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OVERVIEW

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Electric vehicles as facilitators of grid stability and flexibility: A multidisciplinary overview

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Abstract

Electric vehicles (EVs), as facilitators of grid stability and flexibility, provide a critical solution to the energy infrastructure's evolving demands, underscored by the growing integration of renewable energy sources (RES) and the rapid increase in EV adoption worldwide. This trend is particularly evident in Europe which is experiencing dramatic increases in both the adoption of RES and EVs. Vehicle-to-grid (V2G) technology allows EVs to operate as a two-way power flow to both draw and feed electricity into the grid. This multidisciplinary overview examines the role of V2G systems in enhancing grid performance, identifying corporate vehicle fleets as key flexibility providers, and integration with Smart Grid technologies as a key element for successful V2G implementation. In a scoping analysis of recent literature (2005–2024), we identify challenges such as privacy, security, and regulatory compliance as well as a critical gap in establishing economically sustainable models for aggregators, distribution system operators (DSOs), generation companies (GENCOs), and end-users. Drawing from these insights, we then discuss the necessity for future research to develop models that ensure equitable benefits across stakeholders and the importance of models that can adapt to country-specific mechanisms. The findings from our overview argue that the integration of EVs, V2G, and RES are essential components for developing future energy systems that are resilient, adaptable, decarbonized, and sustainable.

This article is categorized under:

Abbreviations: DER, distributed energy resources; DRP, demand response program; DSO, distribution system operator; GENCO, generation companies; GHG, greenhouse gas emissions; HEV, hybrid electric vehicle; ICEV, internal combustion engine vehicle; IFSP, independent flexibility service provider; NEV, new energy vehicle; PHEV, plug-in hybrid electric vehicle; PV, photovoltaic; RES, renewable energy sources; SAEV, shared autonomous electric vehicles; SME, small and medium-sized enterprise; TSO, transmission system operator; V2G, vehicle-to-grid; V2H, vehicle-to-home; WTW, well-to-wheel.

Cities and Transportation > Electric Mobility
Energy and Power Systems > Energy Infrastructure
Energy and Power Systems > Energy Management

KEYWORDS
electric vehicles, energy flexibility, smart charging, smart grid, vehicle-to-grid

1 | INTRODUCTION

Globally, the energy sector is undergoing a transformation toward sustainability and innovation, with new energy technologies such as photovoltaics (PVs), wind power, electric vehicles (EVs), and battery storage at the forefront of this revolution. Under this transition it is anticipated that patterns in electricity demand and supply—as well as the services that electricity fulfills—will also change dramatically, with electromobility growth positioned to play a significant role (World Energy Outlook, 2023). As we navigate the complexities of integrating renewable energy sources (RES) and enhancing grid stability, the role of EVs can be expanded beyond transportation, offering promising solutions for electricity grid stability and flexibility (Patil & Kalkhambkar, 2021).

The interplay between energy consumption patterns, energy providers, and the inherent volatility of RES underscores the need for dynamic and innovative approaches to demand-side energy management (Elio et al., 2021). As the global demand for electricity grows, particularly from emerging economies, the integration of renewable energy is rising, either overtaking, or poised to soon overtake, fossil fuel-based sources. This shift necessitates the development of new smart charging strategies and technologies that not only accommodate but also capitalize on the variability and intermittency of RES (Khalid et al., 2024; Ohanu et al., 2024). Among these technologies, vehicle-to-grid (V2G) emerges as a pivotal solution, promising to turn the challenges of energy sector transformation into opportunities for a more resilient and adaptable grid. Broadly speaking, VG2 refers to an advanced smart grid technology that not only coordinates the charging schedules of EVs so they are most beneficial to the grid, but also enables them to supply energy back to the grid, thereby enhancing both grid demand and supply response and improving overall stability. V2G allows parked or idle EVs to act as distributed energy resources, charging, storing, and discharging energy back to optimize grid operations. This bidirectional energy flow, facilitated by specialized converters, can improve the overall efficiency, reliability, and sustainability of the power system (Allehyani et al., 2024; Parazdeh et al., 2022; Wagner, 2014). As vehicles spend, on average, 1 h out of a day driving and the remainder parked (*Still Standing Still*, 2021), VG2 unlocks the unused battery resources of EVs during periods when they are not being used to fulfill transportation services. Given the planned widescale adoption of EVs in the phase-out of internal combustion engines, coordinated VG2 could lead to concrete impacts in terms of grid decarbonization via reduction fossil-fuel power plants to increase grid flexibility and meet peak demand and integration of RES (Hussain et al., 2023). Europe is particularly well-situated to undertake this V2G transformation, with plans to have at least 30 million zero-emission cars on the road by 2030 and the existing share of passenger battery electric vehicles (BEVs) is growing rapidly as depicted in Figure 1 (Mobility Strategy—European Commission, 2021; Passenger Cars in the EU, 2023). This coincides with the goal that the share EU energy consumption will be 45% renewable by 2030 (*Renewable Energy Targets—European Commission*, 2022).

However, the potential of V2G is not without its uncertainties, complexities, and barriers, which range widely from the technical and structural to the financial and acceptance by the public (Tan et al., 2016; Yilmaz & Krein, 2012). Therefore, our overview focuses on the state-of-the-art knowledge regarding grid-related EV applications, emphasizing the opportunities and challenges of transportation electrification and its role in demand response. We aim to synthesize existing research and developments in V2G technology, providing a comprehensive examination of how EVs can be effectively integrated into the grid to enhance energy management, meet increasing demands, and support the sustainable transition of the energy sector.

1.1 | Existing reviews comparison

The landscape of V2G review literature is diverse, offering many perspectives. To effectively determine the research questions and focus of this overview, it was essential to thoroughly examine existing reviews addressing similar topics.

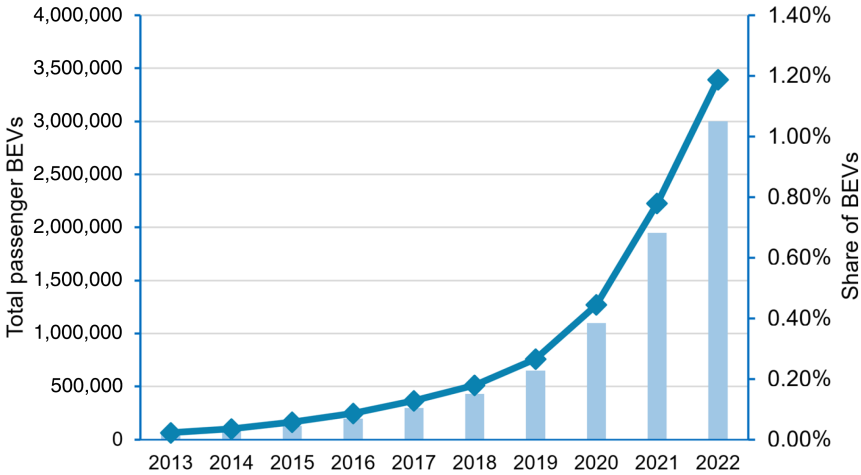


FIGURE 1 Total number and share of passenger BEV on the road in the EU in 2013–2022 (Passenger Cars in the EU, 2023).

Analyzing previous studies provided a foundational understanding which were used to identify key gaps and opportunities for further exploration.

1.1.1 | Concepts

Several concepts, trends, and technologies associated with V2G have been examined in previous reviews, revealing its multifaceted role in the energy sector. A V2G technology is sometimes described as a virtual powerplant (Wagner, 2014). Review (Qin et al., 2023) captures its promise for balancing energy production and consumption, integrating concepts such as dynamic charging and autonomous EVs. Reviews such (İnci et al., 2022) or (Xie et al., 2024) suggest that V2G could substantially support grid sustainability and renewable energy integration despite challenges like battery degradation and uncertainties like changing weather patterns due to climate change that could limit their effectiveness. (Wan et al., 2024) further identifies V2G's potential to significantly influence the future energy landscape through services such as peak-to-valley arbitrage, demand response, and frequency regulation despite technical, economic, and social challenges requiring further research and strategic regulatory support. Other literature has surveyed the concept of flexibility in smart grids using V2G, describing challenges in demand-side management as well as future directions (Hussain et al., 2023). Additionally, the integration of Energy Internet (EI) with Smart Grid (SG) technologies is investigated for its potential to enhance utility energy services and demand-side management, although issues like scalability and pricing remain obstacles (Parvin et al., 2022).

