Energy Reports 15 (2026) 109169

Contents lists available at ScienceDirect

Energy Reports

journal homepage: www.elsevier.com/locate/egyr

Review article

Evolution of V2G acceptance: A review of influencing factors over time

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ARTICLE INFO

Keywords:
V2G
V2H
Bidirectional charging
Social acceptance
Adoption

ABSTRACT

Vehicle-to-Grid (V2G) technology represents a key advancement in integrating electric vehicles with the power grid, enabling bidirectional energy flow to improve grid stability and optimise energy use and storage. Despite its technical feasibility, adoption remains hindered by social acceptance that evolves over time. The reviewed period from 2017 to 2025 has been marked by significant turbulence in sectors directly affecting V2G, including energy markets, mobility trends, and policy frameworks. Given that V2G has long been technically feasible yet struggled to achieve widespread acceptance, these disruptions present a unique window of opportunity. In light of this, rather than offering the usual snapshot perspective, this review focuses on the connections between its perception and trends influencing it. Aiming to identify the key drivers that could propel it toward widespread implementation. This review unconventionally combines academic literature with diverse grey literature, providing a broader perspective by incorporating industry developments and identifying trends. Factors are classified into three categories - emerging, persistent, and diminishing - capturing their changing significance over time. Our findings suggest that while financial incentives and lack of standardisation remain crucial, motivations for V2G acceptance are shifting, with sustainability and energy autonomy gaining importance. Some previously critical concerns, such as range anxiety and battery degradation, are diminishing as technology advances. Beyond identifying trends, we propose strategies to overcome key barriers, providing a deeper understanding of evolving consumer priorities and technological advancements.

1. Introduction

With the expansion of renewable energy installations, an array of new challenges has emerged. Unlike traditional power plants, renewable electricity production is fundamentally volatile, leading to power output fluctuations that are virtually uncontrollable. This calls for a gradual shift from the conventional paradigm that demand leads, and generation follows to one where, on the contrary, generation leads, and demand follows (EEA, 2023; Xu, 2019; EY and eurelectric, 2025).

Although the rising installations of residential photovoltaics (PVs) is a welcomed and incentivised trend, it comes with the drawback of grid congestion (Braat et al., 2021). Distributed flexibility can help alleviate that and support a higher integration of renewable energy. End users (e.g. households) are in a suitable position, able to store surplus energy and return it to the grid during periods of energy scarcity (Xu, 2019; Brown et al., 2018).

The idea of bidirectional charging is known as the Vehicle-to-Grid technology (Kempton and Tomić, 2005). V2G allows the battery of an electric vehicle (EV) to be connected to the power grid and mediates a flow in a currently desired direction depending on the production or consumption surpluses. Therefore, EV users are being turned from consumers into prosumers, and as a result, EVs are turned from being part of the problem into its potential solution (Xu, 2019).

Bidirectional charging differs considerably from other technologies with clear purposes and outputs. Certain technologies function effectively on their own, but bidirectional charging depends on the integration into the broader energy and mobility infrastructure (Brown et al., 2018; Dong et al., 2023). Understanding the motivations, barriers, and drivers as well as the real perceived benefits of various potential user groups is therefore necessary to design and implement viable products and services (Sovacool et al., 2017).

Regardless of the technical feasibility of V2G technology and its known benefits, real-world adoption remains limited. It is so, partly but not exclusively, because of the low social acceptance (Baumgartner et al., 2022; Kester et al., 2019). That is an area that is notably under-researched (Bibak and Tekiner-Moğulkoç, 2021; Ghotge et al.,

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https://doi.org/10.1016/j.egyr.2026.109169
Received 27 July 2025; Received in revised form 2 January 2026; Accepted 3 March 2026
Available online 30 March 2026

2022; Sovacool et al., 2018).

Energy and mobility have undergone substantial turmoil in recent years, driven by geopolitical shifts, policy changes, and market dynamics. Instead of merely summarizing past findings and providing a static snapshot based solely on academic publications, this paper takes a different approach. We have integrated diverse grey literature to identify key trends and future outlooks. To the best of our knowledge, only Goncearuc et al. (2024) included grey literature in their analysis, whereas none of the other recent reviews did, at least not in a comparable extent. Compared to Goncearuc et al. (2024) our findings are more user-centric, seeking to understand how users perceive and interact with the technology. Crucially, our approach differs by focusing on barriers that appear widely and persistently across research over decades, while avoiding niche factors often covered by only a handful of publications. This enabled us to identify and document reliable trends. A full inclusion of all known factors, including the often under researched ones, would render the trends inconclusive.

The selected grey literature includes surveys, global mobility analyses, market research studies, and trial project reports. Although academic papers ensure procedural rigour, they often focus on a single country or region, have limited respondent pools, or rely on simulations, reducing their broader applicability. We acknowledge that grey literature can carry biases, but it provides a more comprehensive view of long-term shifts across a wider geographical scale. Additionally, some reports are now published regularly, enabling year-over-year comparisons.

This study mainly focuses on Europe, as most of the selected publications and research originate there. This concentration likely stems from mature local EV markets, favourable EU policies, and a strong emphasis on socially oriented funding - such as the extensive, multi-year Horizon Europe program, which prioritizes societal challenges. While the empirical focus lies in Europe, with the United States and Australia discussed as comparable user-centric and market-driven contexts to provide insight into unique market dynamics and user preferences such as seeking grid resilience in remote areas, the growing body of V2G literature from China illustrates a distinct governance and system approach (Li et al., 2025; Xu et al., 2025; Zhang et al., 2025; Hove, 2023). Chinese V2G initiatives are predominantly designed as grid-oriented, flexibility and balancing mechanisms, coordinated by public authorities and system operators, rather than as household-level optimization tools. This regional disparity aligns with broader trends in V2G user survey research, which has surged alongside global EV market expansion, yet remains heavily concentrated in Europe, the United States, and Australia, left China, comparatively underexplored, despite its EV leading position (Zhang et al., 2025). With respect to that, in chapters examining factors and trends that are, or may be, significantly region-specific, we emphasize it.

2. Research method

This section outlines the review process, explaining the rationale behind the selection of particular literature, exclusion criteria, and categorization. The review process was guided by the procedure proposed by Van Wee and Barister (2015) for structuring a literature review paper.

2.1. Primary literature selection process

The core of the selected literature pool was query-based. First, three key terms representing areas of interest-V2G, acceptance, and user - were chosen. Alternatives for each term were then added to refine the final search query. Various tests, such as whether using the U.S. or U.K. spelling of "behavior" affected search results, were conducted before finalizing the following query:

*("vehicle-to-grid" OR "v2g" OR "bidirectional charging" OR "smart-charging" OR "v2h" OR "vehicle-to-home") AND ("acceptance" OR "adoption" OR "consumer attitude" OR "awareness" OR "perception" OR "willing" OR "consumer behaviour") AND ("user" OR "consumer" OR "driver")**

Three widely renowned databases were opted for, Web of Science, Scopus and Dimensions. Together with this search query two additional criteria were selected, i.e. the publications needed to be available with a full text in English and be published between 2017 and 2025. The reasoning behind the time frame is twofold. First, Sovacool et al. (2017) published a comprehensive review summarizing knowledge up to that point and a year later a comprehensive overview of V2G trial projects was published by Everoze and EVConsult (2018). Second, the past nine years have been particularly eventful due to major disruptions (i.e., the energy crisis, consequential geopolitical shifts, and the rapid expansion of the EV market).

After removing duplicates caused by overlaps across the three databases, an initial set of 317 publications was obtained. In the following stage, the titles were scanned. The criteria focused on bidirectional charging from a user-centric perspective, including usage, motivators, hurdles, and applications. This phase was deliberately inclusive, keeping publications that might offer valuable insights, even if they seemed only tangentially relevant resulting in a set of 106 publications.

Next, abstracts and full texts were screened to exclude irrelevant publications. The criteria were: relevance to bidirectional charging technologies (e.g., V2G, V2H); focus on user perceptions or adoption; and potential implications for grid integration and energy resilience. For example, although the study by Delmonte et al. (2020) primarily addresses smart charging, it was included due to its exploration of consumer attitudes toward managed charging practices, which are relevant to V2G adoption given the behavioural parallels. This direct link between smart-charging and V2G was made by an industry expert cited by EY and eurelectric (2025): *"The general perception is that V2G is the ultimate solution to address grid balancing challenges and optimise renewable energy use. But it all starts with what we have available already today - which is unidirectional smart charging - which controls when EVs can charge at maximum possible power and when the charging power should be reduced. V2G is a good next step for further optimisation, and can take off once other fundamentals, such as regulations, tax and surplus renewables capacity, and multi- layer grid capacity improvements have matured and are properly in place. (p.3)"* - Similarly, Babaei and Wong (2024) was retained for its emphasis on the resilience potential of EVs, highlighting a promising use case of V2G in emergency situations.

At the end of this process, 38 publications remained. Through a bidirectional snowballing approach, 11 more publications were added, bringing the subtotal to 49 before adding grey literature. The extraction process, along with the number of publications from each database, is shown in Figs. 1 and 2.

2.2. Addition of grey literature

Unlike academic literature and databases, which are generally meant to be used for review, grey literature requires a different strategy. The search was guided by two main approaches: a database of publications collected during previous research combined with a targeted search using search engines and AI tools to identify relevant reports, articles, posts, and other non-academic publications.

A key focus was on the EV driver surveys, as they reveal user preferences. Other sought-after publications were reports from all the V2G trial projects conducted up until the point of the search. The third group, with a common denominator, were publications by consultancy companies that publish every year and have access to data from all around the world. The remaining publications were identified through an exploratory search process without a predefined target, aiming to cast a wider net and uncover any potentially relevant insights.

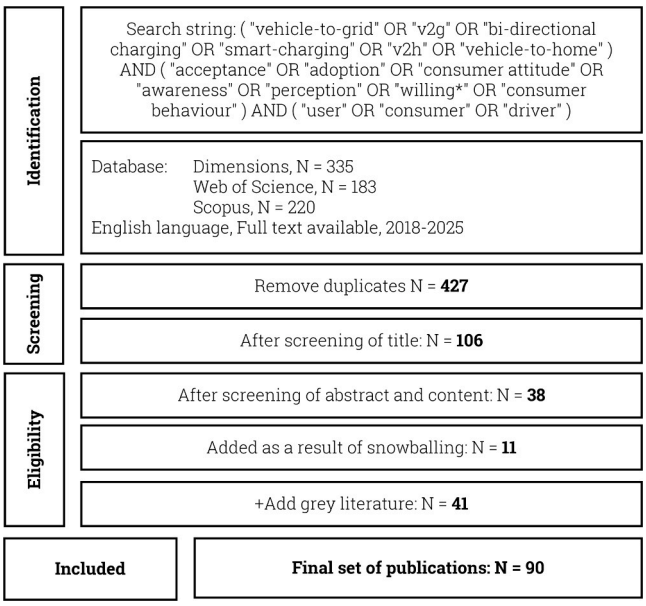

Fig. 1. PRISMA chart.

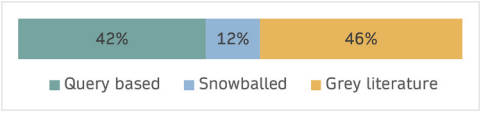

Fig. 2. Publication type distribution.

Below are examples of grey literature sources and their reasoned relevance. Their order is based on their geographical scope - from global to national.

*EY Mobility Consumer Index (*EY, 2024*)*

- This publication does not focus on V2G directly, yet it includes interesting findings such as high user preference to combine their EVs with home energy systems.
- Conducted annually since 2020, it offers insights into global trends and shifts in consumer perception over a considerable period.
- A similar case applies to McKinsey's Annual Mobility Survey. Although it focuses on EVs rather than V2G, its robust dataset - drawn from over 3000 participants across continents with year-over-year comparisons - yields valuable insights into shifting behaviours, such as increasing willingness to purchase used EVs and reduced reliance on owning a "backup" ICE vehicle.

