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Review

Control Strategies, Economic Benefits, and Challenges of Vehicle-to-Grid Applications: Recent Trends Research

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Abstract: With the rapid growth in the number of EVs, a huge number of EVs are connected to the power grid for charging, which places a great amount of pressure on the stable operation of the power grid. This paper focuses on the development of V2G applications, based on the current research status of V2G technology. Firstly, the standards on V2G applications and some pilot projects involving more representative V2G systems are introduced. Comparing V2G applications with ordered charging and unordered charging, the social and economic benefits of V2G applications are highlighted. Analysis of the social benefits of V2G applications concerns three points: the grid demand response, personalized charging, and the coordination of renewable energy sources. And analysis of the economic benefits of V2G applications is divided into three parties: the grid, the aggregator, and individuals. From the perspective of innovative EVs expanding the application scenarios through V2G technology, V2G applications for commercial EVs, emergency power applications, and vehicle-to-vehicle energy trading are introduced. The current challenges related to V2G applications are presented: users' willingness to participate in V2G applications, battery loss, charging and discharging tariffs, privacy and security, and power loss. Finally, some research recommendations for the development of V2G applications are given and the current state of research in regard to those recommendations is presented.

Keywords: electric vehicles (EVs); V2G; control strategy

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1. Introduction

According to a statistical report released by the International Energy Agency, the global ownership of EVs will exceed 26 million in 2022, which will be more than five times the number of EVs in 2018. Figure 1 demonstrates the global EV ownership numbers from 2010 to 2022 [1]. The number of EVs on the road globally is projected to reach 245 million by 2030. Figure 2 shows the predicted growth in the number of EVs on the market by 2030 [2]. According to the latest statistics, by the end of 2023, the number of new energy vehicles in the world had reached 20.41 million, accounting for 6.07% of the total number of vehicles. The number of pure electric vehicles was 15.52 million in 2023, accounting for 76.04% of the total number of new energy vehicles, and the number of newly registered new energy vehicles was due to reach 7.43 million in 2023, accounting for 30.25% of the total number of newly registered vehicles, which is an increase of 2.07 million compared with that in 2022, with a growth rate as high as 38.76%, from 1.2 million vehicles in 2019 to 7.43 million vehicles in 2023. The number of EVs is growing at a high rate [3]. With respect to the global new energy vehicle market, China has more than 60% of the world's new energy vehicle market share [4].

The charging of EVs is very intermittent and random, and the large-scale charging of EVs via the power grid has brought unprecedented challenges to the stable operation of the power grid. Khalid et al. proposed that a large number of EVs connected to the grid not only causes many power quality problems, but also seriously affects the load performance on the user's side [5]. Yu Yinghan et al. reported that a large number of EVs connected to a distribution network will be superimposed on the basic power consumption of the network, resulting in an increase in peak power consumption, which further increases the pressure on grid operation and is not conducive to the stable operation of the grid [6]. Wang Junliang et al. proposed that large-scale access to the grid by EVs will not only affect the degree of grid load imbalance, but will also increase the EV access point voltage, the short-circuit current and system fault current, and the EV charging process will produce serious harmonic pollution [7]. Song Hui et al. analyzed the problems concerning grid voltage quality caused by scaled EV access to the grid, including harmonic pollution, voltage drops, and three-phase voltage imbalances [8].

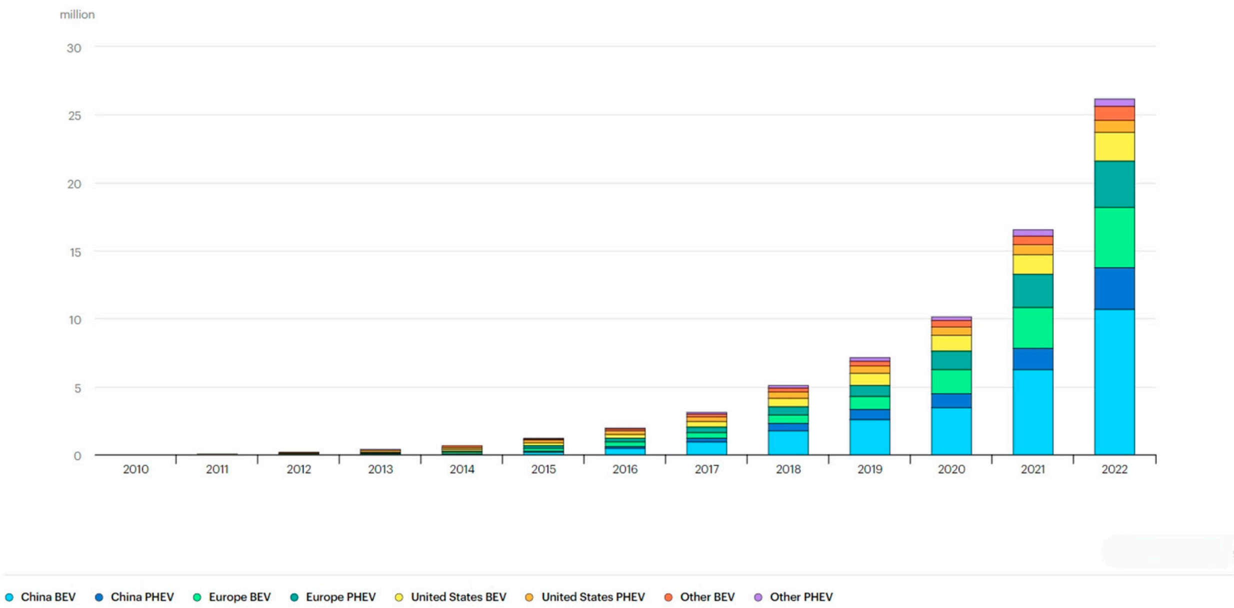

Figure 1. Global electric car stock, 2010–2022 [1].