1.1.2 | Grid integration

There are several review articles examining the optimal design and integration of EVs within the future electricity grid. For example, (Patil & Kalkhambkar, 2021) provides a valuable review of challenges and benefits associated with EV grid integration for various stakeholders (GENCOs, DSOs, aggregators, end-users) and examines optimal scheduling and smart charging strategies, however, the field has advanced significantly since its publication. Focusing on the future implementation pathways for V2G technology, (Yu et al., 2022) examined various grid architectures, including nanogrids, microgrids, and clusters, concluding that specific power architectures like the advanced ILC-based hybrid and hybrid parallel–series cluster architectures offer optimal performance for V2G integration. While these previous reviews often emphasized extensive transformation of existing power infrastructure, (Lund et al., 2015) highlights the potential of utilizing the inherent flexibility in existing power systems. Existing power grids have built-in capabilities to handle variable RES, and therefore may require less intensive modifications than previously envisioned. Moreover, current trends suggest that dedicated flexibility solutions like large-scale energy storage may become even more prominent in the future (Lund et al., 2015). Das et al. (2020) further describes the EV impact on the charging network mainly regarding the harmonics it's converters generate, issues also discussed by (Bass et al., 2001; Taghvaie et al., 2023; Tasnim et al., 2023). The future impacts of integrating EVs into the grid can be broadly summarized based on the challenges that grid-connected EVs could pose and in turn the opportunities that may arise (Figure 2).

1.1.3 | Economy

Economic considerations are central to several reviews that identify the potential of V2G to substantially shape the future energy landscape. (Krueger & Cruden, 2018; Ravi & Aziz, 2022) further argue for the necessity of larger-scale pilot projects to better understand V2G's economic feasibility, indicating that this is crucial for seeding initial adoption and building government support. At the same time, they emphasize that long-term sustainability in this field will likely require collective engagement from both government and industrial sectors. Recent literature (Grasel et al., 2024; Zecchino et al., 2019) suggests that load leveling and participation in the secondary frequency market presents the largest economic benefits for V2G. Other factors driving the level of economic benefits include the vehicle technology, the battery capacity, the charging technology, and the achievable charging power (Heilmann & Friedl, 2021). Furthermore, in an analysis of policy measures implemented within the EU until 2014 revealed that tax incentives, infrastructure development, and financial support for R&D have been key drivers in promoting electromobility (Cansino et al., 2018). Heilmann and Friedl (2021) also states that the literature often reports inconsistent and contradictory findings regarding the economic advantage of providing grid flexibility services while (Wan et al., 2024) advances and calls for further research and strategic regulatory support to address technical, economic, and social challenges.

1.1.4 | Distribution

Coordination between Transmission System Operators (TSOs) and DSOs is another crucial aspect of V2G integration. Efficient collaboration, amid the complexities of digitalization and the integration of distributed energy resources (DERs), is identified as vital for successful V2G operations (Uzum et al., 2024). The shift from centralized to decentralized grid structures and integration of RES such as solar and wind into smart grids highlight the necessity for further research to address challenges related to uncertainty and complexity (Babayomi et al., 2023; Nadeem et al., 2023; Ohanu et al., 2024). In addition, studies (Leippi et al., 2022; Machlev, 2024; Montes et al., 2024) emphasize the need for future research on multi-objective optimization for EV fleet charging, considering complex battery degradation models and real-life user studies.

In conclusion, while these reviews provide valuable insights, they collectively point to a future where research must dive deeper into integrating other variable RES and more advanced smart charging solutions (Barman et al., 2023). Given the rapid pace at which technological, infrastructure, policy, and social dimensions are evolving in the emerging V2G space, there is a clear need for reviews that synthesize and analyze these new developments. Such reviews should seek to aggregate existing knowledge and provide critical analyses that can guide researchers, policymakers, and

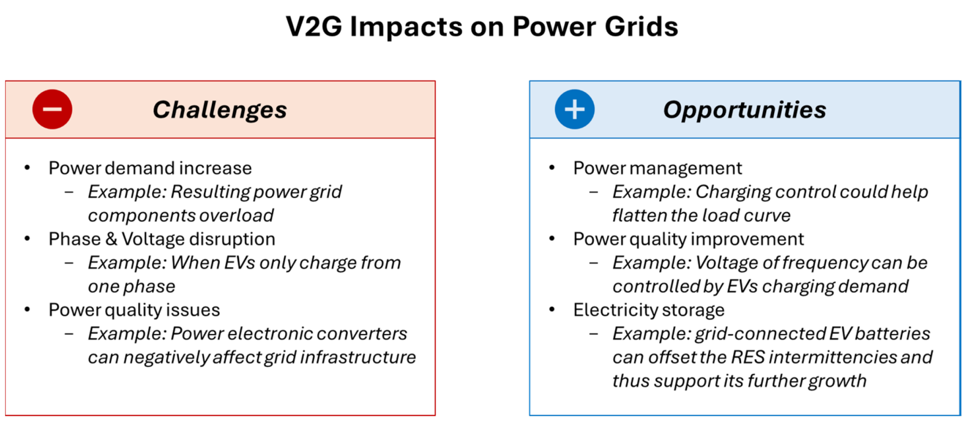


FIGURE 2 EV grid integration challenges and opportunities.

industry stakeholders toward informed decisions and strategic advancements in V2G technology. This need has shaped the formulation of the core research questions that anchor this overview:

1. Despite existing studies detailing the benefits and challenges of V2G, there remains a significant gap in understanding how V2G contributes to grid participation, necessitating further exploration into its operational benefits.
2. While the stakeholders likely to engage in future V2G markets have been identified, the specific roles and especially the impact of V2G as a flexibility provider must be better-defined, highlighting the need for a deeper examination.
3. This review seeks to summarize and distill state-of-the-art insights about the implementation of V2G technology and development the grid—presented in broadly accessible manner—focusing particularly on Europe.

1.2 | Aim of the overview

With this objective in mind, this overview is structured around three critical research questions—informed by previous literature—that guide the subsequent analysis and discussion about V2G:

1. What role will V2G play in improving grid flexibility and stability?
2. What are the characteristics of V2G flexibility providers?
3. How can Europe best accommodate future V2G development?

The motivation underlying exploring these questions comes from several compelling and interconnected factors. Energy self-sufficiency and stability are recognized by (UNEP, 2022) as critical to both companies and nations worldwide as they accelerate their efforts toward carbon neutrality (IEA, 2021) and V2G technology emerges as one of the crucial paths toward sustainable energy solution (PricewaterhouseCoopers, 2023) that has the promise of not only being technically feasible but also economically and socially viable. This research also extends beyond the typical scope of V2G studies, aiming to provide a deeper, more nuanced understanding of its capabilities and limitations. What sets this study apart is its comprehensive approach to evaluating V2G technology, considering the technical and operational aspects and the economic, policy, and social dimensions. This multifaceted perspective is important for developing a holistic understanding of V2G's role within the broader energy ecosystem and identifying avenues for future research activities.