*Geotab Study – How Long Do Electric Car Batteries Last? (*Geotab, 2024*)*

- This frequently cited study offers important findings regarding one of the most feared aspects of owning EVs and using them bidirectionally – battery degradation.
- Based on a very large sample of EV data this study casts light on the difficult-to-research phenomenon of battery degradation over long-term usage.

*Consumer Monitor 2023 (*European Alternative Fuel Observatory, 2024*)*

- Surveyed over 19,000 respondents across the EU, providing a diverse and relevant dataset.
- Statistics highlighting regional disparities included.
- Contained questions specifically monitoring interest in V2G.

*Nationaal Laadonderzoek 2023/2024 – Dutch National Survey on Charging (*RvO Nederland, 2023, 2024)

- Even though its focus is on a single country, the Netherlands has one of the highest EV adoption rates and significantly overloaded grid, making it a prime candidate for V2G.
- The 2024 edition offered a valuable YoY comparison of trends given consistent samples.

*Project Sciurus Trial Insights – Findings from 300 Domestic V2G Units (*Cenex, 2021*)*

- This report provided real-world data from a large-scale V2G trial.
- Although a similar case was conducted and published in academic papers (Ghotge et al., 2022), this study operated on a much larger scale, using a commercially viable bundle, offering unique insights into their preferences and opinions following a hands-on experience.

Lastly, a noteworthy trend was the increasing presence of V2G-related questions in various consumer surveys. Although only the RvO (2023, 2024) surveys provided YoY data, other reports - such as those from Shell Recharge (2023), CTEK (2023), and European Alternative Fuel Observatory (2024) - have begun including them as well, suggesting potential for direct YoY comparisons in the future.

Given that this review follows a qualitative synthesis approach, some interpretative bias is inevitable (e.g., relying on multiple publications from a single institution that make them publicly available, with the risk that motivations for publishing in this area are driven by certain commercial interests, interpreting ambiguous user feedback as supportive when context suggests caution, especially in early-stage or subsidized pilots, or unconsciously preferring publications with clear and well-presented data). Despite those risks we do believe in the value of grey literature as it provides timely insights, and real-world perspectives often absent from academic publications. To mitigate the bias, we emphasized transparency and ensured they served as a complementary material to contextualize and enrich findings derived from peer-reviewed sources.

2.3. Validation of the selection process

To assess the robustness of the presented findings and the consistency of the literature selection, we've performed a validation process. In five recurring iterations, twenty (~one quarter) of the reviewed publications were randomly excluded from the analysis. For each iteration, the particular conclusions were revisited and compared to the full-sample synthesis to observe whether the same thematic patterns, trends, and interpretations persisted.

When assessing the impact of excluding portions of the reviewed material, it became evident that certain thematic factors demonstrated stronger resilience than others - usually and logically those where trends are clearer and where more data is available.

Across the five validation iterations, the factors *Easy-to-Use Charging Controls* and *Insufficient EV Market* proved particularly robust. Even after the exclusion of multiple relevant sources, its core interpretations and takeaways remained unchanged. Similarly, *Financial Compensation* emerged as a consistently well-supported and widely cited factor; in all tested subsets, its conclusions remained stable and uninterrupted. Only in one iteration did the exclusion of key publications limit the ability to describe specific variations in preferences across age groups.

For *Charging Standards*, the observation that users prefer a unified payment system - rather than managing multiple cards, chips, or apps - was vulnerable, being supported only by Shell Recharge (2023).

In the case of *Supporting the Renewable Energy Transition*, two minor issues were observed. In one subset, the link between EV ownership and heightened environmental interest became inconclusive, as almost all publications mentioning this link were excluded. In another iteration, the removal of non-European studies resulted in geographically

narrower findings, with trends lacking the global contextualisation.

Regarding *Individual Energy Security*, the overall tendency of users to take responsibility for their household energy management remained evident and strong. Nevertheless, in some exclusion sets, the link between residential energy use and interest in V2H solutions weakened, while in another iteration, the absence of year-on-year data on smart charger installations limited the ability to confirm the observed growth trend. That was however only an illustrative addition rather than a core thought of that section.

The factor *Lack of Awareness* appeared relatively more sensitive to exclusions. When Geske and Schumann (2018) was removed, the long-term European trend became less conclusive as this study offered quite unique data from 2013, though other available data confirmed a steady increase in recent years. In other combinations, the reverse occurred: recent YoY evidence was lost, but sufficient cross-sectional studies remained to sustain the interpretation. In the final iteration, the exclusion of comparative studies between European nations and Australian context reduced the granularity of regional insights, even though the general trend remained.

Overall, as this validation revealed variation in the degree of evidential support across individual factors, no case resulted in a substantially altered conclusion or reversal of the key takeaways. The synthesis thus appears reasonably robust given the scope, diversity, and nature of the reviewed materials. The process seems to confirm that, despite relying on a mix of academic and grey literature, the resulting interpretations rest on a reasonably solid evidential foundation suitable for the presented qualitative analysis.

3. Results

The final selection included 90 publications: 38 obtained through query-based searches, 11 collected via snowballing, and an additional 41 from grey literature.

Interest in V2G research continues to grow, with 2025 on track to reach a record number of related publications. While the number of publications including the keyword ‘V2G’ in the title or abstract (according to dimensions.ai) has steadily increased worldwide over the years (as shown in Table 1), the growth in 2025 appears to be slightly slowing to around 10% year-on-year. Despite this, the number of publications selected for this review remains relatively stable across the initial years 2018–2022. The recent spike is mostly driven by the inclusion of newly available grey literature including recurring relevant reports and surveys.

Once the review set was established, the next step involved establishing a thematic framework for analysis and categorizing the identified factors. Building on the structured search and screening stages, this process began with identifying general thematic areas and key factors discussed in earlier academic literature. Previous reviews offered different approaches to classification. The key one by Sovacool et al. (2017) proposed four categories: Technical, Financial, Socio-Environmental, and Behavioural. A more recent one by Bibak and Tekiner-Moğulkoç (2021), introduced a similar framework, categorizing factors as Environmental, Technical, and Economic. This review takes a different approach, focusing on the evolution of factors over time and their shifting importance in influencing social acceptance, to provide guidance into how to design the products and policies to reflect the behavioural preferences. To reflect this focus, three categories were defined: Emerging, Persistent, and Diminishing factors.

Given the relatively limited number of available publications, identifying clear patterns based on mentions or other quantifiable metrics proved challenging. Additionally, the diverse nature and structure of the selected publications complicated that even further.

Therefore, the categorization followed a qualitative synthesis of both academic and grey literature. Drawing on evidence from international reports, market analyses, and observed industry developments, each factor was assessed according to whether its importance appeared to be emerging, persistent or diminishing. This preliminary categorization guided the subsequent synthesis phase, during which each reviewed publication was examined in relation to the identified factors to build a coherent picture of their evolution throughout the review period. For tracing temporal trends, greater weight was given to studies providing large samples or consistent year-over-year data, ensuring that the derived patterns rest on solid fundament. Complementary insights were then integrated to enrich the overall context.

After reviewing the dataset, the most frequently recurring factors were identified and, where necessary, grouped under broader categories. For example, “battery degradation compensation” and “discount on electricity tariffs” were merged under financial compensation, as both reflect the same underlying motivation for economic reassurance. A detailed discussion of each factor, supported by relevant publications and the rationale for its classification, is provided in the subsequent chapters.

The selection of factors was partly informed by findings from previous reviews, e.g. Goncearuc et al. (2024) and van Heuveln et al. (2021), but a crucial criterion was the ability to contextualize them using available grey literature which often captured emerging practical insights absent from academic sources. This approach explains the inclusion of factors like Supporting Renewable Energy Transition. Whereas other publications usually only mention the observation that EV drivers tend to be more considerate about the climate, we wanted to pursue the potential synergy of such motivations further.

With academic literature forming the basis for identifying relevant factors, the categorization process demanded a more intricate approach, involving cross-referencing diverse sources, critical interpretation, and the integration of statistical data from related fields. This process is further illustrated through the following examples:

For EV market share, data reflecting a slowdown in growth was combined with industry reports on automakers' revised plans and targets, sales challenges, and potential reasons behind these disruptions. In the case of financial compensation, it was evident that it is a very highly

Table 1
number of publications inc. the keyword 'V2G'.

Year	2017	2018	2019	2020	2021	2022	2023	2024	2025
No. of publication inc. the keyword 'V2G'	234	266	310	381	403	555	696	897	*1065*
YoY increase		14%	17%	23%	6%	38%	25%	29%	-
Number of reviewed publications	1	5	3	5	6	7	11	25	27

regarded issue recurring in almost all the publications with no notable sign that there is a solution or real application reassuring users. Range anxiety could serve as an example of a diminishing factor. There are clear data showing that in some regions drivers are getting more comfortable with the range. Other data consistently shows that experience with an EV diminishes these concerns considerably as it goes hand in hand with the increasing average size of batteries.

There were cases, where categorization was not so straightforward. Battery degradation, for instance, presented a challenge. Whereas there is little evidence of a notable decrease in the perception of this factor as a deterrent to V2G usage, we found evidence suggesting batteries actually perform significantly better than expected. Both simulation and real-world data indicate that this concern has a strong case to be minimized as more vehicles enter the market and more proven cases of their longevity reach public awareness.

Overview of time-based factors:

3.1. Emerging factors

Emerging factors arise from evolving dynamics that are beginning to influence the acceptance of V2G. These factors are shaped by ongoing changes in energy systems, user expectations, technological developments and market signals.

3.2. Persistent factors

Persistent factors refer to longstanding barriers that have been consistently known as impactful for V2G acceptance over time. They either don't get enough attention or are so severe that not even applied precautions and solutions are sufficient to minimise them. The attention therefore has to stay strong and new solutions and attitudes are to be applied to overcome them.

3.3. Diminishing factors

Diminishing factors are those that once posed substantial challenges to V2G adoption but are now either losing relevance or showing clear signs of doing so. This decline is typically driven by technological advancements, market shifts, or changing user perceptions. Whilst they are no longer central concerns, understanding their reduction can provide valuable insights into the broader evolution of V2G acceptance.

The following Fig. 3 visually represents which publications are mentioned in the following chapters of distinctive factors. In columns are the nine factors divided into three categories. Filled field indicates that this publication covers the corresponding factor.

3.4. Emerging factors

3.4.1. Individual's energy security

For a considerable period, topics like energy systems, distribution grid, household consumption and energy bills weren't of interest to most, at least in the European countries. That changed substantially with the energy crisis of 2022 when not only did prices spike but the energy availability as such became uncertain (Statkraft, Energy Perception Report, 2022; International Energy Agency, 2023). The steep surge in electricity prices compelled the public to become significantly more aware of their energy consumption and their energy's origins (EY and eurelectric, 2025; European Commission, 2024). This trend is observable in multiple areas. According to Google Trends the search for the term "kWh" increased notably during 2022 in many European countries. The roll-out of smart meters accelerated, as did the number of installed PVs (International Energy Agency, 2023; International, 2023; De Paola et al., 2023). Whereas the situation has since become somewhat more stable, the lasting effect of the crisis remains as described by Chatzouli et al. (2025): *"the sudden price increase in 2022 raised user awareness toward demand side management and the potential financial benefits. While prices stabilized after 2023, they are still notably higher than before the 2022 energy crisis levels, with the high average daily price fluctuations that appeared toward the end of 2021 being persistent. (p.1)."*

It is therefore clear now that the interest in alternative ways to generate, monitor and store electricity has become substantial. It should be clarified that although V2G is regularly used as an umbrella term for any type of bidirectional charging it has multiple sub-variants. The two most known are Vehicle-to-Load (V2L) used mostly to power basic power tools or appliances and the second one – particularly interesting in the previously described context – Vehicle-to-Home (V2H). This variant makes it possible to use the battery of an electric vehicle to cover the energy needs of a household, ideally working together with PV in the same way as residential batteries would. Even though residential batteries are a preferable storage solution in the eyes of multiple experts, the end users seem to show different interest (Noel et al., 2019; FfE, 2025).

