

RESEARCH ARTICLE

Participation of electric vehicles in auxiliary service market to promote renewable energy power consumption: Case study on deep peak load regulation of auxiliary thermal power by electric vehicles

Xiaolong Yang^{1,2,3} | Dongxiao Niu^{1,3} | Lijie Sun^{1,3} | Keke Wang^{1,3}  | Gejirifu De^{4,5} 

¹School of Economics and Management, North China Electric Power University, Beijing, China

²School of Economics and Management, Northeast Electric Power University, Jilin, China

³Beijing Key Laboratory of New Energy and Low-Carbon Development, Beijing, China

⁴School of Electrical and Electronic Engineering, North China Electric Power University, Beijing, China

⁵State Grid Economic and Technological Research Institute Co., LTD., Beijing, China

Correspondence

Keke Wang, School of Economics and Management, North China Electric Power University, Beijing 102206, China.
Emails: wkk_ncepu@126.com; wkk@ncepu.edu.cn

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Abstract

With the rapid development of new energy sources and the increasing proportion of electric vehicles (EVs) connected to the power grid in China, peak load regulation of power systems will face severe challenges. Therefore, in this study, we analyzed the relationship between the electricity consumption characteristics of EVs and the peak load regulation (PLR) mechanism of power systems, and we proposed an operation mode for virtual power plants with EVs to participate in the auxiliary service market and facilitate deep peak load regulation in the thermal power units. Based on the electricity demand-side management theory and cost-benefit analysis method, we constructed a decision model for economic deep peak load regulated operation (DPLR) of the auxiliary thermal power units in a virtual power plant with EVs, aiming to optimize the operation efficiency. The case study showed that a virtual power plant that included EVs can effectively reduce the total PLR cost of the system and the peak valley difference of the net load as well as improve the economic benefits of the thermal power units. The results indicated that the virtual power plant had improved economic efficiency. Therefore, the results of this research can help improve the PLR capacity of the grid and significantly promote the consumption of intermittent renewable energy.

KEYWORDS

deep peak regulation, electric vehicle, optimal operation mode, peak shaving, virtual power plant

1 | INTRODUCTION

In China, the installed capacity for renewable energy, such as wind and solar power, has grown rapidly in recent years. At the end of 2018, the total installed capacity of wind and solar power in China was approximately 358 GW, with an average increase of 31.30% in the past five years, accounting for 18.9% of the total installed capacity.¹ Because of the random and intermittent supply characteristics of these renewable energy sources and the influence of climate change, global warming, and other factors, the peak-to-valley difference of the grid has been continuously increasing, leading to an increase in the peak load regulation (PLR) pressure of the power grid.²

On October 9, 2020, the *New Energy Vehicle Industry Development Plan (2021-2035)* issued by the State Council highlighted the need to support the extensive integration of new energy vehicles with energy, transportation, information, and communication industries and promote the coordinated and integrated development of electrification, networking, and intelligent technology. With the development of electric vehicle battery technology,³ according to the latest *Global Electric Vehicle Outlook 2020* report by the International Energy Agency, the total number of electric vehicles (EVs) globally is estimated to reach 245 million by 2030, with approximately 50% originating in China.⁴ A high proportion of EVs connected to the power grid may cause power quality issues, such as overload of the distribution network, increase in line loss, and lower voltage.^{5,6} EVs have dual attributes of load and power supply in the power grid; therefore, by formulating reasonable charging and discharging control strategies, the rapid response of EVs can effectively provide auxiliary service for the grid, such as PLR, frequency regulation, and reserve capacity service, in case of peak load and emergency.⁷ For thermal power enterprises, the auxiliary service provided by EVs can not only increase the operation efficiency of thermal power units but also decrease the investment in standby power sources. Increasing EV charging flexibility is conducive to reducing power system costs, impacting spot prices of electricity, affecting the balance of energy supply and consumption, and mitigating carbon emissions.⁸ Therefore, in the context of the continuous increase in the total electricity consumption and renewable energy installed capacity, as well as the increasingly complex operating environment of the grid, controlling the systematic charging and discharging of EVs, assisting thermal power units in PLR, and ensuring the safe, stable, and economic operation of the grid, is an important research problem.

With the rapid development of the EV industry, the charging behavior,⁹ business models,¹⁰ pricing strategies,^{11,12} charging facilities,^{13,14} environmental impact,¹⁵ and related policies^{16,17} of EVs have gained the attention of the academic community. Albanese et al¹⁸ took Italy as an example to

analyze the impact of EVs' participation on the power market. And the results show that electric vehicles can reduce energy costs by replacing internal combustion engine vehicles and promote the power market to absorb photovoltaic power generation more economically. At present, owing to the increasing impact of the development of intermittent renewable energy sources on-grid operation, scholars from various countries have conducted extensive research on the influence of EVs on the power grid when participating in the auxiliary service market.^{19,20} Yang et al²¹ proposed an index system and adopted a calculation method to evaluate the impact of large-scale EV load on the economic value of power systems from three perspectives: construction economy, operation economy, and social economy, and they analyzed the impact of different charging modes on the grid. Jing et al²² analyzed the influence of large-scale EV charging behavior on the load curves of a power grid based on the Monte Carlo method, which considered the price policy, charging modes of EVs, and that of the grid and non-grid agents. Huang et al²³ used the EV time data for arrival, required charging, departure, and maximum delayed charging to group EVs, and they designed a cluster dispatch strategy for optimal dispatch of EVs. Liu et al²⁴ conducted an in-depth analysis of the EV charging industry, analyzed the constituent elements and main body of the charging industry business model from the perspective of the Internet, proposed and constructed an intelligent charging service system, and provided insights for the development of the charging industry. Luo et al²⁵ applied the vector evaluated particle swarm optimization algorithm and established a multi-objective optimal scheduling model of a virtual power plant with EVs. Xia and Yang²⁶ constructed an optimal dispatching model of an active distribution network with EVs, which can effectively reduce the variance of the random charging load curve and ensure the economic operation of the distribution network.