2 | METHODOLOGY AND STRUCTURE

This article aims to provide a comprehensive overview of V2G technology and its role in the modern energy landscape (Figure 3). To do so, we conducted a comparative review of leading research articles on V2G to synthesize the best practices and insights from the field. The purpose of this comparison is to highlight successful models drawn from a diverse

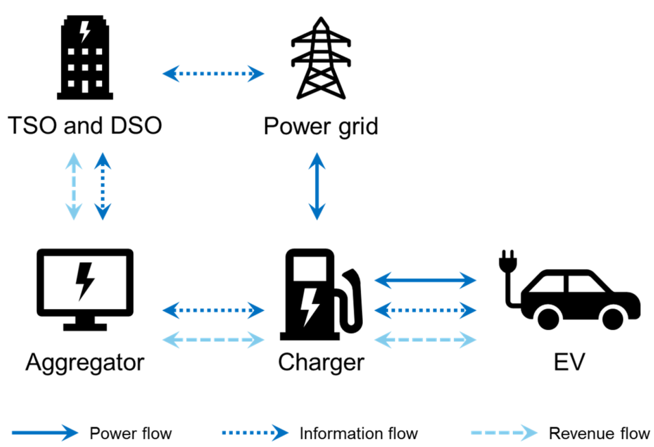


FIGURE 3 Basic scheme of V2G technology, adapted from (Ala et al., 2020).

set of methodological approaches. The review process was informed by the principles of breadth and approachability, ensuring that the content is accessible to students and researchers with varying degrees of familiarity with the topic.

Guided by our research questions, we will further focus our inquiry on the interdependent benefits realized by the four primary market actors essential for V2G success: Aggregators, DSOs, GENCOs, and End Users. Drawing inspiration from the analytical framework presented in a review of EV grid integration (Patil & Kalkhambkar, 2021), our study examines the potential economic and operational benefits for these groups by investigating each research question described in Figure 4. This perspective is vital, as these actors' collective satisfaction and coordinated action are foundational to the practical implementation of V2G systems. The exploration of grid stability technologies, the identification of flexibility providers, and the assessment of the European V2G infrastructure will be analyzed in the context of technological feasibility and regulatory frameworks and through the potential economic and operational enhancements V2G offers to each market participant. By aligning the interests of these diverse yet interconnected actors with the technical and economic dynamics of V2G, our study aims to provide a grounded assessment of V2G's role in the evolving energy paradigm.

We applied a scoping review approach, complemented by text mining analysis, to capture, evaluate, and synthesize the wealth of recent literature. This method enabled a broad examination of EVs role in enhancing grid stability and flexibility, acknowledging the multidisciplinary nature of the subject matter. Unlike systematic reviews, which often seek to provide a focused and exhaustive inquiry into a specific question or topic using all available empirical research, scoping reviews offer an expansive overview of a research area, providing insights into the volume, topical coverage, and characteristics of the existing research (Peterson et al., 2017). This approach is well-suited for topics such as EVs and V2G technology, where research is often multidisciplinary, covers diverse application sets, and is rapidly evolving (Pham et al., 2014). In Figure 5, the overall review methodology is shown.

The methodology for this review involved a targeted search of publications from 2005, when the first V2G keyword was used, to 2024.[1] This bibliometric analysis is based on academic papers published and indexed in the Web of Science. The dataset comprises papers containing relevant keywords within our research domain. Specifically, for the "V2G" full count, we consider both the whole phrase "Vehicle to Grid" and its abbreviation "V2G." The narrower category, "V2G and Energy Flexibility," includes papers that incorporate either "energy flexibility," "flexibility management," or "smart charging." Figure 6 illustrates the long-term growth in academic interest regarding V2G technology. In our analysis, we have identified 2084 academic contributions, specifically mentioning V2G, with a steady growth rate and periodic increases in interest, most notably the latest interest growth starting in 2019.

Despite this growing interest in V2G technology, the portion of research dedicated to the use of V2G for grid stabilization remains relatively modest. Out of the 2084 analyzed contributions, only 50 mentioned its use for flexibility management. This underrepresentation underscores the relevance of the current overview as it fills a clear research gap, pointing to the need for a deeper investigation into how V2G can specifically contribute more effectively to the resilience and adaptability of energy systems. Out of the 2084 articles analyzed, 95 were identified as review articles, which were carefully assessed to aggregate knowledge essential for formulating the research questions and structuring our

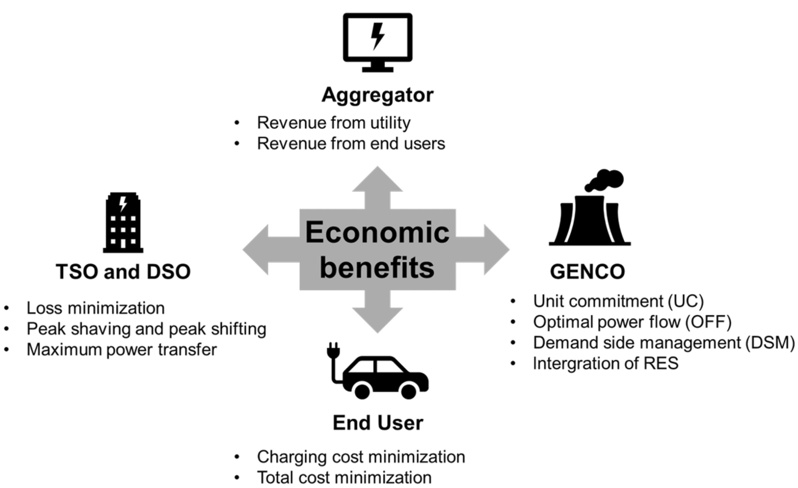


FIGURE 4 Economic benefits for main electricity market actors, adapted from (Patil & Kalkhambkar, 2021).

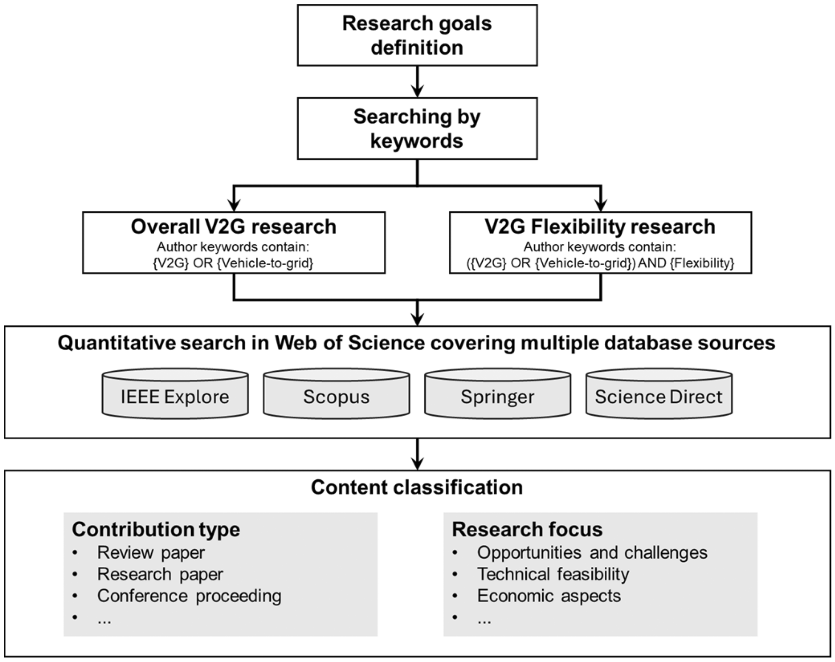
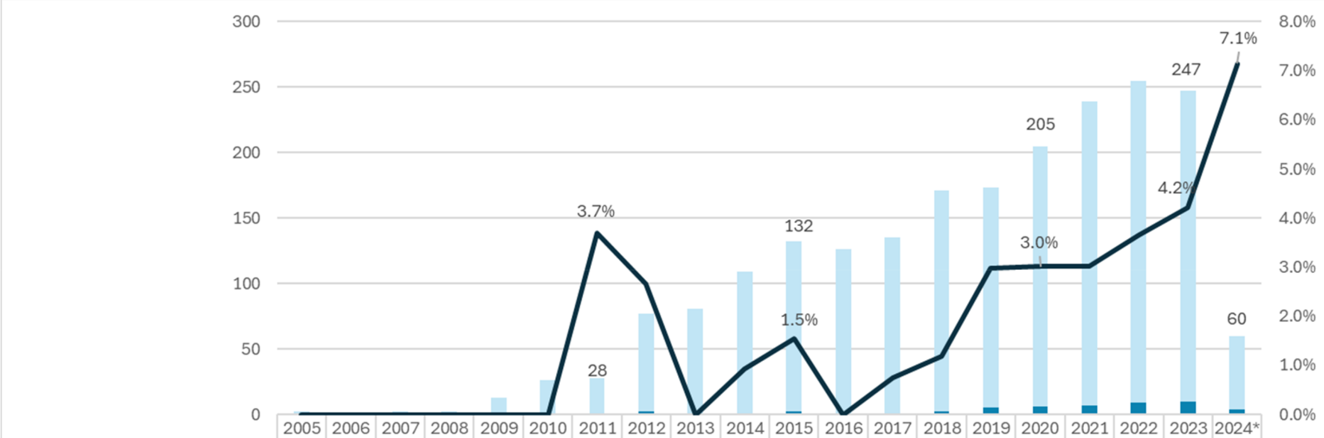


FIGURE 5 Research methodology and approach.