The belief that the residential scale of V2H is a particularly attractive one is supported by the reviewed literature. Philip et al. (2023). state this preference quite clearly: "*This implies higher preferences towards being able to use EVs to power the home, rather than simply for exporting energy to the grid.", This could be attributed to individual benefits such as energy independence and energy cost savings, especially for consumers with rooftop solar (p. 11)".* This notion is further supported by findings of the European Alternative Fuel Observatory (2024) stating that the ability to power one's home is actually a key selling point for V2G adoption. Kühnbach et al. (2024a) agree with those findings adding that in the countries with relatively cheap electricity such as France or Poland, the savings would be considerably lower. Chung and Ryu (2024) similarly highlight regional disparities in preference, adding that the increasing availability of affordable residential batteries may render them a more viable option for future users.

The inclination towards V2H likely stems from limited viable V2G business cases and the fact that EV drivers typically charge their vehicles at home, making household usage the most convenient one (Noel et al., 2019). According to a worldwide survey by Global EV Alliance (2024) home charging accounts for 72% of all charging sessions. European based survey by LCPDelta (2025) found this number to be 65%. Additionally, a US based survey by ChargeLab (2024) found the ratio of respondents that have access to home charging to be 86%. Despite the percentages being slightly lower across multiple European nations, the average remains strong, with CTEK (2023) reporting 60% of respondents choosing home charging, Shell Recharge (2023) at 56%, and 55% found by European Alternative Fuel Observatory (2024). A probable reason for the lower numbers is a comparatively more mature public charging network in Europe taking a higher share of the total charging sessions. Diverse publications consistently highlight a strong preference of respondents for charging at home over public alternatives. – Kubli (2022) reports this to be the case for 76% of respondents, Khezri et al. (2024) finds 77% and Delmonte et al. (2020) over 80%.

Even though a high inclination to home charging doesn't necessarily need to translate into V2H adoption, two substantial signals are showing a potential shift towards this direction. The first one would be observable evidence of a rising ratio of home "smart" chargers. Smart chargers also known as V1G are designed to be able to shift charging sessions to a period of lower energy demand and they are perceived as a step towards full bidirectional charging (EY and eurelectric, 2025; smartEN, 2023). This feature can help the potentially overloaded grid and deliver financial savings to their owners. The statistics for this metric are limited, but in the case of the Dutch relatively EV-mature market, the increase in time is notable as the ratio of chargers being smart increased from 41% in 2021 to 58% in 2024 (RvO Nederland, 2024). Another survey conducted by UK's Department for Transport (2022) indicated a 52% ratio in 2022, but in this case the YoY comparison is not available.

The second, substantially clearer, observation indicating a likely upcoming shift in this direction is the overwhelming interest in combining EVs with residential PVs. There's a clear rationale behind that

	Emerging factors			Persistent factors			Diminshing factors			
Publication	Individual's Energy Security	Supporting Renewable Energy Transition	Insufficient EV Market	Financial Compensation	Easy-to-Use Charging Controls	Charging Standards and Interoperability	Range Anxiety	Battery Degradation and Warranty	Lack of Awareness	Elsewhere
ACER & CEER (2024)		■								
Adnan et al. (2018)			■			■				
Akyga (2025)						■				
Alfie Ireland & OVO Energy (2020)				■	■					
Babaei & Wong (2024)	■									
Bakhuis et al. (2025)	■	■		■			■			
Baumgartner et al. (2022)		■		■			■	■	■	■
Baumgartner et al. (2024)				■				■	■	
BCG (2025)			■							
Bibak & Tekiner-Mogulkoc (2021)		■	■					■		■
Bohdanowicz et al. (2022)				■						
Brockmann et al. (2025)							■	■		
Cenex (2021)				■		■				
Chatzouli et al. (2025)	■	■			■					
ChargeLab (2024)	■						■			
Chung & Ryu (2025)	■									
CTEK (2023)	■		■	■		■				■
De Paola et al. (2023)	■									
Dean & Kockelman (2024)		■	■							
Delmonte et al. (2020)	■									
Department for Transport (2022)	■									
EEA & ACER (2023)		■								■
ElaadNL & FAN (2022)	■	■								
ESO & Octopus Energy (2023)			■	■		■				
European Alternative Fuel Observatory (2024)	■	■					■		■	■
Everoze & EVConsult (2018)										■
EY (2024)			■				■			
EY & eurelectric (2025)										■
FfE (2025)		■		■						
Geotab (2024)								■		
Geske & Schumann (2018)		■		■	■		■	■	■	
Ghotge et al. (2022)	■	■	■	■	■	■		■		
Global EV Association (2024)	■	■								
Goncearuc et al. (2024)		■	■	■	■	■	■	■		■
Gschwendtner et al. (2021)	■	■				■		■		
Guo et al. (2019)								■		
Hajhashemi et al. (2025)					■					
HERE & SBD (2025)			■							
Hove (2025)					■					
Huang et al. (2021)			■	■			■			
Hu et al. (2025)							■			■
Indra (2023)									■	
International Energy Agency (2023)	■									
International Energy Agency (2024)			■							
International Energy Agency (2025)			■					■		
Kester et al. (2019)				■	■		■	■		■
Khezri et al. (2024)	■	■		■			■	■		
Kostopoulos et al. (2024)		■	■						■	
Krueger & Cruden (2020)					■		■			
Kubli (2022)				■						
Kühnbach et al., (2024)	■	■		■						■
LCPDelta (2025)	■		■	■					■	
Lee et al. (2024)				■						
Li et al. (2025)					■					
Liu et al. (2025)										■
Lombardi et al. (2024)	■									
Lucas-Healey et al. (2024)		■	■	■						
McKinsey (2024a)			■					■		
McKinsey (2024b)								■		
McKinsey (2025)			■							
Mehdizadeh et al. (2023)				■						
Mehdizadeh et al. (2024)				■						
Najman (2024)								■		
National Centre for Social Research (2021)		■								
Neaimeh et al. (2025)		■		■			■			■
Noel et al. (2018)	■									
Noel et al. (2019)	■	■	■					■		
Opinium & E-Flex (2020)	■									
Philip et al. (2023)	■								■	
Philip & Whitehead (2025)					■				■	
Plug In America (2024)		■	■	■			■			
Power Technology (2025)			■							
Priessner & Hampl (2020)	■	■								
Roland Berger (2025)							■			
RvO Nederland (2023)				■			■			
RvO Nederland (2024)	■			■					■	
Shell Recharge (2023)	■	■		■		■	■			■
Shell Recharge (2025)							■			
smartEN & DNV (2023)			■	■		■				
Sovacool et al. (2017)		■			■		■			■
Sovacool et al. (2018)										■
Statkraft (2022)	■									
The Mobility House (2024)								■		
UPSCALE GmbH (2025)	■									
Van Eijk et al. (2025)						■				
Van Heuveln et al. (2021)				■	■	■	■	■		■
Xu et al. (2025)		■								
Ye (2025)		■								
Zhang et al. (2025)										■
Yun et al. (2025)		■		■						

Fig. 3. Overview of factors mentioned by the reviewed publication.

– a study simulating the combination of residential PV with EVs conducted by Lombardi et al. (2024) stated that the available vehicles captured 27% of annual overproduction (i.e., excess solar energy generated during peak hours) and covered significant energy demand. Such a figure would be comparable to the findings of Kühnbach et al. (2024a) expecting a potential cost reduction of 21–36% adding: *"Savings vary by household type, with smaller households achieving lower savings (both relative and absolute) than larger households (p. 7)."*

A growing number of EV owners prefer integrating their vehicles with home energy solutions, according to a study by EY (2024), stating that 44% of respondents wanted their EV bundled with other home energy systems. Similarly, Priessner and Hampl (2020) found that 77% of participants favoured pairing their EVs with energy storage or generation devices. The benefit of this pairing is supported by experts interviewed by Noel et al. (2018)*:" For many experts, solar PV and V2H was a natural connection and perhaps more intuitive than the complex services V2G could provide, such as frequency regulation (p.5)."* The tendency to integrate EVs into an energy-independent unit is also proposed by Gschwendtner et al.:*"Private people should first balance out their own energy demand throughout the day - and the same applies to commercial businesses or industry - to reduce the requirements for system services (p. 7)"* (2021) or Bakhuis et al. (2025). Adding to this, BSW Solar (2018) reported that 91% of German EV drivers want a home PV system, which is in line with findings of USCALE GmbH (2025), reporting 98% of respondents who had PVs, used them for charging EV. On top of that a Shell Recharge (2023) survey found that nearly half (47%) of their respondents already had invested in residential solar - with as high as 67% in Belgium and 71% in the Netherlands.

Speaking of the Netherlands, 49% of local respondents expressed direct interest in bidirectional charging, though only 10% preferred doing so at the public charging points (RvO Nederland, 2024). Additionally, 74% saw bidirectional charging as a way to optimize their residential PV production, though only 39% were willing to sell excess energy back to the grid - both indicating a strong preference for a V2H variant (RvO Nederland, 2024). In the particular case of this country – another reality plays in favour of it. The Netherlands for a long time had a netting scheme policy, meaning that the user's yearly PV production gets subtracted from the electricity consumption and only the difference is billed which disincentivise buying batteries (van den Berg, 2023). With the planned phase-out of this scheme however, a demand for energy storage could emerge and V2H could benefit from it (van den Berg, 2023; ElaadNL, 2022, 2025).

Blackouts in Europe remain rare but they do occur (ENTSOe, 2025), moreover the fear of them happening is increasing (Századvég, 2023). This correlates with the finding that 49% of British fleet managers surveyed by Opinium (2020) were uncomfortable relying solely on the national grid for all their energy needs despite the risk of blackouts in the UK remaining low (Guardian, 2024).

The aspect of energy security and backup power can therefore be valued as a more consequential feature of V2G in regions with an unstable grid. The emergency backup of V2G-capable vehicles was proven for example during the 2011 earthquake in Japan when a fleet of Nissan vehicles provided emergency power (CHAdeMO, 2020). Another more recent case was the one of Tesla Cybertrucks during the California fires (CBT news, 2025). Similarly, during extreme weather in Australia, V2G-enabled EVs played a critical role in stabilizing the grid. Following a severe storm that caused widespread blackouts, a fleet of EVs supplied power back to the grid, helping sustain electricity supply for affected households and showcasing the potential in crisis situations (Smart Energy International, 2024). A review by Babaei and Wong (2024). analyses the role of EVs in emergencies, highlighting their dual nature. While their reliance on public charging infrastructure can pose challenges during evacuations, they also present opportunities: *"Low state-of-charge, sporadic charging infrastructure, or power outages could significantly hamper safe and effective evacuations. Yet, EVs also offer possible resilience benefits to emergency response by more easily charging electronics or sending power back to the grid (p. 1)."* Strategically maximizing and distributing their stored energy could enhance grid resilience and support essential infrastructure.

The aspect of individual energy security appears in multiple regions but may arise from different motivations. In Australia and the US, where energy prices are generally more affordable, the main motivation is often to increase resilience against blackouts. In Europe, financial savings may play a stronger role, although concerns about grid insecurity are also present with blackouts looking more and more like a real prospect. This factor was classified as emerging not because the residential scale would be previously overlooked, but because of a considerable demand, that V2G/V2H could benefit from, seems to be forming.