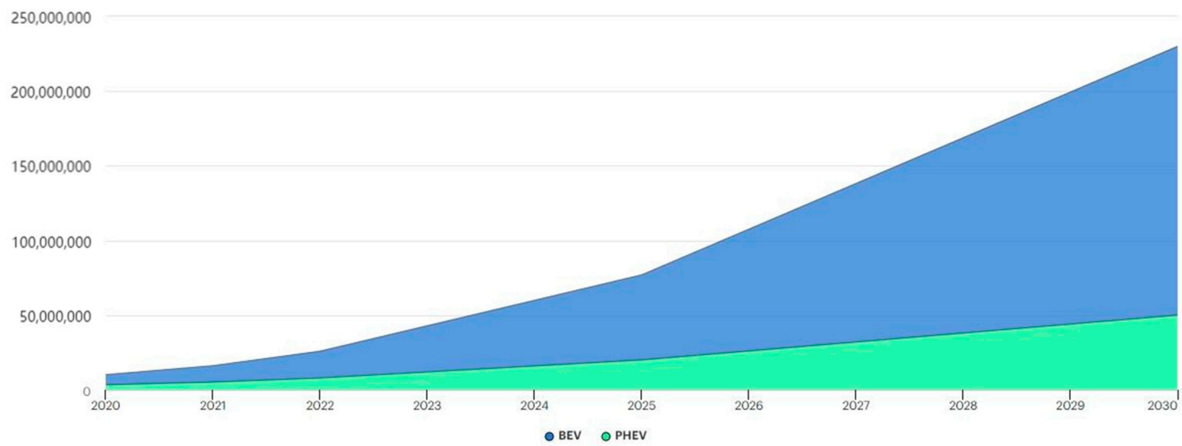

Figure 2. EV stock, 2020–2030 [2].

After years of research and development, vehicle-to-grid (V2G) energy management technology has become an important tool for countries and regions to address critical issues in the energy field. V2G technology enables bidirectional communication and energy exchange between EVs and the grid. By using the electricity stored in the batteries of EVs, V2G technology can help the grid to balance the loads, reduce the peak demand, and integrate renewable energy sources. The widespread use of this technology is driving the energy industry to become more intelligent, more efficient, and more eco-friendly.

In recent years, V2G technology has gradually become a research hotspot in the field of electric vehicles and smart grids, involving practical explorations by many researchers worldwide. Yang Ji et al. aimed to minimize the peak-to-valley difference in the grid load, the mean square deviation of the load fluctuation, and the charging costs for users, and formulated an adjustable power charging strategy to guide the charging of EVs by users [9]. Armenta-Déu C et al. proposed that EVs can reduce the peak-to-valley difference in power consumption of the grid through V2G technology [10].

In recent years, the rapid growth in the number of EVs has led researchers to pay extensive attention to V2G technology, and there has been a proliferation of V2G-related research. In a previous literature review, [11] explored the implications of applying V2G technology in power distribution systems and investigated V2G interface strategies for single and multiple EVs. Moreover, [12] describes the power flow methodology used in the V2G scheme and the challenges associated with the commercial application of V2G technology. The study in [13] examines the implementation challenges of EV infrastructure and charging systems in the context of multiple international standards and charging specifications. In addition, [14] discusses the operation of EVs and their impact on grid stability. While [15] describes the potential of V2G in regard to ancillary services and discusses the potential impacts, challenges, and future market penetration opportunities of V2G technology. Furthermore, [16] reviews the technologies, technical components, and system requirements needed to deploy EVs in the context of grid-related services. However, little attention has been paid to the social and economic benefits of V2G technology and the innovative applications of EVs in the V2G technology environment.

This paper focuses on the practice of V2G standards, the social and economic benefits of V2G technology, cutting-edge research on V2G application areas, the challenges, and the outlook. This article contributes by making the following points:

- A discussion on the social and economic benefits of V2G technology. The social benefits of V2G technology are discussed from three perspectives: the grid demand response, personalized charging, and the coordination of renewable energy sources. The economic benefits of V2G technology are discussed from three perspectives: the grid, the aggregator, and the individual, respectively. And the social and economic benefits of V2G technology are highlighted by comparing the V2G system with ordered charging and unordered charging.
- The cutting-edge applications of EVs in the V2G technology environment concerns three points: V2G applications for commercial EVs, emergency power applications through V2G EVs, and energy interactions between EVs through V2G networks.
- A discussion on the current challenges in regard to V2G applications and a discussion on the existing solutions. The challenges include users' willingness to participate in V2G systems, battery loss, charging and discharging tariffs, privacy and security, and power loss. Finally, some research suggestions are given for the development of V2G technology, and the current research status of theses research suggestion is discussed, including four directions: battery performance degradation, the stepwise utilization of retired batteries, integration with renewable energy sources, and policy.

2. Concept and Implementation of V2G Technology

According to the latest standards [17] released by the International Electrotechnical Commission (IEC), through V2G technology, EVs can not only obtain power from the grid for charging, but they also provide feedback to the grid on the energy stored in the battery, realizing the bidirectional flow of energy, which is the definition of V2G used by the international agency. A conceptual flowchart is shown in Figure 3 [18] below.

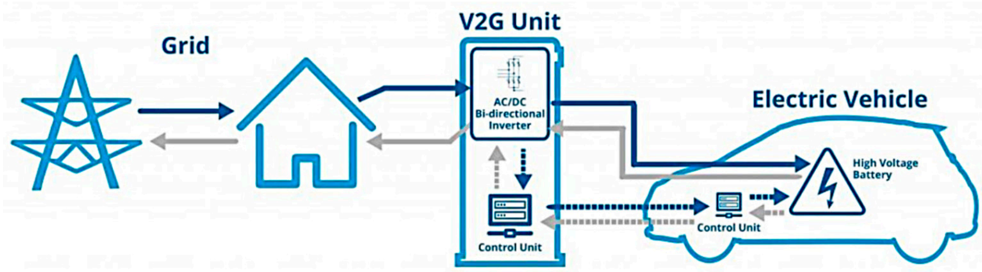

Figure 3. V2G conceptual flowchart [18].

