Research on Vehicle to Grid Strategy of Multi-objective Optimization: A Case Study of Jiangsu Province

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Abstract. In pursuit of the 'carbon peaking and carbon neutrality' objectives and the imperatives of high-quality economic development, the energy system is undergoing a profound shift towards green and low-carbon solutions. Vehicle-network interaction offers the potential for adaptable synergy between energy supply and demand, aligning with the inherent requirements of new energy system development. This strategy aims to achieve efficient allocation of grid resources, provide cost-effective and convenient charging options for vehicle owners, and transform the relationship between electricity consumption and power supply from a traditional separation to a mutually beneficial symbiotic association. In this paper, we employ a multi-objective optimization model and non-cooperative tripartite game model, utilizing load data from Jiangsu Province, to evaluate pricing strategies that can foster a win-win scenario for grid operators and charging users in various conditions. Ultimately, it is found that vehicle-grid interaction not only plays a positive role in the energy transition of electric vehicles, but also expands the value space of electric vehicles, promotes a win-win situation for power grids, operators, and users, and promotes the interconnection of different subjects to realize integrated development.

Keywords: Vehicle to grid; Multi-objective optimization; non-cooperative tripartite game model; Price strategy

1 Introduction

As a significant energy-consuming nation, China is currently experiencing a profound shift towards a greener and lower-carbon energy system. However, as the low-carbon energy industry reaches a certain scale of development, the existing energy infrastructure faces challenges in adapting to the widespread adoption of low-carbon energy production and utilization methods [1]. A crucial challenge in energy transformation is how the future power-centric energy system can effectively accommodate a substantial share of variable renewable energy generation on the supply side while simultaneously addressing the high-demand uncertainties associated with electric vehicle (EV) charging on the demand side. Resolving this structural contradiction is paramount to achieving a successful energy transformation.

Vehicle-to-grid (V2G) represents a crucial transformative pathway, uniting electric vehicles and the power grid that were originally separate entities, and harmonizing the previously distinct realms of electricity consumption and power supply into a mutually beneficial and symbiotic relationship [2]. Technically, V2G capitalizes on the scheduled charging capabilities and

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substantial battery storage of electric vehicles to meet their energy requirements while collaborating with the broader power system. This approach reduces energy consumption during peak hours, enhances power supply utilization during off-peak periods, and mitigates the erratic impact of random charging demands on the power grid. By guiding electric vehicles to align with the operational principles of the power grid, realizing the ideal V2G model can substantially mitigate the challenges posed by renewable energy generation fluctuations and the unpredictable nature of electric vehicle charging demand. It resolves the structural imbalances in matching supply and demand within the emerging power system, effectively transforming these challenges into historic opportunities to expand the value of low-carbon energy technology utilization and to establish a pioneering power system.

Vehicle-to-grid (V2G) is poised to transform electric vehicles from mere transportation tools into versatile loads and energy storage units for the power grid. It accomplishes this by generating additional output beyond the conventional energy system, all while mitigating its own impact on the power grid. This innovation paves the way for a mutually beneficial outcome for the power grid, charging operators, and electric vehicle users. For power grid companies, V2G enables the shifting of charging demand from peak electricity consumption periods to off-peak nighttime hours, effectively alleviating grid peak pressures [9]. Electric vehicle users benefit from time-based tariffs that offer more flexibility in charging options and reduced costs when charging during off-peak hours [10]. Charging operators, incentivized by service fees and policy subsidies, continually optimize their regulatory efforts, enhancing the efficiency of charging infrastructure and expediting cost recovery. In this context, a multi-objective optimization model is constructed to simulate the impact of V2G optimization on the power system's load profile and revenue for multiple stakeholders. The model aims to maximize the multi-objective revenue for grid enterprises, charging station operators, and charging users.

The charging cost for users can be categorized into two components: the charging service fee and the power procurement cost. The power procurement cost can be further broken down into capacity costs (comprising transmission and distribution costs), electricity costs, and the grid's profit margin [4]. Leveraging vehicle-to-grid interaction for organized charging helps alleviate grid strain during peak hours, subsequently reducing the demand for distribution grid capacity and, by extension, the associated capacity costs. Additionally, electricity procurement costs in the wholesale electricity market fluctuate across different time periods. The use of organized charging can steer charging loads away from times with higher power procurement costs, thus lowering the expenses incurred by the grid operator for power purchases. The reduction in capacity and electricity costs creates a favorable environment for all stakeholders involved, including the grid, charging operators, and charging users. With appropriate pricing strategies, it becomes feasible to increase charging service fees and enhance the grid's profitability while simultaneously reducing the charging costs for users.