With the development of power market reform, scholars have carried out some research on the participation of EVs in the power market, including the electric energy and auxiliary service markets.^{27,28} Zheng et al²⁹ constructed a stochastic optimization model that considered the uncertainty of the electricity market and EV charging behavior to explore the optimal bidding strategy for EVs aggregators to participate in the future market. Xu et al³⁰ studied the economic benefits of retired electric vehicle batteries (REVBs) participating in different power markets and used intelligent algorithms to obtain the best operational strategies of REVBs to maximize their profits. With regard to the bidding and trading of EVs in the ancillary service market, Gong et al³¹ proposed an optimal bidding strategy designed for EV aggregators to participate in the spot electricity market, which can minimize the charging costs of EVs while meeting their flexible demands. Based on the controllable load and mobile energy-storage characteristics of EVs, Yang et al³² analyzed the interactive

characteristics and mechanism of EVs participating in integrated energy systems of buildings, and they proposed conventional and emergency auxiliary EV service schemes. With the developing vehicle-to-grid (V2G) technology, Wu et al.³³ proposed a trading method for EVs to enable participation in the regional power market to provide backup services, which can improve profits and meet the requirements of stability and security.

The above-mentioned studies primarily investigated the impact of EVs on the load distribution, optimized dispatching, and ancillary service trading strategies after EVs are connected to the power grid. However, few studies have focused on the economy of EVs participating in the PLR of thermal power units and the role of EVs in peak load shifting and valley filling. Therefore, in this study, we first analyzed the relationship between the energy consumption characteristics of EVs and the PLR mechanism of the power system. Then, we designed the basic framework of the virtual power plant, including EVs, to participate in the auxiliary service market. According to the cost-benefit analysis method, economic factors of thermal power units and virtual power plants with EVs were analyzed in detail, using the daily operation data of a regional power grid. The case study analyzed the impact of EVs on PLR costs, thermal power units, virtual power plants, and EV users after participating in the PLR of thermal power units.

The rest of this paper is organized as follows. Section 2 analyzes the energy consumption characteristics and PLR mechanism of EVs and puts forward the framework of auxiliary service market for virtual power plants with EVs. Section 3, Section 4, and Section 5 construct an economic operation decision-making model for the virtual power plants with EVs to assist thermal power units in deep PLR, including the economic factor analysis, objective function, and related constraints of the virtual power plant and thermal power units. Section 6 takes the typical daily operation of a city

power grid in China as the simulation object and analyzes the effect and economy of PLR. Section 7 concludes the main findings of the study.

2 | MARKET FRAMEWORK FOR VIRTUAL POWER PLANTS WITH EVs TO PARTICIPATE IN ANCILLARY SERVICES

2.1 | Analysis of energy consumption characteristics and PLR mechanism of EVs

To balance the electric power and to stabilize the frequency in the power system, the dispatching center needs to change the output of the generating units through the grid dispatching instructions to adapt to the changes in the power load, which is called the PLR process of the power system.³⁴ However, with the encouragement of the government, development of charging technology, and construction of charging facilities, several EVs have been connected to the power grid in recent years. Owing to the dynamic load characteristics and irregular charging and discharging options of EVs, higher requirements were put forward for the flexible regulation capability in the power system. In the absence of virtual power plant incentives and effective guidance policies, EV users charge EVs based on their travel needs, daily routine, and lifestyle. The relationship among random charging access options, grid load, and renewable energy output is shown in Figure 1.

We can see from Figure 1 that the charging time of EVs is primarily concentrated at approximately 8:30 and 19:00, while most of the EVs are in an uncharged state during the night when the wind power output is strong, and only some of the EVs are charging during the daytime when the solar power output is strong. Therefore, to meet the demand of EV users, if the EV charging power can be reasonably controlled

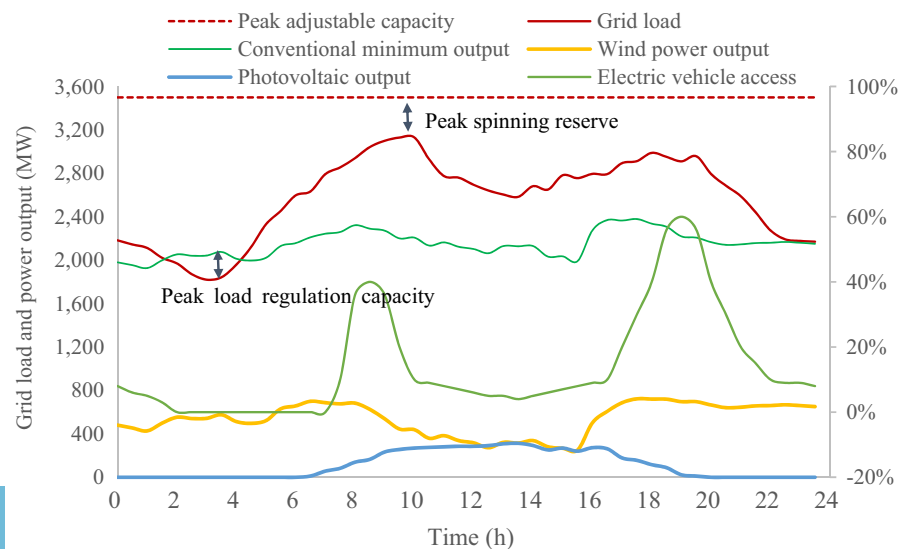


FIGURE 1 Graphical representation of electric vehicle load and power system peak load regulation

at different periods according to the load of the grid lines, it can effectively reduce the PLR power of thermal power and promote the consumption of renewable energy.