In recent years, China has also actively promoted the development and improvement of V2G-related standards. GB/T 29317 [19] defines V2G as an EV power battery connected to a public grid through a charging and discharging device, as an energy storage unit that participates in the public grid power supply mode of operation to achieve a bidirectional flow of energy. GB/T 18487 [20] provides domestic V2G-related technical standards. However, the current domestic V2G technical system standards are still under construction, and China plans to establish a V2G technical system by 2025 and fully build it by 2030. Against the background of V2G technology, EV users can benefit from supplying electricity to the grid to earn revenue and charge their EV when electricity prices are low, thereby reducing energy costs. The application of V2G technology not only improves the efficiency and stability of the energy system, but also provides EV users with more flexible and economical charging options, promoting the transition to clean energy.

According to the latest statistics from the V2G Hub website, there are 134 V2G projects in 27 countries and regions worldwide, mainly concentrated in Europe and North America with 91 and 23, respectively, Japan and Korea both have 9, while there are only 4 in China [21]. From these data, it can be seen that V2G projects are unevenly distributed around the world, but the greater number of deployments in Europe and the United States indicates their positive attitude and leading position in regard to new energy technologies, while China, as the world's largest consumer market for new energy vehicles, has a relatively slow pace of practical exploration of V2G technology, and there is still much room for development.

Thanks to the rapid development of EV technology and V2G technology, more and more countries and regions have carried out practical V2G projects to validate the feasibility of V2G technology. In 2014, LomboXnet, in cooperation with several organizations, conducted the V2G demonstration project "Smart Solar Charging" to integrate EVs with photovoltaic panels. The project combined photovoltaic power plants with EVs to form an intelligent and dynamic charging and storage system. With V2G technology, peak loads on the grid can be reduced. This project was the first V2G project in the world to combine photovoltaic power generation and EVs [22]. In 2016, the Technical University of Denmark (TUD), along with Nissan and other organizations, initiated a practical V2G project called "Parker", which has been delivering FM services in the electricity market across various regions of Denmark for over three years. This project was the first commercial V2G pilot project in the world [23]. In 2018, Octopus EVs in the UK joined forces with a number of organizations to conduct a V2G pilot project called "Powerloop", which explored customers' driving and charging behaviors and their perceptions of V2G services, providing insights and best practice recommendations for future V2G industry stakeholders [24]. In 2023, the State Grid Wuxi Power Supply Company conducted China's largest V2G pilot project called "e-Park" in Wuxi, Jiangsu Province. The project was equipped with 50 sets of 60 kilowatt (kW) V2G DC charging stations. In a 30 min test, the 50 new energy vehicles had a reverse charging power of nearly 2000 kW, enough to meet the normal electricity demand of 133 households in Wuxi for one day [25]. A comparison of the four V2G pilot projects just mentioned is shown in Table 1.

Table 1. V2G pilot project comparison table.

Project Name	Timing	Scale	Mode	Goal
Smart Solar Charging	2014	22 Renault Zoe (40 KW/h) EVs, 22 charging posts.	V2G technology is utilized to store photovoltaic electricity in EVs, which can be fed back into the grid when charging tariffs are high or grid loads are high.	An intelligent system was developed to realize that EVs can be charged directly from a photovoltaic power station via a V2G charging post for DC charging, and the electricity stored in EVs can be fed back into the grid. The system enables four types of power flow: photovoltaic panels to EVs, photovoltaic panels to the grid, EVs to the grid, and grid to EVs.
Parker	2016	10 EVs, 43 V2G-enabled charging posts.	A series of tests and demonstrations on the experimental platform PowerLabDK using EVs and V2G DC chargers. Also, with the world's first V2G commercial pilot (Frederiksberg Forsyning V2G hub).	Validate that EVs can provide ancillary services to the grid by vertically integrating resources and assessing the ability of EVs to meet grid needs. Explore the market, technology, and user barriers to V2G commercialization to pave the way for further commercialization.
Powerloop	2018	135 users signed up for testing in 2021, which continued through 2022.	Packaging EV rental with V2G grid services into a package. Users lease EVs with a V2G package (e.g., Nissan LEAF) for £299 per month, and then users can use the V2G service at least 12 times per month via the mobile app, which gives them an additional £30/month cashback.	Technical validation of V2G-enabled vehicles and chargers to explore the technical, commercial, and practical feasibility of V2G technology in the UK.
e-Park	2023	50 EVs and 50 sets of 60 kW DC charging piles integrated with a photovoltaic power plant and an energy storage plant.	Combining the four functional systems of photovoltaics, an energy storage power station, charging, and discharging, a multifaceted energy management system is established, which uniformly monitors and manages the operating conditions of individual functional systems. It also sets up a time-sharing points system, whereby the owner of a vehicle can earn points by accessing the V2G charging station to feed electricity into the grid. Each point can be exchanged for the charging rights and benefits of 3 kWh of electricity.	Verification of grid responsiveness to EV reverse charging loads and the effect of dissipating photovoltaic generation energy.

3. Social Benefits of V2G Technology

In recent years, much attention has been given to V2G technology, an electrical energy interaction between the grid and EV users that improves the operational efficiency and stability of the grid and brings significant social benefits to the grid. Compared to ordered charging and unordered charging, V2G can bring more significant social benefits. A detailed comparison is presented in Table 2. By flexibly utilizing the batteries of EVs, V2G technology is expected to revolutionize the way we manage energy. The social benefits of V2G technology are analyzed here according to specific application scenarios and needs, including the grid demand response, personalized charging, and renewable energy coordination.

Table 2. Comparison of social benefits.

Social Benefit	V2G	Ordered Charging	Unordered Charging
Grid Demand Response	The charging and discharging behavior can be adjusted according to the grid demand, which helps to reduce the peak-to-valley difference, frequency fluctuations, and other grid demands. This can enhance the stability of grid operation.	Being able to avoid charging at peak times helps reduce peak-to-valley differences, but it is not as flexible as V2G.	Unable to respond to grid demand, unordered charging increases the grid load, and is not conducive to the stable operation of the grid.
Personalized Charging	Personalized charging and discharging services can be planned according to user preferences and needs through unified system scheduling.	It is not possible to provide a personalized charging plan. This is because charging behavior is influenced by the reality of electricity usage.	Inability to predict and control charging behavior and provide personalized charging services.
Coordination of Renewable Energy	EVs can harmonize the stochastic and fluctuating nature of renewable energy sources through the role of energy storage and supply, and through the efficiency of their utilization.	When there is too much renewable energy generation, EVs can function as energy storage, but not energy supply.	Inability to provide energy storage and functionality to reconcile the stochastic and volatile nature of renewable energy.

