutions to secure V2G networks. For instance, encrypted peer-to-peer energy transactions prevent unauthorized access, ensuring data integrity and system resilience against cyber threats [87]. Interoperability remains a key challenge for V2G implementation. The lack of compatibility between Tesla's proprietary charging network and CHAdeMO standards has hindered seamless V2G integration across platforms. Similarly, consumer awareness of V2G benefits is limited. A 2022 survey revealed that only 25 % of EV owners in the US were aware of potential financial incentives for participating in V2G programs, highlighting the need for targeted educational campaigns and incentives [88].

Further investigation and resolution are necessary to address the scalability constraints and grid integration issues in large-scale V2G installations. Furthermore, the lack of consistent policy incentives and financial support for V2G initiatives poses a difficulty that can be overcome by implementing uniform and substantial policy measures that promote adopting V2G technology. To overcome these deficiencies and obstacles, different parties involved will need to work together to

Table 3
Gaps and Challenges in V2G Technologies.

Research Gap	Description	Proposed Solutions
Lack of Standardized Protocols	The absence of global communication standards hampers interoperability between EVs and grids.	Develop ISO 15118-based protocols for seamless V2G communication.
Battery Degradation	Frequent charge–discharge cycles reduce battery lifespan.	Implement AI-powered BMS for optimized charging.
Limited Consumer Awareness	Consumers lack an understanding of V2G benefits and incentives.	Conduct targeted awareness campaigns and offer financial incentives for participation.
Cybersecurity Risks	Vulnerabilities in V2G networks expose them to potential cyberattacks.	Employ blockchain-based security protocols and real-time threat detection systems.
Insufficient V2G Infrastructure	Limited availability of bidirectional chargers and grid connection points.	Increase investments in V2G-compatible infrastructure development.

fully use the capabilities of V2G power transfer [88]. The challenges in existing literature are shown in Fig. 6.

Bibliometric analyses

The methodology utilized for the bibliometric study on "V2G Integration in EVs" entailed a systematic and thorough approach, as shown in Fig. 7. The criterion for selecting publications for bibliometric analysis encompassed a variety of publication dates from the Scopus database, ensuring a current and pertinent dataset [89,90]. The selected source for data collection was Scopus, a well-regarded academic database [91]. The research used a renowned bibliometric tool called Biblioshiny by R-Studio and VOS-viewer. These techniques enabled the extraction and visualization of significant patterns within the literature [92]. The data analysis procedure involved multiple facets, commencing with an extensive examination of published literature to discern prominent patterns and influential works [93]. The study analyzed author keywords to identify dominant topics and then explored the bibliographic coupling of organizations to gain insights into collaborative networks. Analysis of country citations and journal and institution citations yielded valuable insights into the global impact of research. In addition, mapping country collaboration allowed for the visualisation of research initiatives involving collaboration between different countries [94]. An analysis was conducted to track the thematic development of keywords to comprehend the changing emphasis and developing subjects in the field. Implementing a comprehensive and diverse strategy allowed for a thorough and detailed examination of the research environment regarding the integration of V2G in EVs. This method yielded useful observations regarding this interdisciplinary topic's current state and development [95].

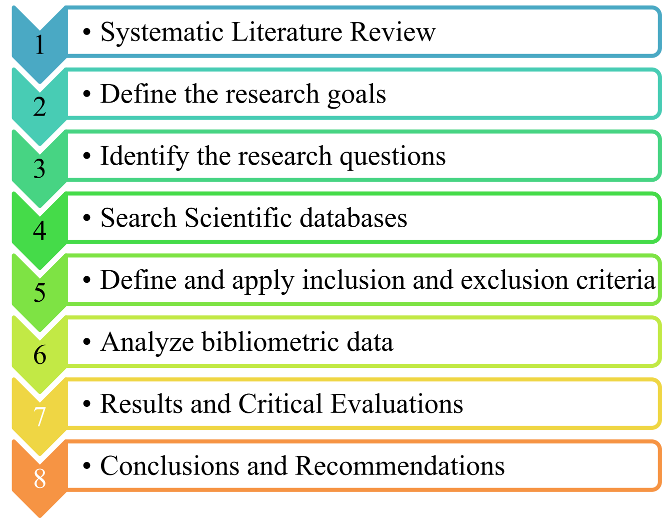

Fig. 7. Flow Chart of Methodology.

Selection criteria for bibliometric analysis

The literature search was performed using "titles, keywords, or abstracts" in the Scopus database. The subsequent search was executed as per [96,97]:

- The subsequent inclusion and exclusion criteria were implemented during the search phase [98].

Fig. 6. Challenges in Existing Literature.

- Conference proceedings and journal articles were the only sources incorporated. Grey literature materials such as books, conference papers, book chapters, and technical reports were excluded.
- The inclusion criteria were restricted to Research articles published from 1970 to 2023.
- Only journal articles written in the English language were incorporated.

A total of 21,535 articles met the relevance criteria specified in this search. The primary objective of this project was to examine the concept of V2G in EVs as a sustainable and eco-friendly approach to urban mobility. Consequently, the search results must meet the specific criteria the request sets. The search engine would have ignored journal articles that did not focus on low-carbon and sustainable EV systems and grid connectivity. The fundamental reason for using this methodology is to achieve transparency and traceability by replicating and verifying results using the given search criteria. Table 4 provides a comprehensive summary of a dataset containing academic publications. It offers specific information about the timeframe covered, patterns of citations, dynamics of authorship, and categories of documents. The dataset covers a significant period, from 1970 to 2023, comprising 16,457 documents. The average number of citations per document is 22.11, and the average age of the documents is 5.01 years.

The dataset exhibits a remarkable annual growth rate of 14.51 %, indicating a vibrant and developing nature. The records are sourced from a wide variety of 3,062 different sources, demonstrating the extensive coverage of the collection. Author collaboration is a notable factor, with an average of 3.84 co-authors per document, with foreign collaborations making up 20.63 %. The dataset contains a diverse range of terms, consisting of 24,571 keywords supplied by authors and an extra 38,962 supplementary keywords. The presence of 28,072 distinct authors emphasizes the extensive range of authors, and the document formats encompass a variety of categories such as articles, conference papers, reviews, conference reviews, and short surveys. Table 4 offers a thorough dataset overview, revealing its structure, expansion, and cooperation patterns among academic community members.

In bibliometric analysis, mainly using tools like Biblioshiny or VOS viewer, a strategic selection of keywords is essential for accurately capturing the breadth of literature on V2G integration in EVs. Core keywords such as “V2G,” “Electric Vehicles,” and “Bidirectional Charging” serve as the foundation for this analysis, enabling to explore the primary concepts and technologies involved. Technical keywords, including “Battery Degradation in EVs” and “Smart Charging,” facilitate a deeper understanding of the operational aspects and challenges associated with V2G systems. Economic and market keywords, such as “Techno-economic Analysis of V2G” and “Revenue Generation from V2G,” allow for an evaluation of the financial viability and market potential of V2G initiatives.

Table 4
Primary Information of the Scopus Database: V2G.

Description	Results
Main Information About Data	
Timespan	1970:2023
Average Citations Per Doc	22.11
Document Average Age	5.01
Annual Growth Rate %	14.51
Documents	16,457
References	403,738
Sources (Journals, Books, Etc)	3062
Authors Collaboration	
Single-Authored Docs	694
Co-Authors Per Doc	3.84
International Co-Authorships %	20.63
Document Contents	
Author’s Keywords (De)	24,571
Keywords Plus (Id)	38,962
Authors	
Authors Of Single-Authored Docs	574
Authors	28,072
Document Types	
Article	6922
Conference Paper	8560
Conference Review	314
Review	649
Short Survey	12

Environmental and sustainability keywords like “Decarbonization of Transport” and “Sustainable Mobility” highlight the broader implications of V2G integration on reducing greenhouse gas emissions and promoting clean energy solutions. Additionally, policy and regulatory keywords, including “V2G Policies and Regulations” and “Government Incentives for V2G,” emphasize the importance of the regulatory framework in facilitating or hindering V2G adoption. Finally, research and innovation keywords, such as “V2G Pilot Projects” and “Consumer Attitudes Toward V2G,” provide insight into emerging trends and public perceptions, enabling a comprehensive review of the current state and prospects of V2G technology. By effectively utilizing these keywords in Biblioshiny, researchers can conduct thorough bibliometric analyses that reveal significant patterns, trends, and gaps in the literature surrounding V2G integration in electric vehicles.

Bibliometric tools and techniques

Bibliometric methods and approaches are essential for analyzing and evaluating scholarly literature, offering scholars and institutions significant insights into the academic publication scene. Biblioshiny, developed by R-Studio and VOS-Viewer, is one of the many tools utilized.

Biblioshiny by r-studio

Biblioshiny is a bibliometric analysis tool created using the R programming language. It is specifically built to have a user-friendly interface that can be accessed through a web-based platform. R-Studio’s Biblioshiny offers a wide array of features for conducting bibliometric analysis, making it an important tool for scholars who want to examine and depict patterns in their academic data [99]. A notable characteristic of the software is its capability to conduct co-authorship analysis, enabling users to discern collaboration patterns among authors. Moreover, Biblioshiny enables the examination of keyword co-occurrence, revealing the prominent thematic correlations in the literature [100]. The tool’s interactive and dynamic visualizations improve the comprehensibility of intricate bibliometric data, allowing users to personalize and enhance their studies. Researchers can investigate citation networks, examining the effects and influence of particular papers or authors. The integration of Biblioshiny with R allows users to utilise the powerful statistical capabilities of the computer language, enhancing the depth and accuracy of their bibliometric analysis. Biblioshiny is a potent tool for academics, particularly those with different degrees of programming proficiency, due to its user-friendly interface and seamless integration with the R environment [101,102]. Fig. 8 displays the diverse characteristics of the Biblioshiny tool developed by R-Studio.

Vosviewer

VOS-viewer is a robust and flexible bibliometric analysis tool extensively utilized in the academic and research community to represent and examine intricate networks within the scholarly literature visually. VOS-viewer, created by Nees Jan van Eck and Ludo Waltman, is notable for its user-friendly interface and ability to convert complex bibliometric data into visually beautiful maps that are easy to understand [103]. The program is widely recognized for its capacity to manage extensive datasets, rendering it highly beneficial for academics investigating a wide range of subjects. VOS-viewer’s network visualization is a prominent feature that enables users to visually represent connections between different things, such as authors, keywords, or

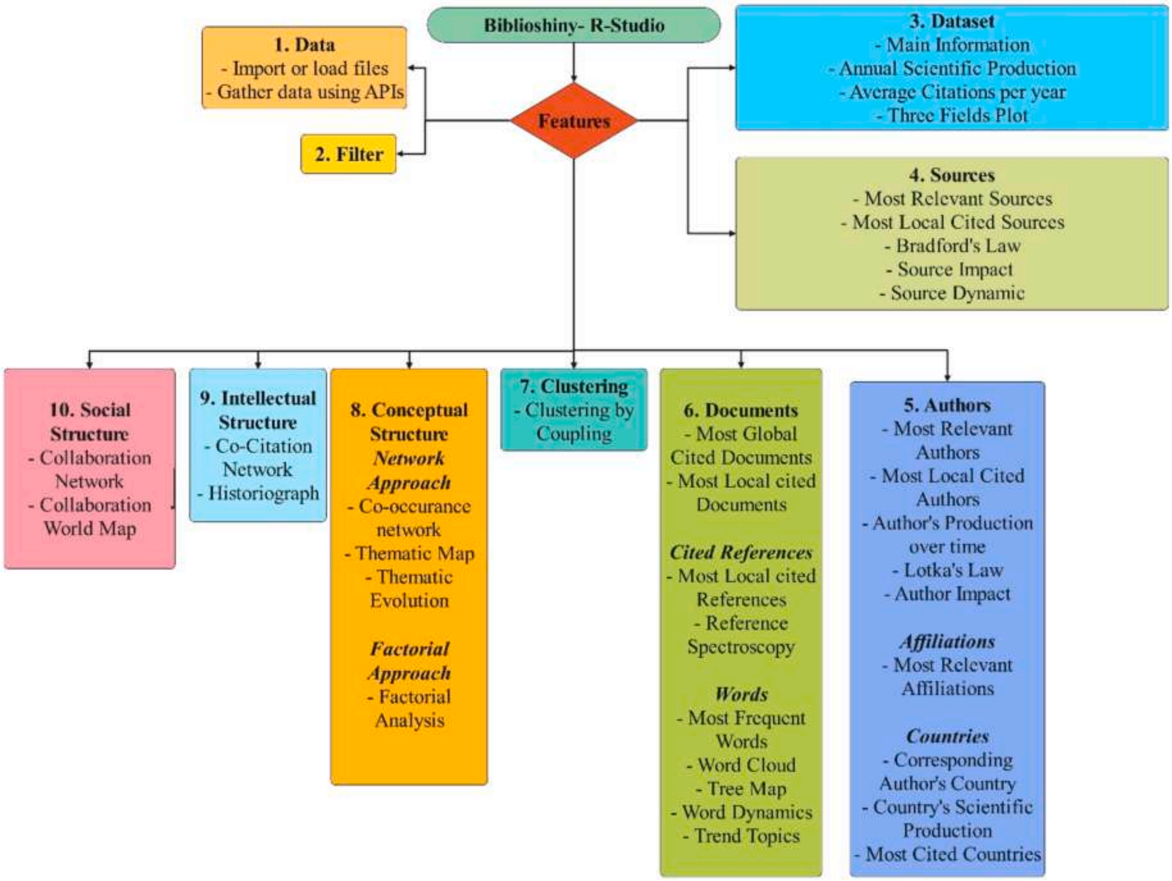

Fig. 8. Features of Biblioshiny.