2.2 | Basic framework of EVs participating in auxiliary service market

To guarantee the quality of electric energy and ensure the safe, reliable, and stable operation of the grid, threshold restrictions on the market subjects participating in the auxiliary service market have been set, such as minimum charging power and shortest charging time. Thus, it is difficult for scattered EV users to directly participate in the auxiliary service market. The virtual power plant, which is an important technology for achieving an intelligent distribution network, provides an advanced technical solution for EVs to participate in the auxiliary service market.³⁵ The virtual power plant is a new generation of intelligent control technology and creates opportunities for an interactive business model that aggregates and optimizes the clean and low-carbon development of “generation-grid-load.” It does not need to reform the power grid and can fully utilize the distributed power resources with the aid of advanced communication technology.³⁶ Therefore, the EV resources can be integrated with the virtual power plant acting as the carrier, to meet the

requirements of market subjects. The specific participation mode is presented in Figure 2.

3 | ECONOMIC FACTORS OF VIRTUAL POWER PLANT WITH EVs

3.1 | Analysis of income factors

1. Income from selling electricity to EV users

As a load side user, EV users need to purchase electric energy from a virtual power plant to meet their travel mileage requirements and pay the corresponding charging electricity and related service fees to the operator. Therefore, the income from selling electric energy to EV users can be specifically expressed as follows.

$$R_{\text{evpp-se}} = \sum_{n=1}^N P_{\text{evpp-c},n}(t) \times \omega_{\text{evpp-c}}(t) \times T_{\text{evpp-c},n} \quad (1)$$

$$\omega_{\text{evpp-c}}(t) = \begin{cases} \omega_{\text{evpp-cp}} & t_{ps} \leq t \leq t_{pe} \\ \omega_{\text{evpp-cv}} & t_{vs} \leq t \leq t_{ve} \\ \omega_{\text{evpp-cb}} & t_{bs} \leq t \leq t_{be} \end{cases} \quad (2)$$

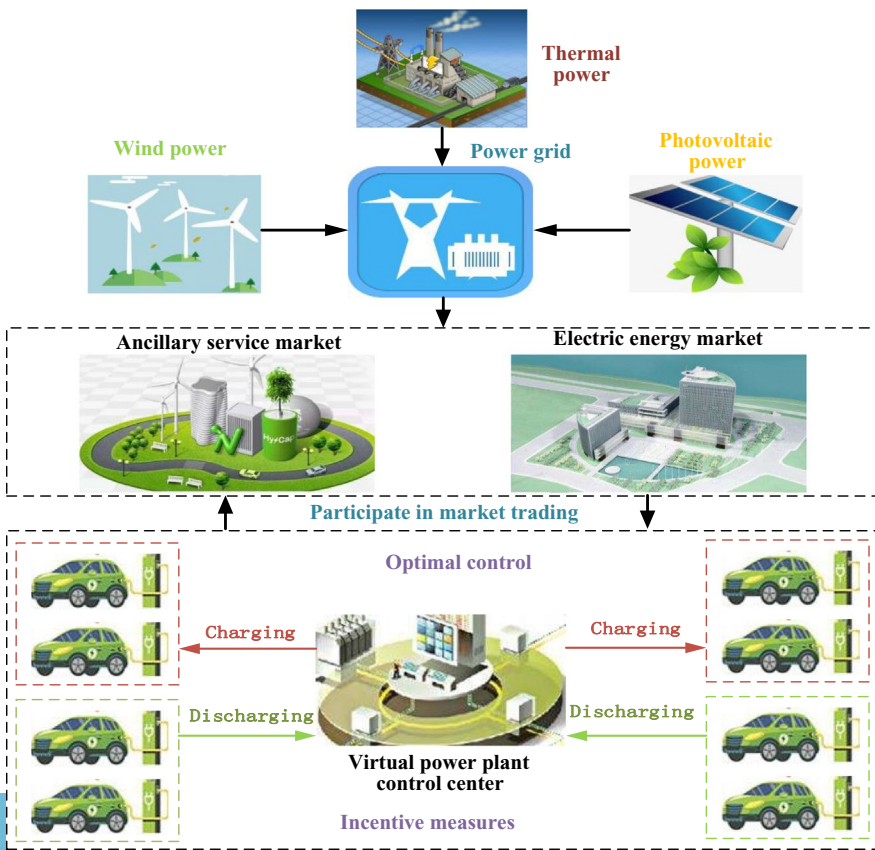


FIGURE 2 Basic framework of virtual power plant with electric vehicles participating in auxiliary service market

where $R_{\text{evpp-se}}$ represents the sales income of electric energy provided by the virtual power plant to EVs, N the total number of EVs charging simultaneously in the virtual power plant, $P_{\text{evpp-c},n}(t)$ the charging power of the n -th EV at time t , $\omega_{\text{evpp-c}}(t)$ the charging price of EVs at time t , $\omega_{\text{evpp-cp}}$, $\omega_{\text{evpp-cv}}$, and $\omega_{\text{evpp-cb}}$ the charging prices of EVs at peak, high, and valley load periods, respectively, and $T_{\text{evpp-c},n}$ the charging time of the n -th EV, which is related to the travel and regular life habits of EV users.³⁷