3.1. Grid Demand Response

According to the load demand of the grid, the charging and discharging behaviors of EVs are adjusted, and the peak and valley regulation, frequency regulation, and the reactive power control of the power system are performed to achieve load balance and stable operation of the grid.

(1) Peak Variation Control

Through V2G technology, EVs can return electric energy at the peak of electricity consumption, using peak tariffs to gain economic benefits and reduce the load pressure on the grid, while charging in the low valley of electricity consumption, using low valley tariffs to reduce charging costs, and achieve the efficient use of electric energy. Tan Qinliang et al., based on the consideration of the large-scale participation of EVs in V2G peak shifting, focusing on the impact of seasonal factors on the participation of EVs in the application of V2G technology, established a multiobjective planning model with the minimum system operation costs, the minimum load fluctuation on the grid side, and the maximum economic benefits on the user side to optimize the power supply structure and increase the overall economic benefits of the system. Finally, taking the Hebei Province region as an example, the results show that there is a seasonal characteristic to the peak effect, in which the summer effect has the best impact and the winter effect has the worst [26]. Xiao Li et al., in response to the random entry of a large amount of EVs into the grid, which causes the peak-to-valley difference of the grid load to increase, proposed a two-layer optimal scheduling strategy for EV charging and discharging based on V2G technology, by formulating the charging load and discharging output in each time period as an upper-layer model, and based on users' willingness to participate or not and users' scheduling ability as a lower-layer model, and using multiple swarm optimization and genetic algorithms to analyze the model, and the results show that the proposed model is not only able to smooth the peaks, but is also able to reduce the peaks and valleys. The results show that the proposed model can not only smooth the load fluctuations, but also maximize the economic benefits for users [27].

(2) Frequency Control

Through V2G technology, the battery energy storage system in EVs is used to supply power to the grid, or absorb power from the grid, during grid frequency fluctuations to maintain the grid frequency in a safe range. Xin Song et al. proposed a switching integral reinforcement learning scheme for collaborative grid frequency control that combines V2G control with power plant frequency control to mutually achieve frequency regulation and, finally, verified the effectiveness of the scheme using an IEEE-14 bus test system [28]. Xiangyu Chen et al., in order to coordinate a large number of EVs distributed in different geographical locations, proposed a generic hierarchical framework for V2G systems that provides frequency regulation services and, finally, the results of the simulation experiments showed that the framework has good frequency regulation capability [29]. KC Leung et al. presented a game theoretic approach using noncooperative and cooperative games to incentivize EVs to provide frequency regulation services to the grid, where the aggregator, as a leader, determines the price of the electricity transaction, and the EV users, as followers, determine their charging and discharging strategies. The simulation results show that the proposed game theoretic approach can incentivize EVs to smooth the power fluctuations in the grid [30].

(3) Reactive Power Control

In V2G technology, the battery energy storage system in EVs is used to supply or absorb reactive power from the grid by adjusting the charging and discharging behavior of EVs, as needed, to help achieve the goals of maintaining a stable voltage and optimizing the power factor in the grid. Chen Tianjin et al. proposed applying a virtual synchronization control strategy to the V2G system of EVs. First, the charging and discharging system is designed according to the principle of virtual synchronization. Second, parameters, such as virtual inertia and damping in the controller, are adjusted so that the V2G system has the operating characteristics of a traditional grid. Finally, simulation experiments verify that the V2G system has good active and reactive tracking performance and can quickly respond to grid anomalies and regulate the charging and discharging power, or feed reactive power back to the grid, which improves the stability of the grid and its interference immunity [31]. Jindi Hu et al., to exploit the aggregated reactive power V2G capability of large-scale distributed EV chargers, proposed a distributed model predictive control strategy for balanced and unbalanced distribution networks, and integrated them into a real-time balanced and unbalanced distribution network with voltage regulation. Finally, numerical values were obtained from an IEEE European low-voltage test feeder system, the results were validated, and the results showed that the proposed strategies achieved good voltage regulation performance [32].

3.2. Personalized Charging

According to the user's behavior and charging needs, a personalized charging and discharging plan is developed to meet the grid demand, while satisfying the user's needs and improving the user experience. Hong Ruijie et al., using EV users' idle time and acceptance of the discharge cut-off capacity as criteria, followed a detailed division of EV groups, established charging and discharging load curves for EV users with different preferences, more accurately simulated EV users' discharging behavior, and established an optimization function model with the goal of increasing aggregator revenue to further improve EV V2G charging and discharging strategies. Finally, private passenger cars and official passenger cars are used as examples, and the results show that this strategy further improves the economic and social benefits [33]. According to Su et al., in response to the inertia, lack of damping, and frequency fluctuation problems caused by large-scale EVs entering the grid, based on virtual synchronous generator technology and fuzzy control technology, an intelligent charging and discharging control strategy for EVs that considers the charging demand of the user is proposed. Finally, simulation experiments are carried out in the case of different battery states and user demands, and the results show that in the case of meeting the user's demand, the grid frequency fluctuations are reduced, and the stability of grid operation is improved [34].