publications [104]. The software utilizes sophisticated algorithms to uncover patterns and correlations within these networks, allowing users to pinpoint clusters of connected information. For example, in integrating V2G with Electric Vehicles, VOS-viewer can assist in identifying thematic clusters associated with particular technologies, research patterns, or collaborative networks among universities.

VOS-viewer can analyze networks such as co-authorship, bibliographic coupling, and co-citation networks. Due to this adaptability, researchers can investigate different aspects of academic communication and collaboration [105]. Furthermore, the application offers customization features, allowing users to modify factors such as node size, color, and label to improve the comprehensibility of visualizations. In addition, VOS-viewer effortlessly incorporates data from prominent bibliographic databases like Scopus, Web of Science, and PubMed, streamlining the process of importing data for users. The software's ability to work with various file formats allows it to be easily used and adjusted to meet different research requirements [106]. To summarize, the VOS-viewer is an indispensable tool for researchers involved in bibliometric study, providing an effective and visually captivating method to investigate and comprehend intricate connections within scholarly literature. VOS-viewer's network visualization capabilities, user-friendly features, and interoperability with key databases make it an essential tool for scholars seeking profound insights into the structure and dynamics of academic knowledge landscapes [107].

Data analysis process

Researchers employ a methodical strategy when utilizing Biblioshiny and VOS-viewer for data analysis to extract significant insights from bibliometric data. In Biblioshiny, the procedure commences typically by importing the bibliographic data, which encompasses details regarding authors, publications, and citations. Subsequently, users can employ the user-friendly online interface to conduct diverse analyses, including co-authorship analysis, keyword co-occurrence analysis, and citation network investigation [108]. The application produces interactive visualizations that enable researchers to dynamically explore and personalize their data's depiction. Moreover, incorporating the R programming language offers enhanced statistical functionalities for more comprehensive analysis. Users can generate visual representations of networks that show the relationships between co-authors, citations, and keyword co-occurrences. The tool utilizes clustering methods to detect theme groupings within the dataset [109]. The generated visualizations are dynamic and interactive, allowing users to examine, analyze, and personalize the display of bibliometric data. This provides a complete perspective on the underlying structures and connections within the academic literature. These technologies enable scholars to perform comprehensive bibliometric studies, facilitating a more profound comprehension of collaboration patterns, research themes, and the influence of scholarly works [110,111].

Trends and patterns in V2G research

The latest research on V2G has revealed notable trends and patterns that indicate an increasing focus on integrating renewable energy sources into the grid. Scientists have investigated the two-way energy transfer of EVs to help maintain the stability of the power grid, mainly when there is sporadic generation of renewable energy. Furthermore, there is an increased emphasis on the significance of V2G systems in delivering grid services and engaging in ancillary markets, enhancing grid dependability and efficiency. Investigations have focused on developing communication protocols and smart grid technologies to facilitate secure and efficient interactions among EVs, charging infrastructure, and the grid. Furthermore, research has focused on analyzing policy and regulatory factors that hinder or encourage the widespread implementation of V2G technology. Additionally, efforts have been made to comprehend the effects of V2G on the deterioration of electric car batteries. These trends demonstrate a diverse strategy to promote incorporating V2G systems into the changing field of sustainable energy solutions.

Publication trends over time

Fig. 9 presents a simplified representation of publication trends over time. It especially shows the annual number of papers published from 1970 to 2023. Upon detailed analysis of the data, significant patterns and changes in research output throughout this period become apparent. From 1970 to the early 1980 s, there was a clear lack of publications, with only occasional occurrences of one or two pieces each year. This indicates that the study of this particular field is still in its early stages.

Nevertheless, since the mid-1980 s, there has been a noticeable increase in publications, suggesting a rising interest or acknowledgment of the topic. A consistent rise in research production was noticed during the late 1990 s and early 2000 s, which stands out as the most significant trend. The annual publication count undergoes a significant spike, surpassing ten in the late 1990 s and steadily rising in the following years.

This growth becomes even more noticeable in the early 2010 s, indicating a period of substantial expansion in the field. In the early 2010 s, there was a significant shift, as the number of articles exceeded 200 in 2010 and then dramatically increased to over 600 in 2012. The number of publications surpassed 1,000 in 2017 and has consistently increased in the following years. In 2022, a significant peak with 2369 articles will be produced, indicating a strong and thriving research environment. The statistics for 2023 indicate a significant decline in the number of publications, with a total of 1314. Multiple variables may contribute to this decrease, such as data collection constraints, research emphasis changes, or fluctuations in financial support and resources. It is crucial to read this reduction cautiously, acknowledging that it can indicate a transitory departure rather than a long-lasting trend. The chart highlights the ever-changing character of research efforts in the selected field, with clear periods of expansion and stabilization. The significant and consistent increase in the quantity of published articles over time suggests that the topic has undergone development growth and gained more interest from researchers. The transient decline in 2023 necessitates additional investigation into possible causative elements and emphasizes the importance of comprehending the surrounding circumstances when scrutinizing enduring publication patterns.

Geographic distribution of research

The diagram in Fig. 10 provides a detailed analysis of the geographical dispersion of research, revealing the frequency of papers associated with different countries or areas and publication counts are depicted in Table 5. China's dominance in the worldwide research environment is evident, with a remarkable frequency of 13,919 publications, highlighting its formidable position. China's dominance in this area aligns with its strategic investments in research and development, which demonstrate its dedication to increasing scientific knowledge. The United States closely trails after with 8,837 publications, reinforcing its longstanding position as a prominent contributor to worldwide academic production. India's significant research effort, as evidenced by 5,326 articles, demonstrates the country's increasing impact and involvement in academic pursuits. The frequency of 3,140 papers from Germany underscores the country's substantial research contributions, showcasing its expertise in diverse academic fields. Italy, the UK, Canada, and Iran also demonstrate significant research activity, adding to the extensive and varied involvement in research across continents. This table highlights the international scope of academic study, demonstrating governments' diverse and complex research capabilities worldwide. The variations in frequency among countries suggest differences in research agendas, areas of focus, and academic capabilities, offering significant insights into the global panorama of intellectual activities. The geographic analysis highlights distinct regional focuses in V2G research.

Research predominantly centers on grid integration and renewable energy utilization in China, driven by government-led initiatives for renewable energy dominance. With strong government support, the country has made significant strides in developing V2G systems that assist in balancing energy supply from intermittent sources like solar and wind. China is also leading efforts to integrate EVs with the national grid to stabilize demand peaks.

United States efforts focus on battery optimization, as seen in advancements in BMS and large-scale V2G pilot programs, such as those in California. The U.S. leads in battery optimization for V2G applications. Research in California, for example, focuses on enhancing BMS to ensure that frequent charge–discharge cycles do not degrade the EV battery life. The U.S. also leads in large-scale pilot programs, exploring how V2G can be integrated into urban and rural grid systems.

Europe emphasizes standardization and policy development, supported by EU-funded projects aligning with the European Green Deal. These regional trends reflect priorities shaped by local energy policies, market demands, and technological capacities. The EU strongly emphasizes policy-driven research that supports V2G as part of a broader

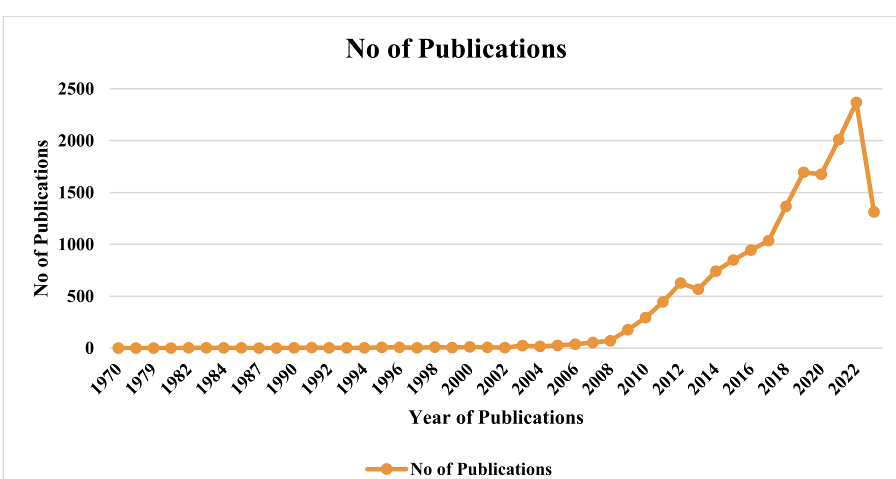

Fig. 9. Research paper publications from the Scopus database: V2G.

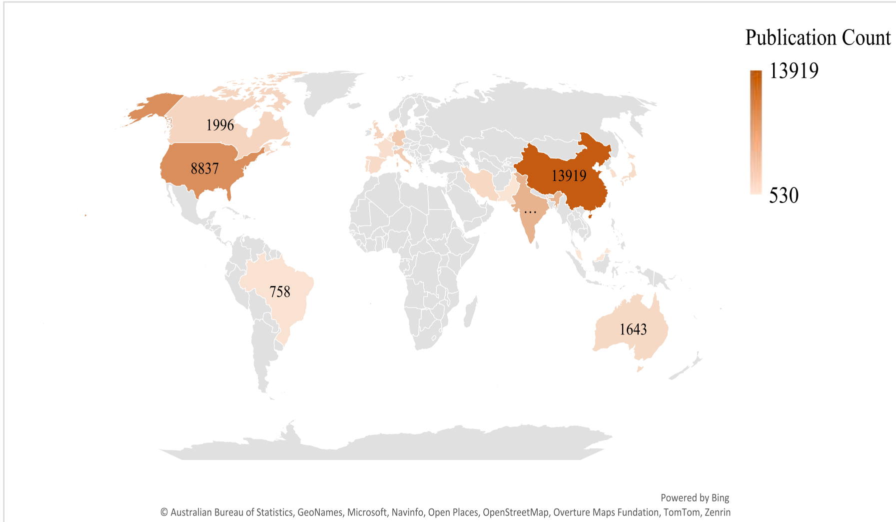

Fig. 10. Geographic Distribution of V2G Research.

Table 5
Geographic Distribution of Research in Top 20 Countries.

Countries	Publication Count
China	13,919
USA	8837
India	5326
Germany	3140
Italy	2879
UK	2161
Canada	1996
Iran	1769
Australia	1643
Spain	1470
Japan	1378
Portugal	1227
France	1202
South Korea	1093
Denmark	1088
Netherlands	925
Brazil	758
Pakistan	619
Belgium	605
Malaysia	530

green energy agenda. Countries like Germany and the UK have focused on creating interoperable standards for charging infrastructure to facilitate widespread V2G adoption, making it a critical development area for cross-border energy systems.

