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Review

# Feasibility and Challenges for Vehicle-to-Grid in Electricity Market: A Review

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**Abstract:** Electric vehicles (EVs) play a crucial role in the global transition towards decarbonization and renewable energy resources (RERs). As EVs gain popularity, this has resulted in various challenges for the power grid, such as an intensified peak-to-valley load differential, causing transformer overloading. Vehicle-to-grid (V2G) technology has emerged as a promising solution due to its controllable charging and discharging capabilities. Mature business schemes can incentivize the development of V2G technology. However, the business schemes of V2G technology are still unclear. Therefore, this paper provides a comprehensive review of the business schemes associated with V2G technology, especially focusing on its feasibility and challenges with respect to the electricity market. In this paper, several business schemes with respect to the electricity market are explored by conducting extensive literature reviews, including peak-to-valley arbitrage, the spot market, demand–response (DR), frequency regulation, voltage regulation, spinning reserve, and black start. Next, application scenarios and real-world use cases of the V2G technology's business schemes are investigated. Furthermore, the challenges faced by the V2G technology's business schemes are assessed by considering the technical, economical, and social aspects. By identifying these challenges, it is important to highlight the existing shortcomings and areas of interest for V2G technology's research and development. This review contributes to a deeper understanding of V2G technology and its implications for the energy sector.

**Keywords:** business schemes; vehicle-to-grid (V2G); electric vehicles (EVs); electricity market



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## 1. Introduction

Energy is the foundation upon which modern industrial society is built and remains an enduring challenge for humanity. In recent years, global fossil fuels have been gradually depleting, resulting in a continuous increase in their prices. According to statistics, crude oil prices have reached their highest level since 2013, with European natural gas prices nearly tripling and Asian prices doubling, while coal prices have also reached record highs [1]. Fortunately, the rapid development of renewable energy resources (RERs) has provided people with a glimpse of the pathway for future energy development [2–4]. In 2022, the share of wind and solar power in global electricity generation increased from 10% in 2021 to 12%, while the combined share of all clean electricity sources (RERs, hydroelectric power, and nuclear power) reached 39% of global electricity production [5].

Similar energy transitions are also occurring in the transportation sector [6]. Due to decarbonization policies and advancements in battery technology, the production and sales of electric vehicles (EVs) are rapidly increasing [7]. EVs are vehicles that utilize batteries or other rechargeable energy as their power source [8]. Based on the types of power sources, EVs can be classified into four categories: battery electric vehicles (BEVs), hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), and fuel cell electric vehicles (FCEVs) [9]. Globally, sales of EVs have been increasing year by year. According to the statistics from the International Energy Agency (IEA), the global number of EVs over the past decade is shown in Figure 1 [10].

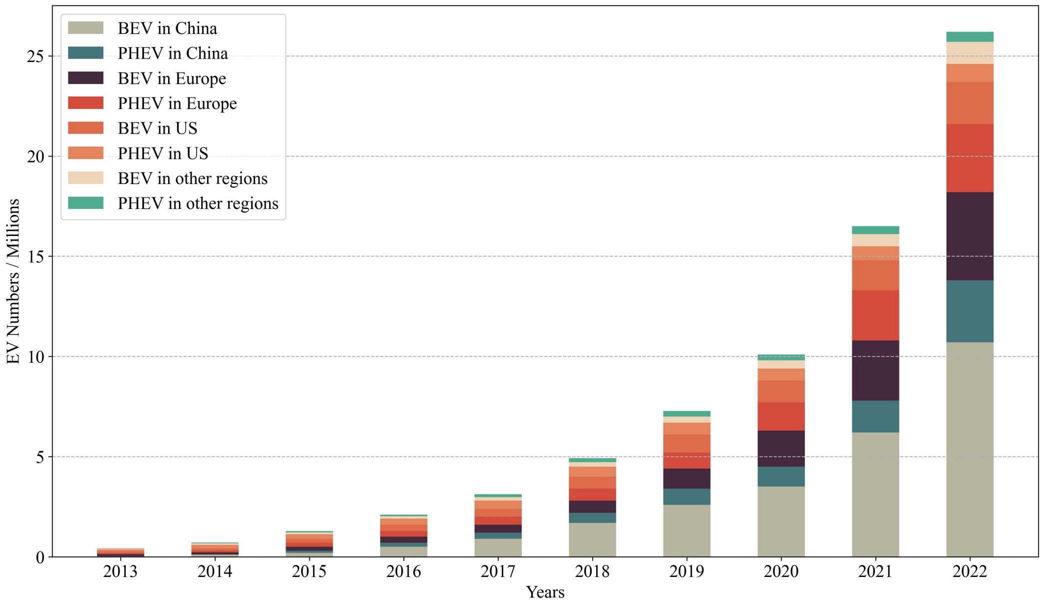


**Figure 1.** Global number of EVs from 2013 to 2022.

However, the widespread integration of EVs into the power grid also brings certain challenges and impacts. Research has shown that the charging behavior of EVs is closely related to people's production and living patterns, exhibiting noticeable regularity [11]. This results in a large number of EVs charging at the same time, increasing the load on the power grid and further exacerbating the peak-to-valley difference in the daily load. Especially during peak hours, it is likely to exceed the capacity of the distribution transformer, posing a potential safety threat [12]. The original load curve and the load curve of charging a large number of EVs are shown in Figure 2.

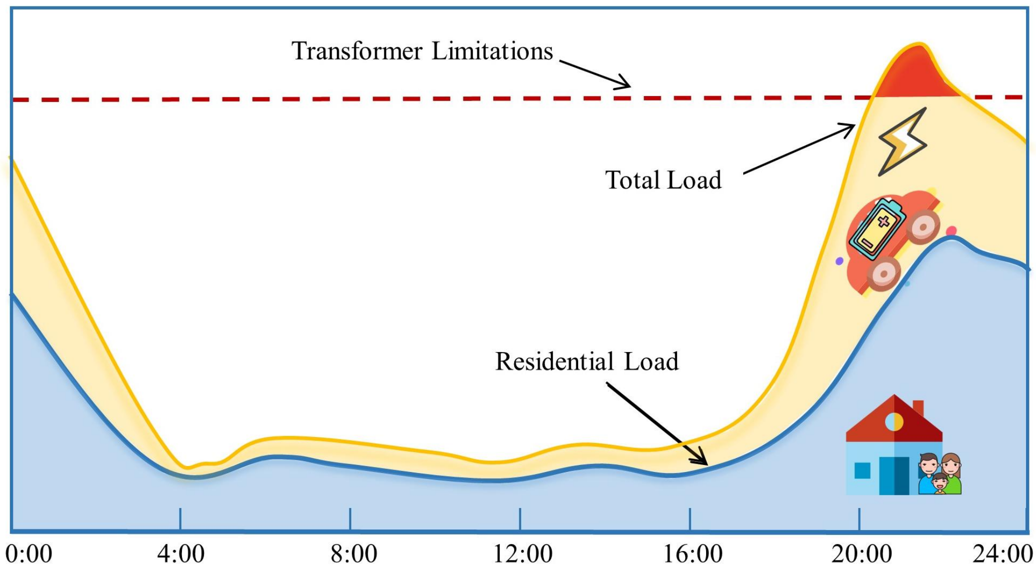


**Figure 2.** The load curve of charging a large number of EVs from a distribution transformer.

Vehicle-to-grid (V2G) technology, proposed by Kempton and Letendre in 1997 [13], can effectively address this issue by utilizing EVs as energy storage devices. By employing bidirectional charging and discharging systems, EVs can be connected to the power grid, enabling the bidirectional flow of energy [6]. Research has shown that, on average, EVs in the United States are parked and idle for about 95% of the time, presenting a significant resource for the power grid [14]. V2G technology-enabled EVs can participate in peak-to-valley arbitrage, the spot market, frequency regulation, demand–response (DR), emergency backup, and other grid services during their idle periods. This not only enhances the stability of the power grid, but also allows EV owners to make profits from providing these services, all while ensuring that the user's driving experience is not compromised [15–17]. The V2G technology's business schemes can create a win–win situation for EV owners, aggregators, and the power grid, ultimately enhancing overall social welfare.