3.3. Coordination of Renewable Energy

EVs are combined with other renewable energy sources through V2G technology to form a new energy management system. This system not only meets grid demand and improves grid stability, but also increases the utilization rate of renewable energy sources. Lin et al. first applied V2G technology in a multi-energy complementary system based on a common AC bus; then, they proposed a V2G autonomous active–reactive control strategy based on a virtual synchronous machine, which simulates the electromechanical transient characteristics of a conventional generating set through the optimal design of key parameters, such as virtual inertia and damping coefficients, and realised that the system autonomously performs voltage and frequency regulation to solve the grid index fluctuation problem [35]. Jia Shiduo et al. proposed a multilayer coordinated optimization strategy for ETH-IES (electric–thermal–hydrogen integrated energy system), which includes feedback correction for V2G loads. Finally, an ETH-IES industrial park was used as an example, for research and analysis. The results showed that the proposed strategy improves the system operation economy and tracks the planned value of the main network contact line, and it also realizes a win-win situation for EV users and the operator [36]. Yu Zichun et al. proposed a two-phase optimal scheduling method for a regional integrated energy system that considers the V2G response of electric buses. This method addresses the problems of wind and light dissipation and total load fluctuations caused by the access from high-penetration renewable energy sources and electric buses to the system. The final simulation results demonstrate that the proposed method can improve the wind and light dissipation capacity and operational economy of the regional integrated energy system, while reducing the total load fluctuation of the power system [37]. Bingjie Shang et al., due to the stochastic nature of wind power generation, which not only affects the stability of the power grid, but also causes the phenomenon of wind power abandonment, which leads to the waste of resources, proposed that EVs can be used as storage batteries for wind power, thus improving the ability of the power grid to consume wind power [38]. By combining V2G technology with renewable energy, a new energy management system can be developed. This offers a novel solution for energy management.

4. Economic Benefits

When applying V2G technology, it is crucial to consider the economic benefits for the grid, the user, and the aggregator. Participating in the V2G system can provide economic benefits for EV users, such as reduced charging costs and potential profits. Aggregators are responsible for managing EV participation in the V2G system, including recruitment, registration, and energy market transactions. Aggregators offer flexible power resources to the market by optimizing vehicle charging and discharging behavior. This promotes the stable operation of the grid and provides economic benefits and other services to vehicle owners. Aggregators aim to obtain economic returns, while ensuring the safety and effectiveness of vehicle participation in the V2G system by working with the grid operator. They also strive to maximize the economic benefits for EV users. The grid considers the use of load regulation concerning EVs to make the grid stable during the operation of V2G technology [39]. Therefore, the focus is on the benefits for both aggregators and EV users. Compared with ordered charging and unordered charging, V2G technology has a significant advantage in terms of economic efficiency. Table 3 compares these three charging methods.

Table 3. Comparison of economic benefits.

Targets	Economic Benefits	Charging Method		
		V2G	Ordered Charging	Unordered Charging
Grid	Operating costs	It can reduce the cost of grid operation to a great extent. This is because V2G technology can flexibly dispatch the power stored in EVs' batteries, reducing the reliance on conventional power generation facilities.	It can reduce grid operating costs, but not to the same extent as V2G. Although it can avoid peaks and valleys when charging, thus optimizing the allocation of power generation resources and electric energy resources, the electric energy can only be used by EVs themselves.	Instead of reducing grid operating costs, they may increase them. This is because unconstrained charging may lead to increased peak loads, increasing the risk of grid stress and under supply.
	Investment in energy storage devices	It can effectively reduce the investment in energy storage equipment. This is because the grid can utilize the batteries in EVs to store excess power and wait for it to be dispatched for use when needed.	Charging is not carried out during peak power consumption, and charging occurs after peak power consumption or when there is excess power. Compared to V2G, ordered charging cannot feed power into the grid and can only be used for self-consumption, thus limiting the effect of grid investment in energy storage equipment.	In contrast to V2G and ordered charging, unordered charging typically does not decrease the grid's investment in energy storage devices, but it may instead increase it. Because unordered charging may lead to increased peak loads and grid stress, the grid may need to invest in additional energy storage equipment to manage load fluctuations.
Person	Reduce charging costs and gain additional revenue	EV users can participate in electricity market trading, choose low tariff hours for charging, and utilize stored electricity to participate in V2G services, thus reducing charging costs and even obtaining additional revenue.	Users are able to reduce the cost of charging through time-of-use tariffs, but they are unable to participate in electricity market transactions, so they do not receive additional revenue.	There is no way to reduce the cost of charging or gain additional revenue. Because unordered charging does not take into account the price of electricity and does not participate in electricity market transactions.
Aggregator	Make profit	Aggregators can make a profit by participating in electricity market transactions on behalf of EV users, receiving a fee for their services.	Aggregators can plan charging schedules for EV users, direct EV users to charge when electricity prices are low, and then charge a fee for the service.	With unordered charging, aggregators cannot make a profit from it.

(4) User Benefits Maximization

Maximizing the economic returns of users is an important design objective of many V2G control strategies. Vinay Chamola et al. proposed an intelligent framework based on the Internet of Things (IoT) and edge computing to effectively manage V2G operational strategies. The proposed framework creates an optimal charging schedule for each EV user, which helps to stabilize the grid and improve its reliability and energy efficiency, while maximizing the profit of EV users [40]. Alicia Triviño-Cabrera et al. proposed a mathematical framework based on a mixed integer linear programming problem, with the objective of maximizing the revenue of EV users. Finally, the method was validated using an IEEE-37 node test feeder, which showed that the method provides maximum economic benefits to EV users, while improving the operation of the grid [41]. Mehrdad Ebrahimi et al. proposed a new stochastic day-ahead residential charging model with the objective of minimizing the expected customer charging costs, including the cost of electrical energy and the cost of battery aging, while satisfying the customer service quality constraints, and the results showed that the model maximized the benefits to EV users [42]. Ma Yongxiang et al. proposed a master–slave game pricing strategy that considers the economic benefits of both the virtual power plant and the EV users and, then, studied and analyzed the results through arithmetic examples. The results show that the method can smooth the load fluctuation of the grid well, reduce the peak-to-valley difference of the load at the same time, and maximize the economic benefits for the users participating in the V2G service [43].