Key journals and conferences

During the data collection process from the Scopus database, conference publications were excluded and not considered for the analysis. Fig. 11 provides a detailed summary of the leading 20 journals in the discipline, displaying the quantity of articles produced in each. "Energies" is the leading journal, with 739 articles highlighting its importance as a comprehensive resource for energy-related research. "Applied Energy" has a strong presence in energy studies, with 356 articles focusing on practical energy applications. "IEEE Access," featuring 332 articles, is a prominent open-access platform covering various issues in electrical engineering and its associated disciplines. The magazine "Energy" is a prominent and comprehensive source covering many topics. It has contributed 281 papers to the field. The "IEEE Power and Energy Society General Meeting" is a prominent conference publication that showcases 277 articles and is a major platform for research in power and energy systems. The "International Journal of Electrical Power and Energy Systems" is dedicated to electrical power systems and contains 190 articles.

On the other hand, "Electric Power Systems Research" enhances power systems research with 165 articles. Additional prominent publications inside the top 20 are "Journal of Energy Storage,“ "Renewable and Sustainable Energy Reviews," and "Journal of Power Sources." These journals underscore the interdisciplinary character of energy research, encompassing areas such as storage technologies, sustainability, and power sources. These periodicals jointly contribute to the progress of knowledge in several aspects of energy research.

Keyword analysis

Keyword analysis is an essential component of bibliometric research that entails examining and interpreting the keywords employed in scholarly publications. This study offers valuable insights into the fundamental themes, patterns, and central focus areas within a specific research field. Keyword analysis is valuable in the V2G integration study for identifying commonly used and influential terms. This analysis enables researchers to determine the main subjects and areas of focus in the literature. By analyzing the frequency and simultaneous appearance of specific terms, scholars may reveal the changing patterns and trends within the discipline, effectively monitoring the shifts in study emphasis throughout the years.

Author keywords

The 50 most prominent author keywords in the domain of EVs and V2G are shown in Fig. 12. Integration indicates a varied and multifaceted terrain. EVs, the most prevalent keyword, primarily emphasize electrified mobility. The presence of keywords such as Smart Grid, Microgrid, and Renewable Energy indicates a significant focus on integrating EVs into intelligent and sustainable energy systems [112]. Vehicle-to-grid (V2G) and its acronym (v2g) emphasize the importance of investigating the bidirectional energy exchange between EVs and the power grid. Optimization and energy storage are key areas of study, aiming to improve efficiency and tackle the issues associated with storing energy in the context of electric mobility. The increasing use of terminology like Smart Charging, Energy Management, and Charging Stations highlights the need to create intelligent and effective charging infrastructure for EVs. Distributed Generation and Distributed Energy Resources represent a decentralized method of generating power and emphasize the contribution of EVs to distributed energy systems. The

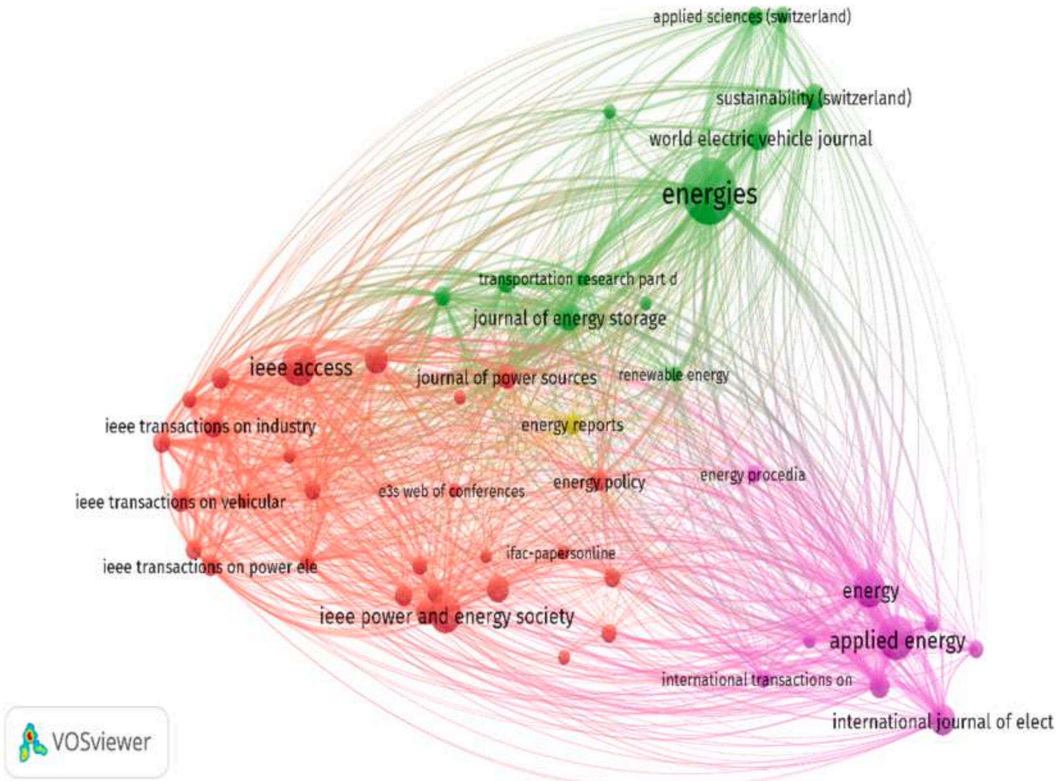

Fig. 11. Key Journals Sources V2G.

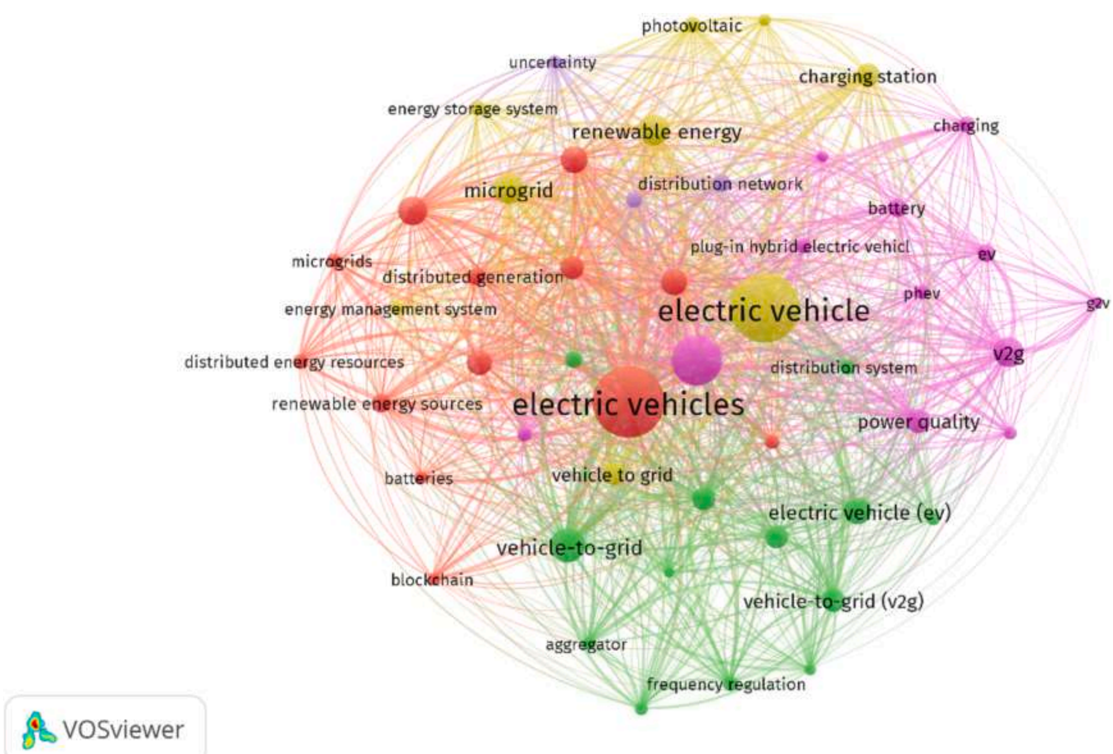

Fig. 12. Top 50 Author Keywords.

focus on Power Quality, Frequency Regulation, and Ancillary Services indicates grid stability and reliability maintenance.

Furthermore, the inclusion of distinct EV-related words such as Electric Vehicle (EV), EVs, and Plug-in Hybrid Electric Vehicle (PHEV) indicates a detailed examination of several categories of electric vehicles. Battery, Battery Degradation, and Batteries emphasize the importance of energy storage technologies and the difficulties related to battery performance and lifespan. Innovation and emerging technologies, such as Blockchain, are apparent in terms of the pursuit of advanced solutions in the electric vehicle (EV) and vehicle-to-grid (V2G) domain [113]. In general, the keyword analysis thoroughly examines several subjects, including technical features such as Power Quality and Optimization and broader concepts like Renewable Energy and Smart Grids. This demonstrates the interdisciplinary character of study in this sector.

Thematic evolution of keywords

A themed review was conducted to analyze the frequently used terms encountered by many research scientists between 1970 and 2023. The theme graph in Fig. 13 displays keywords such as “secondary batteries,“ “electric vehicles,” and “automobiles.” The depicted graph spans the time frame from 1970 to 2015. The most often used terms between 2016 and 2018 were “electric power transmission networks,” “smart power grid,“ “electric vehicle,” “dc-dc converters,” and “lithium-ion batteries.” During the period from 2019 to 2023, the terms that were often used included “electric power system control,“ “electric power distribution,” “smart grid,“ “greenhouse gases,” “electricity,” and “unmanned aerial vehicles (UAV).”.

Mapping of country collaboration

The purpose of this analysis is to demonstrate the joint efforts that have been made by many nations in order to produce research articles addressing the transition from trucks to grids for electric vehicles. Following careful consideration, it has been decided that the darkened bubble maximum will serve as a representation of the cooperation. Fig. 14 illustrates the network of countries that have collaborated with one another. China is the country that maintains the greatest number of partnerships with the United States of America, followed by India, the United Kingdom, Germany, Denmark, Canada, France, Australia, Switzerland, the United Arab Emirates, and Turkey.

Citation analysis

Citation analysis is a systematic method used in bibliometrics to assess the influence and importance of academic works in the academic community. This analysis evaluates the frequency with which a specific document, such as an article or book, is referenced by other publications. The quantity of citations functions as a quantifiable indicator of the impact of the work, indicating its prominence and significance within the academic community. Researchers analyze citation numbers and patterns to gain insights into the context and characteristics of references. This meticulous analysis aids in determining if a piece of work is referenced favorably, unfavorably, or impartially, enhancing one’s comprehension of its influence. Citation analysis goes beyond analyzing individual publications, enabling academics to assess the influence of authors and journals by considering the total number of citations they have received. By examining citation data, researchers acquire valuable understanding regarding knowledge development, ascertain the individuals who have had a significant impact, and assess the importance of specific research outputs. Citation analysis is essential for mapping the intellectual landscape and helps scholars, institutions, and publishers evaluate the academic influence of published works. Fig. 15 is the spectroscopic analysis of Citations.

Highly cited publications

The given data shows a compilation of extensively referenced articles, as depicted in Fig. 16. Each publication is recognized by its primary author(s) and the matching count of citations it has received. The numerical values assigned to each publication represent the number of citations, which measure the importance and significance of these works in their particular areas of study. An example of this is the research conducted by Dunn in 2011, which has received a remarkable 10,734 citations, demonstrating its significant impact on the academic world. Lin’s paper, in 2017 accumulated 4,147 citations, but Kamaya’s work, in 2011, obtained 3,238 citations. Palomares, Clement-Nyns, and Yilmaz have authored papers that have received significant attention, with citations of 2,969, 2,329, and 2,085, respectively. The list includes more significant publications, including Cabana’s 2010 article with 2,078 citations, Weiland’s 2010 work with 1,991 citations, Kempton’s 2005 contribution with 1,780 citations, and Wu’s 2012 paper with 1,770 citations. These publications, which have received significant citations, demonstrate their considerable influence on research in their respective fields, underscoring the recognition and significance attributed to these works by the academic community.