	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024*
Vehicle to Grid	2	1	2	2	13	26	27	75	81	108	130	126	134	169	168	199	232	246	237	56
V2G and Energy Flexibility	0	0	0	0	0	0	1	2	0	1	2	0	1	2	5	6	7	9	10	4
% V2G Flexibility	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	3.7%	2.7%	0.0%	0.9%	1.5%	0.0%	0.7%	1.2%	3.0%	3.0%	3.0%	3.7%	4.2%	7.1%

FIGURE 6 Evolution of the frequency of occurrence of the terms V2G and Energy Flexibility in the scientific literature indexed in the Web of Science.

current overview. Additionally, article identification and classification was also conducted using specific terms related to V2G, such as "V2G economy," "V2G history," or "V2G RES integration."

3 | BACKGROUND AND CONTEXT

Given the interdisciplinary nature of this overview, the following sections establish the background and context of the energy and transportation sectors. This foundation acts as both the boundary conditions and a framework, crucial for understanding the principles and broader landscape in which V2G technology operates.

3.1 | Energy sector transformation

The modern energy sector operates as a complex web of interrelated components. The consequences of these interdependencies become evident when the necessary equilibrium between energy consumption and production is disrupted. Instances where energy demand exceeds production capacity can lead to the looming possibility of blackouts, threatening the stability and reliability of the grid. Conversely, energy production that exceeds consumption can push the grid toward hazardous overload levels (McWilliams, 2022). Therefore, each transmission and distribution system operator must integrate power plants capable of rapidly increasing energy production or devices designed to consume excess energy during times of overload (C. Chen, 2018). Hence, to ensure the smooth operation of the energy ecosystem, it is crucial to understand these real-time interconnections and fully implement dynamic control mechanisms, such as flexibility mechanisms, as shown in an example Figure 7, where flexibility is “the ability of a power system to cope with variability and uncertainty in both generation and demand, while maintaining a satisfactory level of reliability at a reasonable cost, over different time horizons” (Ma et al., 2013).

Previously, grid uncertainties often originated from the demand side. However, the growth of generation from RES introduces intermittency and variability that is strongly dependent on external factors such as wind speed, solar irradiation, ambient temperature, and humidity (Shafiullah et al., 2022). As a result, flexibility control mechanisms are needed to help address grid strain issues related to RES integration, such as the “duck curve” problem where, at midday, electricity generation from PV is at its peak and grid demand is lower. However, PV generation is lower later in the day, and grid demand is at its peak. Consequently, other generation sources, such as natural gas-peaking power plants, must rapidly ramp up production to meet these high-demand periods. This leads to grid stress and inefficiency and, consequently, can produce higher levels of carbon emissions (Office of Energy Efficiency & Renewable Energy, 2017; Olczak et al., 2021).

3.2 | European Union strategy for reducing emissions

The European Union's (EU) climate policy gained substantial momentum following the 2015 United Nations Climate Change Conference in Paris and the subsequent signing of the Paris Agreement. Committed to achieving climate neutrality by 2050, the EU advances this objective through its Green Deal strategy for Europe. This strategy periodically revises the EU's climate targets and shapes directives and regulations to guide member states toward unified action in attaining these goals. A recent example of such recalibration is the “Fit for 55” package, which aims to align EU legislation with the union's climate objectives. These objectives are concretely outlined as reducing net greenhouse gas emissions by at least 55% by 2030 compared to 1990 (Claeys et al., 2019; Ovaere & Proost, 2022; Pietzcker et al., 2021). In alignment with the Green Deal's emphasis on sustainable energy solutions, the EU introduced a taxonomy in 2020 to classify environmentally friendly activities. The objective is to direct investment toward these sustainable activities, which will further increase the volatility of electricity generation and promote the need to address demand flexibility (Schütze et al., 2020).

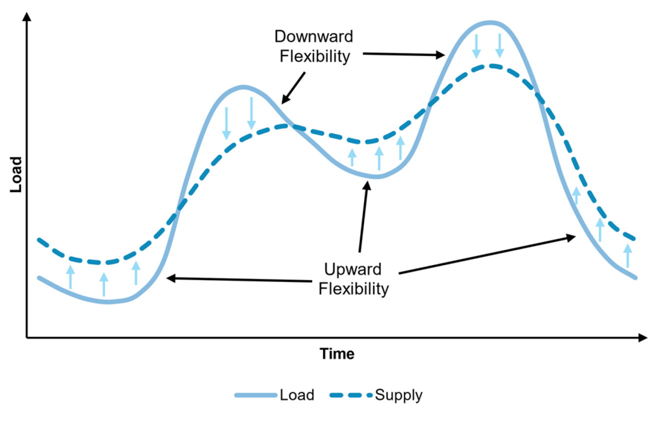


FIGURE 7 Concept of downward and upward flexibility.

3.3 | Transportation emissions

Utilizing RES has the potential to significantly reduce the main source of greenhouse gas emissions (GHG), as shown by EU data—the energy supply sector. Following this, domestic and passenger transportation emerges as the second most impactful contributor, as shown in Figure 8 (EU CO_2 Emissions Shares by Sector, 2023). In tandem, these sectors accounted for a combined 53.9% of the total CO_2 emissions generated in 2021. Additionally, the transport domain prominently emits carbon dioxide (CO_2), nitrogen oxides (NOx), and particulate matter (PM2.5 and PM10), significantly contributing to respiratory health concerns, with some of these pollutants identified as carcinogenic (Hooftman et al., 2018).

Numerous studies using life-cycle assessments have demonstrated that EVs significantly reduce GHG emissions compared to internal combustion engine vehicles (ICEVs). A study from 2023 in China (Zhang et al., 2023) estimated potential GHG emissions reductions of new energy vehicles (NEVs) and hybrid electric vehicles (HEV) by 6.56%–44.4% compared to ICEVs. However, in 2020, BEVs offering over 700 km of driving range showed a 33.08% deficit compared to ICEVs. A German study (Buberger et al., 2022) encompassing 790 passenger vehicles indicated that BEVs had higher production emissions but considerably lower driving emissions, contingent on electricity generation methods. When sourced from RES, plug-in hybrid vehicles (PHEVs) curtail emissions by 73%, while BEVs achieve an 89% reduction compared to ICEVs. Furthermore, a study (Doust & Otkur, 2023) conducted in Kuwait, comparing the Toyota Camry (ICE) and the Lexus UX 300e (EV), determined that the BEV produced less than half of the total CO_2 emissions on a well-to-wheel basis.

3.4 | Automotive market development

Building upon the premise that the proliferation of EVs forms a cornerstone of this study, we recognize the remarkable expansion of the EV market as both a catalyst for heightened electricity demand and a burgeoning opportunity for grid flexibility. The increase in EV adoption, particularly in Europe represents a significant shift toward more sustainable transport modalities that have tangible implications for energy systems (*Electric Car Sales, 2016*–2023, 2023). The surge in EV sales reflects a growing consumer shift toward cleaner energy as it directly affects the grid's capacity and the need for innovative solutions like V2G to accommodate this rise. As the number of EVs continues to climb, so does the potential for these vehicles to contribute to grid stability and flexibility.