(5) Aggregator Revenue Maximization

Aggregator revenue maximization is one of the key objectives in some V2G control strategies. By effectively managing and optimizing the charging and discharging behavior of EVs, aggregators can maximize their revenue. Samy Faddel et al. proposed an algorithm to optimize the bidirectional V2G technology operation uncertainty of an EV aggregator. The proposed algorithm maximizes the profit of the aggregator, while providing EV users with lower charging costs. The final simulation results show that this algorithm not only generates maximized profits, but also reduces the battery degradation cost of EVs to help extend their lifetime [44]. Benedikt Tepe et al. proposed that the aggregator can group EVs into different groups based on their power and energy capacity profiles instead of randomly combining them before trading the energy and finally providing balanced power, for example, on the Central European Frequency Containment Reserve Market, as well as energy arbitrage trading on the European Power Exchange intraday continuous and day-ahead auction spot markets, using these examples to analyze the feasibility of the scheme, which shows that by intelligently grouping EVs, aggregators can increase the revenue per vehicle in the market by up to seven times compared to randomly grouped EVs [45]. Dai Zhaohua et al. proposed an EV charging and discharging optimization strategy from the perspective of a supply and demand side game that combines users' charging and discharging habits and established an EV charging and discharging optimization model based on the relationship between the supply and demand side game, with the objectives of maximizing the aggregator's revenue and minimizing the EV users' electricity consumption costs. Finally, a simulation was conducted to solve the problem, and the results show that the proposed charging and discharging strategy can cause the charging and discharging loads of EVs to play the role of peak shaving and valley filling in the base load curve, reduce the charging and discharging costs of EV users by 40.4%, and increase the revenue of the aggregator by approximately 40.1% [46].

5. Cutting-Edge V2G Application Research

With the rapid development of the energy transition, an increasing amount of cutting-edge research is being conducted to expand the application areas of V2G technology. As an energy management technology with great application potential, V2G technology not only improves the stability of grid operation, but also promises to realize a wider range of applications in more fields.

5.1. Research Prospects of Commercial EVs in Regard to V2G Technology

Although in recent years most V2G applications have focused on private EVs, an increasing number of researchers have started to explore the possibility of including commercial EVs in V2G applications. Commercial EVs mainly refer to commercial vehicles, such as EV taxis and buses, which usually have larger battery capacities and more frequent charging cycles and, thus, can provide more electricity for grid services. Ren Feng et al. proposed the strategy of calling electric taxi vehicles for peak shaving and valley filling, using the K-means algorithm to determine the most suitable electric taxi clusters to be called in a certain region. Based on demand response tariffs, a revenue model of electric taxis involving the combined effect of the conventional operation mode and V2G mode was established, and the final simulation results showed that the strategy can not only achieve a better peak shaving effect, but also achieve better returns [47]. Jonatas Augusto Manzolli et al. conducted a case study using real data from a small electric bus fleet consisting of 11 electric buses in a medium-sized city in Portugal to validate the feasibility of bus participation in the V2G system, and the results show that with a battery replacement cost threshold below 100 V/kWh, it may be economically attractive for public transport operators to sell electricity to the grid for a given remuneration package. Considering battery degradation and electricity sales, operating costs can be reduced by 38% by 2030 [48].

5.2. Research Prospects of EVs as Emergency Power Supplies

After years of development and research, EVs can not only provide electricity services in the V2G mode, but also have many other applications. The charging and discharging behaviors of EVs can be flexibly adjusted according to market demand. In emergency situations, EVs can also serve as a backup power source to provide emergency power support. Hu Siyang et al., based on EV V2G technology and considering the discharge capacity of EVs and using them as an auxiliary power source in conjunction with emergency power supply vehicles, quickly restored lost loads, which effectively reduced the loss of power, while having the advantages of good flexibility and being able to reduce the cost of configuring traditional emergency energy sources, such as emergency energy storage and emergency power supply vehicles; additionally, they proposed an optimization strategy for the restoration of the power supply based on V2G technology. The final simulation results verify the feasibility of the proposed method [49]. Yang Qiming et al. proposed an urban distribution network resilience enhancement strategy based on vehicle-to-grid (V2G) technology to enhance the ability of urban power grids to cope with typhoon disasters, which involves using EVs as an emergency power source to supply areas affected by power outages caused by typhoon disasters [50]. However, these two methods have not been practically applied to verify their feasibility and reliability and are biased toward idealization.

5.3. Research Prospects of New Energy Trading Models in the Context of V2G Technology

With the development of EVs and V2G technology, researchers are exploring new energy trading models to achieve more efficient and sustainable energy use. Xiuli Wang et al. proposed a model in which EV users can share and trade surplus electricity through V2G technology. Simulation experiments were carried out, and the results show that the proposed electric power trading model can achieve a win-win situation for both trading parties [51]. Liu et al. proposed a model for a localized vehicle-to-vehicle energy trading system based on a federated blockchain. This system allows EV users to exchange electrical energy in a V2G network. The proposed model employs a new secondary double auction mechanism to determine the trading price [52]. This method determines the transactions between EV users. This reduces the management cost of the grid and eases the pressure on grid operation by enabling direct charging of EVs from the grid. This, in turn, increases the pressure on grid operation. Although these methods are still at the theoretical stage, they are expected to play an important role as technology progresses and the market develops. These research results provide strong support for future diversified applications of EVs in the V2G mode.

6. Challenges Faced

V2G technology is an emerging and disruptive innovation in the rapidly evolving energy sector. It is widely recognised as one of the key pathways involved in the energy transition. V2G technology transforms EV users from mere consumers to active participants in the energy system, bringing new flexibility and sustainability to the energy system. However, its practical application faces many challenges. The following section will address the challenges associated with V2G technology and provide corresponding solutions.

6.1. Willingness of EV Users to Participate

V2G technology is a promising means of energy management that has attracted much attention. However, its successful application depends on the active participation and cooperation of EV users. Although V2G technology offers many potential economic benefits to users, their willingness to participate is affected by various factors. Joachim Geske et al. conducted a survey of EV users in Germany. The results showed that 'mileage anxiety' and 'minimum range' are important factors that affect EV users' willingness to participate in V2G programs. If these problems can be solved, the EV user participation rate can be high, even without a reward for participation [53]. Bing Huang et al. explored the factors affecting the willingness of EV users to participate in V2G programs in the Netherlands. The study revealed that EV users in the Netherlands are generally unwilling to participate in V2G programs due to their concerns about the minimum battery level of their EVs after participating in V2G. Fast charging technology is preferred over normal charging due to the speed [54]. Mileage anxiety remains a significant challenge in the application of V2G technology. Users may be concerned about consuming too much battery power during the V2G process, which could result in insufficient vehicle range. This could lead to the embarrassment of having no power available when they need to use the vehicle themselves. Therefore, a larger battery capacity or faster charging technology could be helpful for the application of V2G programs.