Technical analysis of top-cited papers

Dunn et al. (2011) examined various battery systems designed for grid applications. These systems included sodium-sulfur batteries, which are commercially available, redox-flow batteries, which are economical, and the conversion of lithium-ion batteries from electric vehicles and commercial electronics for grid storage [114]. Lin et al. (2017) comprehensively reviewed the current knowledge concerning lithium anodes. The authors highlighted recent progress in materials design and advanced characterization techniques while examining potential avenues and prospects for the future advancement of lithium anodes across diverse applications [115]. Kamaya et al. (2011) developed $Li_{10}GeP_2S_{12}$, a lithium superionic conductor with a three-dimensional framework. Its lithium ionic conductivity reached 12 mS cm − 1 at ambient temperature, surpassing liquid organic electrolytes. This solid-state battery’s electrolyte offered simplicity in device manufacture, stability, safety,

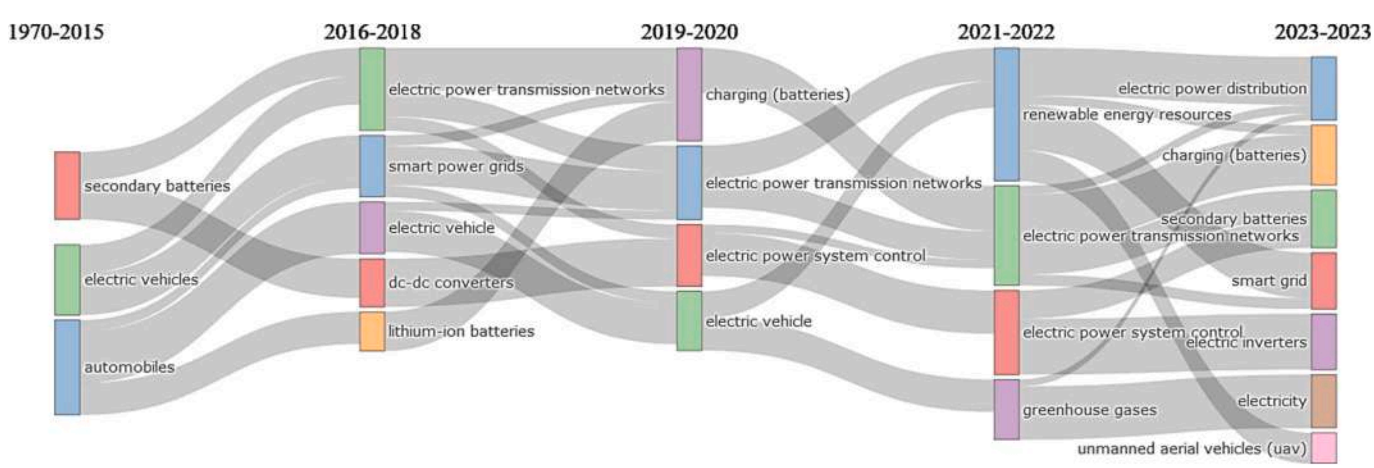

Fig. 13. Thematic Evolution of Keywords.

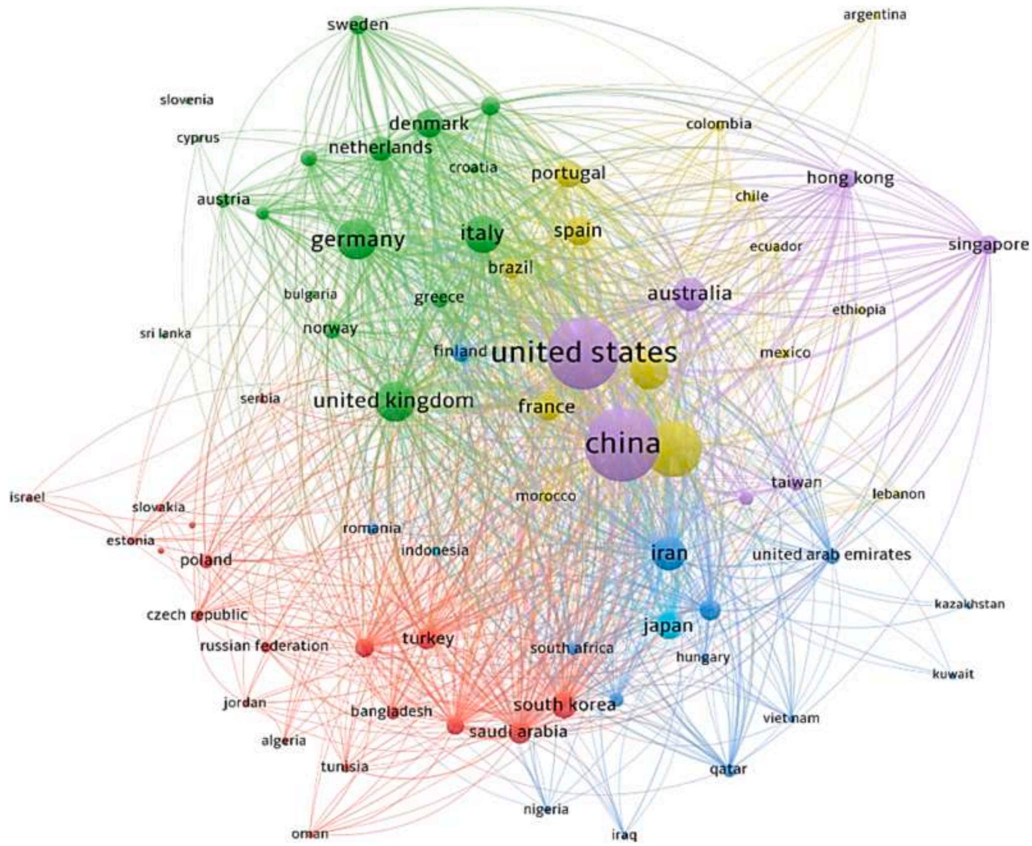

Fig. 14. Country Collaboration Map.

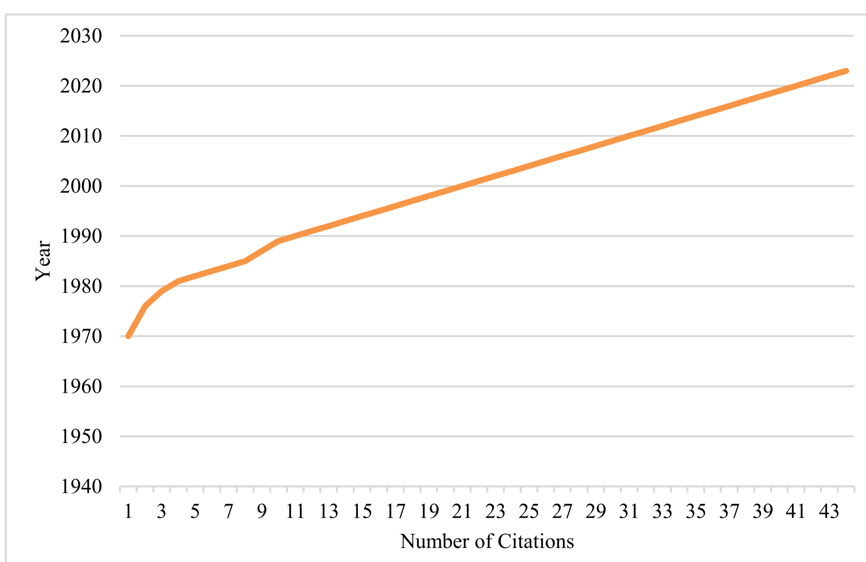

Fig. 15. Citation Analysis Spectroscopy.

and remarkable electrochemical properties, including high conductivity and a large potential window [116].

Palomares et al. (2012) compiled the most recent data on Na-ion battery materials to provide a foundation for future research in this battery technology and a comprehensive overview of previously investigated systems [117]. Kristien Clement-Nyns et al. proposed coordinated charging in 2009 to decrease power losses and improve the load factor of the primary grid. The optimal charging profile for plug-in hybrid electric vehicles was calculated to reduce power losses. Accurate prediction of household burdens was deemed impracticable; therefore, stochastic programming was implemented. Two primary techniques, quadratic and dynamic programming, were examined [118]. In 2013, Murat Yilmaz et al. assessed plug-in EVs and hybrid battery chargers, power levels, and infrastructure. Unidirectional or bidirectional power transfer distinguished off-board and on-board charging systems. Integrating the electric drive reduced weight, space, and cost constraints on onboard adapters. Charging infrastructure reduced on-board energy storage costs and requirements [119].

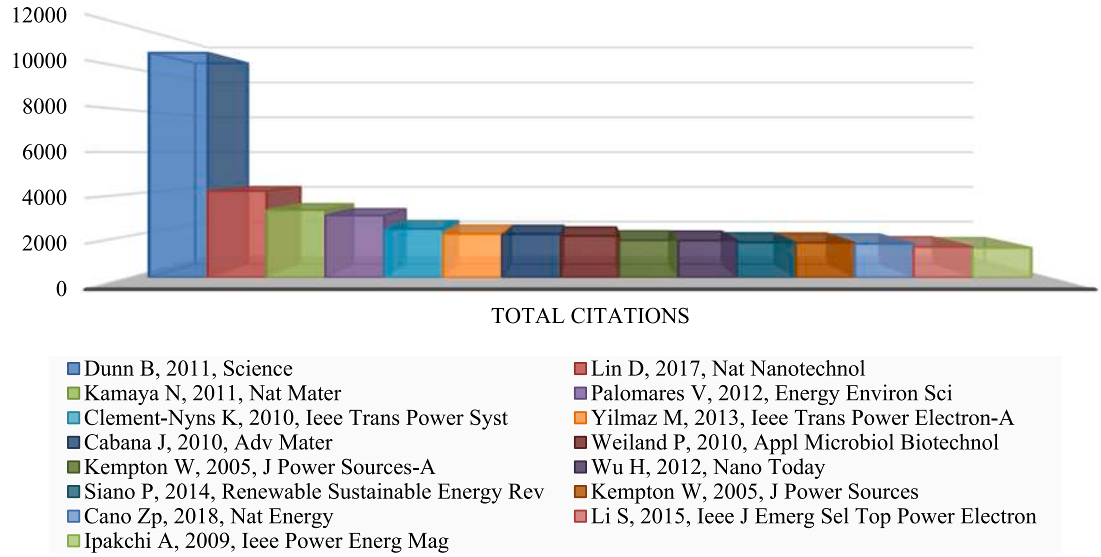

Fig. 16. Citation Analysis of Publications.

Recently developed phases undertaking conversion reactions as positive and negative electrode materials for Li-ion batteries were discussed in 2010 by Jordi Cabana et al. Compared to conventional intercalation reactions utilizing graphite and $LiCoO_2$, these materials exhibited specific capacities between two and five times greater. The report detailed these obstacles and the scientific progress required to assess the viability of this strategy, which impeded the practical implementation of these electrode materials [120]. Kempton et al. estimated grid power capacity for three electric drive vehicles and examined the revenue and costs of supplying electricity to peak power, spinning reserves, and regulation markets in 2005. The research showed that Vehicle-to-Grid (V2G) electricity offers many benefits, including additional money from cleaner automobiles, power grid stability, lower system costs, and renewable energy redundancy [121]. Hui Wu et al. (2005) studied three significant difficulties related to large-volume material changes and showed how nanostructured materials design might address them. The authors identified three generations of nanostructure design: solid nanowires, hollow nanostructures, and clamped hollow structures. Silicon-based nanoscale design ideas apply to other battery materials with large-volume changes [122].