The expansion of recharging infrastructure is requisite for the growth of EV adoption and the European Union has set clear targets in this domain. For every battery-electric car registered within a Member State, publicly accessible recharging infrastructure must offer a power output of 1.3 kW. Furthermore, to ensure the network's robustness and reliability, the EU (European Commission, 2023) mandates the installation of fast recharging stations, delivering at least 150 kW, at intervals of every 60 km along the trans-European transport (TEN-T) network starting from 2025. The

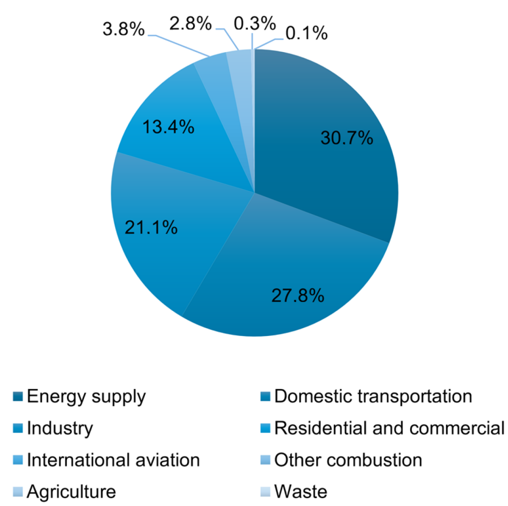


FIGURE 8 CO_2 emission shares in the EU-27 in 2022, by sector (EU CO_2 Emissions Shares by Sector, 2023).

scientific literature corroborates this strategic development, which supports the assertion that a charging power of 3.6 kW per individual charging point suffices (Dvořáček et al., 2020) and many AC chargers are favored over a few fast DC ones (Luke et al., 2021). The optimal charging infrastructure is a popular research topic with many challenges. Each geographical area means a different task to solve such as placement of the stations (Z. Chen et al., 2017; Ngo et al., 2020; Vandet & Rich, 2023) and different methodologies are proposed to reach the “ideal deployment” (Micari et al., 2017; Morro-Mello et al., 2019; Polisetty et al., 2023). For a review of this literature, see (Gupta et al., 2021; Karmaker et al., 2023). Additionally, the applications of artificial intelligence is also starting to shape the field (Ahmad et al., 2022; Fescioglu-Unver & Yıldız Aktaş, 2023).

Renewable generation is rising and will overtake coal as the largest source of electricity by early 2025 (*Renewables 2022—Analysis and Forecast to 2027*, 2023). The increasing renewable production is expected fully cover the additional demand increase (*Renewable Energy Market Update—Outlook for* 2023 *and 2024*, 2023; WE Forum, 2024). However, the predicted growth of electricity demand from EVs poses future challenges also related to when new peaks may occur, such as charging at night, with coordinated smart charging strategies proposed as a potential solution (Gong et al., 2020; Powell et al., 2022).

4 | RISE OF THE VEHICLE TO GRID TECHNOLOGY

The development of sustainable transportation and BEVs dates back to the early 20th century, with some pivotal inventions occurring as early as the 19th century, encompassing personal transport like bicycles, automobiles, and public transport systems. These early electric transport initiatives gradually faded by the mid-20th century, hindered by limitations such as restricted driving ranges and speed. The broader adoption of BEVs during this period was overtaken by the advent of internal combustion engine vehicles, offering greater affordability and efficiency, epitomized by the widespread acceptance of Henry Ford's Model T in 1908 (Franko et al., 2023; Ramsebner et al., 2021).

Under this backdrop, the 1970s marked a renewed interest in electromobility, spurred by the energy crises and growing environmental awareness. Despite this resurgence, the inherent drawbacks of electric cars at the time, including limited performance and range, saw interest wane once more. It was not until 1996 that General Motors released the EV1, an electric vehicle (EV) designed from the ground up, which quickly garnered a cult following. This was closely followed by Toyota's introduction of the Prius in 1997, the first mass-produced hybrid vehicle. Subsequent years saw an influx of PHEVs and BEVs from various manufacturers, aided by significant reductions in battery costs and technological advancements, signaling the onset of electric mobility's rapid market growth (*Timeline: History of the Electric Car*, n.d.). Amidst the evolution and resurgence of electromobility, the foundational research for V2G technology was already taking shape, paving the way for its significant role in the future energy landscape.

The journey of V2G technology began not with grid-scale storage in mind but rather as a vehicle-to-home (V2H) solution. Technology historian Matthew Eisler highlights that V2G was originally conceived to enable emergency power-sharing from one vehicle to another or to a home, a concept brought to life by AC Propulsion in the early 1990s with the Tzero sports car, featuring bidirectional charging capabilities (Amamra & Marco, 2019). These early innovations laid the groundwork for Willett Kempton and Steven Letendre's seminal 1997 proposal to utilize EVs as energy storage for the grid. Their vision expanded the scope from V2H to include the vast potential of V2G integration, recognizing EVs as dynamic storage devices that could offer services like peak-shaving and frequency regulation to enhance grid stability (Kempton & Letendre, 1997).

Building upon this, a comprehensive review by Kempton and Tomić in 2005 further elucidated the multifaceted roles EVs could play in grid support. They noted that V2G technology is unsuitable for baseload power, which requires a constant and unvarying supply of electricity, and instead emphasized its efficacy for quick-response services. The review highlighted V2G's potential in offering solutions for peak-shaving and frequency regulation, particularly apt for addressing the fluctuations in the electricity grid, which accounted for 5–10% of electric costs in the US at the time (Kempton & Tomić, 2005). This research established vital concepts foundational to V2G research and its applications and Kempton's ongoing contributions (e.g., Kempton et al., 2001; Tomić & Kempton, 2007) refine and expand our understanding, underscoring his enduring influence as a leading scientist in the V2G domain.

5 | Q1—WHAT ROLE WILL V2G PLAY IN IMPROVING GRID FLEXIBILITY AND STABILITY?

With the first research question, we explore the pivotal role of V2G systems in enhancing grid stability amidst the increasing integration of RES.

5.1 | RES integration

Prior literature has examined the benefits and circumstances under which RES and DER can be effectively integrated into the modern energy grid. These studies emphasize optimizing energy usage, reducing emissions, and maintaining reliable power supply through various flexibility tools. How can V2G technology help with integrating the anticipated RES growth into the grid in the context of current RES integration technologies?

Integrating RES into the power grid requires innovative technologies and DERs to enhance grid flexibility and manage the expected surge in power demand by 2050. The "Grid Structure Optimization" method presented in (Vijay & Mathuria, 2022) represents a significant advancement, accurately estimating the flexibility region for DERs and ensuring tailored solutions for RES integration, considering both slow and fast response systems. With the potential of DER in mind, the following study (Zhou et al., 2024) analyzes the use of EVs parked in buildings to address challenges with renewable energy and power grids. A key finding is that the timing of when vehicles arrive and leave significantly impacts the effectiveness of this approach. The study also provides new models to predict vehicle schedules and optimize this system for lower costs and emissions. With power demand projected to grow significantly by 2050, decentralized solutions like smart grids and battery storage can reduce grid congestion by 10%–15%. While not eliminating the need for upgrades, these technologies are crucial for short-term congestion management and reducing long-term expansion needs (Bauknecht et al., 2024; Firdous et al., 2024). Another key finding in the energy storage domain is the significant improvement in energy storage efficiency that EVs offer when integrated with renewable energy grids. The superior round-trip efficiency of EV batteries plays a crucial role, reducing the overall energy dissipation and the need for hydrogen storage by up to 50%. This reduction is particularly impactful, demonstrating that V2G systems can serve as a more efficient complement to renewables than advancements in hydrogen storage technologies alone (Michaelides et al., 2023). Further exploration into renewable-based microgrids reveals how the incorporation PHEVs and battery energy storage devices may be leveraged to solve energy imbalances. For example, a novel scheduling method from (B. Singh & Sharma, 2022) achieves a notable 30% reduction in daily energy loss, highlighting the technical viability and efficiency benefits of V2G integration. Other similarly strategies optimizing the charging and discharging of EVs to manage renewable energy's unpredictability are introduced in (C. Li et al., 2022; Shi et al., 2020). By minimizing operating costs and effectively aligning wind/solar generation with charging demand, this approach stabilizes the grid, and maximizes renewable energy use, positioning V2G as a dynamic solution for managing RES variability. The importance of coordinated EV charging schedules to integrate wind power and reduce costs is then highlighted in (Sharifi et al., 2020). This concept also addresses battery health and user concerns, showing V2G's potential to harmonize renewable energy integration with consumer engagement. Lastly, a shift toward a revised energy market design is advocated to capitalize on RES and V2G integration fully. By promoting flexible demand and supply through clear price signals and shorter trading intervals, this approach envisions a sustainable electricity system that fully embraces V2G technology (Auer & Haas, 2016).