2. Compensation income from discharging electricity to the grid

In addition to electric load in virtual power plants, EVs can be regarded as mobile distributed energy-storage units with the support of advanced power grid technology. For example, V2G technology can be used to revert the on-board electric energy of EVs to the grid system. Therefore, the income of the virtual power plant, in discharging electricity from integrated EVs to the power grid, can be expressed through Equation (3).

$$R_{\text{evpp-dc}} = \sum_{m=1}^M P_{\text{evpp-d},m}(t) \times \omega_{\text{evpp-d}}(t) \times T_{\text{evpp-d},m} \quad (3)$$

where $R_{\text{evpp-dc}}$ represents the income from discharging electricity from EVs to the power grid, M the total number of EVs discharging electricity simultaneously, $P_{\text{evpp-d},m}(t)$ the discharging power of the m -th EV at time t , $\omega_{\text{evpp-d}}(t)$ the compensation price of discharging electricity provided to the virtual power plant at time t , and $T_{\text{evpp-d},m}$ the discharging time of the m -th EV. The time length $T_{\text{evpp-d},m}$ is optimized by the virtual power plant control center according to the amount of peak load reduction required by the power grid.³⁸

3. Income from deep PLR service

With the gradual advancement and expansion of the supply-side structural framework, the resources available for utilization by the power supply side are gradually decreasing, and conventional control methods cannot meet the power generation and consumption demands. Therefore, the supply-side framework has provided a wide scope for EVs to participate in deep PLR. The income of virtual power plants from EVs participating in the deep PLR can be expressed through Equation (4).

$$R_{\text{evpp-plrs}} = \sum_{n=1}^N \sum_{i=1}^I [P_{\text{evpp-plrs},n}(t) \times \omega_{\text{evpp-plrs},i} \times T_{\text{evpp-plrs},n}] \times \varphi \quad (4)$$

where $R_{\text{evpp-plrs}}$ denotes the compensation income of participating in the deep PLR, $P_{\text{evpp-plrs},n}(t)$ the charging power of the n -th EV participating in the deep PLR at time t , $\omega_{\text{evpp-plrs},i}$

the actual compensation price corresponding to the i -th grade when providing a deep PLR to the power grid, $T_{\text{evpp-plrs},n}$ the charging time of the n -th EV participating in the deep PLR, the time length of $T_{\text{evpp-plrs},n}$ is optimized by the virtual power plant control center according to the amount of valley filling power required by the grid, and φ the proportional coefficient of distribution of the virtual power plant to the EV users.

3.2 | Analysis of cost factors

Apart from the cost of operation and maintenance (O&M) and resource integration during the operation, the virtual power plant with EVs requires purchasing electric energy from the spot market to provide charging services for the internal EV users. Meanwhile, the virtual power plant also requires paying discharge compensation to EV users during the participation of EVs in auxiliary service. Therefore, the primary operating cost of the virtual power plant with EVs is calculated as follows.

$$C_{\text{evpp}} = C_{\text{evpp-pe}} + C_{\text{evpp-dc}} + C_{\text{evpp-om}} + C_{\text{evpp-ot}} \quad (5)$$

$$C_{\text{evpp-pe}} = Q_{\text{evpp}} \times (\omega_{\text{pg}} + \omega_{\text{tr}}) \quad (6)$$

$$C_{\text{evpp-dc}} = \sum_{m=1}^M P_{\text{evpp-d},m}(t) \times \rho_{\text{evpp-d}}(t) \times T_{\text{evpp-d},m} \quad (7)$$

where C_{evpp} represents the total operating cost of the virtual power plant, $C_{\text{evpp-pe}}$ the power purchase cost of the virtual power plant in the electricity spot market, Q_{evpp} the total electricity purchased by the virtual power plant in the spot market, ω_{pg} the deal price in the spot market, ω_{tr} the transmission cost of electric energy, $C_{\text{evpp-dc}}$ the discharge compensation fees paid by the virtual power plant to the EV users, $\rho_{\text{evpp-d}}(t)$ the discharge compensation price provided by the virtual power plant to the EV users at time t , $C_{\text{evpp-om}}$ the O&M cost of the charging pile and other equipment, and $C_{\text{evpp-ot}}$ the other costs required for the internal resource integration of the virtual power plant.

4 | ECONOMIC FACTORS OF THERMAL POWER UNITS

4.1 | Analysis of income factors

1. Electricity sales revenue

Thermal power units primarily sell electric energy to various customers to earn the corresponding income, which can be calculated as the product of the on-grid electricity and feed-in tariff.

$$R_{\text{og}}(P) = Q_{\text{on-grid}}(P) \times \omega_{\text{on-grid}} \quad (8)$$

where $R_{og}(P)$ represents the electricity sales revenue, $Q_{on-grid}(P)$ the on-grid electricity, which is the electricity input by the thermal power units to the power supply enterprise (power grid) at the metering point of on-grid electricity, and $\omega_{on-grid}$ the feed-in tariff of electricity generated by thermal power plants, which is the metering price at which the power grid or electricity users purchase electricity from power generation enterprises.