In 2014, Pierluigi Siano surveyed demand response (DR) potentials and benefits within smart grids. The paper outlined innovative technologies and systems, such as smart meters and energy controllers, crucial for coordinating efficiency and DR in smart grids. Real industrial case studies and research projects were referenced and discussed in the context of these enabling technologies [123]. Willett Kempton et al. presented V2G business concepts and tactics in 2005. The authors described V2G deployment procedures and highlighted its ability to store renewable energy as manufacturing costs fall. Their calculations show that V2G can stabilize wind energy on a wide scale if a percentage of the vehicle fleet is reserved for operational and regulatory reserves. They selected jurisdictions expected to lead V2G adoption [124]. Cano ZP et al. examined commercially viable batteries and hydrogen fuel cells in 2018. They targeted long-range, low-cost, high-utilization transportation areas underserved by lithium-ion electric vehicles. To properly enable electric car markets, technology must enhance particular energy, cost, safety, and power grid compatibility [125]. Table 6 shows the key findings and citations of the most valuable research articles used by various authors as references in their prominent articles.

Future directions: V2G

EVs are becoming increasingly integrated into our daily lives. A groundbreaking technology known as V2G is ready to transform our understanding and interaction with energy. EVs can both receive electricity from the grid and return their stored energy, effectively functioning as small-scale power stations [126]. This presents a multitude of potential opportunities for the future of sustainable energy. Imagine a future in which millions of stationary EVs and fully charged batteries are part of an extensive and decentralized energy storage network [127]. During periods of high demand, they can return their excess electricity to the power grid, thereby stabilizing the demand and decreasing the need for peak generators that rely on fossil fuels. This reduces emissions and enhances grid stability, rendering it less vulnerable to blackouts. Consider it a formidable force of energy troops prepared to be deployed at the command of the grid [128].

However, V2G serves a purpose beyond mere interaction with the power infrastructure. It is a mediator, effortlessly incorporating sustainable energy sources such as solar and wind. Excess renewable energy can be stored in EV batteries during periods of abundant sunlight and wind, guaranteeing its availability even during periods of low solar or wind activity [129]. This establishes a sustainable energy system in which renewable sources dominate, and electric vehicles serve as their dedicated storage units. The advantages transcend the grid. Envision your electric vehicle serving as a residential energy storage system, supplying power to your home during periods of high demand or a power outage [130]. Integrating V2H (Vehicle-to-Home) technology can significantly improve energy self-sufficiency and ability to withstand challenges, particularly in areas susceptible to risks. It is akin to possessing a personal power station in your driveway, readily available to illuminate your life whenever required. Naturally, this visionary concept demands more than mere hopeful speculation. Consistent technology and infrastructure are essential for smooth interactions between EVs and the power grid. Advanced charging algorithms must be developed to optimize energy exchange according to individual requirements and grid demands [131].

Furthermore, it is imperative to implement resilient cybersecurity protocols to safeguard against cyber assaults and guarantee the confidentiality of data. The future may present challenges, but the potential of V2G technology is unquestionable. This innovation is not merely a fascinating technique for electric vehicles; it is a crucial component in constructing a more environmentally friendly, robust, and fair energy landscape [132]. Through ongoing research, technological progress, and favorable legislation, V2G technology has the potential to revolutionize the methods by which we produce, store, and utilize energy. This can lead to a future that relies on renewable energy sources and is driven by

Table 6
Technical findings of top-cited papers.

Author/ Year/Ref.	Key Findings	Citations Count	Remarks
Dunn et al. (2011) [114]	Battery systems for grid applications were investigated, including redox-flow and sodium-sulphur batteries, in addition to the conversion of lithium-ion batteries.	10,734	Highlighted prospective benefits and drawbacks of technologies analyzed for grid application and storage.
Lin et al. (2017) [115]	An overview of lithium anodes, focusing on recent advances in materials design and characterization and future applications.	4147	This article challenges and advances in lithium anode technology to provide insight for future research and development.
Kamaya et al. (2011) [116]	Suitable for solid-state batteries, $Li_{10}GeP_2S_{12}$ is a lithium superionic conductor with high conductivity, stability, and safety.	3238	Presented an innovative solid-state battery electrolyte that offers notable benefits, establishing a foundation for subsequent battery advancements.
Verónica Palomares et al. (2012) [117]	A comprehensive overview of previously studied systems and a foundation for future research were established by compiling recent data on Na-ion battery materials.	2969	Analyzed the current state of Na-ion battery technology, pinpointing potential avenues for additional research and development.
Kristien Clement-Nyns et al. (2009) [118]	Utilizing stochastic programming techniques, coordinated charging for plug-in hybrid electric vehicles is proposed to reduce power losses and increase grid load factor.	2329	Methods recommended for optimizing electric vehicle charging profiles to increase the grid's stability and efficacy.
Murat Yilmaz et al. (2013) [119]	Power levels, infrastructure, and plug-in electric vehicle and hybrid battery converters were evaluated, and the advantages and disadvantages of on-board and off-board charging systems were highlighted.	2085	Identified areas for development in the infrastructure and technology deemed essential for the widespread adoption of electric vehicles.
Jordi Cabana et al. (2010) [120]	The potential for increased specific capacities of phases undertaking conversion reactions for Li-ion batteries was illustrated compared to conventional intercalation reactions.	2078	Examined novel electrode materials for lithium-ion batteries, elucidating the potential advantages and obstacles associated with their deployment.
Kempton et al. (2005) [121]	With an emphasis on the advantages of V2G technology, the estimated grid power capacity for electric vehicles and the revenue and costs of supplying electricity to various markets were investigated.	1780	The potential of V2G technology to improve grid stability and facilitate the integration of renewable energy sources was assessed, with recommendations for future research.
Hui Wu et al. (2005) [122]	Examined difficulties associated with substantial volume changes in materials and suggested the design of nanostructured materials as a remedy, delineating three iterations of nanostructure design.	1770	Analysed novel methodologies for mitigating volume change concerns in battery materials, providing valuable insights that can inform forthcoming material design approaches.
Pierluigi Siano (2014) [123]	Undertook an investigation into the potential and advantages of demand response in the context of smart grids, emphasizing the contribution of cutting-edge technologies like smart meters and energy controllers to improving grid efficiency.	1673	Utilizing real-world case studies to examine the potential of demand response technologies to enhance the efficacy and stability of the electrical grid.
Willett Kempton et al. (2005) [124]	Demonstrated business strategies and concepts for V2G, evaluated its potential to stabilize wind energy, and recommended jurisdictions likely to be at the forefront of V2G adoption.	1662	Examined business models and implementation strategies for V2G technology, emphasizing its capacity to integrate renewable energy sources and stabilize the grid.
Cano ZP et al. (2018) [125]	Analyzed batteries and hydrogen fuel cells that are commercially viable, with a focus on underserved sectors of the electric vehicle market, and identified technological advancements required for widespread adoption.	1611	Examining nascent technologies within the electric vehicle industry, analyzing their capacity to overcome existing constraints and stimulate market expansion.

innovative solutions. Prepare yourself, as the journey towards a V2G revolution is just commencing, and it is an experience you wouldn't want to overlook [133].

Identified gaps in current V2G literature

The V2G technology, which enables electric cars (EVs) to supply electricity to the grid, has great potential for fostering a cleaner and more robust energy future. However, like any groundbreaking technology, V2G encounters several obstacles that hinder its wider use. An obstacle of significant magnitude is the absence of standardization [134]. Currently, V2G technology can be likened to a scenario where a highway is occupied by cars communicating in several languages. The lack of standardized communication protocols and compatible infrastructure between different power grids and areas creates significant challenges in facilitating smooth energy exchange.

Furthermore, although bidirectional charging technology is available, it lacks the necessary speed and efficiency. Consider it akin to a gradual and continuous replenishment, in contrast to the swift and immediate refueling process we are accustomed to at petrol stations. The lack of responsiveness can deter EV owners from engaging in V2G programs [135].

The condition of the battery is another area of worry. Like humans, EV batteries also have a finite lifespan, and numerous charging and discharging cycles might have a negative impact. Scientists are developing sophisticated algorithms and monitoring systems to enhance battery efficiency and prolong lifespan. However, further efforts are required to guarantee that V2G technology does not reduce battery life for EV owners [136]. In addition to the technical challenges, there are also economic and regulatory obstacles to overcome. Encouraging EV owners to function as small-scale power generators necessitates providing them with transparent economic incentives and equitable pricing structures. Consider proposing a significantly lower energy stored in your car – not enticing.

Furthermore, it is imperative to implement favorable rules and laws to effectively tackle liability concerns, overcome grid integration obstacles, and resolve ownership issues. Consider it as maneuvering through a complex legal labyrinth without a guide – certainly not a seamless journey. Ultimately, it is imperative to close the existing disparity in knowledge [137]. Additional empirical data is required to comprehensively comprehend the actual performance of V2G technology in various contexts. Attempting to implement V2G deployment without a blueprint is like constructing a home without a plan. Moreover, researching consumer behavior and preferences is essential to developing efficient programs incentivizing electric vehicle owners to participate. Consider it as comprehending your audience before staging a play – knowing what drives individuals is crucial to their involvement [138].

Recommendations for future research

The potential of V2G technology, in which EVs can function as two-way energy conduits, holds great promise, as shown in Fig. 17. However, to achieve clean energy, significant obstacles must be overcome, akin to potholes. Standardization is essential for facilitating smooth and uninterrupted data transmission, like establishing a universal language that allows EVs to connect to any energy source [12]. Accelerated DC-DC converters need to increase the rate of energy transfer, rendering V2G a rapid and convenient refueling station for our portable power generators on wheels. Battery health management systems, which protect these energy sources, necessitate sophisticated algorithms to maximize utilization and prolong their lives, guaranteeing a lengthy and fruitful V2G career. To persuade EV owners, it is necessary to provide them with economic incentives such as attractive market models and pricing schemes that offer rewards for their efforts in decreasing peak demand and mitigating carbon emissions [43]. A well-defined plan is necessary for the legal and regulatory domain, encompassing frameworks that address concerns related to liability, obstacles in integrating with the grid, and issues about ownership. This will guarantee a seamless transition. The data collected from V2G pilot projects in the real world will serve as a guide to help us navigate beyond the technological aspects. This data will help bridge the gap between technology and human behavior by incorporating social science and consumer research. Moreover, V2G has the capacity to go beyond grid assistance by effectively integrating with renewable energy sources and demand-side control programmes [139]. This collaboration establishes a robust and environmentally friendly energy system for a more sustainable future. By prioritizing these crucial domains, we can convert V2G from a hopeful idea into a concrete actuality, supplying our residences, enterprises, and urban areas with environmentally friendly and dependable power, ultimately paving the way for a V2G revolution that will alter our connection with energy [140].

Challenges and opportunities: V2G

The alluring concept of V2G, in which electric vehicles serve as two-way energy conduits, is on the verge of becoming a reality, offering the potential for a more environmentally friendly and intelligent energy landscape. However, like any groundbreaking expedition, the path toward universal acceptance is fraught with obstacles disguised as

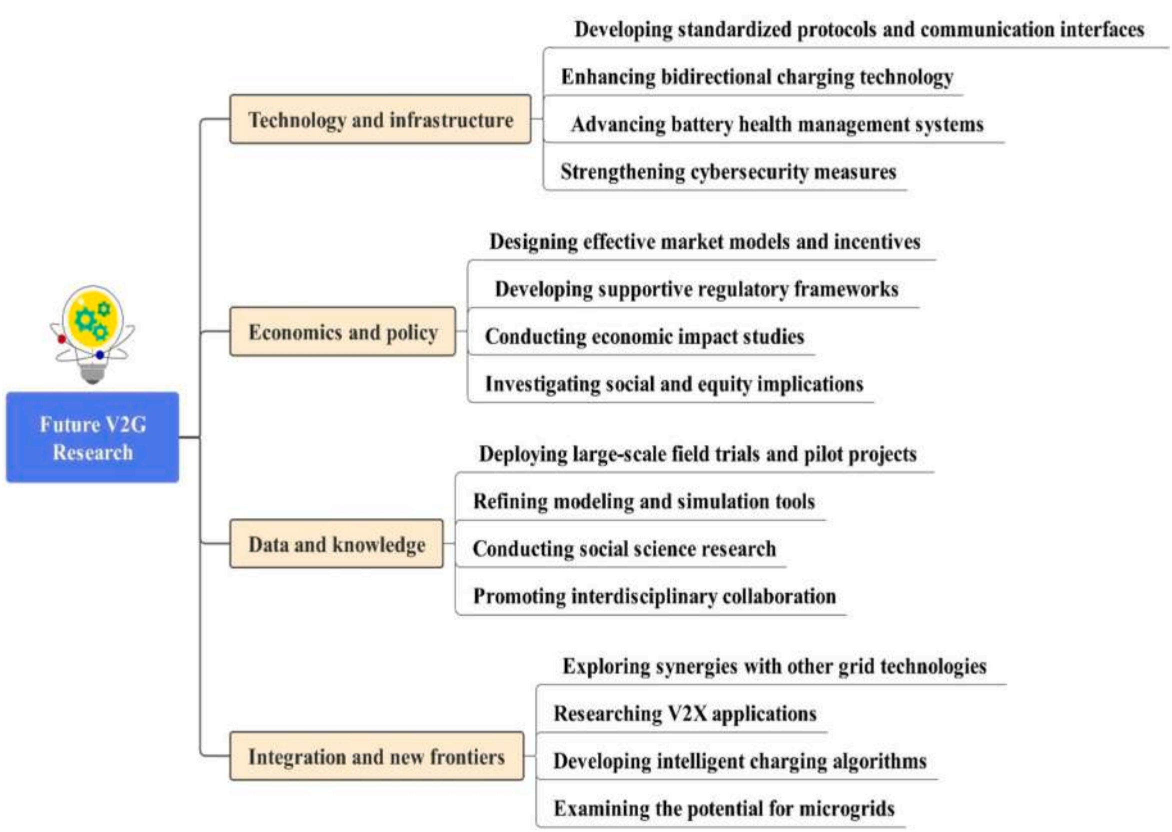

Fig. 17. Future research recommendations.