Experience on how to integrate RES can also be drawn directly from country-specific studies. For instance Germany's initiative (Büttner et al., 2024) to connect its electricity sector with other energy domains (gas, heat, mobility) showcases the potential for cross-sector integration to contribute to carbon emission reduction. Despite necessitating grid upgrades, the flexibility options provided by these new connections can significantly offset upgrade costs. This model exemplifies how strategic grid management and flexibility can achieve cost and emission reductions, presenting a comprehensive approach to energy sector integration. An Australian study (M. Li et al., 2024) further expands on the theme of flexibility by simulating a competitive bidding process for integrating RES into a fully renewable grid. The findings suggest that combining different flexibility options, including long-term storage technologies, emerges as the most cost-effective approach, reinforcing the importance of a diversified flexibility strategy in the renewable energy transition.

Together, these insights weave a narrative of how current grid flexibility trends and technologies are pivotal to integrating RES into the grid. From optimizing grid structures and leveraging EVs to embracing cross-sector energy integration and managing distributed PV systems, the strategic deployment of these technologies will be crucial in navigating the challenges and opportunities of a renewable-powered future. Overall, given that RES has been a very intensively researched topic for many years, we did not identify a major research gap. Nevertheless, the potential for new technologies is considerable, and across intensive research, there is room for more economically and environmentally efficient solutions than those currently available.

5.2 | Smart charging

Integrating smart charging into the energy grid encapsulates a broad spectrum of strategies to enhance grid performance, optimize energy use, and mitigate emissions. These strategies range from demand response programs (DRPs) to the innovative use of EVs for balancing renewable energy availability.

Smart grids are instrumental in seamlessly integrating RES into the power grid, addressing user acceptance and operational flexibility challenges. (Khalid, 2024) proposes a bottom-up approach to navigate these challenges, emphasizing the need for strategic planning and innovative solutions to ensure grid resilience. DRPs and Spinning Reserves are set to play pivotal roles in microgrid performance, with DRPs notably reducing operating costs by smoothing demand profiles, especially when integrated with RES. A robust optimization method employed by (Shojaei et al., 2022) underscores the effectiveness of DRPs in achieving cost savings, further highlighted by a 3.31% reduction in costs. Building on the theme of optimizing energy use, another study investigates the economic advantages of leveraging EVs for smart charging to address the curtailment of variable renewable energy. Employing location-based incentives and considering EV arrival patterns (Park et al., 2022) enhances energy efficiency and minimizes economic losses, marking a significant improvement over traditional curtailment methods. However, the impact of smart charging on greenhouse gas emissions is contingent upon the availability of renewable energy within the grid. When renewable resources are scarce, smart charging may inadvertently increase emissions. Conversely, with a higher penetration of renewable energy, smart charging could substantially cut emissions by up to 37.8% by shifting between high and low load periods. An adjusted smart charging mode is proposed by (Zhong, Hu, et al., 2024) to balance emission reductions with electricity costs, indicating the nuanced relationship between smart charging and environmental impact. The principle of lowering electricity prices by managing demand originated from the Merit Order ranking system. By reducing the need for power during high demand (peak shaving), efficient base-load power plants and cost-effective RES contribute to a larger share of the energy mix. This shift increases the proportion of less expensive energy, reducing the spot market electricity prices, as illustrated in Figure 9. Therefore, EVs and their smart charging can effectively contribute to flattening the power demand curve by shifting power demand to less busy times. The accompanying figure demonstrates this correlation, showing how decreased demand reduces reliance on costly energy sources and lowers electricity prices (Ajanaku & Collins, 2024; Antweiler & Muesgens, 2021; Hanemann & Bruckner, 2018).

Balancing economic objectives with decarbonization efforts in smart EV charging in (Zhong, Zeng, et al., 2024) emerges as a key strategy for reducing overall costs by 14.5%–35.1%. This balance is influenced by charging behavior, charger power, and the cost of CO_2 emissions, offering insights into optimizing future EV charging practices.

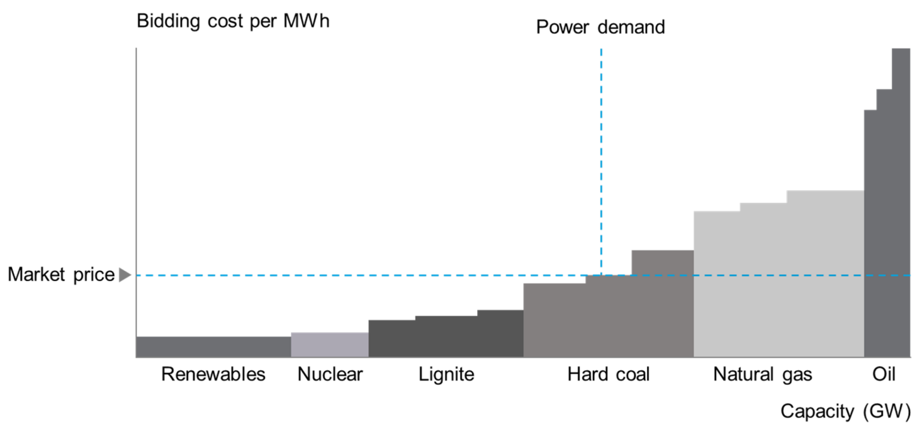


FIGURE 9 Merit order principle.

California's experience points to a nuanced view of the financial viability of V2G. In 2021, Wang and Craig (2021) discovered that V2G could bring more annual revenue to EVs than regular smart-charging EVs. However, they also found that V2G revenue might be lower than expected due to declining electricity prices and the need to consider the whole EV fleet participating in V2G. This highlights the importance of a comprehensive approach to evaluating V2G revenue potential. Moreover, a comprehensive framework (Morvaj et al., 2016) for optimizing energy use in low-voltage grids emphasizes the proactive integration of EVs. Controlling EVs' discharge abilities and managing reactive power can significantly reduce carbon emissions (up to 96%) while ensuring grid stability and user comfort, showcasing a forward-looking approach to integrating EVs and RES for a sustainable energy future. The functionality of smart charging systems is deeply influenced by user behavior and pricing structures. While stepwise tariffs may exacerbate peak load issues, dynamic tariffs and local capacity management present viable solutions for preventing grid overload. This underscores the need for carefully designed pricing models to support effective smart charging initiatives (Daneshzand et al., 2023). Furthermore, this research proposes an improved way to manage EV charging and discharging in a V2G system. The key novelty is a two-step optimization process. First, a day-ahead schedule is created to minimize charging costs while considering grid needs. Second, real-time data is used to fine-tune the schedule for even better results, including frequency and voltage regulation. The approach from (Amamra & Marco, 2019) reduces EV charging costs and provides valuable support to the power grid, especially during peak hours. (Yin & Qiu, 2022) then proposed a new method for V2G systems that uses a stochastic differential approach to guide flexible energy service providers on pricing in the long term. This method leverages the flexibility of V2G systems to minimize costs and balance the market in the face of short-term price fluctuations, resulting in significant cost savings. Another cost-saving service was proposed in Suel et al. (2024)—car sharing with V2G onboard. However, it relies on car sharing users' willingness to adjust their booking times, and the research suggests offering financial incentives to encourage flexibility while also considering factors like user demographics and trip characteristics.