2. PLR service revenue

When a thermal power unit provides a paid PLR service to the power grid, it receives compensation based on market trading and the amount of electricity involved in peak regulation, which can be expressed as:

$$R_{plrs}(P) = \sum_{i=1}^n [Q_{plrs,i}(P) \times \omega_{plrs,i}] \quad (9)$$

where $R_{plrs}(P)$ represents the revenue of the thermal power units from participating in the deep PLR, $Q_{plrs,i}(P)$ the electricity participating in the deep PLR at the i -th grade, and $\omega_{plrs,i}$ the actual market-clearing price of the thermal power unit at the i -th grade.

4.2 | Analysis of cost factors

1. Cost of electricity generation

The cost of units generating thermal power is generally represented by the energy consumption characteristic curve of coal-fired units, which can be expressed as follows.

$$C_{plrsog}(P) = \sum_{i=1}^n Q_{plrs,i}(P) \times \omega_{on-grid} - \sum_{P=P_{min}}^{P_b} (F(P) \times T_{p,i}) \times \omega_{coal} - Q_{plrs,i}(P) \times C_{other} \quad (14)$$

$$C_{og}(P) = \sum_{P=P_{min}}^{P_{max}} (F(P) \times T_{p,k}) \times \omega_{coal} + \sum_{P=P_{min}}^{P_{max}} (F(P) \times T_{p,k}) \times C_{other} \quad (10)$$

$$F(P) = aP^2 + bP + c \quad (11)$$

where $C_{og}(P)$ denotes the cost electricity generation of the thermal power units, $F(P)$ the energy consumption characteristic curve of the thermal power units, P the actual output of thermal power units, a , b , and c the energy consumption characteristic coefficients of the thermal power units, which are related to the types of units, ω_{coal} the actual price of standard coal, $T_{p,k}$ the operation time of thermal power units at

different output powers P , and C_{other} costs excluding those for coal consumption.³⁹

In addition, if the thermal power units participate in the deep PLR, there will be additional costs because of the lower load operation.

$$C_{co}(P) = \beta S_{unit} / 2N_t(P) \quad (12)$$

where $C_{co}(P)$ denotes the cost of the thermal power units participating in the deep PLR, β the operation loss coefficient, S_{unit} the purchase cost of thermal power units, and N_t the rotor cracking cycles of the thermal power unit at time t , which is related to the output power P of the thermal power unit.

In addition, when the load of the unit is lower than a certain proportion, it is necessary to add fuel oil to stabilize combustion. Therefore,

$$C_{oil}(P) = Q_{oil}(P) \times \omega_{oil} \quad (13)$$

where $C_{oil}(P)$ represents the oil input cost of the thermal power unit operation under low load, $Q_{oil}(P)$ the fuel oil required by thermal power units, and ω_{oil} the real-time oil price.⁴⁰

2. Cost of less power generation caused by participating in PLR

When participating in the auxiliary service of PLR, thermal power units must reduce the output power of the generating units to coordinate with the grid for adjusting the load. Therefore, thermal power units reduce output power and generate less electricity, leading to less revenue from electricity sales. The cost of less power generation in thermal power units due to participation in PLR can be calculated as:

where $C_{plrsog}(P)$ is the electricity loss of the thermal power units participating in PLR, P_b the benchmark load value of thermal power units participating in PLR, and $T_{p,i}$ the running time required to generate electricity to participate in PLR.⁴¹

5 | OBJECTIVE FUNCTION AND CONSTRAINTS

The virtual power plant can participate in the auxiliary service market by optimizing EV aggregation. According to the analysis of economic factors in Sections 3 and 4, the objective function with maximum operation benefit can be expressed as follows:

$$\max L_{\text{evpp}} = R_{\text{evpp-se}} + R_{\text{evpp-dc}} + R_{\text{evpp-plrs}} - C_{\text{evpp}} \quad (15)$$

Subject to,

$$\begin{cases} 0.3E_r \leq E_t \leq 0.9E_r \\ 0 \leq m \leq M \\ 0 \leq n \leq N \end{cases} \quad (16)$$

where E_t denotes the state of charge (SOC) of the EVs at time t , and E_r the rated capacity of EVs. To meet the travel mileage requirements, the minimum SOC of EVs is assumed to be 30% of the rated capacity, and the ideal upper limit of battery capacity as 90% of the rated capacity.

To maximize the unit operating benefits in thermal power units, the revenue function is established as follows:

$$\max L = R_T - C_T = \begin{cases} R_{\text{og}}(P) - C_{\text{og}}(P) & P_b \leq P < P_{\text{max}} \\ R_{\text{og}}(P) + R_{\text{plrs}}(P) - C_{\text{og}}(P) - C_{\text{co}}(P) - C_{\text{plrsog}}(P) & ; P_a < P < P_b \\ R_{\text{og}}(P) + R_{\text{plrs}}(P) - C_{\text{og}}(P) - C_{\text{co}}(P) - C_{\text{oil}}(P) - C_{\text{plrsog}}(P) & P_{\text{min}} < P \leq P_a \end{cases} \quad (17)$$

Subject to,

$$\begin{cases} P_{\text{min}} \leq P \leq P_{\text{max}} \\ \omega_{\text{plrs,min}} \leq \omega_{\text{plrs,t}} \leq \omega_{\text{plrs,max}} \\ 0 \leq Q_{\text{plrs,i}}(P) \leq Q_{\text{plrs,max}}(P) \end{cases} \quad (18)$$

where P_{max} is the maximum output power of thermal power units, P_{min} the ultimate minimum load value of thermal power units, $\omega_{\text{plrs,min}}$ the lowest quotation of thermal power units participating in deep PLR, $\omega_{\text{plrs,max}}$ the highest quotation of thermal power units participating in deep PLR, and $Q_{\text{plrs,max}}(P)$ the maximum electricity of thermal power units participating in the deep PLR.