2 Models and Data

2.1 General non-cooperative game model

The multi-objective optimization model serves as a tool for assessing pricing strategies capable of achieving mutually beneficial outcomes for the grid, operators, and charging users in diverse scenarios. At its core, the multi-objective optimization model aims to simulate the optimal scheduling approach for the power system, accommodating extensive electric vehicle charging demand while maximizing revenue for the grid, operators, and users throughout the study period. This modeling approach also places emphasis on maintaining a balance between power supply and demand while ensuring the feasibility of the technical infrastructure [6].

In the vehicle to grid model, there are three types of subjects considered: the power grid, charging pile operators, and charging users. The multi-objective optimization model can portray the impact of different subjects' revenue priority on the grid load and the total revenue of multiple subjects [7].

Grid company model. Specifically, the grid company's revenue changes come from the following parts: a. Revenue from electricity sales: after adjusting the time-sharing tariff, there are differences in the price and amount of electricity sold by the grid company at different times, and therefore the revenue from electricity sales will change. b. Cost of purchasing electricity: in accordance with the model of the grid company's agency for purchasing electricity, the change in the amount of electricity purchased and the cost of electricity purchased at different points in time after adopting orderly charging will be different, and therefore will cause gains or losses. c. Capacity tariff: the adjustment of charging behavior by users and operators will lead to the adjustment of the maximum demand for capacity, thus affecting the capacity tariff revenue. d. Grid capacity cost: through orderly charging, the peak hour load can be reduced, so the capacity cost of the grid will be adjusted accordingly. The grid load and charging load data in this paper are from the typical day load data of July 2022 in Jiangsu Province, China. The revenue of the grid company can be portrayed by equation (1):

$$R_G=\sum_t\left(p_{gs,t}^{opt}e_{charge,t}^{opt}-p_{gs,t}^{ini}e_{charge,t}^{ini}\right)-\sum_t\left(p_{gb,t}^{opt}e_{charge,t}^{opt}-p_{gb,t}^{ini}e_{charge,t}^{ini}\right)+\left(Cap_{op}^{opt}-Cap_{op}^{ini}\right)p_{cap}-\left(Cap_{g}^{opt}-Cap_{g}^{ini}\right)C_{cap} \quad (1)$$

where R_G is the revenue of the grid company, $p_{gs,t}^{ini}$ and $p_{gs,t}^{opt}$ are the unit price of electricity sold before and after optimization, $e_{charge,t}^{ini}$ and $e_{charge,t}^{opt}$ are the amount of electricity traded before and after optimization, Cap_{op}^{ini} and Cap_{op}^{opt} are the size of the operator's capacity before and after optimization, p_{cap} is the unit capacity charge, and Cap_{g}^{ini} and Cap_{g}^{opt} are the size of the grid capacity before and after optimization, respectively. And C_{cap} is the unit grid capacity cost.

Charging operator model. Revenue changes of charging operators come from the following components: a. Revenue from charging service fee adjustment: by adopting time-sharing service fee, it will affect the service fee revenue at different times. b. Charging station capacity electricity fee: by adopting orderly charging, the maximum demand of the charging station capacity changes, which affects the expenditure of capacity electricity fee accordingly. c. Charging station capacity electricity fee: by adopting orderly charging, the maximum demand of the charging station capacity changes, which affects the expenditure of capacity electricity fee accordingly. The charging operator revenue change can be portrayed by equation (2):

$$R_{Op}=-\left(Cap_{op}^{opt}-Cap_{op}^{ini}\right)p_{cap}+\sum_t\left(p_{ser,t}^{opt}e_{charge,t}^{opt}-p_{ser,t}^{ini}e_{charge,t}^{ini}\right) \quad (2)$$

Where $\mathrm{R_{Op}}$ is the revenue of the charging operator, $p_{ser,t}^{ini}$ and $p_{ser,t}^{opt}$ are the unit price of the service charge before and after optimization.