6.2. Battery Depletion

Battery depletion is a significant challenge in V2G applications. Frequent charging and discharging cycles accelerate the aging of batteries and reduce their capacity and performance. Justin D.K. Bishop et al. evaluated the impact of V2G services on EV batteries. The results of the study showed that the battery capacity of EVs participating in V2G services degrades at an accelerated rate [55]. Yan Xiaoyu et al. investigated the causes of capacity degradation of lithium ion batteries and showed that the charging and discharging power and the number of battery cycles are responsible for the capacity degradation of lithium ion batteries [56]. Uddin K et al., in their paper, argued that the current V2G pilot study, which employs a simplistic approach to online charging and discharging of EVs, is economically unfeasible. This is due to the frequent charging and discharging of EVs, which accelerates battery degradation, reduces battery life, and results in additional economic losses for EV users [57].

V2G participation accelerates the degradation of EV battery capacity, which inevitably has many negative impacts on users. First, a shorter battery life means that batteries need to be replaced and maintained more frequently, which can cause some economic loss to users and increase operating costs, and economic loss is also an important consideration, as more time and money need to be spent on battery maintenance. Second, the reduced range affects the convenience of using the vehicle and the user experience. Finally, the problem of the disposal of used batteries may increase, which will undoubtedly put some pressure on the need to protect the environment. Ali Ahmadian et al. studied the cost effectiveness of battery degradation in EVs in V2G mode and developed a comprehensive model of the effect of a charging/discharging strategy on vehicle battery pack degradation, and the simulation results showed that V2G implementation without battery degradation is economical [58]. Shubham Bhoir et al. developed a battery model to estimate battery degradation in EVs while participating in the V2G system. They conducted a case study to evaluate the expected profit of participating in the V2G system and calculated the cost of EV degradation for EVs with and without V2G service participation. This provides EV users with a reference to consider when participating in V2G services [59]. Haris M. Khalid et al., for the problem of battery capacity degradation due to cyclic charging and discharging of batteries, proposed a regression method based on the median expectation for parameter estimation of vehicle batteries in a V2G system and, finally, validated it using the D-SAT Chroma 8000ATS hardware platform (Chroma ATE Inc., Taoyuan, Taiwan), and the results showed that the method can accurately estimate battery dynamics [60]. The timely detection of the state of the battery helps EV users develop better countermeasures, which in turn reduces battery loss. In the face of an increasing number of retired EV batteries, Zhou Ruifeng proposed that retired batteries be given new energy sources as energy storage batteries, which is a secondary use of EV batteries [61].

6.3. Optimizing Charging and Discharging Tariffs for V2G Systems

Electric vehicle (EV) users participate in vehicle-to-grid (V2G) programs to sell the electricity stored in their EV batteries to the grid or other parties when there is demand, generating revenue. For example, during peak electricity consumption, EV users can sell electricity to the grid at a higher price than usual and recharge the battery at a lower price when the peak is over. Therefore, it is necessary to set reasonable charging and discharging tariffs to guide more EV users to participate in the V2G system, which is one of the challenges in current V2G applications. Tan Zefu et al. noted that domestic static time-sharing tariffs or ladder tariffs are relatively homogeneous, and most studies on tariffs aim to stabilize charging loads as the primary purpose [62]. However, such studies lack tariff divisions that take into account the sense of participation of EV users, and there are fewer dedicated time-sharing tariff schemes that include EV users' charging and discharging behaviors. In contrast, research on charging and discharging tariffs for EVs participating in the V2G system in Europe and the United States is more diverse, with more flexible pricing strategies for charging and discharging in the United States, including critical peak pricing, peak time rebates, and real-time pricing, while Europe focuses on meter-based pricing intelligence [63]. From the above, it can be seen that Europe and the United States have more diverse and flexible schemes for electricity pricing, while the domestic ones are more homogeneous, so this provides a reference for the further development of the V2G system in China.

6.4. Privacy Protection

Privacy protection in regard to V2G technology aims to prevent the leakage or misuse of EV users' personal information. As EVs become more popular and V2G technology develops, users' charging and travel data may contain sensitive information, such as travel routes and charging habits. Therefore, it is crucial to adopt effective privacy protection measures. Chen Fuan et al. proposed a blockchain-based certificate-less ring signing confidential privacy protection scheme to achieve the privacy protection of transaction information for vehicle users and the secure transmission of communication messages in V2G systems. The scheme uses ring signing confidentiality technology to ensure the anonymity of vehicle users in the service process and the authenticity and integrity of data transmission [64]. Huberjee et al. proposed a multifunctional privacy-preserving data aggregation scheme for V2G networks in response to the problem that the current privacy-preserving data aggregation schemes are not functional enough to meet the demands of increasingly rich applications [65]. To prevent EVs from being tracked by their IP addresses, Mahmoud Hashem Eiza et al. proposed an efficient, secure, and privacy-preserving proxy mobile Ipv6 (ESP-PMIPv6) protocol for protecting mobile IP communications in V2G networks [66]. Shubhani Aggarwal et al. suggested an efficient blockchain-based authentication scheme for energy transactions in V2G networks to address security issues during energy transactions between EVs and charging stations [67].

In summary, privacy protection in terms of V2G technology is crucial because it involves not only the protection of personal private information, but also the security and trustworthiness of the V2G system. At present, various privacy protection schemes based on blockchain, cryptography, and security protocols are emerging, which provide an effective guarantee of the safe operation of V2G systems. With the continuous progress and improvement of technology, privacy protection in the V2G field will be further strengthened to protect the interests of users and systems.