difficulties. Standardization is essential to facilitate uninterrupted data transmission, similar to establishing a uniform language for electric vehicles to connect to any energy source. The slow rate of current charging technology requires acceleration, converting V2G pit stops into rapid refueling for our mobile micro power plants. Battery health management systems, which protect these energy sources, necessitate sophisticated algorithms to maximize utilization and prolong their durability, guaranteeing a lengthy and fruitful V2G tenure. To persuade EV owners, it is necessary to provide them with economic incentives such as attractive market models and pricing schemes that offer rewards for their efforts in decreasing peak demand and mitigating carbon emissions [141,142]. A well-defined plan is necessary for the legal and regulatory domain, encompassing frameworks that address concerns related to responsibility, obstacles in integrating with the power grid, and issues about ownership. This will ensure a seamless transition. The V2G pilot projects will use real-world data to guide the gap between technology and human behavior using social science and consumer research. Ultimately, V2G has a vast range of possibilities extending well beyond its capacity to support the grid. It can collaborate with renewable energy sources and demand-side control programs, forming a robust and environmentally friendly energy ensemble for a more sustainable future. By prioritizing these crucial domains, we may convert V2G from a prospective idea into a concrete actuality, supplying our residences, enterprises, and urban areas with environmentally friendly and dependable power [143]. The V2G revolution will fundamentally transform our energy dynamics, enabling communities to harness clean energy and fostering innovation. This shift will position cars as energy consumers and providers of clean energy, propelling us toward a more sustainable future.

Technical challenges in V2G integration

The enticing prospect of EVs transforming into small-scale power stations, known as V2G, is on the horizon. However, achieving widespread adoption of this concept involves overcoming significant challenges. Fig. 18 shows the Technical Hurdles on the road to the V2G Revolution. The initial obstacle might be likened to traversing a border with only unintelligible language in one's lexicon – V2G necessitates a universally understood set of communication protocols spanning various grids and geographies. Envision EVs effortlessly connecting to any "energy outlet" without encountering compatibility issues [144].

Furthermore, the current charging technology's slow pace is reminiscent of the tedious process of watching paint dry, especially when compared to the efficiency of a petrol station pit stop. We require a transformative shift in energy production, optimizing the performance of DC-DC converters and enabling V2G technology to recharge our mobile power stations efficiently. Battery health management systems, which protect these energy sources, necessitate sophisticated algorithms to optimize utilization and prolong their lives, guaranteeing a lengthy and fruitful V2G tenure [145]. To attract EV owners, it is necessary to abandon insignificant financial incentives. Instead, we should focus on developing persuasive market strategies and pricing systems that reward EV owners for their efforts in reducing peak electricity consumption and combating climate change. A well-defined plan is necessary for the legal and policy framework, which should include measures to address concerns related to liability, obstacles in integrating the grid, and issues related to ownership [141,146]. This will ensure a seamless transition. In addition to the technological aspects, the practical data obtained from V2G pilot projects will serve as a roadmap, connecting technology and human behavior by employing social science and consumer research [147]. V2G has many possibilities extending well beyond its capacity to assist the grid. It can collaborate with renewable energy sources and demand-side control programs, resulting in a robust and environmentally friendly energy ensemble for a more sustainable future. By prioritizing these crucial domains, we may convert V2G from a prospective idea into a concrete actuality, supplying our residences, enterprises, and urban areas with environmentally friendly and dependable power. The V2G revolution will fundamentally transform our energy dynamics, enabling communities to harness energy, fostering innovation, and leading us towards a future when vehicles serve as energy consumers and clean energy suppliers, propelling us towards a more sustainable and environmentally friendly future [135].

Communication and safety standards

Integrating Distributed Energy Resources (DERs), such as EVs, into the electrical grid depends on various organizations' evolving standards. The standards address interconnection, safety, functionality, and communication protocols. Interconnection standards, such as IEEE 1547 and related documents, define the requirements for DER-grid integration, including bidirectional Electric Vehicle Supply Equipment (EVSE). Safelines- such as UL 1741-safeguard product- while functionality lines like SAE J3072 provide paths toward certification for mobile inverters with AC V2G capabilities. Communication protocols provide the means for V2G to manage energy and support the demand response function. Several main communication protocols include utility management protocols, IEEE 2030.5, demand response behavior opener, OCPP supporting communication between the Charge Station Operator and the EVSE to the Charge Station, and EV-EVSE ISO15118. Despite these advances, considerable gaps and challenges remain. V2G standards are still being developed and lack a complete coverage of all system aspects. Additional safety requirements for mobile inverters, disputes regarding testing responsibilities, scarce hardware availability, and early stages of deployment hinder its extensive implementation. Cybersecurity, supply chain limitations, and inadequate service-oriented control schemes aggravate these challenges. Interoperability is also key in ensuring seamless communication of diverse systems and standards. Standards like ISO 15118, IEEE 2030.5, and OCPP are essential for achieving interoperable frameworks but lack global dominance, creating fragmented implementations. Regulators must address these challenges to promote safe, efficient, and widespread adoption of V2G-enabled EVs. Establishing communication and safety protocols guarantees the

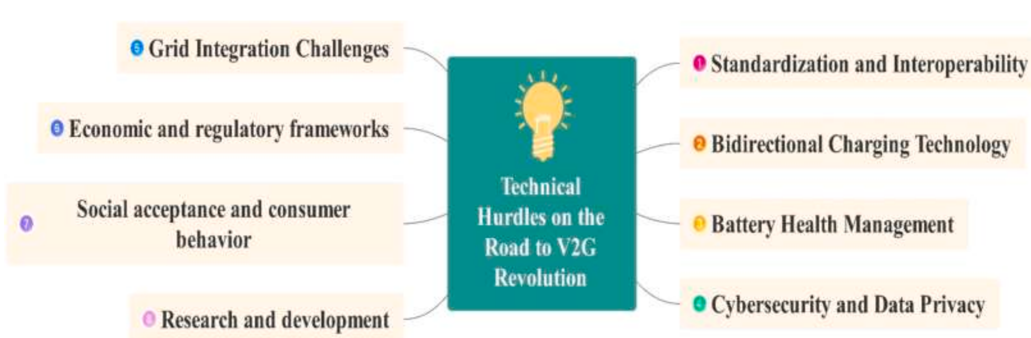

Fig. 18. Technical Hurdles on the Road to V2G Revolution.

compatibility and secure functioning of electric car charging infrastructure in V2G systems. The data presented encompasses various standards about communication protocols, charging system prerequisites, and safety parameters. IEC 62196–1 and IEC 62196–2 specifically address the conductive charging of electric cars [148]. They establish precise standards for the dimensions and compatibility of AC pin and contact-tube accessories. ISO/IEC 15,118 specifies the communication interface for V2G systems, whereas standards such as IEC 61140 and IEC 60529 focus on ensuring protection against electric shock and determining the level of protection offered by enclosures. These standards jointly create a foundation for the dependable and safe communication and operation of V2G systems [149].

- *IEC 62196–1 and IEC 62196–2:* The guidelines primarily address the conductive charging of EVs and outline specific criteria for plugs, socket outlets, vehicle connectors, and inlets. Their focus is on addressing the interoperability and interchangeability of charging systems for both alternating current (AC) and direct current (DC) [150].
- *IEC 62196–3:* This standard applies to charging EVs via conductive methods. It outlines specific specifications for the size and compatibility of the connectors used, including pins and contact-tube couplers. For dedicated DC charging, these connectors should handle a maximum voltage of 1000 V DC and a maximum current of 400 A [151].
- *IEC 61850-x:* These standards explicitly address communication networks and systems within substations. It establishes a framework for the communication infrastructure in V2G systems [152].
- *ISO/IEC 15118:* This standard aims to establish the V2G communication interface, which guarantees standardized communication protocols for the interaction between electric cars and the grid [153].
- *IEC 61851–1, IEC 61851–21, IEC 61851–22, IEC 61851–23, and IEC 61851–24:* The standards encompass multiple facets of EV conductive charging systems, delineating overarching prerequisites, EV specifications for conductive connection, and communication protocols between off-board DC chargers and EVs [154].
- *IEC 61140:* This standard protects against electric shock and establishes standardized requirements for the installation and equipment in V2G systems [155].
- *IEC 60529:* This standard establishes the levels of protection offered by enclosures (IP code), guaranteeing that the V2G system components are sufficiently safeguarded against environmental conditions [156].
- *IEC 60364–7-722:* This standard provides specifications for low-voltage electrical installations, specifically emphasizing the provision of electricity to EVs in V2G systems [157].
- *ISO 6469–3:* This standard outlines safety requirements for electrically powered vehicles used on public roads, focusing on preventing electric shock and assuring the safety of those utilizing V2G infrastructure [158].

These standards enhance the strength, dependability, and safety of V2G systems, creating a structure for the smooth communication and secure functioning of electric car charging infrastructure within the larger smart grid context [159].

Santos, Francisco [160] developed a charging emulation system using the ISO 15118 protocol to integrate renewable energy in EV charging. Testing showed dynamic adjustments to charging based on real-time energy availability, enhancing sustainability and reducing grid reliance. Ramasamy [161] analyzed ISO 15118 (Plug&Charge) and the Qualcomm QCA7005 for EV smart charging. The study reviewed EV charging trends, PLC technology, and hardware architectures for V2G functionality based on ISO 15118 and HomePlug Green PHY. Kilic [162] analyzed Plug and Charge (PnC) technology for EVs, addressing new challenges from ISO 15118-20 and certificate validation requirements. A three-level solution involving EV, PKI, and cloud components ensures secure and interoperable charging for future networks. Jaman, Verbrugge [163] developed and tested a V2G system using a Combo CCS Type 2 charger with ISO 15118-2 protocol. A MATLAB/Simulink model validated the system's performance, highlighting efficiency, signal delay, and accuracy, and compared simulated outcomes with hardware results for calibration insights. Tsikteris, Diamantopoulos Pantaleon [164] surveyed the cybersecurity certification requirements set by the SunSpec Alliance for Distributed Energy Resource (DER) devices, including remote software updates, communication, authentication, security, logging, and testing. The study identified SunSpec standards on remote software updates, secure communication protocols, strict authentication, and robust logging. It also covered deploying the SAE J3072 standard through the IEEE 2030.5 protocol to ensure safe EVSE-PEV interactions for V2G functionality. The SunSpec Modbus standard and Device Information Models were analyzed for the improvement of DER interoperability and adherence to grid standards. In conclusion, this paper also provides insights on energy storage cybersecurity specifications and blockchain requirements proposed by SunSpec.