Collectively, these studies illustrate a multi-faceted approach to smart charging and grid integration, from demand response and renewable energy curtailment to privacy concerns and market participation. Strategies like DRPs and the use of EVs show promise in reducing costs and emissions. However, research gaps still need to be addressed, particularly in understanding the long-term impacts of smart charging on grid dynamics and user behavior. Addressing these gaps is essential for optimizing smart charging practices and successfully integrating RES and EVs into a future-ready energy grid.

6 | Q2—WHAT ARE THE CHARACTERISTICS OF V2G FLEXIBILITY PROVIDERS?

In the realm of flexibility provision for the electric grid, various stakeholders emerge as potential key players, with their roles and challenges intricately linked to the broader dynamics of the energy market and technological innovation. The flexibility providers can range from large organizations with fleet management systems to small and medium-sized enterprises (SMEs), independent flexibility service providers (IFSPs), and individual consumers, all engaging with the V2G systems in different capacities and facing unique challenges.

Corporate vehicle fleets emerge as potential flexibility providers, particularly those that embed Vehicle-to-Grid Electric Vehicles (V2G-EVs) into their operations. Research (Meelen & Schwanen, 2023) reveals that organizations follow various pathways—sustainability, market sustainability, and professional sustainability—influencing how V2G-EVs are integrated within their practices. The embedding of V2G technology into daily organizational routines may thus present a significant source of grid flexibility. However, the landscape may shift with the increasing presence of SMEs. In 2022, about 24.3 million SMEs were active in the EU-27, and these SMEs accounted for 99.8% of all enterprises in the non-financial business sector (European Commission et al., 2023).

The case (X. Li et al., 2020) of Shanghai, China, where multiple companies have participated in peak shaving, illustrates the broader economic implications for stakeholders within V2G systems. A fair distribution mechanism for V2G profits among power plants, vehicle users, and other participants is crucial for fostering a healthy V2G ecosystem. Furthermore, several hypotheses were confirmed, such as "The lower the cost of electric vehicle battery, the more the net income of single user" (X. Li et al., 2020). In Europe, the stakeholder landscape is diverse, encompassing various business models and interests. While the Scandinavian focus groups' study (Sovacool et al., 2020) outcomes might not be generally applicable, they have identified at least 12 stakeholders types such as: automotive and battery manufacturers, vehicle owners, energy suppliers, TSOs and DSOs, fleet operators, or aggregators. As all the models, such as the ones shown in Figure 10 regarding the stakeholder's optimal participation, are very complex, further research is needed to explore the evolving roles of these stakeholders and how to navigate the complexities of V2G business models.

Coordination between flexible electricity consumers, or "prosumers," and aggregators presents a model for grid balancing services. Prosumers with RES or responsive demand capabilities could reduce electricity costs. However, this may be less beneficial for prosumers with a high solar capacity who are not engaged in active flexibility services (Gržanić & Capuder, 2023). Consumer behavior, influenced by social learning in retail electricity markets, also affects, lowers demand, and reduces price volatility. Retailers may find it challenging to predict demand patterns as consumers frequently adjust their energy usage and plans. This dynamic points to the need to design electricity packages that enable energy savings and reduce volatility (Fang & Wang, 2023). Building on coordination between prosumers and aggregators, DSOs can directly manage prosumer batteries and PV systems as part of distributed flexibility services. The approach in (Holweger et al., 2023) provides a cost-effective alternative to extensive grid upgrades and remains effective until solar generation exceeds 145% of annual demand, offering a scalable solution for integrating PV systems seamlessly into the grid. The role of IFSPs in the electricity market is also crucial (T. Chen & Vandendriessche, 2023; Poplavskaya & de Vries, 2020). They can enhance efficiency, but their market entry is often constrained by existing suppliers and Balance Responsible Parties. Regulatory challenges in accommodating IFSPs need to be addressed to facilitate their wider participation.

Examining grid flexibility through V2G systems underscores the potential roles of organizational fleets, SMEs, and various stakeholders in enhancing grid stability. Despite insights from regions like California and Shanghai on the economic aspects of V2G, a full understanding of stakeholder participation, profit distribution, and the challenges faced by prosumers and aggregators is still lacking. A notable research gap exists in detailing the operational and financial mechanisms for V2G flexibility providers, including the specifics of aggregator roles and compensation. Additionally, ensuring that EVs are reliably available for user needs amid conflicting stakeholder priorities presents a further complexity in V2G integration. This gap highlights the urgent need for further investigation to ensure the equitable and effective integration of V2G systems into the energy grid.

7 | Q3—HOW CAN EUROPE BEST ACCOMMODATE FUTURE V2G DEVELOPMENT?

As Europe strides toward strengthening its power infrastructure to accommodate the increasing number of RES and to manage the anticipated growth in demand, partly spurred by EVs, a crucial aspect of this evolution is the readiness to overcome challenges presented by V2G systems integration. This section examines the current challenges of V2G deployment, including the state of V2G infrastructure readiness, with a particular focus on the nuances of controlling

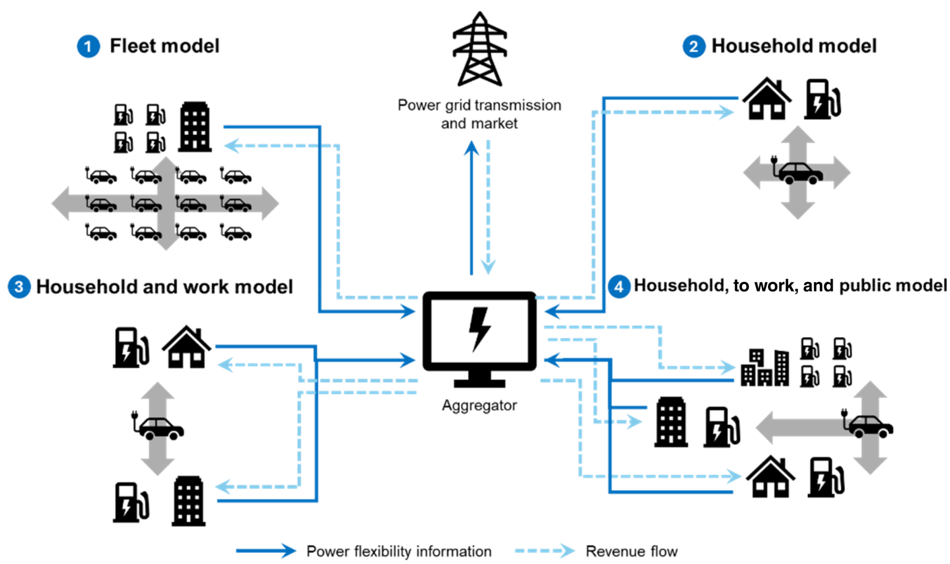


FIGURE 10 Four models of company fleets and private V2G models, adapted from (Sovacool et al., 2020).

V2G setups as well as the network and privacy concerns that are paramount when integrating these systems into the grid. Recognizing the importance of robust hardware for reliable infrastructure, recent literature describes the complex challenges posed by V2G technology, notably in ensuring user privacy and secure network communication.

Integrating V2G into existing power networks poses several challenges, ranging from the technical to security and regulatory. On the technical side, there are emerging challenges related to how best manage bidirectional power flows, which can disrupt the traditional unidirectional power flow models that most modern grids operate under (Diahovchenko et al., 2020). Research from (A. R. Singh et al., 2024) further identifies key EVs and V2G services power network implementation challenges as managing grid congestion, local voltage variations, and the complexity of load management strategies. On the network side, integrating communication protocols at the power bus distribution level within the charging network is crucial for effectively controlling V2G capabilities, such as regulating flexible power demand and supply. Another significant challenge is upgrading the existing information and communication technologies infrastructure to enable secure, real-time data exchange between EVs and grid operators. These upgrades are essential for managing the charging and discharging processes of EVs, which play a critical role in balancing the grid during peak and off-peak periods (Diahovchenko et al., 2020; Wohlschlager et al., 2022). These developments are critical for managing the bidirectional power flows introduced by V2G and addressing the complexities of real-time energy management. Shared autonomous electric vehicles (SAEVs), with their potential to utilize V2G technology, are expected to be a key solution in reducing global GHG emissions. However, their integration poses significant challenges for existing infrastructure, particularly in optimizing the placement and sizing of charging stations to balance investment costs with operational efficiency. The use of V2G by SAEVs requires careful coordination of charging and discharging activities, making it essential to overcome these challenges to fully realize both the environmental and operational benefits of V2G integration (Peer et al., 2024; Tian et al., 2024).