3.5. Supporting renewable energy transition

During the review, two essential motivators emerged across the publications: personal benefits, such as securing one's own energy supply together with cost reduction and - environmental motivation.

EV drivers seem to show high interest in participating in environmental issues as 90% of those surveyed by Global EV Alliance (2024) see climate change as a big problem. Shell Recharge (2023) identifies the correlation between driving an EV and other environmentally positive consumer decisions to recur consistently adding that since driving EVs, 59% of their respondents became more aware of their home energy usage. The strong relationship between EV usage and environmentally conscious behaviour is further confirmed by Bakhuis et al. (2025), who found that only 20% of respondents considered environmental aspects unimportant. Plug In America (2024) adds that 40% of EV drivers indicated clean air and environmental protection as their primary purchase consideration. Finally, Baumgartner et al. (2022) found that many users were willing to adopt climate-neutral charging strategies, even at the expense of achieving a lower state of charge for their EVs. A willingness to engage in the energy transition and to alter behaviour to support the system is therefore evident.

The trend towards decarbonisation of energy systems is nothing new - with the German *Energiewende* strategy as an example dating back to 2010 (Federal Foreign Office, 2017). The political agenda and the energy crisis of recent years boosted these tendencies even further. Since both wind and solar energy are inherently volatile a crucial part of the energy transition is to incentivise decentralisation and higher flexibility - as explained by EEA & ACER (2023): *"The energy system must adapt at scale to provide adequate flexibility resources (from both the demand and supply side) to adjust to fluctuating renewable electricity supply (p. 6)"*. Additionally, a simulation-based study by Kühnbach et al. (2024a) projects V2G to potentially deliver over € 100 billion in energy system savings by 2040. The positive impacts of V2G have also been observed outside Europe, with Yun et al. (2025). concluding that in an ideal V2G-optimised scenario, peak net load could be reduced by up to 22.9% by 2030 in South Korea. Additionally, regulatory reforms at the EU level have strengthened efforts to enhance demand response. The Electricity Market Directive (2019/944) and Regulation (EU 2019/943) set common rules for energy generation, transmission, distribution, and storage while ensuring fair market access for independent aggregators (Kühnbach et al., 2024a). An important 2024 EU electricity market reform requires states to establish targets for non-fossil flexibility, including demand-side response and energy storage strategies (Kühnbach et al., 2024a).

A report by ACER (2024) focused on the ways to engage consumers stating the following: *"There is a huge potential for consumers to engage actively in and become part of the decarbonisation process (p. 12)."*, it further highlights smart meters and bidirectional EVs as key technologies to enable user engagement. Although usage of bidirectional vehicles is still very limited, smart meter roll-out rates have risen rapidly with 13 EU countries having a rate above 80% already (ACER, 2024). Smart meters are an important step in enabling engagement, as confirmed by an interviewee of the National Centre for Social Research (2021): *"I just*

think it's generally made everyone in the house a bit more aware of what we use and how much we use. (p. 28)". Other respondents of this study agreed that smart meters enabled them to reduce their carbon footprint and environmental impact (National Centre for Social, 2021). It does seem that access to electricity prices drives engagement as Chatzouli et al. (2025). found that 56% of surveyed EV drivers check their charging schedules and postpone charging accordingly to optimise costs.

V2G is a considerably more complex measure than a relatively simple smart meter implementation. Realising this limitation, the valuable takeaway from the extensive roll-out of smart meters is that once the technology becomes available – a substantial share of the population is willing to participate in it.

As evidenced by the literature, users realise V2G's potential and are interested in unlocking it. Ghotge et al. (2022). discovered that users perceived V2G charging as more environmentally responsible compared with immediate charging. Enabling more renewables to be integrated into the grid is further identified as a motivation by Geske and Schumann (2018), Priessner and Hampl (2020), Cenex (2021), ElaadNL (2022), Bibak and Tekiner-Moğulkoç (2021), Kostopoulos et al. (2024), Lucas-Healey et al. (2024), Khezri et al. (2024) and ACER (2024). Despite these publications generally sharing that finding, interesting discrepancy was observed by Neaimeh et al. (2025), who found that albeit many users believed V2G could affect grid stability, not all interpreted this impact as a positive one: *"the most contributing factor is a belief that V2G contributes towards a more stable electricity network. This worked as both a positive and negative predictor (p.5),"* highlighting different perceptions of its benefits and risks.

Literature indicates both motivation and willingness to adjust behaviour for energy system needs. 57% of Shell Recharge (2023) respondents indicated they would accept slower charging speeds if it enabled greater renewable grid integration, and 81% said they would be willing to delay charging to help prevent energy demand spikes. More than half of the respondents of Dean and Kockelman (2024) stated that they would participate in the V2G scheme for emergency power backup purposes, if adequate financial compensation was provided and the range of their vehicles would not fall below 50 miles.

The perception of V2G as a supporter of the grid is not only on the side of users, it is shared by experts as well: "*…some experts expect a balance between reinforcement and smart solutions depending on local grid conditions, flexibility supply and the resulting costs of the respective solutions. Distribution grid reinforcement is considered one of the main values of V2G (p. 6)"* (Gschwendtner et al., 2021). " With respect to regional differences, where in some countries, V2G is viewed as an inherent part of the future energy system, France, for example, plans to rely on alternative approaches, as "V2G is not seen as added value given alternative, less complex flexibility options (FfE, 2025). This stand is shared by experts interviewed by Gschwendtner et al. (2021) who prefer different solutions depending on a regional context:" *…others are convinced that grid reinforcement will not be required if smart solutions are applied [Int3, Int6]. In addition, some experts expect a balance between reinforcement and smart solutions depending on local grid conditions… (p.6)*". They also add that grid upgrades will have to take place, nevertheless.

Europe's current primary energy flexibility needs are on a daily/short-term basis rather than seasonal, making V2G especially well-suited to address them. Moreover, this need is expected to grow at an even faster pace, further supporting its potential (ACER, 2024). Despite varying paces, the shift towards a fossil-free energy system is occurring almost worldwide, and there is little evidence to suggest it will suddenly stop. Therefore, we believe this trend will continue, and since renewables are volatile by nature, any means of offering balancing power are to be increasingly sought after. Additionally, recent V2G studies from China (Li et al., 2025) illustrate how energy-system contexts fundamentally shape V2G's perceived value and role. Whereas Europe continues to phase out coal power plants while investing in renewables, China is simultaneously scaling both: coal provides essential dispatchability and grid stability amid rapid renewable expansion. Renewables are now covering approximately 84% of electricity demand growth in recent years - with coal's generation share declining to around 56–58% (Ember, 2025). A gradual phase-down of coal is planned for the coming decade. V2G could help accelerate this transition as a system-level flexibility resource to reduce coal-fired peaking. Empirical analyses in major cities like Beijing show emissions reductions primarily from avoided coal peaking and improved load balancing during high demand (Xu et al., 2025). Policy discussions characterize V2G as a grid management tool aligned with national goals for stability, renewable integration, and peak management, underscoring strong state coordination in linking EV adoption to power system needs (Ember, 2025). Ongoing pilots and policies for vehicle-grid integration further underscore V2G's alignment with China's vision, where it can help reduce curtailment of renewables and mitigate the need for coal as a backup flexibility resource in the medium term (Ye, 2025).

3.6. Insufficient EV market

The widespread adoption of V2G is inherently linked to the availability of EVs on the market. Its limitation is perceived as a major barrier by both users and industry experts (Noel et al., 2019; Kostopoulos et al., 2024; Adnan et al., 2018; Huang et al., 2021; McKinsey, 2025; BCG, 2025; International Energy Agency, 2025).

Ever since the first EV models became available around the year 2010 the annual sales were more or less growing (International Energy Agency, 2023, 2025, 2024). Together with favourable policies and incentives, some markets such as Norway experienced staggering inclines (International Energy Agency, 2024). After Tesla entered the market with the more affordable Model 3 and Y and other car makers offered more EV models, the trend towards electrification seemed to be very strong. Nevertheless, the covid pandemic put a halt to that, disrupting supply chains and affecting the whole industry.

Despite growing enthusiasm, with a year-over-year increase from 47% to 55% in belief that "EVs are the future of road travel" (CTEK, 2023) and increased intentions to purchase EVs both Europe +7pp) and the US (+5pp) between 2024 and 2025 according to McKinsey (2025) - these stated preferences have not quite translated proportionally into actual sales. Recent signs suggest that the EV market boom is slowing down" After *several years accelerating down the transition highway, electric vehicle demand has recently hit a plateau in some major markets, including the US and much of Western Europe. (p. 2)"* - (EY, 2024). This observation is shared by the International Energy Agency (2024) and Wall Street Journal (2024).

A notable regional disparity in EV driver's experience has emerged. A study by McKinsey (2024) offers worrying statistics showing that whereas in Europe only 19% of EV drivers are considering a return to ICE, in the United States this number was 46% and in Australia even 49%. Encouragingly a more recent findings from LCPDelta (2025) indicate that in Europe only 15% of drivers plan to switch back to ICE cars.

Despite strong global EV growth, largely driven by China, where EVs account for almost half of the sales in 2024 resulting in a market share reaching 10%, growth in Europe has stagnated. In the United States, EV sales continued to rise, but the pace was about one-quarter of the previous year, highlighting that while global adoption is increasing, it is not uniform across regions (International Energy Agency, 2025). The slowdown in Europe is likely caused by two main factors. First, policy changes, notably the phasing out or reduction of subsidies in Germany, France, and the Netherlands, combined with unchanged EU CO_2 targets for cars between 2023 and 2024, have tempered demand (International Energy Agency, 2025; Power Technology, 2025). Rising concerns around total cost of ownership may also play a role, as rapid advancements in EV technology can render vehicles just a few years old significantly less competitive, contributing to early depreciation of BEVs that typically exceeds that of internal combustion engine vehicles by 2–6 percentage points annually (BCG, 2025). Combined with vanishing tax

credits and high leasing rates, this creates notable residual value risks for owners.

One likely explanation for that are the ongoing issues with public charging infrastructure, particularly affecting the non-Tesla drivers. According to Plug In America (2024), 92% of non-Tesla EV users in the US report having experienced frequent problems with public charging. Tesla's Supercharger network generally provides a smooth and reliable experience but charging stations from other providers often fail to deliver their promised charging speeds, suffer from authentication system failures, or are entirely out of service. These recurring issues, where drivers find themselves unable to charge their vehicles despite being at a charging location, can be highly frustrating (Politico, 2023). These issues are not limited to the US, a report by HERE and SBD (2025) found that one-third of EV drivers have experienced a charging-related problem, with 7% encountering them regularly. If such experiences happen frequently, they can understandably lead to EV owners abandoning electric mobility altogether.

An aspect more worrying in the context of V2G is not just the EV share in general, but the ongoing lack of bidirectionally compatible models. This constraint is evident in the case of UK's Octopus Energy, one of the few providers offering a V2G tariff, which is exclusively available for Nissan EVs (ESO, Octopus, 2023). The ongoing scarcity of V2G-compatible models has been confirmed by multiple studies (Bibak and Tekiner-Moğulkoç, 2021; Goncearuc et al., 2024; smartEN, 2023). This issue, along with a summary of currently announced compatible vehicles, is explained in the Discussion section.

There are cases where manufacturers promote bidirectional compatibility as an attractive selling point, primarily at the V2L level, which is the simplest and least dependent on infrastructure. This approach is understandable, as consumer interest in bidirectional capabilities is evident. In a V2G trial project, 60% of participants stated that, based on their experience, their next EV would likely be a V2G-compatible Nissan model (Alfie Ireland and OVO Energy, 2020). To add to that, Dean and Kockelman (2024) found that consumers are willing to pay between $280 and $776 for the bidirectional compatibility depending on whether it would be V2L, V2H or V2G.