This paper presents a comprehensive review of V2G technology, especially the feasibility and challenges with respect to the electricity market. Firstly, a business scheme framework that enables mutual benefits for EV owners, aggregators, and the power grid is proposed. Based on this framework, an extensive literature review is conducted to demonstrate the feasibility of the framework with respect to the electricity market. Then, a comprehensive analysis of existing V2G technology's application scenarios and real-world use cases globally is performed. Finally, challenges in the application of V2G technology are outlined from the technical, economical, and social perspectives. The main contributions of this paper are summarized as follows:

- A V2G technology's business scheme framework that enables multiple entities to benefit and its feasibility with respect to the electricity market are analyzed.
- Various classifications of V2G technology's application scenarios are presented, and global V2G technology's real-world use cases are surveyed, which serves to validate the feasibility of V2G technology.
- The challenges faced by V2G technology at present are categorized into the technical, economical, and social aspects.

The rest of the paper is organized as follows: Section 2 introduces the concept and framework of the V2G technology's business schemes. Section 3 explores the feasibility of the V2G technology's business schemes in specific types of electricity market, including peak-to-valley arbitrage, the spot market, DR, and ancillary services. Section 4 examines the application of the V2G technology's business schemes in various application scenarios and presents real-world cases. Section 5 discusses the challenges faced by the V2G technology's business schemes from the technical, economical, and social perspectives. Section 6 gives a summary of this paper.

## 2. V2G Business Schemes: Concept and Framework

### *2.1. Concept*

To understand the V2G technology's business schemes, it is essential to understand the concept of V2G technology. As one of the pioneers who introduced V2G technology, Kempton proposed the basic concept and three required elements of V2G technology in 2004 [18]. The basic concept of V2G technology is that EVs provide power to the grid while parked. Each EV must have three required elements: (1) a connection to the grid for electricity flow, (2) a necessary control or logical connection for communication with the grid operator, and (3) controls and metering on-board the vehicle. In Ref. [19], B. Bibak wrote that "The V2G technology is a flow of energy, information, and money between the EV owners, aggregators, and the power grid to make a stable balance between the demand and supply".

At its core, the concept of business schemes pertains to the strategies employed by private sector or market-oriented entities, including companies, enterprises, and even public or social ventures, with the objective of generating or acquiring value [20]. For industry practitioners, business schemes innovation is seen as a key lever for implementing the circular economy at the organizational level, as it allows for a systemic transformation of a company's core logic and alignment of incentives among various stakeholder groups [21]. It is worth noting that a business scheme is a complex mechanism that cannot be accomplished by a single entity alone. It inevitably involves a series of participants and beneficiaries, the business schemes can only succeed when each participant can benefit from it. In summary, the concept of V2G technology's business schemes encompasses two aspects: technical and commercial. V2G technology serves as the technical foundation, while the commercial aspect focuses on how to leverage V2G technology for profitability.

For an emerging technology, the economic incentives brought by business schemes can naturally drive its development. Therefore, the integration of V2G technology with feasible business schemes, which are designed to receive market-based incentives, becomes a crucial problem. Based on the current legal situation in Poland, K. Zagrajek analyzed the feasibility of V2G technology participation in the Polish electricity market and proposed a business model [22]. C. Corinaldesi examined the economic impact of different charging strategies on EVs and concluded that implementing rational charging strategies can enhance economic efficiency [23]. M. Incia suggested that EVs can be aggregated into virtual power plants (VPPs), enabling the implementation of V2G technology's business schemes [24]. X. Yang's systematic summary analyzed the uncertainties and constraints associated with the use of EVs in VPPs [25]. Y. Qin's research on China examined the feasibility of V2G technology's business schemes as VPPs participation in the energy trading, DR, and ancillary services with respect to the electricity market with highly optimistic conclusion [26]. There are also statistics that show, the global V2G technology's market size is projected to grow from $11.3 million in 2023 to $59.2 million by 2030, exhibiting a compound annual growth rate of 26.6% during the forecast period [27]. Therefore, V2G technology's business schemes may have broad profit potential and market prospects in the future.

Existing research has explored the feasibility of V2G technology's business schemes from various perspectives, including the technical, legal, and economical aspects. Based on existing foundation, this paper further systematically investigates the latest studies regarding V2G technology participation in various types of electricity markets. It also classifies the application scenarios of V2G technology based on location and participation modes in a rational manner. The latest V2G technology's demonstration projects and the challenges currently encountered are also presented.

### 2.2. Framework

To better elaborate the framework of V2G technology's business schemes, it is imperative to contextualize V2G technology within a tangible application scenario. In the background of decarbonization and RERs, the topology of a typical wind-solar-storage residential or industrial park microgrid containing V2G technology is illustrated in Figure 3. In this microgrid, the distributed energy sources include solar and wind power, while the loads consist of conventional residential loads and EV clusters loads. The EV clusters are controlled by dedicated V2G aggregators, which can be regarded as energy storage units with uncertain capacities, as individual EV may join or leave the clusters at any time, resulting in changes in the cluster's capacity and state of charge (SOC). The power of the entire system is converged through a low-voltage AC bus for internal interactions, and then connected to the external distribution network via transformers to enable exchange of power. The microgrid internally consists of sources, loads, and energy storage, possessing a certain level of self-sufficiency.

From the typical microgrid containing V2G technology illustrated in Figure 3, we can explore the framework of V2G technology's business schemes. In this system, there are three entities related to V2G technology, the EV owners, the V2G aggregators, and the power grid. The EV owners have ownership of their EVs, and their driving behaviors directly determine the real-time capacity and SOC changes of the entire EV clusters. Considering that the capacity of a single EV is too small to directly participate in the electricity market, the concept of V2G aggregators is proposed [28]. By entering into V2G technology's contracts with EV owners, the V2G aggregators obtain temporary control rights over the charging and discharging of idle EVs [29]. The V2G aggregators regulate the participation of EV clusters in the electricity market to make profits. The cost of these profits is the control right over charging and discharging of idle EVs and battery degradation, thus a portion of the profits should be paid to the EV owners in accordance with the V2G technology's contracts [30]. It is estimated that an EV owner can earn approximately 100 to 1100 EUR per year by participating in V2G technology [31]. From the perspective of the power grid, although it is unable to obtain financial profits, the participation of V2G technology in the electricity market can assist in peak shaving and provide ancillary services, thereby providing indirect benefits to the power grid. The V2G technology's business schemes framework and benefit flow are illustrated in Figure 4.