6 | CASE STUDY

6.1 | Parameter settings

In this example, the daily load curve of a certain day in a month, which has the same occurrence time of the maximum load and the minimum load and has no distortion of the curve, is selected as the analysis object according to all situations that need PLR for a city's power grid. The total installed capacity of the thermal power units was 3000 MW, the installed capacity of the wind power was 735 MW, that of photovoltaic power was 265 MW, and that of renewable energy accounted for 25% of the total installed capacity. The maximum

and minimum loads on a certain day were 3130.12 MW and 1820.47 MW, respectively. The conventional minimum output was composed of 50% output of thermal power units and the actual output of wind and photovoltaic power. The specific load of the grid and conventional minimum output are shown in Figure 3.

As shown in Figure 3, at approximately 1:30-4:00 at night, the grid load is lower than the conventional minimum output, and a deep PLR is required with a maximum load difference of 233.23 MW. The total deep PLR power obtained by accumulating the demand under different powers during the load regulation period was 362.28 MWh.

1. Virtual power plant with EVs

The average number of controllable EVs was assumed as 6000, and the SOC of each vehicle as 40% of the rated capac-

ity before participating in the auxiliary service market. The charging price of EVs was calculated based on the electricity price during the peak and valley periods, and the specific prices are listed in Table 1.

Other related parameter settings are listed in Table 2. Compensation price of peak load regulation (PLR) takes the value according to the average value of the quotation range when the average load factor P of the thermal power unit satisfies $P_a < P < P_b$. According to the operation of the virtual power plant, the initial value of proportional efficiency of PLR income distribution is set at 10%, and the sensitivity analysis is carried out in the case analysis to further understand the impact of redistribution on the income of EV users. According to the operating conditions of the virtual power plant, the initial value of the proportional coefficient of PLR income distribution is set to 10%, and the sensitivity analysis is carried out in the case analysis to further interpret the impact of redistribution on the participation income of EV users. Transmission and distribution price is set based on the 35 kV voltage level of general industrial, commercial, and other electricity consumption in the transmission price table of regional power grid where the city is located. The values of charging power, average battery capacity, average daily mile, electricity consumption per hundred kilometers, and other parameters refer to the parameter configuration table of Tesla model 3.⁴² The maximum charging and discharging power of the virtual power plant with EVs was 42 MW, and the capacity for participating in PLR was 150 MWh. The safe, reliable, and stable operation of the grid and the full consumption of wind and photovoltaic power are prioritized.

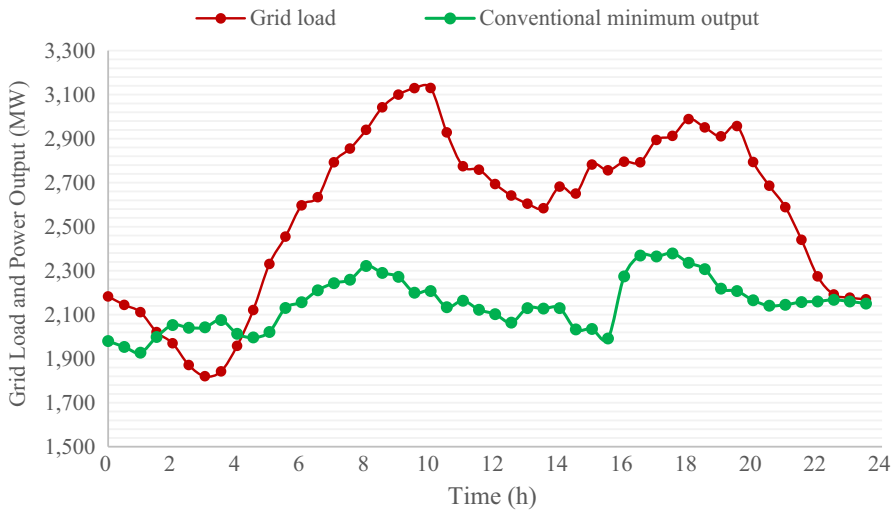


FIGURE 3 Power curve of the grid

TABLE 1 Peak and valley charging price parameters in the region

	Period	Electricity price (RMB/kWh)	Service price (RMB/kWh)
Peak load	19:00-21:00	1.0824	0.35
High load	8:00-11:00/13:00-19:00/21:00-22:00	0.9004	0.35
Valley load	11:00-13:00/22:00-Next day 8:00	0.4164	0.35

TABLE 2 Relevant parameters of virtual power plant operation

Parameter	Value	Unit
Compensation price of peak load regulation (PLR)	0.2	RMB/kWh
Proportional coefficient of PLR income distribution φ	10	%
Operation and maintenance (O&M) cost of virtual power plant	0.15	RMB/kWh
Transmission and distribution price	0.15	RMB/kWh
Charging power	7	kW
Charging and discharging efficiency	90	%
Average battery capacity	50	kWh
Average daily mileage	50	km
Electricity consumption per hundred kilometers	12	kWh

EVs adjusted 25% of the demand for PLR, while thermal power yet regulated the rest.