Charging user model. The change in the user's revenue mainly comes from the change in the charging tariff, which consists of the grid's electricity sales tariff and the operator's service charge. Therefore, the change of user's revenue can be portrayed by equation (3):

$$R_{EV}=-\sum_{t}\left(p_{ser,t}^{opt}e_{charge,t}^{opt}-p_{ser,t}^{ini}e_{charge,t}^{ini}\right)-\sum_{t}\left(p_{gs,t}^{opt}e_{charge,t}^{opt}-p_{gs,t}^{ini}e_{charge,t}^{ini}\right) \tag{3}$$

Considering that ordered charging is Pareto-improved, i.e., while performing ordered charging, each subject should gain more than the initial gain. Therefore, constraints should be added when performing multi-objective optimization: $R_G\geq 0;\ R_{Op}\geq 0;\ R_{EV}\geq 0\ \text{and}\ \sum_a w_a R_a \geq 0.$

2.2 Multi-objective optimization model

The multi-objective function and constraints of the problem can be summarized as shown in equation (4) and (5):

$$\boldsymbol{max}\ R=(R_G,R_{Op},R_{EV}) \tag{4}$$

$$s.t.\ \ R_G\geq 0;\ R_{Op}\geq 0;\ R_{EV}\geq 0 \tag{5}$$

A multi-objective optimization model is established to maximize the comprehensive efficiency of charging price as much as possible for the benefit of grid companies, charging operators and users [8]. We use the linear weighting method for model solving to transform the multi-objective optimization model into a comprehensive objective for optimization based on the priority of each objective. The method converts the multiple objectives into a single-objective optimization problem by representing them as the objective function of the model as shown in equation (6):

$$\boldsymbol{max}\sum_{a} w_a R_a \tag{6}$$

Where R denotes the benefits of each type of subject, w is the empowerment of a certain type of subject in the multi-objective optimization process, and a is the type of subject. The specific weights are set for four scenarios: equal weight, grid company priority, charging operator priority and user priority.

Since the capacity cost data is not published, but the capacity tariff is distinguished from the electricity tariff in the two-part transmission and distribution tariff. Therefore, the capacity tariff calculated by Jiangsu 1-10 (20) kV demand is selected here as the capacity cost of the grid, which takes the value of RMB 51.2/kW-month. In addition, considering the differences in the load characteristics of different users in the power system, the simultaneous rates of different users also need to be taken into account when considering the capacity cost. Therefore, referring to the results of the calculation of the simultaneous rate of users, the average value of the simultaneous rate of different users is taken as 0.7 as the basis for the calculation [3]. Therefore, the capacity cost of the grid is finally 51.2/0.7 = 73.14 Yuan/kW-month. For the power purchase cost, there is no actual data available on the wholesale market for medium- and long-term transactions versus spot transactions. Therefore, the time-of-use tariff minus the purchase and sale price differential is chosen as a proxy variable for the power purchase cost. The power purchase price difference is calculated by referring to the average purchase and sale price difference of RMB 207.98/kWh in Jiangsu Province in the Electricity Price Regulation Bulletin issued by the Energy Bureau. The initial charging operator service fee is chosen as the measurement benchmark, which is currently RMB 0.3/kWh in Jiangsu Province.

To ensure the prioritization of benefits among various stakeholders, distinct weights are assigned to each subject to assess the achievement of a mutually beneficial outcome for the grid, operators, and users while maximizing their respective benefits. If equal weights are applied, with w set at 1/3, the value of each party's gain, denoted as $w_a R_a$, can be determined. In instances where equal weights are not employed and different priorities are established for individual subjects, the weight (w) is readjusted to ascertain the value of each party's profit [5].

2.3 Solve the non-cooperative tripartite game model

Establishment of non-cooperative tripartite game model. In the three-party game model of users, power grid companies and operators, the participants of the game have individual rationality, and when each participant reaches its own relative optimal decision under the strategy combination given by other participants, the game reaches equilibrium. The model is shown in equation (7):

$$\begin{cases} p_G = arg\, max R_G \\ p_{op} = arg\, max R_{op} \\ p_{EV} = arg\, max R_{EV} \end{cases} \tag{7}$$

Where p_G is the electricity price vector updated by the power grid company in each period. p_{op} is the electricity price vector updated by charging operators at different periods. p_{EV} is the electricity price vector of the client for each period.

Analysis of solving process of non-cooperative tripartite game model. (1) Given the particle swarm size N_p, the maximum number of iterations k_{max}, the inertia weight ω and the acceleration factor e in the formula are updated, and the accuracy requirement is set to ε. (2) For each particle, the power grid company strategy p_G is randomly generated, and the particles p_{op} and p_{EV} are randomly generated according to p_G, thus forming the solution $X' = (p_G, p_{op}, p_{EV})$ of each particle.