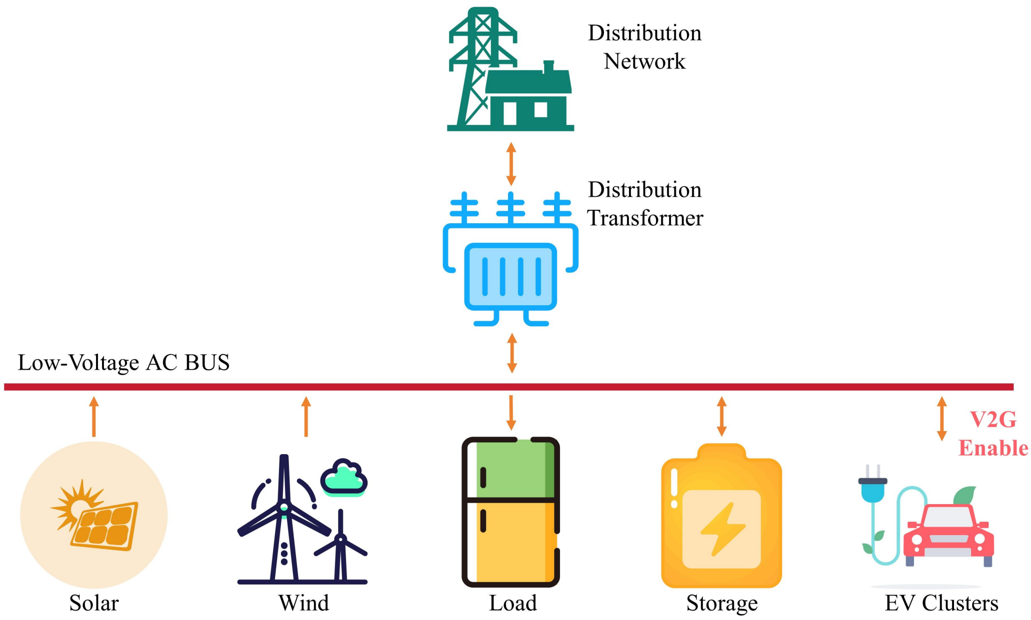


**Figure 3.** A typical wind-solar-storage residential or industrial park microgrid containing V2G.

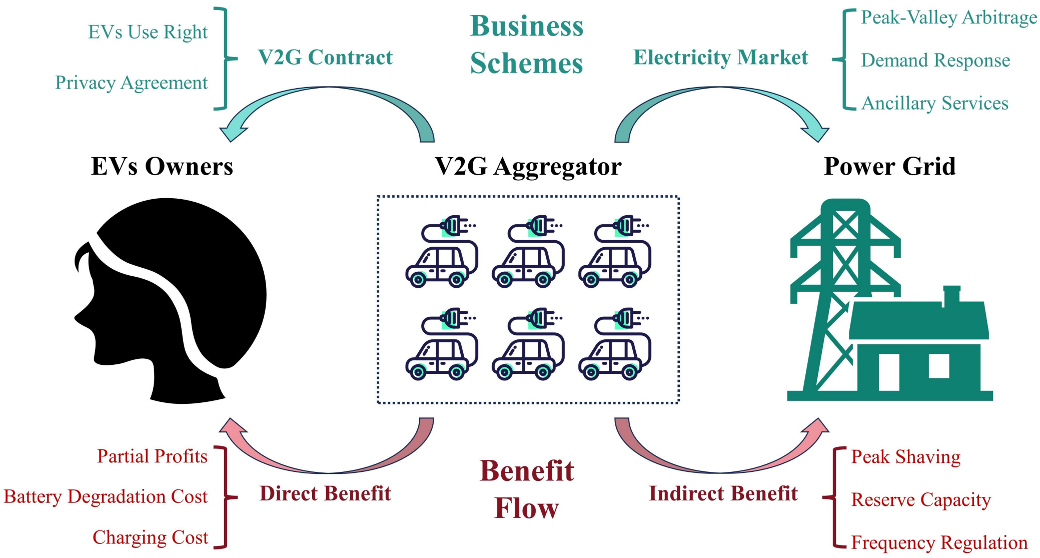


**Figure 4.** V2G technology's business scheme framework and benefit flow.

## 3. Feasibility in the Electricity Market

In Section 2, the concept and framework of V2G technology's business schemes are analyzed. The profit source of the V2G aggregators lies in utilizing EV clusters to participate in the electricity market, thereby supporting the interests of various participants in the V2G technology's business schemes. In Section 3, the feasibility of V2G technology participation in various specific services of the electricity market will be explored. Considering its similar characteristics with energy storage, the types of V2G technology participation in the electricity market are also similar to energy storage. The available capacity of V2G technology is constrained by the anticipated departure time and target SOC, while the online duration is limited by idle period. A large amount of research indicates that V2G technology mainly participates in the electricity market services including peak-to-valley arbitrage [32], the spot market [33], DR [34], and ancillary services [22,29,35–37]. The ancillary services mainly include four aspects: frequency regulation, voltage regulation, spinning reserve, and black start [17,38].

### 3.1. Peak-to-Valley Arbitrage

With the rapid increase in electricity demand, the disparity between peak and valley loads is gradually widening, which is detrimental to the stability of the power grid [39]. Therefore, the concept of time-of-use (TOU) tariff is proposed, which means using economics to guide people to use electricity rationally [40]. Take the industrial TOU tariff in Zhejiang Province of China in December 2023 for example, the peak tariff is 1.203 CNY/kWh, and the valley tariff is 0.314 CNY/kWh [41]. Peak-to-valley arbitrage refers to the fact that the energy storage is charged at the time of the valley tariff and discharged at the time of the peak tariff. Two charging and two discharging can be done in a day, which brings huge profit space.

Similarly, V2G technology can be used for peak-to-valley arbitrage. EV owners use the valley tariff to fully charge at night, and when they arrive at their workplace, the idle EVs are managed by the V2G aggregators, thus making profits from the tariff difference. At the end of the workday, the V2G aggregators pay the fee according to the V2G technology's contracts and reserve a certain amount of power to enable the EV owners to return home safely [42]. The business scheme of peak-to-valley arbitrage using V2G technology is shown in Figure 5.

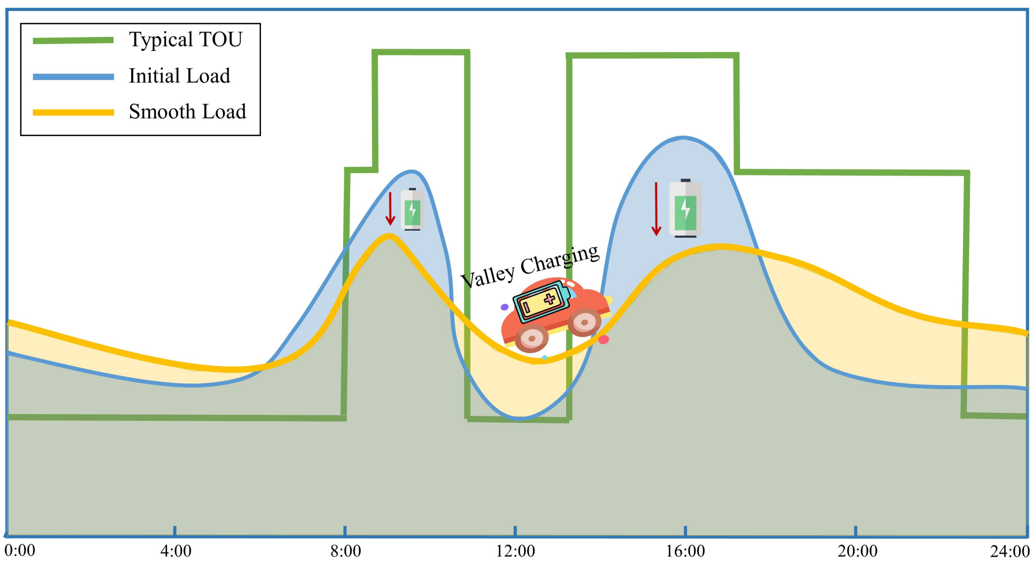


**Figure 5.** Peak-to-valley arbitrage using V2G technology.

Currently, numerous studies have investigated the economic feasibility of V2G technology participation in peak-to-valley arbitrage, with results being generally optimistic. L. Shi and M. Guo studied the ability of V2G technology participation in peak-to-valley arbitrage, and concluded that V2G technology can shift 2.7% to 4.3% of charging load from peak to off-peak hours at the city level, which can save a lot of electricity expense [43]. J. Chen and Y. Zhang studied the energy management strategy of V2G technology in distributed photovoltaic housing in Shanghai, and they found that transfer of power from valley sources and photovoltaic generation can enhance the utilization efficiency of both, while simultaneously yielding substantial economic gains [44]. B. Tepe and J. Figgener studied the benefits of V2G technology participation in peak-to-valley arbitrage, and the results showed that large EV battery around 80kWh is particularly beneficial for arbitrage trading [45]. M. Sarker and D. Olsen comprehensively considered the transformer life cost and V2G technology's arbitrage income, and their research showed that V2G technology participation in peak-to-valley arbitrage can not only obtain the tariff difference income, but also reduce the maximum load of the transformer, thereby improving the transformer life [46].