2. Thermal power units

The performance parameters of the thermal power units were analyzed taking a 600 MW unit as an example. The unit cost of the thermal power unit and that of standard coal

consumed by the units of thermal power plants were approximately 3646 RMB/kWh and 514.15 RMB/ton, respectively, and the feed-in tariff of thermal power was 259.5 RMB/MWh. According to the test results of the boiler parameters and unit performance, $a = 0.000169$, $b = 0.27601$, and $c = 11.46196$ for the energy consumption characteristic curve function of coal-fired units.⁴³

According to the auxiliary service market operations, the quotation mode of the PLR auxiliary service was “ladder type.” If the average load rate P of the thermal power unit satisfied $P_a < P < P_b$, the quoted price was $\omega_{plrs,1}$, and the quotation range was 0-0.38 RMB/kWh. If the average load rate of the thermal power unit (P) satisfied $P_{min} < P \leq P_a$, the quoted price was $\omega_{plrs,2}$, and the quotation range was 0.38-0.95 RMB/kWh, where $P_a = 40\%$, $P_b = 50\%$. The relationship between the rotor fracture cycle (N) and the output power (P) of the thermal power units was $N(P) = 0.005778P^3 - 2.682P^2 + 484.8P - 8411$.

When the units were in the deep PLR stage, the operating loss factor during the fueling phase was $\beta_0 = 1.5$, that during the nonfueling phase was $\beta_1 = 1.2$, the fuel oil consumption rate during the fueling phase was 4.8 t/h, and the oil price was 6130 RMB/t. The specific parameter settings of the thermal power units participating in the PLR are shown in Table 3. The process of thermal power units participating in deep PLR is shown in Figure 4.

6.2 | Results and analysis

1. Effective analysis of the PLR

Based on the simulation results of the case study, the virtual power plant with EVs enabled the thermal power units to conduct a DPLR, which effectively improved the peak-to-valley difference of the grid load. The PLR effect is shown in Figure 5.

TABLE 3 Parameters related to PLR of thermal power units

Parameter	Value	Unit	Details
UC	600	MW	Capacity of single thermal power unit
a	0.000169	-	Parameters of energy consumption characteristic curve of thermal power unit
b	0.27601	-	
c	11.46196	-	
β_1	1.2	-	Loss factor during the nonfueling phase
β_2	1.5	-	Loss factor during the fueling phase
ω_{coal}	514.15	RMB/ton	Unit price of standard coal
$\omega_{on-grid}$	259.5	RMB/MWh	On-grid electricity tariff of thermal power
ω_{oil}	6130	RMB/ton	price of oil
$Q_{plrs,max}(P)$	362.28	MWh	Total electricity demand for PLR
$\omega_{plrs,1}$	0-0.38	RMB/kWh	Compensation quotation during PLR phase I
$\omega_{plrs,2}$	0.38-0.95	RMB/kWh	Compensation quotation during PLR phase II
P_b	50%	-	Critical value of power during PLR phase I
P_a	40%	-	Critical value of power during PLR phase I
P_{max}	600	MW	Maximum output of thermal power unit
P_{min}	180	MW	Ultimate load value during deep PLR

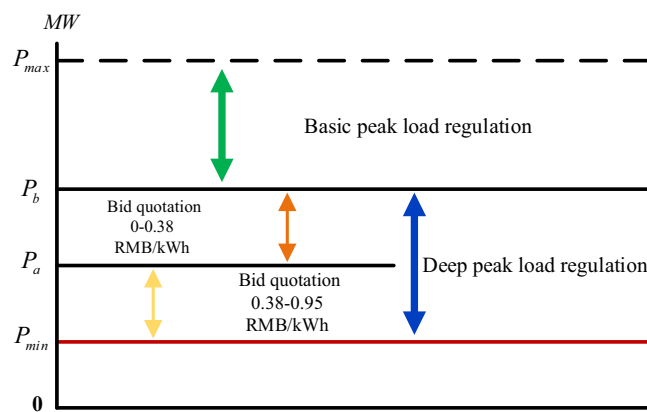


FIGURE 4 Schematic diagram of thermal power enterprises participating in deep PLR

As seen from Figure 5, the daily peak-to-valley difference of the net load curve was 1162.32 MW before the EVs participate in the PLR. After the participation of the EVs in the PLR, the daily peak-to-valley difference of the net load

curve decreased to 1078.33 MW, which was a 7.2% reduction. Therefore, from the perspective of the PLR effect, reasonable charging and discharging of EVs can increase the load demand during the low net load period and decrease the load demand during the peak of the net load period, which is conducive to promoting wind power consumption while reducing the regulation power of thermal power units. During the low load period of the power grid, peak load regulation is required. If the thermal power units cannot meet the PLR demand with the conventional minimum output, the wind power and hydropower can only be abandoned, resulting in the waste of clean energy power. At this time, according to the current simulation of 6000 EVs, 25% of the PLR demand is regulated by EVs, which can promote 90.57 MWh of clean energy consumption, and ultimately the peak shaving and valley filling can be achieved through the positive cooperation and interaction between users and the grid.

2. Economic analysis of the PLR

On one hand, as the main operator, the virtual power plant can obtain inexpensive electricity from the spot market through the wholesale market, and then provide charging services for EV users in a decentralized retail mode, earning an income of 102 186.67 RMB. On the other hand, by aggregating the controllable load resources of EVs to participate in auxiliary services, the income from PLR and discharging compensation was 87 885.51 RMB. The operating cost of the virtual power plant was calculated as 155 589.12 RMB; therefore, its net revenue was 34 483.05 RMB.

As participants in the operation of a virtual power plant, EV users received compensation of 9998.93 RMB through charge–discharge price difference and PLR distribution income, which was a price discount of 0.1104 RMB/kWh, accounting for 26.51% of the low charging price.