Security and privacy concerns are recognized as critical challenges to address in deploying V2G technology (Shang & Li, 2024; Shui et al., 2024). (Han & Xiao, 2016b) explores privacy-enhancing techniques like anonymous authentication and data aggregation to secure two-way communication within smart grids to tackle privacy and security issues. Using V2G means letting someone else decide when the car charges or discharges its battery based on information about the vehicle operator. This can be particularly tricky to manage with strict privacy laws like the GDPR, which protects the data, and who is responsible for these protections. This scenario underscores the significance of developing and implementing robust privacy and security measures within V2G systems to foster user trust and broader adoption. Recent research initiatives (Huang et al., 2023; Rezapour et al., 2021; Xia et al., 2021) have introduced innovative solutions targeting these privacy and security concerns. Novel approaches using fog computing[2] for charging identity authentication improve efficiency and user privacy by minimizing cloud server reliance and utilizing group signatures for secure user authentication. Additionally, new authentication protocols have been developed in (Roman et al., 2019) to protect user privacy, data confidentiality, and EV location, offering a more efficient solution compared to existing models and enhancing security against known attacks. Studies also propose balanced data management systems for V2G networks that safeguard user privacy while meeting utility companies' monitoring needs, potentially increasing user trust in V2G technology (Han & Xiao, 2016a). Furthermore, advancements in three-party key agreement protocols for V2G communication emphasize the reduction of communication and computation costs while ensuring strong privacy and security (Shui et al., 2024).

When developing sufficient V2G infrastructure in Europe, establishing an adequate regulatory framework is essential for ensuring readiness and accessibility across different countries. A comparison of European market rules by (Pedro et al., 2023) reveals varied barriers for small-scale players in the electricity grid's balancing services market. Switzerland, Belgium, and Germany are noted for having fewer barriers, with expectations for Portugal and Spain to follow suit, indicating a broader move toward accommodating small-scale flexibility options. Policy evaluation methods in (Zirganos et al., 2022) for EV promotion emphasize the creation of effective strategies centered on emissions reduction and energy efficiency. These criteria are critical in informing the integration and evolution of V2G systems, where environmental and efficiency goals are paramount. In tandem, methodological frameworks, like those developed in Poland (Tucki et al., 2019), evaluate the impact of EVs on energy and air quality, offering analytical tools to enhance the V2G research paradigm, where the focus on emissions and energy efficiency can serve as essential indicators of V2G success. The V2G pilot project (Qin et al., 2023) underway in China exemplify the potential of V2G systems to provide flexibility and stability in the power grid. The insights from these initiatives highlight the importance of developing robust business models, technological requirements, and supportive policy frameworks, offering Europe a blueprint for advancing its V2G infrastructure. Norway's experience with DSOs transitioning to third-party flexibility provision suggests a need for a deeper understanding of the operational and regulatory challenges in V2G implementation. (Sæle et al., 2023) exemplifies a broader European challenge—balancing the ownership and control of grid assets with introducing innovative V2G systems. Similarly, Belgium's legal framework for integrating IFSPs (T. Chen & Vandendriessche, 2023) illustrates the necessity of supportive regulatory environments that encourage fair commercial negotiations and provide standardized compensation mechanisms, which are crucial for the equitable and efficient operation of V2G systems. The V2G integration within organizational contexts in the UK and perceptions among Australian fleet users stress that V2G adoption extends beyond infrastructure. It encompasses the interplay with daily practices, organizational behavior, and broader sectoral responsibilities. This highlights the significance of not only technological readiness but also the adaptation of daily routines and the organizational environment, which can either enable or hinder the seamless embedding of V2G systems (Lucas-Healey et al., 2024; Meelen & Schwanen, 2023). As reflected in a survey of EV owners by (Baumgartner et al., 2022), consumer preferences demonstrate an affinity toward environmentally conscious choices within V2G systems. This indicates a broader consumer readiness to align personal sustainability values with V2G usage, even if it means accepting compromises, such as reduced battery ranges or financial incentives.

This section has reviewed some of the potential challenges associated with deploying V2G systems, with a focus on Europe while also considering the global implementation landscape. As Europe enhances its power infrastructure to accommodate these changes, it faces nuanced technical, privacy, security, regulatory and network management challenges. Despite these challenges, advancements in fog computing, authentication protocols, and data management are promising in enhancing user trust and adoption. Nevertheless, further research is required. The section also suggests a need for more research on deploying these technologies within varied regulatory environments and learning from global examples. For instance, insights from California's financial viability studies and Shanghai's peak shaving experiences provide essential lessons on the economic implications and benefits of V2G systems. These insights highlight the importance of a comprehensive V2G integration approach that considers all stakeholders and regulatory contexts to ensure Europe's successful transition to a flexible, efficient, and sustainable energy grid.

8 | CONCLUSION AND FUTURE RESEARCH DIRECTION

In conclusion, the presented exploration into integrating V2G systems within the European energy landscape has highlighted significant progress and emerging challenges. The transition toward enhancing grid stability and flexibility through V2G technology showcases Europe's commitment to a sustainable energy future, emphasizing the critical role of EVs and RES. However, complexities such as technological barriers, privacy concerns, and the dynamics of stakeholder participation and regulatory frameworks remain pivotal challenges to overcome. Privacy and network security are urgent concerns, requiring innovative solutions to build trust and encourage broader adoption of V2G systems. While technological advancements offer promising mitigation pathways, adapting these solutions within Europe's diverse regulatory landscape necessitates focused research. Insights gained from various implementations underscore the importance of a comprehensive approach to V2G integration, emphasizing the need for clear regulatory and operational frameworks.

Future research must address several gaps to fully harness the potential of V2G systems in Europe. A crucial area is developing an economically sustainable model that benefits all key stakeholders. This model must consider each country's unique mechanisms and regulatory environments, ensuring that V2G systems can operate efficiently and equitably across Europe. Furthermore, there is a pressing need for comprehensive research into the economic mechanisms of V2G flexibility providers, mainly focusing on the roles of aggregators, compensation structures, and interactions with DSOs and GENCOs. Such studies are crucial for developing a robust V2G ecosystem, as these economic frameworks are currently lacking.

Bridging these research gaps—privacy and security, regulatory and operational framework, and economical setup between the stakeholders—will be paramount as Europe moves toward a more dynamic, efficient, and sustainable grid. The insights provided in this overview lay the groundwork for future investigations into V2G technology's complexities, aiming to unlock its full potential and secure its crucial role in Europe's energy systems. With continued innovation, collaboration, and strategic focus, V2G technology is critical to transforming the energy landscape into more resilient, adaptable, and sustainable, benefiting all stakeholders.

AUTHOR CONTRIBUTIONS

Ondřej Štogl: Conceptualization (lead); data curation (equal); formal analysis (equal); funding acquisition (equal); investigation (equal); methodology (equal); project administration (lead); resources (equal); visualization

(equal); writing – original draft (lead). **Marek Miltner:** Conceptualization (supporting); data curation (equal); formal analysis (equal); funding acquisition (equal); investigation (equal); methodology (equal); project administration (supporting); resources (equal); validation (equal); visualization (equal); writing – original draft (supporting). **Chad Zanocco:** Formal analysis (equal); methodology (equal); validation (equal). **Marzia Traverso:** Supervision (equal). **Oldřich Starý:** Funding acquisition (supporting); project administration (supporting); supervision (equal).

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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ENDNOTES

[1] Although the term V2G was first used as early as 1997, only articles that included V2G as a keyword were included in the analysis. The search for relevant articles was conducted up to March 2024.

[2] Fog computing is a computing approach that happens between edge devices and the cloud data to take advantage of both.

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