### *3.2. The Spot Market*

The spot market, as an integral part of the electricity market, provides a means for the immediate purchase and sale of electricity. The operation of the spot market is typically based on the principle of supply-demand balance and generally consists of two primary components: day-ahead market and real-time market, which can enable more efficient optimization of electricity resources [47]. V2G technology can participate in the spot market by purchasing or selling electricity back to the grid.

Currently, there have been limited studies focusing on the V2G technology participation in the spot market. Based on German energy policy, reference [48] calculated the economic viability of V2G technology participation in the spot market. The results indicated that the profits of V2G aggregators increase with the number of EVs they have, and only when the quantity of EVs reaches a certain threshold can the breakeven point be achieved. Reference [49] proposed a bidding strategy for the V2G aggregators in the spot market, based on bayesian updating method. The results demonstrated that this strategy can enhance the bidding success rate of the V2G aggregators and assist in peak shaving operation for the power grid. Reference [50] proposed a control strategy for the V2G aggregators to participate in the day-ahead market and real-time market using model predictive control, and its effectiveness is validated. Reference [51] proposed a bidding scheme for the residential-based V2G aggregators to participate in the spot market and balancing market. The results indicated that communities can obtain profits by participating in this bidding scheme. Reference [52] investigated the effects of different EVs charging strategies on the spot market prices, and the results indicated that V2G strategy has the largest influence on the spot market prices among all charging strategies. Reference [53] presented an optimal charging and discharging strategy for EVs by distribution system operators participating in the spot market. The results demonstrated that V2G technology participation in the spot market can achieve a win-win situation for EV owners, distribution system operators, and the power grid.

### *3.3. DR*

The power system is experiencing a period of rapid development, and the peak load is increasing, which may lead to the instability of the power supply. DR is regarded as an effective solution to the issues of uncertain and fluctuating power supply [54]. DR refers to when the power supply is tight or the reliability of the system is threatened, the power consumers change the inherent customary mode of consumption, reduce or shift the power load for a specific duration in accordance with the power supply, so as to ensure the stability of the power grid and obtain compensation from the power grid operator.

The energy storage characteristics and flexibility of V2G technology determine its suitability for participating in DR. In situations where the power supply is tight, appropriate economic compensation can be provided to EV owners as an encouragement for them to discharge power from their EVs. Conversely, when the grid load is sufficient, certain preferential measures can be offered to EV owners to encourage charging and storage of electrical energy for future use. Figure 6 illustrates the business scheme of DR using V2G technology.

Research has shown that V2G technology is particularly well-suited to participate in DR at the microgrid level. V. Onishi proposed a mixed integer linear programming model with the objective of minimizing sustainable costs, considering DR and TOU, for a hybrid model consisting of renewable microgrids and EVs. The results indicated that the energy and environmental costs of the system can be reduced by approximately 42% [55]. M. Beyazıt's research indicated that using V2G technology for DR in a microgrid environment can reduce end-user energy costs and peak load demand, and that V2G technology has greater advantages in the case of multiple microgrids operating collaboratively [56]. S. Rajamand proposed a DR scheduling strategy for microgrids contained V2G technology based on benders decomposition and lagrange multipliers. Compared to without V2G technology and DR, the EV scheduling cost decreased by 14.67% with this method [57]. X. Lyu and T. Liu proposed a two-stage robust economic dispatch model based on DR and V2G technology for integrated energy systems at the park-level, considering the uncertainties of RERs and EVs. Instance studies demonstrated that V2G technology can reduce peak load, production costs and carbon emissions in park-level energy systems [58]. P. Harsh's research proposed a new incentive-based DR scheme for microgrids with V2G technology capabilities. This scheme aimed to maximize the motivation of DR participants while ensuring fairness [59].

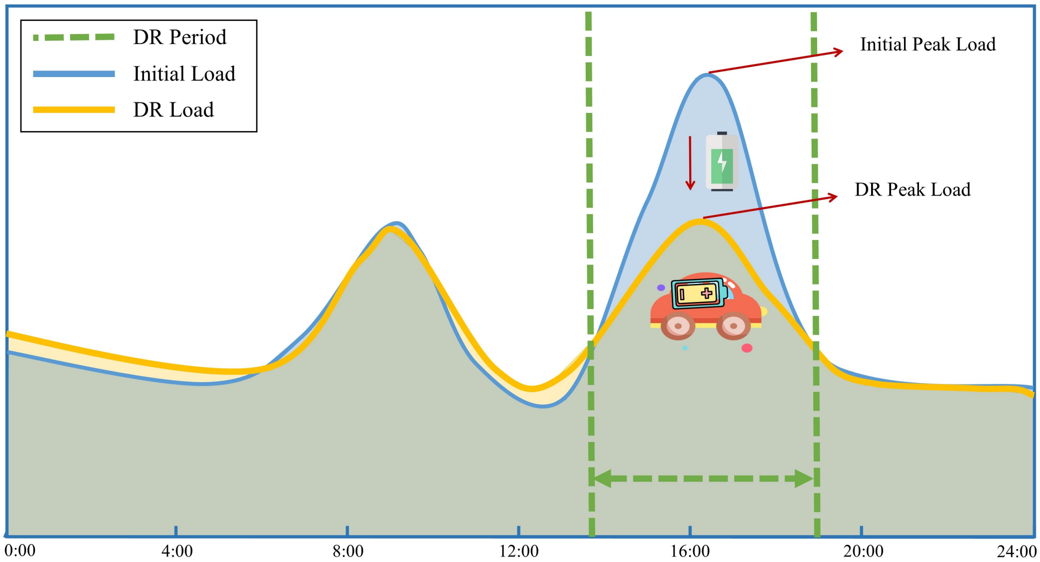


**Figure 6.** DR using V2G technology.

Currently, the mainstream research on V2G technology participation in DR is conducted in the context of distributed microgrids, which is determined by the natural decentralization and small capacity of EVs. It is worth noting that some studies on load aggregators participation in DR also mention V2G technology [34]. It also demonstrates the feasibility and economy of the business scheme of V2G technology participation in DR.

### *3.4. Ancillary Services*

#### 3.4.1. Frequency Regulation

The frequency regulation market is one of the most important markets in the ancillary services market, and it is also the earliest market where energy storage achieved commercial applications. V2G technology can offer similar service. However, the power released by single EV is too small and needs to be aggregated to achieve the minimum threshold for participating in the frequency regulation market [60]. Therefore, in the business scheme of V2G technology participation in the frequency regulation market, the V2G aggregators are particularly important. The business scheme of V2G technology participation in the frequency regulation market is shown in Figure 7.

V2G technology participation in the frequency regulation market has been studied extensively and the research content is relatively mature. In 2010, S. Han developed a V2G frequency regulation aggregator regarding the optimal control strategy for the first time [60]. In 2012, C. Wu and H. Mohsenian-Rad proposed a game-theory model to understand the interaction between V2G technology participation in frequency regulation market and V2G aggregators [61]. In the same year, Ref. [62] proposed a set of power allocation schemes when EV clusters managed by aggregators provided V2G technology frequency regulation service. The focus is on how to allocate power among EVs, rather than optimizing aggregators' profits. In 2013, S. Han conducted an economic feasibility study on V2G technology participation in frequency regulation under the condition of battery degradation. He proved that V2G technology participation in the frequency regulation market can gain more profits than the battery degradation cost [63]. In 2015, A. Lam and K. Leung proposed a capacity estimation method for V2G technology participation in the frequency regulation market, and the upper and lower limits of the regulated capacity can be obtained [64].