The algorithm flow chart is shown in **Figure 1**.

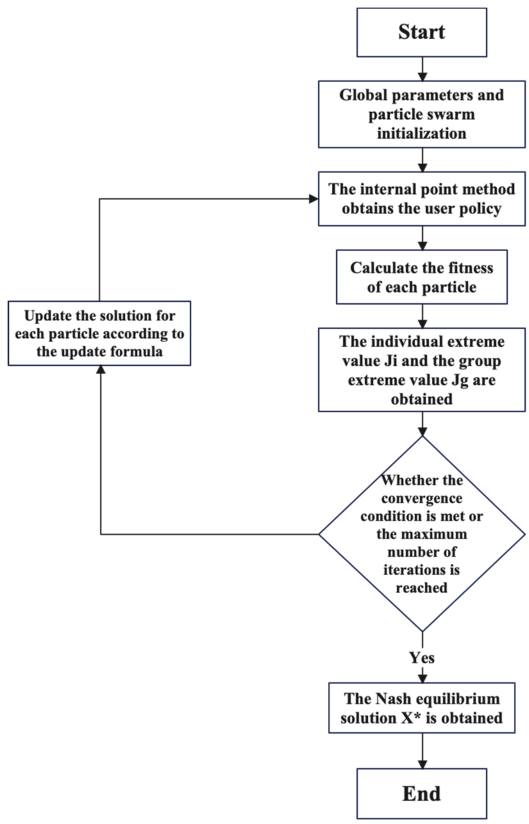

Fig. 1. Flow chart of solving non-cooperative tri-party game model

3 Results

Figure 2 shows the EV charging load curves optimized with different subjects' revenue priority as the objective. From the figure, it can be seen that the EV charging loads under different subject revenue priority scenarios are reduced from 8:00 to 21:00, and at the same time, the loads are shifted to the night time from 22:00 to the next day at 6:00 p.m. Corresponding to the grid load curves in **Figure 3**, the charging loads do not have a significant impact on grid loads because of the current small stock of EVs, but with the growth of the EV stock year by year, the peak charging loads will have a great pressure on the evening peak power balance of the power system in 2030. The evening peak power balance of the power system is under great pressure. the daily load peak-to-valley difference in 2030 under the initial disordered charging scenario is about 30,000 MW, which accounts for up to 26% of the maximum load. The multi-objective optimization model shows that vehicle to grid interaction can reduce the peak-to-valley difference of the grid, reduce the load peak-to-trough scheduling and operating cost pressure on the grid, and play a significant role in shaving peaks and filling valleys and smoothing the load profile.

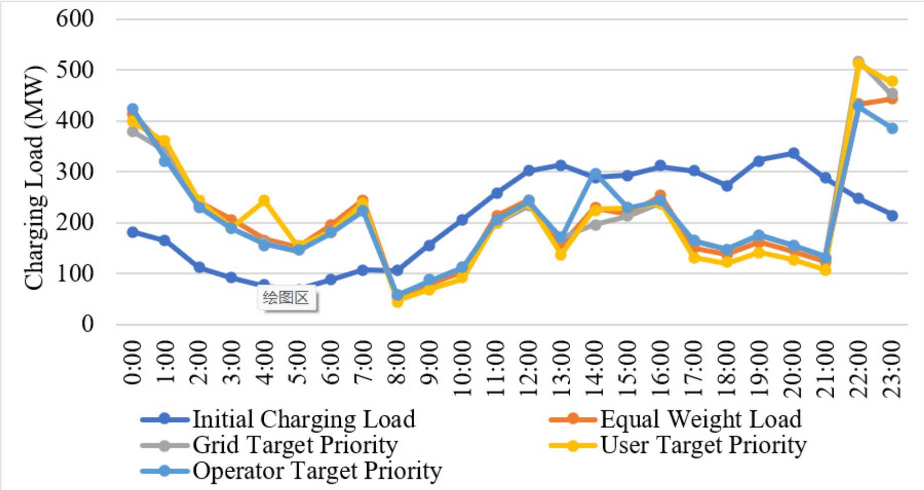

Fig. 2. The effect of prioritizing from different subjects on charging loads.