Battery management in V2G systems

Although the integration of V2G technology shows potential for advancing grid intelligence, managing batteries remains a significant technical challenge. The main issue is the increased battery deterioration caused by the regular charging and discharging cycles during V2G usage [164]. Superficial discharges and quick charging can strain battery components, ultimately reducing longevity. Various methods are currently being investigated to tackle this difficulty. Intelligent charging algorithms can be utilized to optimize charging and discharging cycles [165]. These algorithms prioritize minimizing stress on the battery by focusing on minimal depth-of-discharge (DoD). Furthermore, optimizing the battery's temperature before charging or discharging can enhance its efficiency and lifespan. Sophisticated battery management systems (BMS) can constantly monitor the battery's condition and adjust the charging profiles to prolong the battery's lifespan [166].

V2G systems add a level of intricacy: energy management. When deciding on the best techniques for charging and discharging, it is important to consider factors such as grid demand, electricity rates, and the preferences of individual users. To successfully traverse this intricate situation, it is imperative to utilize sophisticated communication protocols and intelligent control systems [167]. These systems gather up-to-the-minute information on the state of the power grid, user choices, and the condition of individual batteries. By analyzing this data, they can enhance the functioning of V2G systems, guaranteeing the optimal utilization of energy while minimizing the deterioration of batteries [168]. Thermal management is an important factor to consider. Batteries provide thermal energy during the processes of charging and discharging. V2G systems must efficiently regulate this thermal output to avoid overheating, which can exacerbate battery deterioration. V2G infrastructure can incorporate thermal management systems employing air or liquid cooling.

Furthermore, ongoing research is being conducted to examine innovations in battery design that incorporate enhanced heat management capabilities [169]. By integrating these technologies, V2G systems may address battery degradation concerns, optimize energy management, and assure efficient and dependable operation. With the advancement of battery technology and V2G systems, we may anticipate the emergence of more inventive solutions. This will lead to a future where V2G technology is crucial in creating a sustainable and efficient electric grid [170].

A comprehensive overview for assessing V2G integration

Incorporating V2G can revolutionize the power grid by making it a more sustainable and intelligent system. Nevertheless, evaluating its efficacy necessitates a comprehensive strategy considering many performance indicators. Here, we explore these crucial areas in greater detail:

- ***Stability of the Grid:*** Electricity reliability depends on a stable grid. V2G integration improves grid stability in numerous ways: Grid frequency must be within a certain range for devices to work. V2G systems can inject or absorb electricity to maintain grid frequency as flexible reserves. The mean and standard deviation of grid frequency during V2G operation can evaluate its efficacy. Reduced variances indicate grid stability [171]. Demand for electricity strains the grid, pushing the building of expensive, polluting power plants. To store electricity during peak hours, V2G vehicles can be used. Reduced grid peak demand improves operational efficiency and may prevent the need for additional power generation. The difference in peak demand when V2G integration is operational versus when it does not measure the advantage. To deliver power efficiently, voltage must be within acceptable limits [172]. By selectively injecting or absorbing electricity at grid nodes, V2G systems can regulate voltage. The mean and standard deviation of voltage at crucial grid points can be used to monitor this. A decrease in voltage fluctuations indicates better regulation. V2G integration enhances electrical infrastructure robustness and dependability, reducing disruptions and ensuring power supply [173].
- ***Power Flow Optimization and Energy Efficiency:*** Energy efficiency is crucial today. V2G integration optimizes grid energy use and is a key metric of V2G round-trip efficiency. Charge the vehicle and then discharge electricity back to the grid to assess energy loss [174]. The ratio of vehicle energy delivered to grid charging energy is computed. More energy-efficient systems have higher round-trip efficiency [146,175]. Transmission and distribution of electricity incur losses. Charge and discharge cars closer to where electricity is needed with V2G integration to reduce losses. Compare line losses with and without V2G integration to quantify this. Line losses are significantly reduced, improving grid efficiency [176]. Renewable energy sources like sun and wind are intermittent. V2G systems can buffer excess renewable energy during high generation and release it into the grid during low generation. This increases renewables on the grid, reducing fossil fuel use. We can quantify V2G systems' effectiveness by tracking renewable energy storage and discharge [177].
- ***Economic Advantages:*** *A Mutually Beneficial Outcome for Parties Involved:* Integrating V2G technology provides economic advantages for both utility companies and consumers: Utilities can gain benefits from decreased peak demand costs, enhanced power plant efficiency resulting from more seamless operation, and potentially reduced electricity prices through more integration of renewable energy. Consumers can save by reducing peak demand costs and using time-based electricity pricing, encouraging charging during off-peak hours [178,179]. V2G participants can earn money by selling electricity back to the grid when demand is high or taking part in ancillary service markets. These markets allow grid operators to access extra resources to ensure the grid's stability [180]. For V2G initiatives to be economically feasible, the upfront investments must be recouped within a reasonable period. Stakeholders can evaluate the financial feasibility of V2G initiatives by computing the return on investment (ROI), which considers the benefits generated concerning the initial investment. The economic advantages motivate the further use of V2G technology, resulting in a mutually beneficial situation for utilities, consumers, and project developers [181].
- ***Environmental Impact:*** V2G technology provides a substantial benefit in combating climate change and pollution. Conventional power systems frequently depend on power plants fueled by fossil fuels to satisfy the highest electricity demand. These plants emit substantial quantities of greenhouse gases, particularly carbon dioxide, a primary driver of global warming [182]. The integration of V2G technology breaks this cycle in two distinct manners. Firstly, V2G technology strategically utilizes the stored energy in EVs to meet the electricity demand during peak hours, thereby reducing the dependence on environmentally harmful power plants [183].

Furthermore, V2G technology enables a more extensive incorporation of sustainable energy sources such as solar and wind power. Renewable sources of energy produce electricity without emitting any greenhouse emissions. V2G technology, reduces greenhouse gas emissions by storing surplus renewable energy during high production and returning it to the power grid when demand is at its peak. [184,185] This displaces the need for fossil fuel-based generation and substantially decreases overall emissions [186]. Fossil fuel power facilities significantly contribute to air pollution, especially in urban areas. Emissions of nitrogen oxides, Sulphur oxides, and particulate matter are released, causing harmful impacts on both human health and the environment. Integrating V2G technology decreases dependence on these power plants during periods of high demand. This improves air quality, particularly in densely populated urban areas where power plants are frequently clustered. V2G technology helps enhance public health and promote a more sustainable environment by mitigating emissions from these power plants.

Comparative evaluations of V2G implementations in different regions

Table 7 summarizes recent studies focused on RES integration and the rapidly increasing adoption of EVs. These studies address such critical aspects as load management, emissions, grid stability, and economic and environmental impacts of renewable energy and EV technologies across different regions and contexts. Research has emphasized regional variability in the feasibility and impact of EV technologies. The higher share of renewables in France and Brazil makes their implementation of EVs sustainable, while regions such as Indonesia face challenges with their fossil-fuel-based grids. Similarly, studies in France and Salzburg have proven that EMS and coordinated charging strategies can enhance the grid's performance for a diverse energy mix. Common issues include high infrastructure expenses, coordination complexities, and the integration of intermittent RES. Studies on LFC and grid extension need to emphasize the need to account for temporal load interactions to prevent overestimation in conventional grid planning. The reasons for the limited adoption of V2G, which include regulatory gaps, a lack of consumer acceptance, and underutilization in some regions, are regularly mentioned.

These studies argue for enhanced development of AI, ML, and real-time communication technologies in enhancing grid management and the integration of electric vehicles. Mechanisms to increase dynamic pricing, the implementation of second-generation charging stations, and customized V2G strategies are provided for improvement in user satisfaction and economic viability. These include the importance of decarbonizing energy grids and increasing the use of renewable energy sources to support regional goals toward achieving sustainability in high carbon-intensive grid regions. Significant progress has been made in integrating RES and EV technologies; however, continuous innovation and regional adaptation will be crucial in overcoming the challenges and maximizing their environmental and economic benefits.

Integrated analysis: linking technological and policy trends with bibliometric insights

This section provides a focused analysis integrating technological advancements and policy frameworks with bibliometric trends to ensure thematic cohesion across the manuscript. The bibliometric evaluation strongly emphasizes BMS and policy development, which are pivotal for addressing challenges in V2G integration. This section synthesizes these themes, linking bibliometric patterns with research gaps and future directions.

Table 7
Summary of Key Research Studies on Renewable Energy Integration and Electric Vehicle Impact".

Reference	Focus	Methodology	Region/ Context	Quantitative Analyses	Key Findings	Challenges/ Limitations	Future Prospects
[187]	Load Frequency Control (LFC) in modern power systems, with emphasis on reliability and stability.	Review and analytical discussion.	Modern power systems with RES integration.	Exploration of LFC schemes in single-area and multi-area systems, focusing on decentralized control.	Decentralized LFC improves real-time balance and integrates with ancillary services like DSM, microgrids, EVs, and HVDC.	High infrastructure costs, coordination complexities, cyber threats, and integration challenges of intermittent RESs.	AI, machine learning, and real-time communication technologies to enhance LFC performance.
[188]	V2G technology and regional variability in application scenarios.	Agent-based modeling.	Japan's 47 prefectures.	Evaluate V2G potential and demand–supply adjustments in energy markets.	EV ownership significantly influences regional V2G potential; there is a high disparity in the utilization of V2G systems.	Underutilization or overburdening of V2G systems; Idle capacity in some regions.	Develop region-specific strategies and diverse business models to optimize V2G systems.
[189]	Greenhouse gas emissions from electric bus charging and fleet transition.	Life cycle assessment (LCA).	Australian bus fleets (e.g., Sydney and Inner West).	Emissions are calculated across production, transport, installation, operation, and decommissioning.	Operation emissions dominate (98.8 %); grid decarbonization is essential for net-zero emissions. Transition to electrified buses has the potential to reduce climate impact.	High grid carbon intensity; Regional variability in emissions parameters.	Decarbonize the grid and prioritize renewable energy for charging infrastructure.
[190]	Viability of EV implementation in high-vehicle-population countries.	Review and viability index calculations (WTW emissions).	Top 10 countries with the most significant vehicle populations.	Evaluates emission factors and lifetime emissions of EV batteries.	EV viability varies based on renewable energy share in the grid; Sustainable for France and Brazil, marginally viable for China and India, and not viable for Indonesia.	High indirect emissions in grids with low renewable energy shares.	Increase renewable energy shares in national grids for sustainable EV adoption.
[191]	Electrification of sub-Saharan African paratransit systems and grid impact.	Simulation using Grid-Sim software.	Johannesburg, South Africa.	Analyzes load profiles, energy demand, and CO2 emissions of electrified minibus taxis.	Solar charging stations and external batteries reduce peak power draw by 66 % and emissions by 58 %.	Crippled electricity networks and operational challenges in integrating EV fleets.	Promote solar and hybrid solutions to mitigate grid impact and reduce emissions.
[192]	Integration of RES and EV charging to mitigate grid security issues.	Simulation and modeling of energy mixes and EV load curves.	Four French regions with diverse energy mixes.	Analyzes green charging ratio (GCR) with and without energy management systems (EMS).	High GCR in windy regions without EMS; EMS improves GCR significantly in sunny regions.	Local congestion, voltage deviations, and dependence on seasonal RES availability.	Deploy EMS and workplace charging stations to enhance GCR in underperforming regions.
[193]	Barriers to V2G implementation in Nordic countries.	227 semi-structured expert interviews.	Nordic countries (17 cities).	Identifies 35 barriers categorized into 4 clusters.	Barriers include skepticism of V2G benefits, economic viability, consumer acceptance, and regulatory issues.	Lack of widespread awareness and confidence in V2G benefits; Regulatory gaps.	Address regulatory and economic challenges, improve consumer outreach, and refine V2G strategies.
[194]	Integration of V2G technology and MPC-based EMS at ski resorts.	Real data analysis and scenario modeling.	Ski resort in Trentino-Alto Adige, Italy.	Economic and environmental impacts of PV generation and charging strategies analyzed.	PV power significantly reduces costs and CO2 (7 %);Self-consumption improves (~100 %) with charging strategies.	V2G for energy arbitrage shows minor cost/CO2 reductions (~2%).	Sensitivity analysis highlights the potential for cost reductions (up to 15.2 %) with increasing energy price gaps.
[195]	Impact of EVs and HPs on low-voltage (LV) grids.	Load flow simulations with real-life LV grid data.	Four LV grid regions with varying characteristics.	Static and time-series load approaches compared for voltage and thermal congestion.	Neglecting temporal interactions overestimates grid extension needs; combined approaches improve grid planning accuracy.	Challenges in integrating temporal load profiles into traditional planning models.	Advocates for advanced planning methods considering consumer-specific behavior.
[196]	Price-based DR for managing EV charging loads.	Analytical and simulation modeling with GA optimization.	Multiple EV charging regions.	EV charging prices are calculated dynamically; Impact on cost and utility revenue is assessed.	Non-discriminatory dynamic pricing mitigates unfair costs and improves user satisfaction.	Ensuring dynamic pricing doesn't adversely affect utilities' revenue or cause rebound peaks.	Improved DR programs with dynamic, fair pricing models, enhancing cost distribution and satisfaction.
[197]	Coordinated EV charging to address peak consumption challenges.	Discussion and case study of communication frameworks.	Smart grids model region in Salzburg.	Examines vehicle-to-grid communication options and their applicability.	Coordinated charging reduces peak load and supports grid stability.	Communication infrastructure and user adaptability remain barriers.	Second-generation home charging stations to improve grid interaction in smart grids.