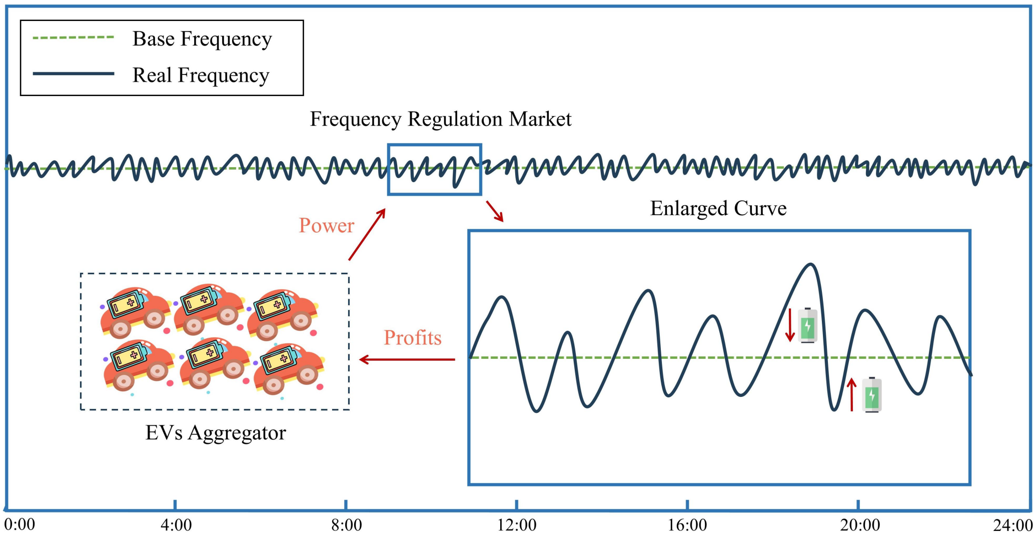


**Figure 7.** Frequency regulation using V2G technology.

In recent years, there have been some new achievements about V2G technology participation in the frequency regulation market, mainly based on the application scenario of V2G technology combined with RERs. Aiming at the problem that a large number of RERs are connected to the grid, a numerical simulation method using time series data was proposed in [65], so as to better observe the contribution of EV clusters to the frequency regulation of the power system. Taking into account the potential threat of denial of service attacks EV communications, Ref. [66] proposed a resilient frequency regulation framework through adaptive V2G technology capacity-based integral sliding mode control. Reference [67] studied the economics of V2G technology participation in frequency regulation services and considered the effect of operating temperature on life of lithium-ion batteries, and found that suitable temperature control could increase profits.

### 3.4.2. Voltage Regulation

Nowadays, a large number of RERs are connected to the power grid, which have a great influence on the voltage stability of the distribution network [68]. Through the power electronic device of the charging piles (CPs), the battery in the EVs can emit reactive power [69]. However, EVs can emit a limited amount of reactive power, and reactive power cannot be transmitted over long distances. Therefore, EVs can only support voltage in a distribution network. This is not conducive to V2G technology participation in the voltage regulation market, so the business scheme is also in its early stage.

At present, there are limited number of researches on the participation of V2G technology in the voltage regulation market. Reference [70] proposed an optimization model for battery SOC in V2G technology participation in the regulation market, which can minimize the battery degradation caused by providing V2G technology services, thereby improving the economic feasibility. Reference [71] proposed a distributed model predictive control strategy for distribution networks, which can utilize V2G technology to aggregate reactive power and integrate it into real-time voltage regulation of the grid. Reference [72] proposed an EV charging model based on water cycle algorithm, which can be used as a reactive power compensation device to improve grid voltage distribution without reducing battery life. Reference [73] considered the V2G technology participation in voltage regulation market, and proposed a discounted stochastic multiplayer game-based method to analyze the competition among the V2G aggregators, which can obtain the optimal strategy that each V2G aggregator should follow.

#### 3.4.3. Spinning Reserve

The spinning reserve market in the power system is a market mechanism based on the reserve capacity. The spinning reserve sources need to have the characteristics of fast response speed and large emergency backup power, and V2G technology just meets these characteristics. By participating in the spinning reserve market, the V2G aggregators can capture profits to support their business schemes.

Current research is concerned with the economic feasibility of V2G technology participation in the spinning reserve market. In [74], the profit maximization problem of the V2G aggregators participation in the day-ahead spinning reserve market was studied by using the three-layer mixed integer optimization method. The algorithm has fast convergence and verifies the theoretical feasibility of V2G technology participation in the day-ahead spinning reserve market. Reference [55] comprehensively considered V2G technology participation in DR and spinning reserve market, and verified the economic feasibility of this business scheme through a numerical analysis in a renewable-driven microgrid system. Based on the community integrated energy system of EV charging stations (CSs), a two-layer optimal scheduling model was established in [75]. The numerical results showed that the active participation of EVs in providing spinning reserve service can significantly improve the economy of community integrated energy system. I. Pavić wrote in [76], "A key finding of the paper is that EV capability to provide spinning reserve introduces additional flexibility to electric power system displacing high cost and emission units". According to current research, the prospects for V2G technology participation in the spinning reserve market are optimistic, but further research and market mechanisms improvement are still needed.

#### 3.4.4. Black Start

The black start power sources need to be able to start autonomously in the case of complete power failure to provide starting power for other critical equipment or power plants. As an energy storage device, the battery of EVs can release power without external power supply and can be used as black start power sources. The V2G aggregators can monetize EV clusters as black start power sources. However, it is worth noting that the emergency scenarios for black start are very rare, and the social benefits of using V2G technology as black start power sources are greater than economic benefits.

At present, the research on the use of V2G technology as black start power sources is still in the theoretical stage. Many researches have mentioned the idea of V2G technology participation in black start [26,77,78], but there is no in-depth feasibility exploration observed yet. J. Lee argued in [79] that battery-electric buses can be used as black start power sources for microgrids, but did not mention the feasibility of being used as black start power sources for large power grids. D. Dominguez explored the possibility of V2G technology offering a black start service, but the conclusion was also unclear [80]. The feasibility of V2G technology participation in black start still needs to be further studied.

## 4. Application Scenarios and Real-World Use Cases

In Section 3, the theoretical feasibility of the V2G technology's business schemes with respect to the electricity market are explored. After that, the application scenarios and real-world use cases of V2G technology will be discussed in Section 4. From the application scenarios and real-world use cases, we will get a deeper understanding of the practical application of V2G technology's business schemes.

*4.1. Application Scenarios*

The application scenarios of V2G technology are diverse. Existing research extensively mentions new concepts such as vehicle-to-building (V2B), vehicle-to-home (V2H), vehicle-to-company (V2C), vehicle-to-everything (V2X), but lacks a unified classification of V2G technology's application scenarios. Based on extensive investigations, this section summarizes a classification method of V2G technology primarily based on the location and the participation mode.

4.1.1. Taxonomy I: Classification by Location

EVs serve as mobile energy storage devices, and theoretically, EVs can be charged and discharged at any location in a power grid. However, due to infrastructure limitations, V2G technology operations for EVs are constrained to locations equipped with bidirectional CPs. Consequently, the application scenarios that require V2G technology capabilities primarily fall into three categories: home-based, workplace-based, and CSs-based. The V2G technology's application scenarios classified by location exhibit significant time-scale variations [42].

Home-based V2G typically occurs during nighttime, as individuals tend to charge their EVs after work to ensure a higher SOC for their commute the following day. Workplace-based V2G predominantly take place during the daytime, allowing EV owners to connect their EVs to CPs at their workplace and make profits through the V2G aggregators. CSs-based V2G can potentially transpire at any time during the day. Generally, people utilize CSs to rapidly replenish their EVs' battery levels in response to urgent transportation needs. However, certain exceptional circumstances arise where EV owners lack CPs at home or workplace, compelling them to rely on CSs for their charging needs. It is worth noting that home-based V2G and workplace-based V2G primarily focus on private EVs, while CSs-based V2G targets not only private EVs but also for commercial EVs (such as buses or coaches). The V2G technology's application scenarios classified by location and their characteristics are illustrated in Figure 8.