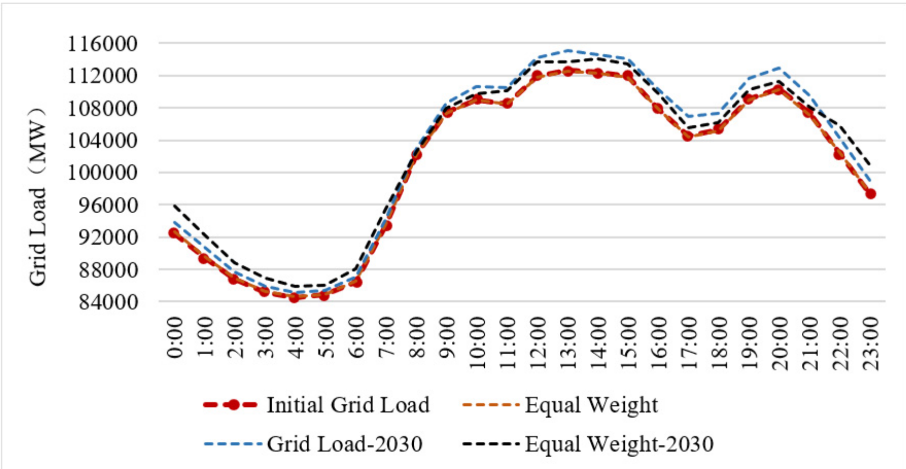

Fig. 3. Comparison of initial grid load curves for equal weighted scenarios.

EV vehicle to grid interaction can not only smooth out the peak-to-valley difference of the power system, but also bring about an increase in the revenues of multiple parties, including power grid enterprises, operators, and EV users. In this part, the impact of the priority of the revenues of different subjects on the revenues of all parties of the vehicle to grid interaction is quantitatively evaluated through four scenarios, and the results of the simulation are shown in **Table 1**. The vehicle to grid interaction model realizes peak shaving and valley filling, which implies the reduction of power system operation cost. In the scenario with equal weights assigned, the primary sources of benefits for the grid stem from savings in power purchase costs, augmented capacity tariff revenues, and a delay in the necessity for capacity expansion. Despite the grid's operational cost amounting to 0.73 million yuan, when accounting for the offsetting of other sources of benefit, the total net benefit for the grid amounts to 0.2 million yuan by the end of the day, thereby fostering the development of the grid. In the grid-prioritized scenario, the grid can gain 0.68 million yuan by saving power purchase cost, increasing capacity tariff revenue, and delaying capacity expansion demand, which is an increase of 0.48 million yuan compared to the equal-weighted scenario gain. The charging operator gains revenue through charging service fees, but due to the adoption of the orderly charging strategy, the demand for charging station capacity will increase, and the charging operator will increase capacity tariff expenses accordingly. In the Equal Weight Scenario, for example, the service charge is increased from an average of 0.3 yuan/kWh to an average of 0.41 yuan/kWh, and after deducting the capacity charge, the operator's total revenue can still be up to 0.2 million yuan. In the Operator Priority Scenario, the operator gain is 3.4 times that of the Equal Weight Scenario. EV users adjust their charging time according to the time-of-use tariff and choose to charge during the low tariff hours, thus saving charging costs. In the equal-weighted scenario, for example, the average price of the total charging cost is adjusted from 1.04 yuan/kWh to 1.14 yuan/kWh, but the total cost in the trough time is only 0.56 yuan/kWh, so more users will choose to charge at this time, and the overall EV users gain 0.34 million yuan. If the user is prioritized, it can be calculated that the user's total revenue reaches 0.83 million yuan, which is about 2.43 times of the user's revenue under the equal weight scenario, and the above scenarios can be synthesized to find that there is a large profit margin for all three parties, and there is the potential to achieve a win-win situation for all parties.

Table 1. Changes in returns for different subjects in different scenarios.