This factor is considered emerging because what once appeared to be a rapid and unstoppable shift toward EV dominance is now unfolding as a more intricate process. This issue is particularly region-specific, influenced by policies, market dynamics, and global trade barriers. EV market shares could therefore converge and rise steadily or stagnate and create even greater disparities than exist today. With very limited predictability.

3.7. Persistent factors

3.7.1. Financial compensation

A silver lining in the ongoing V2G debate and the increasing number of publications is evident: users expect adequate compensation to justify participation. Whereas the array of its forms throughout the reviewed publications ranges from compensation for battery degradation (Ghotge et al., 2022), direct payments (Kester et al., 2018) to reduction in energy bills (Mehdizadeh et al., 2024), the underlying sentiment continues to be consistent: users perceive participation as more or less challenging and they seek compensation.

According to recent surveys, willingness to participate is relatively high - 58% of respondents would join a V2G scheme if it were profitable according to CTEK (2023) and even higher number of 68% is presented by LCP Delta (2025) in their recent survey. This rises to even 70% in the case of Shell Recharge (2023). In the Netherlands, 49% of drivers are willing to participate in V2G programs, up from 47% the previous year (RvO Nederland, 2023, 2024), with financial incentives cited as a major motivation by 49% of respondents (Bakhuis et al., 2025). Moreover, Neaimeh et al. (2025) found that willingness could be effectively increased through direct experience with V2G, given their participants reported a 15–35% rise in interest having experienced the trial.

The relationship between the willingness to participate and the amount of compensation is nevertheless not always linear and depends on the primary motivations of users, as explained by Bohdanowicz et al. (2022): "*We can observe this in the data, in which higher compensation in the financial incentive group is linked to greater intention to use V2G chargers. Among those with a financial motivation, the degree of intention seems to increase as the size of the reward increases … the relationship between reward level and intention to use V2G charging stations is less clear among those who save energy to avoid unnecessary consumption of resources (modesty motivation). (p. 7)*" This is in line with previous findings of this review that next to financial/personal benefits the crucial driver is to save energy and limit impact on the environment.

The disparities can be either regional or based on age and experience with EVs. Baumgartner et al. (2022) found that experienced EV users tend to expect higher monetary benefits from V2G compared to inexperienced ones. In contrast, Mehdizadeh et al. (2023) discovered that older respondents were more likely to accept lower compensation than their younger counterparts. Similarly, Yun et al. (2025) observed disparities in preferences for financial incentives too, finding that while some participants responded positively to higher rewards, others remained resistant, valuing their personal flexibility over monetary gains.

Although the number of trial projects conducted is limited, the ones that were realised provide intriguing insights into the potentially available amounts. Trials by Alfie Ireland and OVO Energy (2020), Cenex (2021) and ESO, Octopus (2023) report annual savings of their participants ranging from 340 to 840 £. Similarly, a report by FfE (2025) fits within this interval, estimating potential savings of €290–480 per user under current regulations and market prices for the UK. As does the study by Lee et al. (2024). with an estimated annual revenue of 553 $. Finally, findings of Kühnbach et al. (2024a) too are in line with this range projecting the savings to be between 30 – 780€ annually distinguishing the type of charging and the size of the battery.

The actual reachable revenue depends on factors such as battery size, available capacity, contract type, plug-in frequency and other case-specific metrics.

While earlier studies such as Geske and Schumann (2018) downplayed financial compensation, later studies confirm its crucial role in participation. The importance of this factor is highlighted by the sheer number of mentions in all the following publications: Kubli (2022), Khezri et al. (2024), Kester et al. (2019), van Heuveln et al. (2021, Ghotge et al. (2022), Mehdizadeh et al. (2024), Lucas-Healey et al. (2024), Goncearuc et al. (2024), Huang et al. (2021) and smartEN (2023).

Financial compensation is a distinctly persistent and almost universal factor with almost every single publication emphasizing its importance. Although new motivations (e.g. supporting renewable energy) are gaining traction, the expectations of financial incentives stand strong.

3.7.2. Easy-to-use charging controls

The process of "refuelling" a vehicle is becoming increasingly complex. With an internal combustion engine, refuelling is straightforward, the only real challenge being to avoid mixing petrol and diesel. EV charging introduces new complications, such as different connectors, authorization methods, charging speeds, and uncertain charging durations. Bidirectional charging adds yet another layer of complexity. Once a vehicle is connected, energy can flow in both directions, often requiring users to set additional charging parameters.

At the same time, drivers want transparency and control over how exactly their vehicle and battery are charged (Hajhashemi et al., 2025; Philip and Whitehead, 2025). While automation, predictive scheduling, and learning algorithms could reduce the need for direct user involvement, substantial progress is still needed in this area.

Trials indicate that a clear and intuitive charging control interface substantially increases user willingness to participate in V2G. Features such as an app displaying battery usage, the ability to set limits, and real-

time projected financial savings have been shown to enhance acceptance (Geske and Schumann, 2018; Alfie Ireland and OVO Energy, 2020). Additionally, users have expressed a strong preference for an option to override automated charging when they find it necessary (Ghotge et al., 2022). These findings were echoed by Hajhashemi et al. (2025) who found that the override functionality makes users less sensitive to the perceived risks. The same study also recommends the following: *"Specifically, the feature could highlight personalised advantages, such as precise savings on charging costs and measurable contributions to renewable energy use and grid stability. A successful example of user interface that simplifies the understanding of benefits is Electrify Now, developed by an Australian utility company, which helps consumers visualise the cost savings of switching to EVs, solar panels, batteries, heat pump water heaters, and induction cooktops (p. 13)"*. The importance of the override feature is further shared by Philip and Whitehead (2025).

Evidence from recent Chinese V2G studies confirms the contextual nature of behavioural acceptance. In large cities, despite high plug-in rates and predictable routines, V2G flexibility is constrained by user habits and convenience expectations (Li et al., 2025). Despite partial provincial independence, China's EV market operates under a single national government with strong centralization capabilities, enabling it to promote and enforce coordinated strategies more easily than in Europe's fragmented market, where control over charging and plug-in behaviour remains more individualized (Hove, 2023).

Some respondents stated they would only participate if bidirectional chargers were no more complex to use than the regular ones (Ghotge et al., 2022; van Heuveln et al., 2021). Krueger and Cruden (2020) support this, noting that simplicity in control features tends to reduce range anxiety and improve acceptance. For that to happen though, chargers must be both reliable and user-friendly. Existing issues with public charging infrastructure, particularly in certain regions, do little to encourage users to allow their vehicles to be discharged, especially in public locations (Plug In America, 2024; Politico, 2023).

A recent review by Goncearuc et al. (2024) found that while control over charging is recognized as important, interviewed experts do not consider it a top priority. Given that other home energy solutions are already commercially available, energy providers, automakers, wallbox manufacturers, and home energy management system (HEMS) providers regularly offer user-friendly applications with clear interfaces for monitoring and controlling charging. Nonetheless, challenges remain, particularly in requiring users to estimate their mobility needs and determine how much of their battery's charge would be needed for that. Automated solutions might appeal to many, but Chatzouli et al. (2025) actually found that 62% of users would rather manage their own charging than fully relinquish control to an external party.

Although technical feasibility is no longer the main obstacle, the V2G market still suffers from institutional indecision. The coexistence of multiple connectors, incompatible communication standards, and unresolved regulatory frameworks has created a fragmented environment in which few are willing to commit. This collective hesitation reinforces the perception that V2G is not yet ready for everyday use, undermining potential adoption even where the technology itself is mature.

This factor remains persistent due to ongoing issues with charging infrastructure and the limited real-world availability of V2G use cases. Much as the few trials conducted so far have reported general user satisfaction with the way information and control were handled, the data are still too sparse to conclude this challenge as diminishing. Whilst there are signals and efforts to unify the markets, experience with this technology tells us that as long as it's not realised it should be taken with precaution.

3.7.3. Charging standards and interoperability

The success of V2G depends as much on technical functionality as on the regulatory alignment with market suffering from institutional indecision. A fragmented environment in which few are willing to commit reinforces the perception that V2G is not yet ready for everyday use, undermining potential adoption even where the technology itself is mature.

There are multiple types of charging stations, connectors, and communication protocols used to exchange information with a vehicle's ECU. AC charging, common in residential wallboxes, depends on onboard vehicle inverters, limiting power rates and requiring more expensive vehicle hardware. DC charging bypasses this with external inverters, offering higher power and speed but at the cost of more expensive public infrastructure. Even as EVs can ultimately accept both AC and DC charging, compatibility with different socket types varies.

Tesla employs its proprietary North American Charging Standard (NACS) connector, whereas most other manufacturers use the Combined Charging System (CCS) standard (IEEE Spectrum, 2025). In Europe, Tesla vehicles now also support CCS, but in North America, Tesla's NACS is rapidly becoming the preferred connector, as several automakers - such as Ford, General Motors, Hyundai, and Kia - abandon CCS in favour of NACS in the North American market (IEEE Spectrum, 2025). This shift has been driven mostly by issues with the CCS infrastructure, such as faulty or sparsely located chargers (IEEE Spectrum, 2025). Another notable connector is Charge de Move (CHAdeMO), primarily used by Nissan and Mitsubishi (Clean Energy Reviews, 2024). Although CHAdeMO is relatively less common, it has played a crucial role in V2G applications. Historically, bidirectional charging was feasible with CHAdeMO only, used in most V2G trials (Ghotge et al., 2022; Everoze and EVConsult, 2018; Cenex, 2021). While CCS is now considered the European standard, CHAdeMO still holds its relevancy. In Japan, Mercedes planned to offer bidirectional charging for their EQS model (Mercedes-Benz, 2021), but only via CHAdeMO. The same applies to Nissan Leaf in the UK (ESO, Octopus, 2023). Promising, recently launched vehicle, is the Renault 5 E-Tech, featuring V2G functionality, which already operates in a city of Utrecht as part of the MyWheels car-sharing fleet (Renault Group, 2025). On the other hand, Ford F-150 Lightning capable of V2H uses CCS as does Cupra Born - expected to provide a V2H feature soon (smartEN, 2023). Because regulators have largely maintained a neutral stance, market players are left to self-organise, resulting in proprietary "one-to-one" solutions that hinder interoperability (Van Eijk et al., 2025).

Regarding standards needed to facilitate communication between EVs and chargers, the relatively new ISO 15118 complements the dominant CCS plug. However, that is not compatible with the CHAdeMO (CHAdeMO, 2022). An encouraging signal though is that ISO 15118 was designed to support V2G (Goncearuc et al., 2024). These emerging policy actions, such as the EU's amendment of the RfG network code and the enforcement ISO 15118–20 through Alternative Fuels Infrastructure Regulation (AFIR), are expected to reduce fragmentation but will take time to materialise (Van Eijk et al., 2025).

In addition to interoperability challenges between CCS and CHAdeMO in Europe and North America, China's EV market mostly relies on the distinct GB/T plug, which is largely incompatible with CCS-based systems, particularly for bidirectional charging due to differences in architecture, interfaces, power electronics, protocols, and certifications (Akyga, 2025). Although Chinese EVs for European market are equipped with CCS plugs, it creates a challenge for V2G charger makers as their devices are not transferable across regions without adaptations, highlighting that standard fragmentation is a global issue. Regions are developing parallel ecosystems shaped by local regulations and strategies, leading to solid internal consistency but at the cost of international interoperability.

To communicate, a protocol known as OCPP (Open Charge Point Protocol) was established. Currently, the dominant version is the 1.6 but the newer 2.0.1 allows native Plug & Charge which would ease up the billing process widely regarded as problematic by EV users at the public network level (Goncearuc et al., 2024; Shell Recharge, 2023; CTEK, 2023; Van Eijk et al., 2025; OCPP, 2025). According to surveys the necessity of multiple apps, chips and cards to be able to charge using various providers is not particularly welcomed with 47% of respondents

preferring to have a single payment method even if it would mean slightly more expensive charging (Shell Recharge, 2023). In the case of V2G, where users expect to be compensated, a new challenge arises establishing a payment mechanism that allows users to receive payments instead of only making them themselves.