6.5. Power Loss

The occurrence of power losses during V2G applications is an important consideration. Such losses can occur at multiple points, such as conversion losses during EV charging and discharging, transmission losses during grid transmission, and conversion and control losses in V2G systems. These losses not only affect the efficiency of energy utilization, but also may increase system operating costs and exacerbate environmental impacts. Therefore, reducing power losses during V2G applications is one of the keys to improving system efficiency and sustainability. Yosef A. Shirazi et al. studied the problem of power losses during V2G operation and noted that the current studies on V2G technology applications have not sufficiently considered the problem of power losses, they also stated that existing analyses of V2G operating costs greatly underestimate the operating costs. In the end, they called on researchers to seriously consider the problem of power loss in future studies [68]. Therefore, it is important to fully consider the power loss generated during V2G operation for efficient and sustainable system operation. The study of power loss will provide strong guidance for the further development of V2G technology.

7. Research Prospects and Summary

It is anticipated that research in areas related to V2G applications will be a popular topic. This paper summarizes the current research status of V2G technology, including the definition of V2G, its implementation, the social benefits, the economic benefits, cutting-edge application areas, the challenges, and future research directions. An extensive review of the social and economic benefits of V2G technology is presented, as well as cutting-edge V2G applications that have received little attention in the literature reviewed to date. Compared to ordered charging and unordered charging, V2G technology not only has significant social benefits in terms of grid demand response, personalized charging, and coordinated renewable energy, but also has significant economic benefits for the grid, aggregators, and individuals, and this paper discusses the social and economic benefits of V2G in detail. Meanwhile, V2G technology has a wide and innovative application prospect in regard to commercial EVs, emergency power supply, and new energy trading models. However, V2G technology still faces challenges, such as EV users' willingness to participate, battery loss, optimizing V2G charging and discharging tariffs, privacy protection, and power loss. Future research needs to focus on how to solve these problems. Finally, four research directions are proposed, namely: battery performance degradation, the stepwise utilization of retired batteries, integration with renewable energy sources, and policy. Some of the current research in these directions is presented.

With the advancement of the energy transition and the rapid popularization of EVs, V2G technology has attracted much attention as an emerging energy management solution. The concept has triggered new thinking about energy management, transforming EVs into dynamic energy resources, which is expected to revolutionize the energy system. Although the current research on V2G technology has made considerable progress, and various countries have conducted V2G pilot projects to explore the feasibility of V2G technology, there are still a number of challenges to achieve the great potential of V2G technology and realize large-scale commercial applications. In this regard, the following suggestions are made in the hope that they can provide some reference and inspiration for research in related fields:

1. Battery performance degradation: EVs involved in the V2G process will experience frequent charging and discharging for a long period of time, and the increase in charging cycles will lead to an increase in the internal resistance of the battery, which in turn will exacerbate the rate of capacity degradation. For EVs with built-in battery packs, which are equipped with preset optimal charging voltages, it is necessary to limit the discharge current for each operation to prevent overcharging and discharging in order to avoid negative impacts on the battery pack. In the V2G process, injecting (or withdrawing) high peak currents from EV batteries can also shorten the battery life [55,69]. Battery degradation leads to a reduction in battery capacity and a decrease

in charging efficiency, which in turn further increases the number of battery recharges and charging time, which can diminish the ease of use and increase the cost of using EVs [70]. Therefore, the need to predict the health status of EV batteries and take timely measures to optimize the tram charging and discharging strategies will be an important direction for future research. For example, Xiong, R et al. developed an effective health indicator to indicate the health status of lithium ion batteries, as well as a moving window-based approach to predict the remaining lifetime of the battery [71].

2. The stepwise utilization of retired batteries: With the rapid growth in the number of EVs and the development of V2G technology, more and more EVs will be involved in the V2G system in the future, which will produce a large number of retired EV batteries, which is also a problem yet to be solved. The step-by-step utilization of retired batteries is also a hot topic for future research, and the step-by-step utilization of large-scale retired batteries can be solved, which has enormous economic and social benefits. For example, decommissioned batteries can be used as energy storage for power grids or as power supply batteries for 5G base stations to fully utilize the value of decommissioned batteries [72]. They can also be used as storage batteries for renewable energy. In 2014, Nissan developed the retired batteries of 16 Nissan LEAF EVs into a large-scale battery system for reuse, which was used to verify the power output smoothing effect of photovoltaic power generation [73].
3. The deep integration of V2G technology with renewable energy sources: The inherent randomness and volatility of renewable energy sources (wind energy, photovoltaic energy, etc.) make their efficient utilization a major challenge. According to the news released by China's New Energy Consumption Monitoring and Early Warning Center, in February 2024, China's wind power utilization rate was 93.7% and photovoltaic power utilization rate was 93.4% [74]. This means that a large amount of electricity is wasted, and V2G technology can provide a flexible energy storage and regulation mechanism, using EVs as an energy storage device, and utilizing V2G technology to store excess renewable energy in the battery of EVs and then releasing it to the grid when needed, which can improve the level of renewable energy consumption and avoid the waste of renewable energy. It has been pointed out that EVs consuming renewable energy through V2G technology is the most suitable solution to the problem of renewable energy fluctuation [75]. This can improve the level of renewable energy consumption by optimizing the charging and discharging strategies of EVs in the V2G system and achieving intelligent scheduling of EV charging and discharging [76,77].
4. Introducing sound policies to support the development of V2G technology. In addition to technological research, government policy is also an important part of ensuring the steady development of V2G technology. For individuals, a sound V2G policy can protect the rights and interests of individual EV users, and financial support and incentives can attract more EV users to participate in the V2G system. For enterprises, a sound V2G policy can provide market access protection and stabilize commercial operations, and increased financial subsidies are conducive to encouraging the motivation of enterprises in this direction. Policy makers can adjust taxes, formulate V2G technology standards and specifications, provide financial support, and other policies to promote the development and application of V2G technology [78]. The state of California in the United States has introduced the California EVs and Grid Synergy Roadmap—Electric Vehicles as a grid resource to provide comprehensive guarantees for vehicle–grid interactions in terms of business models, policy support, and technical standards. Countries such as the UK and Japan also support multiple V2G projects through grants and adopt policies, such as high subsidies and tax incentives to accelerate the commercialization of demonstration projects [79]. China, as the country with the largest number of EVs in the world, also introduced the New Energy Vehicle Industry Development Plan (2021–2035) in 2020 to encourage the enhancement of EVs' energy interactions with the power grid [80].

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