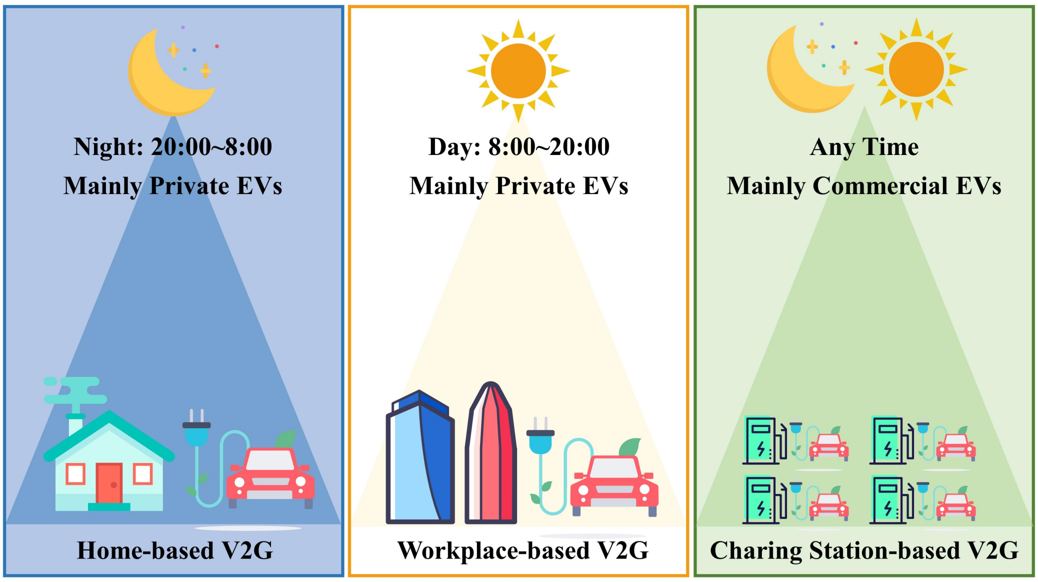


**Figure 8.** V2G technology's application scenarios classified by location and characteristics.

Home-based V2G, also known as vehicle-to-home (V2H), is a common type of V2G technology's application scenarios. Research has shown that if equipped with charging infrastructure, the majority of EV owners prefer to charge their EVs at home, possibly due to safety and convenience considerations [81]. In [82], an energy management strategy was proposed specifically for home-based V2G scenarios with rooftop photovoltaic systems. Reference [83] further highlighted that in the event of a sudden power outage from the grid, home-based V2G can serve as a backup power supply, thereby enhancing the reliability of household electricity supply.

If CPs are not installed at home, the majority of EV owners will choose to charge their EVs at workplace [42]. Considering that the typical workday time spans around 8 hours, EVs at workplace have a significant amount of idle time. Workplace-based V2G offers advantages due to the fact that the power grid's peak load usually occurs during daytime, creating favorable conditions for V2G technology participation in peak-to-valley arbitrage, DR, frequency regulation, and voltage regulation markets. Reference [84] proposed an energy scheduling method based on an office building with integrated photovoltaic systems and EVs, considering V2G technology participation in day-ahead electricity market and TOU tariff.

If neither home nor workplace has CPs, then CSs are the only option. The advantages of CSs-based V2G are as follows: CSs have a large number of EVs, enabling the release of substantial power. Additionally, CSs collect information on the starting and ending times of charging sessions from EV owners, facilitating control by the V2G aggregators. In this case, the obtained profits can be used to partially offset the charging costs.

#### 4.1.2. Taxonomy II: Classification by Participation Mode

V2G technology can participate in the electricity market through various participation modes. The most common mode is through the V2G aggregator's indirect participation in the electricity market, which may result in a portion of profits being obtained by the V2G aggregators. In this paper, this mode is referred to as aggregated-V2G. Additionally, V2G technology has other two direct participation modes in the electricity market, which are referred to as individual-V2G and industrial-V2G respectively. The detailed classification by participation modes are illustrated in Figure 9.

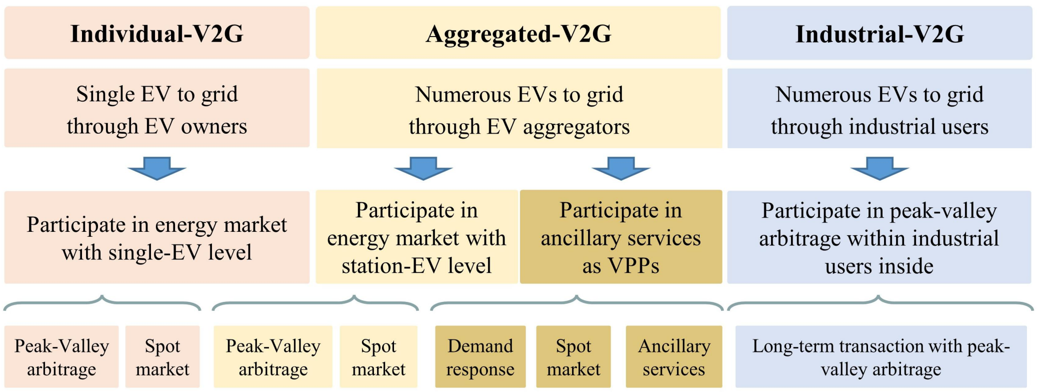


**Figure 9.** V2G technology's application scenarios classified by participation modes.

Aggregated-V2G is the most common mode, where EVs are aggregated through the V2G aggregators to form a VPP or participate in the energy market at the station level. The implementation conditions for aggregated-V2G are relatively mature and are discussed detailed in Section 3. Individual-V2G refers to individual EV directly participating in the energy market. Considering that ancillary services require a certain capacity to participate, individual-V2G can only engage in peak-to-valley arbitrage and the spot market. Currently, Individual-V2G still lacks the necessary implementation conditions and awaits future policy innovations. Industrial-V2G refers to the utilization of employee-owned EVs within industrial users to reduce their purchased electricity tariff, thus earning profits from long-term peak-valley and residential-industrial electricity tariff differentials. Industrial-V2G has already met partial implementation conditions, with certain Chinese automakers currently conducting trials. However, industrial-V2G is still in lack of relevant research or reports and needs to be further studied.

### *4.2. Real-World Use Cases*

With the development of V2G technology, V2G technology-related projects are rapidly being implemented worldwide. According to data from V2G-HUB, as of December 2023, there are already 27 countries, 131 projects, and over 6800 bidirectional CPs in operation globally [85]. An incomplete overview of V2G technology's projects around the world is presented in Table 1.

It can be observed that the Europe has the highest number of V2G technology's projects worldwide, accounting for over half of the total, with the United Kingdom leading the pack. The United States and Asia also have a considerable number of V2G technology's projects, while Australia and Africa are still in the early stages of V2G development.

**Table 1.** An incomplete overview of V2G technology's projects [85].

| Region | Numbers | Representation | Country | Year | CPs | Services |
|---|---|---|---|---|---|---|
| Europe | 88 | Powerloop | UK | 2018 | 135 | arbitrage, load shifting, emergency back up |
| | | Share the Sun | Netherlands | 2019 | 80 | frequency regulation, load shifting |
| | | Bidirectional Lade Management | Germany | 2021 | 50 | frequency regulation, DR, arbitrage, load shifting |
| | | Grid Motion | France | 2017 | 15 | frequency regulation, arbitrage, load shifting |
| America | 24 | Smart MAUI, Hawaii | US | 2012 | 80 | load shifting |
| | | INVENT-UCSD | US | 2017 | 50 | frequency regulation, DR, load shifting |
| | | BC Hydro [86] | Canada | 2023 | unknown | peak shaving, load shifting |
| Asia | 14 | Leaf to Home | Japan | 2012 | 4000 | load shifting, emergency back up |
| | | VGI Core Component Development | Korea | 2018 | 100 | frequency regulation, DR, reserve, load shifting |
| | | Taizhou [87] | China | 2023 | 14 | peak shaving, load shifting |
| | | Wuxi [88] | China | 2023 | 50 | arbitrage, load shifting, emergency back up |
| Australia | 3 | Flinders University V2G Trial | Australia | 2023 | 10 | arbitrage, load shifting |
| Africa | 2 | UNDP Windhoek V2G | Namibia | 2019 | 2 | load shifting |

Analyzing the grid services provided by these V2G technology's projects, the majority offer services such as peak-to-valley arbitrage, frequency regulation, DR, and load shifting. However, fewer projects possess the capability of serving as reserve or emergency back up. Additionally, none of the V2G technology's projects currently under investigation provide services such as the spot market, voltage regulation, and black start. The grid services provided by these real-world use projects align with the theoretical analysis presented in Section 3 regarding the participation of V2G technology in various types of electricity market.