According to Van Eijk et al. (2025), industry progress is hindered by a "chicken-and-egg" dilemma: grid operators, OEMs, charge point operators, and regulators hesitate to commit to one solution before others do, resulting in inconsistent development paths and slow interoperability advances. Large-scale V2G implementation in Europe therefore remains stalled primarily due to a lack of stakeholder coordination rather than technological immaturity. Van Eijk et al. (2025) identified the four core institutional barriers as non-harmonised network codes, DSO integration gaps, charging-standard ambiguity, and uncertainty over control authority. These institutional barriers are limiting the available use case mostly to the V2H where due to its nature a significant share of the above-described hurdles does not need to be addressed.

At the time of writing this review, only four bidirectional chargers seemed to be commercially available. Quasar Wallbox 1 is one of them, with a charging power of 7.4 kW and retail price ranging from 3000 to 7000€ (Clean Energy Reviews, 2024). This version uses a CHAdeMO plug and is offered within the Octopus Energy V2G tariff in the UK (ESO, Octopus, 2023). The newer CCS-compatible version is not available yet. The other two AC options are the V2H capable charger by Ford and GM valued at about 1500$ (Clean Energy Reviews, 2024). The specific last one is DC charger by Sigenergy with a considerably higher charging power of 25 kW designed to work together with residential PV (Clean Energy Reviews, 2024). The higher charging power and other features are reflected in the price exceeding 4000€. Information about the release dates and availability of these products is very unreliable and often unfulfilled, but it's safe to say that the availability is still severely limited.

The lack of unified protocols as a barrier towards acceptance is highlighted by Ghotge et al. (2022), van Heuveln et al. (2021), Goncearuc et al. (2024), Gschwendtner et al. (2021) and Adnan et al. (2018).

A reason to classify this as a persistent factor is its recurring presence in the reviewed literature with a relatively stable level of significance-neither particularly high nor showing any signs of decline. This is primarily attributable to the aforementioned scarcity of commercially viable devices and vehicles, stemming from inconsistent development trajectories and the fragmentation of the limited available solutions, which are often confined to specific vehicle-charger combinations. Progress in this domain is evident but markedly impeded, rather than regional unification, we still observe widely dispersed and mostly isolated pilot projects.

3.8. Diminishing factors

3.8.1. Range anxiety

Whilst modern EVs offer increasingly reassuring ranges, psychological barriers remain. Range anxiety, a long-standing issue in EV adoption, takes on new significance in the context of V2G. The willingness to discharge a car battery for energy needs depends on the user's confidence that the remaining range is sufficient. As long as the perception that it is - remains, it constrains the pool of users willing to experiment with bidirectional functionality.

At the time of the first studies in 2018, the average EV range was around 150 km, whereas today, it frequently exceeds 400 km (European Alternative Fuel Observatory, 2024). This trend is reflected in the literature: declining significance assigned to this factor is observable.

Early studies frequently identified range anxiety as a key limitation to EV acceptance (Kester et al., 2019; Geske and Schumann, 2018; Krueger and Cruden, 2020). At the time, it was considered more critical than financial compensation by Geske and Schumann (2018). Yet its importance began to wane when van Heuveln et al. (2021) argued that financial compensation was a stronger determinant, challenging earlier findings. Huang et al. (2021) further added that available fast charging notably alleviates range concerns.

More recent studies reinforce this trend. Baumgartner et al. (2022) found that range needs are often overestimated, while neither Goncearuc et al (Goncearuc et al., 2024) nor Khezri et al. (2024) identified range anxiety as a particularly important barrier. According to Shell Recharge (2023), user concerns have notably declined, with only 14% hesitant to take long journeys and 47% not needing to charge daily - a notable improvement from 21% the previous year. Similarly, EY (2024) reports a consistent decline in range anxiety concerns, from 33% in 2022 to 29% in 2023 and 25% in 2024.

Experience also plays a key role in reducing range anxiety. A survey by Plug In America (2024) found that the share of users concerned about range dropped from 67% to 36% between the moment of buying the car and after owning it for a while. Among Dutch drivers, only 29% need to charge their EVs on the road more than twice a month because of insufficient range (RvO Nederland, 2024) Importantly one-third of surveyed U.S. drivers reported a decrease in range anxiety as they gained experience with their EV (ChargeLab, 2024) and the same pattern was observed among UK drivers (Neaimeh et al., 2025). Overall, experience appears to cause a positive shift: 90% of respondents in Shell Recharge (2025) indicated they would not return to an ICE vehicle. However, year-on-year interest in purchasing an EV among ICE drivers in the same survey showed a slight decline, likely due to diminishing incentives in several EU countries and because of the other factors discussed earlier.

Nonetheless, there are clear indications that not all drivers considering EVs are ready to rely solely on charging infrastructure. As they acknowledge the benefits of electric driving, many see hybrids as a practical intermediate step, allowing them to experience electrification and simultaneously retaining the convenience of refuelling with conventional fuel. According to data collected by EY (2024) – the sales of hybrids are experiencing uptake. The authors consider them to be a safe "bridge" between ICEs and fully electric EVs for which drivers are perhaps not ready yet. Despite hesitance by some, a recent survey discovered that the ratio of EV-only owners increased in all three surveyed regions - in Europe from 34% to 41%, in the US from 49% to 54%, and in China from 72% to 89%. This trend is also identified by Roland Berger (2025): *"EV ownership has now expanded well beyond a small minority of early adopters, with EVs increasingly serving as main cars and as a direct replacement for ICE vehicles."* The increasing trust in EVs and their range capability was highlighted by McKinsey (2025) as well: *"Across regions, EV purchase intent is highest among customers who already have experience with an EV. Surprisingly, this also includes multicar households that currently have an ICE and a BEV, with the majority indicating they will replace their ICE with a BEV as their next car. This finding contradicts the commonly held assumptions that BEVs are only used as the secondary household car, driven for shorter trips, and that consumers may keep an ICE as backup in their garage forever."*

This factor's decline is observable mostly through the increasing average size of EV batteries and their increasing reliability, resulting in higher confidence and in perceived range limitations declining - there is little reason for this trend to stop.

3.9. Battery degradation and warranty

When discussing V2G, concerns about battery degradation are usually the first to arise. This reaction is understandable, as many assume that frequent charging cycles are the main cause of battery wear. Although the perception of this factor as important remains present, there are noteworthy signals that its significance might be declining.

Multiple publications report disparity between the perceptions of experts and users. Although experts often downplay the importance of battery degradation (Noel et al., 2019; Gschwendtner et al., 2021), user concerns are omnipresent (Kester et al., 2019; Bibak and Tekiner-Moğulkoç, 2021; Ghotge et al., 2022; Geske and Schumann, 2018; van Heuveln et al., 2021). Battery degradation remains to be perceived as a

hurdle preventing wider acceptance but within the recent publications, it's not necessarily classified as a major one. Relatively recent publication of Goncearuc et al. (2024) classifies this factor as of average importance over 23 that it identified. Recent findings by Bakhuis et al. (2025) can also be viewed as encouraging. Only 27% of respondents identified battery degradation as a major barrier, with experienced EV users expressing less concern than non-EV users. This shift in perception is echoed by Neaimeh et al. (2025), who state: *"Compared to legacy studies, conducted when most consumers had little or no real experience with EV charging, we find that the general attitude towards smart charging and V2G has improved significantly across the three major demographic splits (non-EV owners, BEV owners, or trial participants)."* As concerns about battery degradation and range anxiety persist, Neaimeh et al. (2025) emphasize that BEV owners and V2G trial participants demonstrate both greater willingness to engage in V2G and lower levels of concern regarding battery wear. This pattern - where experience reduces anxiety - is supported by Hu et al. (2025). Their qualitative findings show that while some drivers still worry about degradation, those with long-term EV experience tend to view it as insignificant. One respondent even remarked: *"I know a little bit about battery technique. For battery degradation, I do not really think it should be a problem. Of course, degradation is always something that people are afraid of but based on my experience of EV use: I have used electric cars for eight years now. The first one was my own, the second one was also a company car, and now this one, I really do not think battery degradation is a bit of a problem for new cars."* Overall, the literature suggests a consistent pattern: as drivers gain more first-hand experience with EVs and V2G technologies, their concerns about battery degradation diminish.

Multiple studies indicate that the subject of degradation is quite nuanced (Goncearuc et al., 2024; Bakhuis et al., 2025). Battery degradation is a topic where consensus is hard to find. It depends on various factors - battery technology, charging power, temperature, or the particular use case of the vehicle (Guo et al., 2019). Interestingly according to Uddin et al. (2017), if the charging speed is reasonable and conditions stable, the battery health can actually benefit from the bidirectional charging. A notable example would be long-term stationary parking, where allowing a battery's state of charge to fluctuate is allegedly healthier than leaving it idle (Uddin et al., 2017). A study by Brockmann et al. (2025) using an agent-based model found that changes in charging patterns and plug-in timing can affect battery lifespan, with positive effects (+36%) generally outweighing negative ones (-10%). A recent publication by Geslin et al. (2024) delivers encouraging findings, claiming that the traditional lab tests with constant discharge and recharge cycles fail to reflect actual EV usage. By studying 92 commercially available batteries under real-world driving conditions - characterized by frequent acceleration, braking, stopping, and resting periods - they found the battery longevity to be considerably longer than discovered by the previous studies.

The perception of battery as a vulnerable device is likely to stay strong, but an increasing presence of high-mileage EVs with well-performing batteries has a potential to mitigate the perception. The decreasing cost of EV batteries technology (nearing 100 USD/kWh) may explain the reduced perceived importance of this factor, since the steady decline in battery prices has made electric vehicles more affordable and less dependent on subsidies or other cost-related incentives (International Energy Agency, 2025).

A study by Geotab (2024) supports this, showing that the average EV battery degradation improved from 2.3% per year in in 2019 to1.8% per year in 2024, reflecting advancements in battery technology. Another study found that newer battery models require significantly fewer replacements than pre-2016 ones and often last well over a decade (Najman, 2024). According to Tesla Impact Report (2023) based on measurement of over 100 vehicles the average battery degradation on vehicles with over 200 000 driven miles was 12–15% (capacity loss) with the most significant decrease of 3–6% occurring within the first year of use.

As McKinsey (2024) identifies concerns about degradation as a major barrier for 49% of users considering buying EVs, they also observe an increase in the likelihood of considering used EVs, rising from 25% in 2021 to 31% in 2024. Consistent with these findings, a survey by Shell Recharge (2025) reported a year-on-year decline in the share of EVs purchased as new vehicles, dropping from 82% to 78%. The growing trust in used EVs suggests a decreasing fear about battery health.

Together with battery degradation, the concern of voiding warranty as a penalty for bidirectional charging is often cited as a barrier by users. Here we see promising shifts with some EV drivers reporting V2H/V2G options appearing in their vehicles after software updates. For example, in the case of VW Group vehicles, bidirectional charging appears to be subject to predefined limits on both total hours and cumulative energy transfer - likely as a warranty measure, capping the number of V2G sessions and total discharged capacity (go-e, 2023).

The drawback of most research on the effects of V2G is that it is only simulation-based (which according to the above presented Geslin et al. (2024). can create notable disparities). The most relevant insights likely come from observing EVs that have been in use for years and comparing their actual degradation to the initial expectations. There, promising trends are observable, and they gradually mitigate user's concerns. The combination of promising research findings, larger and more reliable batteries, and manufacturers introducing warranty-protecting measures will continue to mitigate these reservations further.