Technological trends and battery management

Bibliometric patterns indicate growing research interest in AI-driven BMS, predictive optimization algorithms, and solid-state batteries. The keyword mapping reveals terms such as "battery degradation," "smart charging," and "energy storage" as recurring themes, reflecting the field's response to challenges in battery life and performance. Studies emphasize AI-based models that can reduce capacity fade by up to 15 % over 5 years, demonstrating practical solutions for minimizing degradation during V2G cycles. Additionally, keywords like "lithium-ion batteries" and "state-of-health monitoring" highlight innovations to extend battery longevity through adaptive charging algorithms and real-time diagnostics.

The bibliometric trends further emphasize advances in solid-state batteries and lithium–iron-phosphate (LFP) chemistries, indicating a shift toward materials that offer higher cycle life and thermal stability. For instance, recent studies underscore the role of predictive maintenance and machine-learning algorithms in optimizing energy storage systems and addressing grid stability and economic viability. These technologies minimize battery wear and support enhanced renewable energy integration by enabling more efficient charge–discharge cycles.

The bibliometric analysis highlights gaps in scalable BMS frameworks, particularly in studies that explore interoperability across different vehicle models and charging infrastructures. Future research should prioritize standardized architectures for battery diagnostics and AI-enhanced monitoring systems, ensuring seamless integration into V2G ecosystems.

Policy frameworks and implementation gaps

The bibliometric analysis further identifies policy and regulation as an underexplored area despite its significance for large-scale V2G adoption. Keywords like "standardization," "protocols," and "cybersecurity" remain limited, suggesting a research gap in developing regulatory frameworks and incentives. While studies highlight specific examples, such as ISO 15118 standards and programs like California's LCFS credits, the findings reveal fragmented approaches rather than cohesive, globally aligned strategies.

As reflected in keyword trends and citation networks, future policies must address interoperability, grid stability, and consumer incentives. For instance, incentives for V2G-compatible infrastructure, such as subsidies for bidirectional chargers and tax credits for renewable integration, must be standardized globally. Additionally, cybersecurity regulations must evolve to protect energy transactions and data exchange in V2G systems, as identified by keyword gaps related to blockchain security and network encryption.

The bibliometric analysis underscores the necessity for multi-stakeholder collaboration, including policymakers, utilities, and automakers, to establish unified protocols for V2G implementation. These frameworks should encourage infrastructure investments and incentivize EV owners to participate in energy markets, thus enhancing grid resilience and flexibility.

Aligning bibliometric trends with research directions

It demonstrates how the evolving V2G research landscape addresses practical and regulatory gaps by linking technological developments and policy needs to bibliometric patterns. The analysis identifies key challenges, battery degradation, cybersecurity risks, and infrastructure scalability as thematic priorities for future work.

- *Technological Focus:* Emerging trends emphasize the integration of AI-driven optimization, solid-state batteries, and predictive diagnostics to improve energy efficiency and extend battery life. Future research should explore scalable solutions for BMS interoperability and renewable energy integration.
- *Policy Focus:* Bibliometric gaps highlight the need for standardized protocols, financial incentives, and cybersecurity frameworks to enable large-scale V2G adoption. Policies must support infrastructure scalability while protecting grid stability and consumer data.
- *Future Research Directions:* Studies should prioritize cross-disciplinary collaborations to address regulatory and technical barriers. Pilot programs in emerging markets and rural electrification initiatives can test scalable solutions and inform global policies.

This integrated approach ensures the narrative reflects a data-driven framework, aligning each section with bibliometric insights and research objectives. It also provides a roadmap for bridging gaps in V2G adoption, guiding future technological advancements and policy implementations.

Future scope and limitations

The current literature on V2G technology reveals a notable deficiency in the comprehensive exploration of its economic and legal dimensions, particularly within highly regulated electricity markets like the European Union. Future research should prioritize understanding the pricing models for V2G services. These are crucial for determining how EV owners can be fairly compensated for discharging energy back to the grid and providing ancillary services, such as frequency regulation and demand response. Developing a detailed mathematical framework for monetizing V2G technology will be essential, as well as incorporating equations to calculate potential revenue streams considering energy prices, capacity payments, and participation in various market mechanisms. This framework must also address the varying costs associated with battery degradation, opportunity costs of charging versus discharging, and regulatory fees. Such comprehensive analyses would equip stakeholders with valuable insights, enabling informed decisions about the economic viability and operational feasibility of V2G implementations in regulated markets.

Despite the potential for impactful findings, current articles often emphasize bibliometric analysis at the expense of addressing critical technical aspects, leading to gaps in understanding the practical implications of V2G technology. Future studies should streamline sections dedicated to bibliometric analysis and focus more on the multifaceted challenges encountered in the technical, economic, legal, and social dimensions of V2G integration. This includes in-depth discussions on technical barriers, such as battery performance and grid stability, economic factors like pricing models and return on investment, legal considerations regarding regulatory frameworks, and social aspects, such as consumer acceptance and behavior [198].

To enhance the relevance and utility of future research, it would be beneficial to incorporate case studies that illustrate real-world challenges and solutions encountered in V2G projects. Furthermore, involving experts from diverse fields—engineering, economics, law, and sociology—could enrich the discourse and provide a more comprehensive overview of V2G technology. This multidisciplinary approach would address existing gaps and foster collaborative strategies to overcome obstacles associated with V2G implementation, ultimately advancing the field and contributing to a more sustainable energy future. However, researchers must also recognize the limitations of such studies, including the potential variability of results across different regulatory environments and technological contexts, which may affect the generalizability of findings.

Protocols such as ISO 15118 are advanced to ensure interoperability among EVs, charging infrastructure, and grid systems. Standardized communication will streamline data exchange, enhance manufacturer compatibility, and enable scalable V2G deployment. Future research should be geared toward large-scale pilot tests of V2G technologies in real-world settings. Such pilots can study the impacts on grid stability, battery health, and integration of renewable energies while offering insights into the technical and economic feasibility. For instance, regional pilot projects can be designed to serve both urban and rural grids to understand location-specific issues. A focus must remain on understanding consumer behavior, awareness, and acceptance of V2G technologies. This would involve investigating financial incentives, willingness to participate from the consumers' side, and perceived benefits versus concerns such as battery degradation. Surveys, behavioral models, and field studies may be conducted to bridge that knowledge gap and inform strategies in this direction. Future studies should include the role of V2G in enhancing grid resilience, especially during peak demand or renewable energy intermittency. Developing advanced grid management algorithms for optimizing EV discharging patterns for balancing load and maximizing renewable energy utilization can be a research area.

Conclusions

This review provides a comprehensive bibliometric analysis of Vehicle-to-Grid (V2G) integration research, highlighting its evolution, current trends, and challenges. The findings emphasize the growing significance of bidirectional energy transfer technologies, which have emerged as a cornerstone of V2G systems. These systems are critical in enabling grid stability, optimizing renewable energy usage, and reducing reliance on fossil fuels. Key insights from this analysis include the increasing focus on integrating EVs into smart grids, advancements in battery technology, and the need for standardized communication protocols to enhance interoperability.

The adoption of bidirectional chargers and smart grid technologies is revolutionizing energy management. Bidirectional chargers, for instance, enable EVs to serve as mobile energy storage systems, supporting grid operations during peak demand and enabling decentralized renewable energy storage. These advancements align with the goals of sustainable energy transitions, as they help reduce greenhouse gas emissions while enhancing grid flexibility and resilience. To address the identified gaps and further the field, the following future research directions are suggested:

- **Integration of Artificial Intelligence (AI) in V2G Systems:** AI can optimize V2G operations by enabling real-time decision-making and predictive analytics. For instance, machine learning algorithms can predict grid demand patterns, optimize energy dispatch from EVs, and minimize battery degradation during charge–discharge cycles. Research should focus on developing AI-powered energy management systems tailored to large-scale V2G deployments.
- **Standardization of Communication Protocols:** Establishing global communication standards, such as ISO 15118, is critical to ensure seamless interoperability between EVs, charging infrastructure, and grid systems. Future research should address technical and regulatory challenges in implementing these standards across different regions and manufacturers.
- **Regional Pilot Programs in Developing Countries:** Pilot programs in developing regions can demonstrate the feasibility and benefits of V2G technology, particularly for supporting unstable grids and integrating renewable energy sources. Case studies in rural areas with high renewable energy potential, such as South Asia or Sub-Saharan Africa, can provide valuable insights into the socio-economic impacts and scalability of V2G systems.
- **Advancements in Battery Technology:** Research should focus on improving battery durability under V2G conditions, such as by developing advanced materials and battery management systems (BMS). Novel technologies like solid-state batteries and enhanced thermal management can mitigate degradation issues and increase the lifespan of EV batteries used in V2G applications.
- **Consumer Behavior and Acceptance:** Understanding consumer behavior is vital for the widespread adoption of V2G technology. Studies should explore factors influencing EV owners' willingness to participate in V2G programs, such as incentives, financial benefits, and awareness campaigns. Examining public attitudes toward energy-sharing initiatives can provide insights for designing user-friendly and inclusive systems.

Implications for policy and industry

Policymakers must prioritize creating supportive regulatory frameworks that promote V2G deployment. These should include financial incentives for EV owners, subsidies for installing bidirectional chargers, and mandates for renewable energy integration in V2G systems. Collaboration between governments, industries, and research institutions is essential to overcome barriers to large-scale implementation. V2G technology has immense potential to transform the energy and transportation sectors by fostering sustainability and resilience. However, realizing its full potential requires a multi-disciplinary approach, integrating technological innovation, policy development, and consumer engagement. By addressing the identified research gaps and embracing future directions, stakeholders can accelerate the transition to a cleaner, more innovative, and more sustainable energy ecosystem.

Additional information

No additional information is available for this paper.

Institutional review board statement

Not applicable.

Informed consent statement

Not applicable.

CRediT authorship contribution statement

Pulkit Kumar: Visualization, Software, Formal analysis, Data curation, Conceptualization, Writing – original draft. **Harpreet Kaur Channi:** Writing – original draft, Visualization, Validation. **Raman Kumar:** Software, Project administration, Methodology, Writing – original draft. **Asha Rajiv:** Visualization, Validation, Software. **Bharti Kumari:** Software, Resources, Project administration. **Gurpartap Singh:** Resources, Project administration, Methodology, Investigation. **Sehijpal Singh:** Validation, Supervision, Project administration, Methodology. **Issa Farhan Dyab:** Investigation, Funding acquisition, Formal analysis. **Jasmina Lozanović:** Resources, Funding acquisition, Formal analysis.

Funding

This research received no external funding.

Declaration of competing interest

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

Acknowledgements

The authors gratefully thank the author's respective institution for their strong support in this study.

Consent for publication

All authors consent to the publication of this manuscript.

Data availability

Data will be made available on request.

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