The largest V2G technology's project globally is the "Leaf to Home" initiative in Japan, which consists of over 4000 V2G CPs. Constructed in 2012, "Leaf to Home" was developed by Nissan and is categorized as a home-based V2G application. Its primary services include load shifting for energy users and emergency back up. Nissan claims that utilizing their product, the Nissan LEAF, can provide enough electricity for an average Japanese household for two days, thus ensuring energy security for smart homes.

In recent years, China has been actively engaged in the implementation of V2G technology's projects. On 15 April 2020, State Grid incorporated V2G technology's resources into the North China peak shaving and ancillary services market and successfully completed settlements [89]. On 13 April 2021, the Great Wall Automobile Industry Park V2G project was officially put into operation in Hebei Province, featuring 50 V2G CPs, aimed at validating the business feasibility of V2G technology [90]. On 1 June 2021, the first V2G CS in Fujian Province was constructed in Fuzhou, including 44 unidirectional CPs and 2 V2G CPs [91]. On 21 February 2023, the Dongfeng Motor V2G Zero Carbon Supercharging Station was officially launched in Wuhan, Hubei Province, equipped with 5 V2G CPs and a complementary energy storage system, enabling nearly zero-carbon operation [92]. In April 2023, the largest V2G technology's demonstration project in Zhejiang Province was commissioned in Taizhou, equipped with 14 V2G CPs [87]. On 23 August 2023, the largest V2G technology's demonstration project in Jiangsu Province was constructed in Wuxi, consisting of 50 V2G CPs and providing battery swapping services [88].

Currently, although majority of V2G technology's projects worldwide are still in the exploration stages, they are of great significance for the future development of V2G technology. Through these demonstration projects, more issues related to technology, economics, and society can be discovered, and the feasibility of V2G technology's business schemes can be verified practically. Additionally, public awareness and cognitive of V2G technology can be increased gradually.

## 5. Challenges

Although V2G technology holds vast potential for development with respect to the electricity market and has seen commercial demonstration projects worldwide, there are still challenges facing the V2G technology's business schemes. These challenges primarily encompass three aspects: technical, economical, and social.

### *5.1. Technical: Communication Complexity and Battery Degradation*

In the implementation of any technology, challenges are inevitable, and V2G technology is no exception. The technical challenges facing V2G technology mainly include communication complexity and battery degradation [93,94]. For the application scenarios of V2G technology, communication complexity has three main aspects: communication stability, communication delay, and communication privacy. V2G technology participation in the electricity market requires the collection of a large amount of information from EVs for centralized optimization, presenting new challenges to communication stability. A charging control strategy for EV clusters under communication failure was proposed in [11], which may also be applied to V2G technology under communication failure. Secondly, communication delay also affects the economics of V2G technology's services. Reference [95] pointed out that communication delay can potentially undermine the frequency regulation performance. Therefore, they assessed the impact of such delays on the current frequency regulation mileage payments and introduced a novel mileage calculation approach designed to incentivize the V2G aggregators to minimize communication delays. Reference [96] studied the effect of communication on multi-node voltage of power distribution systems in real-time V2G technology's scenarios. The results showed that the system performs better with shorter communication timeouts. As people in today's society pay more attention to personal privacy, EVs and their owners are prone to tracking, analysis, and data leakage through mobile IP addresses [97]. Therefore, it is necessary to ensure the privacy of V2G technology's service communication [34,98]. Reference [99] proposed an energy trading scheme based on block-chain and applied it in microgrids with EVs to protect consumer privacy. Reference [100] proposed a role-dependent privacy preservation scheme for secure interaction between EVs and the grid. Reference [101] provided a comprehensive review of various privacy protection issues in V2G technology's networks, and privacy protection technologies are also introduced.

Considering the complexity and importance of V2G technology's communication, various countries and organizations have developed V2G technology's communication protocol standards. As early as 2013, T. Ustun extended the IEC 61850-7-420 standard to apply to control EVs bidirectional charging [102]. In 2019, International Organization for Standardization (ISO) formulated the ISO 15118-1:2019 standard communication protocol, which specifies the V2G technology's communication interface [103]. In 2021, China has also detailed the V2G technology's communication protocol in GB/T 18487.4 to incentive the development of V2G technology [104].

Another technical challenge is battery degradation, as V2G technology consumes more battery cycles than regular vehicle use, leading to a decrease in battery capacity [105].

There are many studies on the impact of V2G technology's services on the degradation of EV batteries, with most researches holding an optimistic attitude. However, some researches suggest that the benefits of using EVs for V2G technology's services may not outweigh the cost of battery degradation. Reference [106] conducted an analysis on the impact of V2G technology participation in ancillary services such as frequency containment reserve, peak shaving, and a combined approach, focusing on the influence on battery lifespan. The findings revealed that the participation in a combined frequency containment reserve and peak shaving method yields the highest profitability, resulting in a net present value of 19,500 EUR over a span of 10 years. Reference [107] proposed a charging and discharging strategy considering battery degradation and applied it to a distributed power grid containing wind power. The results showed that V2G technology without wind power is unfavorable, while considering wind power is economically feasible. Reference [108] pointed out that appropriate V2G technology's services can even extend battery life instead of leaving EV batteries idle for long periods of time. Reference [109] compared the benefits and battery degradation of electric buses participation in V2G technology, and the results indicated that when the cost of battery replacement remains below a threshold of 100 EUR/kWh, public transportation operators may find it economically viable to engage in V2G technology. Reference [110] proposed a stochastic optimization model to evaluate the value of PHEVs in V2G technology, and the results showed that for peak-to-valley arbitrage and providing ancillary services, the degradation cost is more significant than the benefit earned. However, it also pointed out that the future decline in battery prices may achieve positive returns.

In order to address the challenge of communication complexity, future research needs to focus on the development of advanced communication technologies and protocols, regulatory strategies under weak communication, and encryption algorithms that prioritize EV owners' personal privacy. The communication challenges require the collaborative efforts of electrical engineering, communication, and mathematics disciplines. On the other hand, the advancement of battery technology relies on the cooperation of multiple disciplines, including materials, chemistry, and electrical engineering. In the future, batteries with a higher cycle counts and lower price will contribute to the promotion of V2G technology.

### *5.2. Economical: High Fixed Investment and Uncertain Market Policies*

The economical challenges should not be overlooked. The high fixed investment is a major economical challenge for V2G technology's development [111]. In conventional EVs, electricity only needs to be transmitted in one direction, so both the CPs and the onboard charger (OBC) only require one-way electricity transmission. However, V2G technology requires bidirectional energy transfer from the CPs to the OBC, which increases the fixed investment [112]. Additionally, existing one-way CPs and EVs that do not support V2G technology are wasted. Furthermore, the V2G aggregators need to be equipped with high-performance communication and computing devices to achieve stable communication and centralized optimization of the EV clusters. Investors may lack the courage to make substantial fixed investment in such a brand-new business scheme. Reference [15] also pointed out that the energy released by V2G technology essentially comes from the power grid, and there are energy losses during the battery charging and discharging processes. The feedback energy may only be around 90% of the energy used for charging, and these energy losses directly impact the economics.