3.10. Lack of awareness

For years, V2G technology remained a niche concept, mostly confined to experimental small-scale trials. With EV adoption still limited, there was little public interest in bidirectional charging. But as the EV market grew, carmakers started to highlight the V2L, as a practical feature for camping, power tools, and backup power. Helping to push awareness beyond insider circles. What was once a marginal idea is now increasingly recognized as a unique EV benefit backed by the observation that 68% of European respondents of a recent LCPDelta (2025) survey declared interest in V2G.

Awareness of bidirectional charging was historically low. In 2013, only 11% of German respondents had heard of V2G (Geske and Schumann, 2018). A decade later, an EU-wide study found that awareness has risen to 44% (European Alternative Fuel Observatory, 2024). British drivers seem more informed, with 53% aware of bidirectional charging options (Indra, 2023). This aligns with broader findings that UK households tend to have higher awareness than German ones (Baumgartner et al., 2024). In Greece, 55% of respondents knew about the technology, with EV owners demonstrating even higher familiarity in line with previous findings (Kostopoulos et al., 2024).

The Netherlands is a notable case where YoY data are available, with awareness increasing from 56% to 61% - in 2024 (RvO Nederland, 2023, 2024). In contrast, EV-laggard nations like Australia still show low awareness - only 19% of respondents knew about bidirectional charging in 2023 (Philip et al., 2023) and still relatively low 24% according to a more recent study by Philip and Whitehead (2025). Much as disparities remain, the general trend suggests a rising tendency.

Carmakers are playing a role in raising awareness, though their impact is difficult to quantify. More models now offer bidirectional charging, including the Ford F-150 Lightning (Reuters, 2024), Nissan Leaf (Reuters, 2024), Volvo EX90 (Cars, 2022), and the Tesla Cybertruck with V2L (CBT news, 2025). The previously mentioned use of Cybertrucks in California's wildfire-related power outages demonstrated the real-world benefits of bidirectional charging, drawing noteworthy media attention (CBT news, 2025). Tesla, as the EV market leader, has a stronger ability to introduce new technology to mainstream audiences. Projects and trials such as the previously mentioned British Sciurus or MyWheels in Utrecht, could help make the concept even more widely recognized, increase awareness and offer more drivers firsthand experience, helping expand the pool of potential participants.

Full public awareness isn't necessarily required. As long as early-adopter EV owners understand the benefits, consequent real-world applications can drive further recognition. A well-informed minority can kickstart adoption, creating momentum for broader acceptance. Several forces are pushing bidirectional charging into the limelight. Carmakers are incorporating the technology, standards are under development, and studies show a steady rise in awareness. While still not mainstream, V2G, V2H, and V2L are definitely moving from a niche technical concept to a feasible technology gaining stronger attention. With EV market growing the awareness will likely follow - unless a significantly superior alternative for energy storage such as cheap residential batteries emerges.

3.11. Shift visualization

The following Fig. 4 visually illustrates the shift in the importance of distinct factors between the beginning and end of the reviewed period. It is not based on exact values, rather, it is intended to better depict overall trends.

4. Discussion

The main aim of this review was not to present a current snapshot perspective but to examine trends and reassess factor's perceived importance over time. V2G technology is closely linked to the energy and mobility sectors, relying on trends in both domains. Beyond the well-known rise in global renewable energy installations, a notable emerging factor for the acceptance of V2G is the increasing involvement of users in energy systems. Prior to the covid pandemic and the recent energy crisis, technologies such as residential solar, heat pumps, smart meters, and micro–grids - promoting more individualized, flexible energy use - were not as prevalent as they are today. High energy prices, likely to persist, further encourage this shift. V2G - fundamentally a means of enabling energy flexibility, is well-positioned to benefit from these developments.

Albeit grey literature provides valuable insights, it is important to acknowledge its limitations, particularly the lack of formal peer review, which necessitates a cautious approach to interpretation. To mitigate potential biases, a diverse range of grey literature sources was considered, ensuring that conclusions were drawn only from recurring trends and patterns identified across multiple independent sources. Crucially, where available these findings were cross-referenced with academic literature to reinforce their validity. Despite these inherent challenges, the inclusion of grey literature broadened the scope of analysis, offering a more comprehensive perspective on the factors influencing V2G adoption and providing unique insights into user perceptions that might not be as readily captured in traditional research.

The absence of large-scale commercial business cases continues, yet

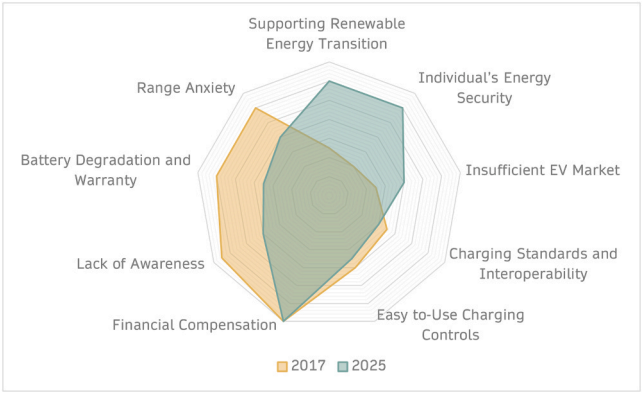

Fig. 4. Factor importance over the years.

there has been a growing focus on V2H applications, where the benefits are more tangible and likely to attract new users. Bidirectional charging, encompassing its three main variants (i.e. V2L/H/G), is well positioned to leverage the growing trend of user engagement in energy systems by first introducing users to the concept through V2L and V2H, which are more tangible and easier to implement. Neaimeh et al. (2025) recommends: *"Practical, low-regret approaches for consumers that expose them to the technology could prove fruitful, such as low-commitment 'taster' tariffs, guaranteed remuneration rates to reduce payback risk, or showroom demonstrators.''* and adds that while increasing general knowledge and adoption has improved consumer willingness, some fears are only addressable through direct experience.

Financial incentives remain critical for potential participants, raising the question of how these incentives will be secured and by whom. Typically, these remunerations are based on users providing energy flexibility when demanded by grid operators. We recommend focusing on identifying use cases, areas, and environments where both potential users and key stakeholders-who have a vested interest-are capable and willing to provide financial incentives, giving the necessary boost to the promising yet currently unrealised arrangement. Specifically exploring whether targeting regions with frequent grid congestion results in higher financial rewards, could be a valuable area for future research. Rural areas are perhaps the ones to aim for given that Kühnbach et al. (2024a) project medium-density and sparsely populated regions as those where savings from grid expansion would be higher than in the densely populated ones. In such areas, grid operators face costly infrastructure upgrades, which could be avoided if distributed energy flexibility provided by V2G services reaches a sufficient level, allowing direct compensation to users. This could create a win-win scenario for both users and operators. That said, whereas lower charging costs and longer battery lifetimes benefit individual EV users, price-sensitive behaviours can synchronize fleet demand and exacerbate peak loads - potentially burdening the grid rather than alleviating congestion and necessitating further expansions or higher operational costs unless effectively coordinated (Brockmann et al., 2025). Leveraging existing flexibility tools, V2G including, could nonetheless transform EVs into a core grid solution, reducing operators' annual investment needs from a forecasted €67bn to €55bn between 2025 and 2050 (EY and eurelectric, 2025).

The inclusion of recent Chinese V2G literature highlights how adoption pathways are shaped by different factors. While Europe, the US, and Australia view V2G/V2H through a user-centric lens - focusing on autonomy, incentives, and decentralized choices - China's approach emphasizes centralized coordination (Hove, 2023). The centralized models however doesn't eliminate behavioural constraints as evidence from Chinese megacities reveals routines, convenience, and expectations still limit user flexibility (Li et al., 2025).

Future research could build on this by developing a structured framework to coordinate grid-level objectives with individual user responses. A bi-level framework can offer a structure, where the upper level represents grid operators optimising congestion relief, renewable integration and grid stability, and the lower level reflects user participation shaped by perceived incentives and autonomy motivations. Such a formulation would allow assessment of how different motivational schemes or regional conditions affect both grid stability and willingness to engage, bridging technical coordination with social acceptance.

In Europe, the financial and environmental benefits of V2G are the primary drivers. While energy security on a consumer level in Europe often relates to affordability, in regions such as Australia and the US, this can be viewed differently. In remote areas prone to natural disasters, those with unstable grid connections or regular local power outages are more common. As EVs can power a household for several days, the prospect of an emergency backup makes bidirectional functionality particularly appealing. Moreover, if the energy transition advances faster than grid upgrades, which so far seems like a probable scenario, Europe might also begin to experience these issues, positioning V2G as a valuable prevention measure.

A critical breakthrough could come from major EV manufacturers, such as Tesla, enabling bidirectional capabilities in their vehicles. Currently, only their Cybertruck offers this feature. Tesla's reluctance to adopt V2G more widely might be linked to its interest in selling its own residential batteries, which would face direct competition from this feature. The introduction of Chinese EVs, some of which offer at least V2L capabilities, might change the landscape, though recent EU tariffs could limit their presence in the European market even though BYD is planning to build a factory in Hungary (BYD, 2023). Volkswagen plans to enable V2G in its ID fleet, and Volvo has announced the same for its new EX90 (Cars, 2022). BMW also announced V2G-compatible models like the iX3 for 2026. However, according to the list compiled by Kühnbach et al. (2024b), many industry promises have yet to be fulfilled. In 2025, only a limited number of vehicles - such as the Nissan Leaf, Renault 5 E-tech, KIA EV9, Ford F-150 Lightning, Hyundai Ioniq, Mitsubishi Outlander, and BYD models - actually support V2G. Some of these are available only in specific markets and require particular chargers and connectors.

Dozens of EV models were expected to offer V2H or V2G by 2023, 2024, or 2025, yet only a few have delivered it. The same holds true for bidirectional wallboxes: many have been announced, but genuine availability remains scarce. As a result, widespread adoption remains uncertain, with past commitments frequently falling short.

Battery degradation is becoming less of a concern, but since V2G is often thought to accelerate it, the issue still needs consideration. An effective solution would be to offer V2G through leased vehicles. EV lessees typically worry less about battery degradation, as the leasing company bears maintenance and risk responsibilities (Hu et al., 2025). For this to work, though, leasing companies must be willing to supply such vehicles and establish conditions that safely enable V2G while protecting their business viability.

A promising and reassuring solution to these concerns could be prolonging their lifecycle through second-life applications and eventually through their effective recycling. Some companies are already repurposing used EV batteries as part of large-scale storage solutions, such as energy buffers for EV charging stations or power storage for high-demand venues such as outdoor stadiums (The Mobility House, 2024; Connected Energy, 2023). The prospect of additional unlocked value and alternative applications from one's battery together with potential financial incentives could help alleviate these reservations.

A high rate of depreciation of EVs could be one of those drivers (Roberson et al., 2024). During the covid pandemic, the value of used vehicles held strong or was even increasing due to scarcity, but now that the supply chain works regularly, stocks of unsold cars are piling up (Wall Street Journal, 2024; Bloomberg, 2023). Rapid and consequential improvements of EVs are perhaps a double-edged sword as potential buyers are hesitant to buy a car that is likely to depreciate quickly.

Finally, it's worth noting that in recent surveys from CTEK (2023), Shell Recharge (2023) and European Alternative Fuel Observatory (2024) questions about V2G were asked for the first time. Hopefully, next year's editions will provide the first YoY comparisons, revealing up-to-date data-driven trends.

5. Conclusions

The evolution of factors influencing the social acceptance of V2G technology demonstrates how technological advancements and societal attitudes shape each other over time. Through a comprehensive analysis of over 50 publications, we have identified key factors shaping V2G adoption, providing a structured yet nuanced overview of the current state of this technology and its application.