Scenarios (Yuan)	Equal Weight	Grid Target Priority	User Target Priority	Operator Target Priority
Total grid revenue	200589.14	680846.91	0.02	65.06
Operator revenue	200567.88	30.70	679206.38	85.20
User revenue	340923.67	247.91	1517.78	827777.29
Grid revenue - Electricity Sales	-725243.75	-310749.35	-835751.42	-1127262.58
Grid revenue - Electricity Purchase	360013.81	331836.71	331662.77	399870.00
Grid revenue - Capacity Charge	183752.19	310470.74	155027.25	299400.09
Grid revenue - Grid capacity	382066.88	349288.82	349061.42	428057.55
Operator revenue - Capacity Charge	-183752.19	-310470.74	-155027.25	-299400.09
Operator revenue - Service Fee	384320.07	310501.44	834233.64	299485.30

The above analysis shows that EV participation in vehicle to grid interaction has considerable techno-economic potential for increasing power system flexibility in the future. Although the infrastructure construction cost and policy incentive cost required to invest in EV vehicle to grid interaction are higher than the current unorganized charging mode, the vehicle to grid interaction mode has significant advantages in terms of saving power purchase cost from the grid and delaying the demand for grid capacity expansion, and the grid company can thus reap the benefits. Through the adjustment of time-sharing tariffs and service fees, the grid's reduced revenue from power sales is transferred to charging operators and users, realizing the increase in operators' service fees and savings in users' charging costs, and realizing a win-win situation for all parties.

4 Conclusions

The multi-objective optimization model in this paper shows that EV participation in vehicle to grid interaction has considerable techno-economic potential for increasing power system flexibility in the future. Although the cost of infrastructure construction and policy incentives to be invested in EV vehicle-to-grid interaction is higher than the current disordered charging mode, the vehicle-to-grid interaction mode has significant advantages in saving power purchase cost from the grid and delaying the demand for grid capacity expansion, and the grid company can gain benefits as a result. Through time-sharing tariffs and service fee adjustments, the grid's reduced power sales revenue is transferred to charging operators and users, and operators' service fees increase while users save on charging costs. Vehicle to grid interaction will expand the electric vehicle from transportation to the grid's flexible load and energy storage unit, in solving its own load impact on the grid at the same time in addition to the existing energy system to create additional output, build a new customer relationship between electric vehicle users, charging operators, power grids win-win situation, the formation of friendly and reciprocal vehicle to grid interaction ecology.

At the same time, we adopt the non-cooperative game model, and from the point of view of power grid enterprises, promote the construction of power auxiliary service market, especially time-sharing peak and valley tariff market mechanism, make full use of low-cost power wasted at night, make comprehensive use of the peak and valley tariff mechanism and preferential policies for EV charging, and guide consumers to form the behavioral habit of orderly charging in line with the load of the power grid by reducing the charging cost, and at the same time, pilot the promotion of bi-directional in the small scale in the developed areas with high EV ownership. At the same time, promote the two-way V2G energy storage model of vehicle-grid integration on a small-scale pilot basis in developed areas with high EV ownership. Try to explore the recycling mechanism of retired batteries for electric vehicles, promote the construction of retired battery storage power stations on a pilot basis, stimulate the formation of the retired battery recycling industry chain from the perspective of grid demand, and alleviate consumer concerns about the impact of participating in V2G on the life of power batteries. Further promote the construction of power long-distance transmission channels, and establish the necessary information communication channels between the power grid and regional microgrids as well as electric vehicle charging and discharging platforms. From the perspective of charging operators connecting power supply and demand, infrastructure retention is the basis of scale, and improving the distribution rate of private charging piles for households is a key link to ensure the participation of electric vehicles in vehicle to grid interactions. Drawing on the experience of implementing policies to promote charging piles in recent years, the construction subsidy for charging and switching facilities has gradually been transformed into an operational incentive for assessing the amount of charging and switching power, and a market competitive environment for the charging and switching facilities industry has been established. Further increase the profits of charging operators through measures such as the peak and valley tariff mechanism and the abolition of restrictions on service fees to mobilize operators' motivation to participate. From the perspective of electric vehicle users, by formulating peak and valley tariff policies to guide electric vehicle users to cooperate with the power system for vehicle to grid interaction, other market trading mechanisms can also be constructed to incentivize consumers to participate in the energy low-carbon transition. For example, in line with the establishment of individual carbon market rules, EV users can participate in the orderly charging volume into tradable carbon allowances, thus obtaining additional revenue to strengthen the economic cost advantage of EVs over fuel vehicles. The introduction of vehicle to grid not only plays a positive role in the energy transition of electric vehicles, but also expands the value space for electric vehicles, promotes a win-win situation for power grids, operators, and users, and promotes the interconnection between different subjects to realize integrated development.

However, the design of the service fee in the existing studies is too simple. In the future, we hope to design the service fee in a more detailed way, so as to ensure that the three parties can maximize their benefits when they win.

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