Uncertain market policies are also challenges for V2G technology. Despite global calls for decarbonization, many countries and automotive companies are actively exploring V2G technology [113,114]. However, the business schemes and practical engineering of V2G technology are still in the early exploration stage. Currently, only peak-to-valley arbitrage can guarantee profitability and the profit margin is limited. The policy prospects for other services with respect to the electricity market are unclear. It is urgent to explore and design new ancillary services that adapt to the characteristics of V2G technology and grid regulation needs. Also, there is no conclusive research to determine whether

V2G technology can be as important for transforming the world's energy landscape as other RERs like solar or wind power. It is more like a complementary technology. After attempting V2G technology, if it fails to meet people's expectations or shows poor feasibility, future policies may take a downturn. The uncertain market policy risks in the future will hinder V2G technology's investments. Therefore, more research and demonstration projects are needed to validate the feasibility of V2G technology, and governments should introduce more incentive policies and future commitments to increase market confidence in V2G technology for both investors and stakeholders.

China has taken concrete actions to clarify the policy direction for future V2G technology. In November 2020, the State Council issued the "Development Plan for the New Energy Vehicle Industry (2021–2035)" [115], which encourages strengthening the interaction between EVs and power grid by V2G technology. In May 2021, policy was released to promote V2G technology's demonstration projects. In January 2022, the "Implementation Opinions on Further Enhancing the Service Guarantee Capacity of Electric Vehicle Charging Infrastructure" was issued [116], which further proposed exploring and promoting orderly charging, V2G technology, and other forms of interaction between EVs and power grid. In December 2023, the "Implementation Opinions on Strengthening the Integration and Interaction of New Energy Vehicles and the Power Grid" was issued [117], aiming to concentrate 60% to 80% of the annual charging volume during off-peak periods in demonstration cities by 2025.

The high fixed investment and uncertain market policies currently facing V2G technology are similar to those encountered by the photovoltaic several years ago. However, the photovoltaic has since overcome these challenges and created a large new market. Similar to the photovoltaic, the high fixed investment can be alleviated in the early stages through government subsidies, which can be phased out once the industry is self-sufficient. The government can also enhance investor confidence through clear policies and commitments. In summary, the government plays a crucial role in addressing the economical challenges.

### *5.3. Social: Trust Issue and Range Anxiety*

Besides the technical and economical challenges, social challenges are easily overlooked. Actually, social challenges are as important as the technical and economical challenges and deserve particular attention, especially for a V2G technology's business scheme, which involves shared resources. If EV owners are unwilling to participate in V2G technology, then the feasibility become irrelevant. Regarding the social challenges, the main concerns include the distrust to V2G technology's contracts and the range anxiety among EV owners.

Studies have indicated that users are particularly concerned about the driving range of EVs, especially for new buyers [118]. As expensive commodities, EVs are not just tools for people but also objects of affection. They are unwilling to subject their beloved EVs to additional usage. A survey in the Nordic region revealed widespread skepticism towards V2G technology, with respondents including a substantial number of experts [119]. In another social survey, 24% of respondents expressed concerns about privacy leaks related to V2G technology, and 39% felt that V2G technology would "take control away from me in a way that I would not like" [120]. Similarly, a survey in the Netherlands indicated that people are generally unwilling to participate in V2G technology and are particularly concerned about discharge cycles and the guaranteed minimum SOC of battery [121]. Improvements in charging speed and infrastructure might help alleviate this situation. In a Canadian survey, consumers voiced concerns and distrust to V2G technology's contracts, with one individual expressing worries, "what happens when the computer glitches, and I go downstairs and I go, 'oh my car's not charged'?" [122]. These surveys reflect that people's cognition of EVs still remains on transportation tools rather than on the intelligent "Energy Hub" for life and work.

Range anxiety is another significant challenge to the implementation of V2G technology. For PHEVs, the situation is somewhat better because they can run with fossil fuel.

However, for BEVs, this issue is particularly pronounced. Numerous researches on EVs have mentioned range anxiety [123–125]. In a survey, out of 21 households, 10 expressed discomfort with V2G technology and stated a preference for maintaining their EVs at 100% charge for "peace of mind", possibly due to considerations of convenience and safety [122]. Reference [126] designed an experimental survey to gauge EV owners' acceptance of V2G technology and found that range anxiety was the most frequently mentioned factor, with low battery levels making them feel inconvenienced and unsafe. Another survey from Netherlands also indicated that range anxiety and battery degradation were the biggest obstacles to V2G technology's acceptance. The survey also highlighted the importance of high transparency regarding electricity usage, related benefits and risks, possibly linked to the distrust to V2G technology's contracts [127].

In summary, the current public acceptance of V2G technology is not high, similar to the early stage of EVs, which have been widely accepted nowadays. From the experience of EVs, it can be concluded that overcoming social challenges requires public education and increased awareness. Maintaining high transparency of V2G technology's contracts and strictly adhering to minimum battery SOC requirements can help alleviate anxiety among EV owners. Future research needs to focus on the psychological factors contributing to the low acceptance of V2G technology by people and how to increase their willingness to participate.

## 6. Conclusions

This review has explored the feasibility and challenges of V2G technology's business schemes with respect to the electricity market. It systematically analyzes the feasibility of V2G technology participation in various types of the electricity markets and classifies V2G technology's application scenarios based on location and participation modes. This review also extensively investigates V2G technology's projects worldwide, particularly in China, and provides analysis and implications of these real-world projects. The latest research on challenges related to V2G technology's implementation is also presented. It aims to provide policymakers, researchers, and industry professionals with insights and recommendations for the development of V2G technology and its business schemes. The main findings of this review can be summarized as follows:

- The transition from fuel-powered vehicles to EVs is an inevitable trend. As a means of interaction between EVs and the power grid, V2G technology is essential for the development of EVs and ensuring grid security and stability.
- The concept of V2G technology is introduced by analyzing a specific microgrid containing V2G technology. The exploration of V2G technology's business schemes indicates broad market prospects and practical economic viability.
- The feasibility of various V2G technology's services with respect to the electricity market are explored, including peak-to-valley arbitrage, the spot market, DR, frequency regulation, voltage regulation, spinning reserve, and black start.
- A detailed classification of V2G technology's application scenarios is investigated. Additionally, analysis and discussion of real-world V2G technology's cases worldwide are presented.
- An overview of the challenges facing by V2G technology's business schemes is investigated, which mainly from three perspectives: technical, economical, and social. These challenges need to be further studied and overcome.

In conclusion, V2G technology has the potential to have a significant impact on the future energy landscape. It enables EVs to not only consume power but also contribute to grid stability, economic efficiency, and decarbonization. However, realizing this potential requires addressing the technical, economical, and social challenges. Future research should focus on developing innovative business schemes, addressing stakeholders' concerns, and establishing supportive regulatory frameworks. The innovation of business schemes is not only reliant on technical advancements but also necessitates the introduction of commercial operational models. In order to alleviate stakeholders' concerns, it is crucial to building a fair and transparent management system. The establishment of a supportive regulatory framework requires collaboration among various stakeholders, including legal entities, government bodies, automobile companies, and EV owners. Through continuous efforts and collaboration, we firmly believe that V2G technology can play a pivotal role in achieving a sustainable and green energy future.

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## Abbreviations

The following abbreviations are used in this manuscript:

| | |
|---|---|
| V2G | Vehicle-to-Grid |
| EVs | Electric vehicles |
| DR | Demand-response |
| RERs | Renewable energy resources |
| BEVs | Battery electric vehicles |
| PHEVs | Plug-in hybrid electric vehicles |
| HEVs | Hybrid electric vehicles |
| FCEVs | Fuel cell electric vehicles |
| VPPs | Virtual power plants |
| IEA | International energy agency |
| TOU | Time-of-use |
| CPs | Charging piles |
| CSs | Charging stations |
| OBC | Onboard charger |
| ISO | International Organization for Standardization |
| V2H | Vehicle-to-Home |

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