Emerging factors highlight a growing shift toward decentralized energy solutions and consumer engagement in energy systems. The increasing prioritization of sustainability, energy autonomy, and the integration of renewable energy reflect how users are actively seeking ways to optimise their energy consumption (e.g., by investing in solar panels, home battery storage, and smart energy management systems). The rising preference for V2H applications reinforces the idea that EVs are no longer just a mobility solution but a valuable energy asset within households. Similarly, the evolving energy landscape, shaped by rising electricity costs and grid flexibility needs, has led to greater consumer interest in self-sufficiency, aligning V2G with broader energy system transformations. Notably, financial compensation remains a persistent motivator, with users expecting clear economic benefits to justify participation, as concerns about usability - such as the complexity of bidirectional charging controls - highlight the need for intuitive and seamless solutions. Additionally, a lack of standardized charging landscape and interoperability still present a major challenge, slowing the development of a robust ecosystem. These factors emphasize that, despite growing interest, practical implementation hurdles still limit real-world adoption.

Recent years have demonstrated that significant disruptions can reshape market environments, presenting opportunities for technologies that have long faced obstacles. By aligning V2G with these dynamic changes, it has the potential to evolve from a niche innovation into an integral component of the energy system.

Certain concerns, such as range anxiety and battery degradation, are diminishing as technology advances. Additionally, growing consumer awareness and industry developments, including major automakers incorporating bidirectional capabilities, signal a broader shift in perception. It is encouraging to note that as the emerging factors are largely positive and open up new opportunities, the diminishing ones were mostly barriers. Taken together, this indicates a favourable acceptance trajectory. While challenges remain, the trajectory suggests a long-term reduction in these barriers as V2G becomes more integrated into the mainstream energy and mobility debate.

CRediT authorship contribution statement

Albert Caban: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Geeske Scholz:** Writing – review & editing, Validation, Supervision. **Zofia Lukszo:** Writing – review & editing, Validation, Supervision.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the first author used tools by Perplexity AI, OpenAI and Google DeepMind in order to find any potentially relevant publications, to analyse texts and to refine wording. After using these tools, the authors fully reviewed and edited the content and takes full responsibility for the content of the publication.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Albert Caban reports financial support was provided by Shell Global Solutions International BV. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The research work presented in this paper has received funding from Shell Global Solutions International B.V. It reflects only the authors' views, and the above indicated organization is not responsible for any use that may be made of the information it contains in.

Appendix

Full table of reviewed papers:

Title	Authors	Year
A comprehensive analysis of Vehicle-to-Grid (V2G) systems and scholarly literature on the application of such systems	Bibak & Tekiner-Mogulkoc	2021
Adoption of electric vehicles in a laggard, car-dependent nation: Investigating the potential influence of V2G and broader energy benefits on adoption	Philip et al.	2023
Annual Review of Environment and Resources The Future Promise of Vehicle-to-Grid (V2G) Integration: A Sociotechnical Review and Research Agenda	Sovacool et al.	2017
Are electric vehicle drivers willing to participate in vehicle-to-grid contracts? A context-dependent stated choice experiment	Huang et al.	2021
Are Greek Drivers Willing to Embrace V2G Technology? A Survey Research	Kostopoulos et al.	2024
Are Norwegian car users ready for a transition to vehicle-to-grid technology?	Mehdizadeh et al.	2024
Assessing Public Opinions of a nd Inter est in Bidirectional Electric Vehicle Charging Technologies: A U.S. Perspective	Dean & Kockelman	2024
Behavioral insights into vehicle-to-grid (V2G) adoption: Beyond economic perspectives	Zhang et al.	2025
Beyond emissions and economics: Rethinking the co-benefits of electric vehicles (EVs) and vehicle-to-grid (V2G)	Noel et al.	2018
Bidirectional charging as a strategy for rural PV integration in China	Hove	2023
Bidirectional Charging Study 2025	UPSCALE GmbH	2025
Can product bundling increase the joint adoption of electric vehicles, solar panels and battery storage? Explorative evidence from a choice-based conjoint study in Austria	Priessner & Hampl	2020
Changing Lanes: EV Strategies in the US, Europe, and China	BCG	2025
Clean Energy Technology Observatory: Smart Grids in the European Union - 2023 Status Report on Technology Development Trends, Value Chains and Markets	De Paola et al.	2023
Consumer Monitor 2023	European Alternative Fuels Observatory	2024
Consumer Willingness to Adopt Electric Vehicle Smart Charging: A Stated Preference Analysis	Philip & Whitehead	2025
Does experience matter? Assessing user motivations to accept a vehicle-to-grid charging tariff	Baumgartner et al.	2022
Dutch National Charging Survey 2023	RvO Nederland	2023
Dutch National Charging Survey 2024	RvO Nederland	2024
Economic Value Assessment of Vehicle-to-Home (V2H) Operation under Various Environmental Conditions	Chung et al.	2024
Electric Vehicle Charging Research	Department for Transport	2022
Electric Vehicle Survey - Owning and Charging an EV in Europe	CTEK	2023
Electric vehicles in emergencies and evacuations: a review of resilience and future research directions	Babaei & Wong	2024
Emissions reduction potential and feasibility of vehicle-to-grid for Beijing's future electric vehicles	Xu et al.	2025
Energy management opportunities for the home	ElaadNL & FAN	2022
Energy Perception Report	Statkraft	2022
Energy Retail Market Monitoring Report 2024	ACER & CEER	2024
Estimating financial compensation and minimum guaranteed charge for vehicle-to-grid technology	Mehdizadeh et al.	2023
Europe's EV sales are recovering: did EU carbon regulations change the game?	Power Technology	2025
EV Charging Index 2025: Steady progress	Roland Berger	2025
EV Driver Survey Report	Plug In America	2024
EV Driver Survey Report 2023	Shell Recharge	2023
EV Drivers' Willingness to Accept Smart Charging: Measuring Preferences of Potential Adopters	Kubli	2022
EV Index 2025 summary report	HERE & SBD	2025
Exploring user willingness to adopt vehicle-to-grid (V2G): A statistical analysis of stated intentions	Bakhuis et al.	2025
Factors influencing consumer acceptance of vehicle-to-grid by electric vehicle drivers in the Netherlands	van Heuveln et al.	2021
Flexibility solutions to support a decarbonised and secure EU electricity system	EEA & ACER	2023
Global EV driver survey 2024	Global EV Association	2024
Global EV Outlook 2024	International Energy Agency	2024
How can smartphone apps increase electric vehicle user acceptance of supplier managed charging?	Hajhashemi et al.	2025
How European consumers perceive electric vehicles	McKinsey	2024b
How 'vehicle-to-grid' technology could boost China's electricity system	Ye	2025
How Long Do Electric Car Batteries Last	Najman	2024
How long do electric car batteries last? What 10,000 electric vehicles tell us about EV battery life	Geotab	2024
How to charge Chinese electric cars in Europe? GB/T adapters for Type 2 and CCS2	Akyga	2025
Impact Analysis of V2G Services on EV Battery Degradation-A Review	Guo et al.	2019
Indra-dex Report	Indra	2023
Industry survey: 500 EV drivers on public charging	ChargeLab	2024
Institutional barriers to vehicle-to-grid implementation in Europe	Van Eijk et al.	2025
Integration of electric vehicle user charging preferences into Vehicle-to-Grid aggregator controls	Krueger & Cruden	2020
Intentions to Charge Electric Vehicles Using Vehicle-to-Grid Technology among People with Different Motivations to Save Energy	Bohdanowicz et al.	2022
Key milestone: V2G as an essential element of electromobility	The Mobility House	2024
Learning by charging: Understanding consumers' changing attitudes towards vehicle-to-grid	Neaimeh et al.	2025
Mobility Consumer Index 2024	EY	2024
Mobility Consumer Pulse	McKinsey	2024a
Moving towards more sustainable fleet management with Vehicle-To-Grid systems	Opinium & E-Flex	2020
Navigating expert skepticism and consumer distrust: Rethinking the barriers to vehicle-to-grid (V2G) in the Nordic region	Noel et al.	2019
New twists in the electric-vehicle transition: A consumer perspective	McKinsey	2025
Participation and sensemaking in electric vehicle field trials: A study of fleet vehicle-to-grid in Australia	Lucas-Healey et al.	2024
Plugging into potential: unleashing the untapped flexibility of EVs	EY & eurelectric	2025
Potential of a full EV-power-system-integration in Europe and how to realise it. Study on behalf of Transport & Environment (T&E) Europe.	Kühnbach et al.,	2024
Powerloop: Trialling Vehicle-to-Grid technology	ESO & Octopus Energy	2023
Project Sciurus Trial Insights: Findings from 300 Domestic V2G Units in 2020	Cenex	2021

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Title	Authors	Year
Promoting novelty, rigor, and style in energy social science: Towards codes of practice for appropriate methods and research design	Sovacool et al.	2018
Public perceptions of electric vehicles and vehicle-to-grid (V2G): Insights from a Nordic focus group study	Kester et al.	2019
Research into maximising the benefits of smart metering for consumers	National Centre for Social Research	2021
Shell Recharge Driver Survey 2025	Shell Recharge	2025
The barriers to widespread adoption of vehicle-to-grid: A comprehensive review	Goncearuc et al.	2024
The Barriers Towards Widespread Adoption of V2G Technology in Smart Grid Environment: From Laboratories to Commercialization	Adnan et al.	2018
The EV Driver Survey 2025	LCPDelta	2025
The flexible prosumer: Measuring the willingness to co-create distributed flexibility	Kubli et al.	2018
The role of electric vehicles in hybrid solar-based small energy communities	Lombardi et al.	2024
Unlocking peak shaving: How EV driver heterogeneity shapes V2G potential	Yun et al.	2025
Unlocking vehicle-to-grid potential of load shifting in China's megacities considering comprehensive real-world behaviors	Li et al.	2025
Use before You Choose: What Do EV Drivers Think about V2G after Experiencing It?	Ghotge et al.	2022
Users' Willingness to Participate in V2G – A Comparison between German and UK Households	Baumgartner et al.	2024
V2G Global Roadtrip	Everoze & EVConsult	2018
V2G Integration in Europe - A comparison of implementation priorities in France, the UK and Germany	FfE	2025
V2G Project Sciurus overview for CHAdeMO	Alfie Ireland & OVO Energy	2020
V2X Enablers and Barriers: Assessment of the regulatory framework of bidirectional EV charging in Europe	smartEN & DNV	2023
Vehicle-to-grid as a competitive alternative to energy storage in a renewable-dominant power system: An integrated approach considering both electric vehicle drivers' willingness and effectiveness	Lee et al.	2024
Vehicle-To-Grid Technology Acceptance for Electric Vehicle Users: A Systematic Literature Review and Future Research Directions	Liu et al.	2025
Vehicle-to-grid, why not? An interview with battery electric vehicle users with various driving patterns in Utrecht	Hu et al.	2025
Vehicle-to-X (V2X) implementation: An overview of predominant trial configurations and technical, social and regulatory challenges	Gschwendtner et al.	2021
What do consumers think of smart charging? Perceptions among actual and potential plug-in electric vehicle adopters in the United Kingdom	Delmonte et al.	2020
When smart charging meets smart users: How price-sensitive plug-in behavior reshapes EV integration	Brockmann et al.	2025
Which electric vehicle users are flexible and price responsive? Uncovering user types in Denmark	Chatzouli et al.	2025
Willing to participate in vehicle-to-grid (V2G)? Why not!	Geske & Schumann	2018
Willingness to Participate in Vehicle-to-Everything (V2X) in Sweden, 2022-Using an Electric Vehicle's Battery for More Than Transport	Khezri et al.	2024
Willingness to pay for electric vehicles and vehicle-to-grid applications: A Nordic choice experiment	Noel et al.	2019
World Energy Outlook 2023	International Energy Agency	2023

Data availability

No data was used for the research described in the article.

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