To better understand the impact of proportional coefficient of PLR income distribution on the income of EV users, the sensitivity analysis of proportional coefficient of PLR income distribution is carried out according to the interval of 5%, with the minimum value of 5% and the maximum value of 25%. It can be seen from Table 4 that when proportional coefficient of PLR income distribution changes by 1%, the electricity consumption cost per kWh will decrease by about 1.75%, and when it is set to 25%, the electricity consumption cost of EV users will decrease by 33.72%.

During the PLR, 75% of the PLR demand was regulated by thermal power units, the electricity to be regulated was 271.71 MWh, and the maximum regulated power was 191.23 MW. Moreover, it was assumed that four 600 MW thermal power units were participating in PLR, the load rate of the units was between 40% and 50%, and the maximum power reduction reached 240 MW, which met the PLR requirements. The calculation showed that the total cost of the

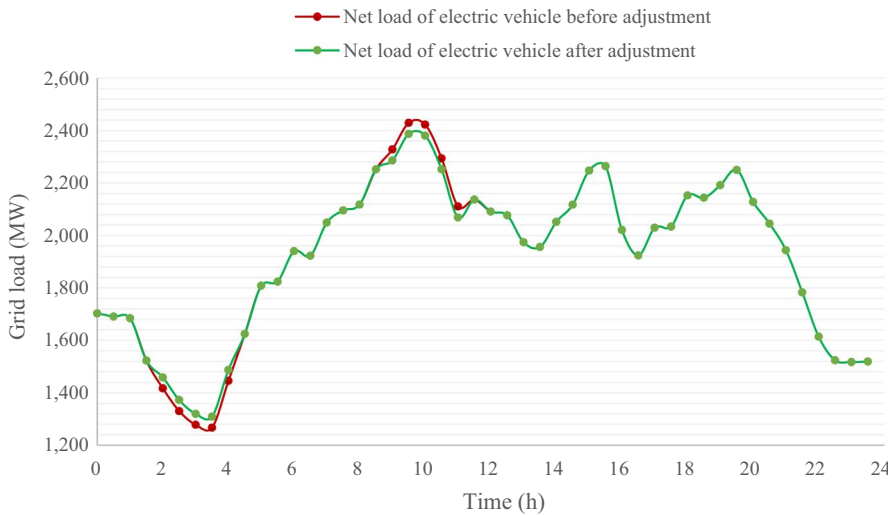


FIGURE 5 Peak shaving and valley filling effect of EVs

TABLE 4 Sensitivity analysis of proportional coefficient of PLR income distribution

Proportional coefficient of PLR income distribution	5%	10%	15%	20%	25%
Income of EV users (RMB)	9093.23	9998.93	10 904.63	11 810.33	12 716.03
Electricity cost reduction /kWh	0.1004	0.1104	0.1204	0.1304	0.1404
Electricity cost reduction compared to valley period	24.11%	26.51%	28.91%	31.32%	33.72%

system PLR was 121 363.8 RMB, and the revenue of the thermal power unit was 145 172.48 RMB.

If no EV was involved in the deep PLR, 90% of the PLR power was assumed to be regulated in the load interval $P_a < P < P_b$ and 10% in the load interval $P_{min} < P \leq P_a$. On one hand, with a further increase in the PLR amplitude of the thermal power units, the variable load loss of the unit increased. On the other hand, to maintain the combustion stability of the boiler, a fraction of the fuel oil input cost was increased. In addition, without the assistance of EVs, the output of thermal power units decreased during the PLR, and the low electricity generated by the units also caused revenue losses. Therefore, when no EV was involved in PLR, the revenue of thermal power units was calculated as 93 259.88 RMB, which was reduced by 35.76%. Because of the economic factors in the thermal power units and the existing compensation mechanism, as well as the increase in PLR amplitude and capacity, the total cost of the system PLR was increased. The calculation results showed that when no EV was involved in the PLR, the total cost of the system PLR was 149 169.76 RMB, indicating an increase of 18.64%. The specific differences are presented in Table 5.

Currently, the market maintenance of EVs is yet limited and some technical problems have been observed in the batteries of EVs, whose capacity does not yet meet the user mileage requirements. Therefore, in this case study, only 25% of the PLR demand was adjusted by EVs. From the perspective of the PLR effect, although the daily peak-to-valley

difference of the net load curve was reduced, the effect was not significant. With the continuous improvement and development in battery technology for large-scale EV applications, the operation mode proposed in this paper will be able to effectively control the adjustment cost of the power system, reduce the peak-to-valley difference of the grid, and regulate the daily load curve.

In the future, when virtual power plants, including EVs, participate in deep PLR, if the principle of “who benefits, who pays” can be followed, the power generation side can reduce the investment in standby power plants and utilize the equipment more efficiently, and the power grid side can reduce the distribution network investment and the loss caused by power curtailment. To promote energy conservation and emission reduction, by reducing carbon emissions and increasing renewable energy consumption, the government needs to develop a reasonable cost sharing and benefits compensation mechanism. With the improvement in the compensation mechanism, this operation mode can further reduce the total PLR cost of the thermal power units.

7 | CONCLUSIONS

In response to the rapid growth of the installed capacity of renewable energy, such as wind and solar power, in China, and the estimated situation of a high proportion of EVs connected to the power grid in the future, the market mechanism and

TABLE 5 Comparison of PLR parameters

Scene	Total cost of system PLR (RMB)	Revenue of thermal power units (RMB)	Peak-to-valley difference (MW)
Excluding EVs	149 169.76	93 259.88	1162.32
Including EVs	121 363.80	145 172.48	1078.33

operation mode of EV-assisted deep PLR for thermal power units with virtual power plants as the carrier, have been proposed in this case study. First, the relationship between the energy consumption characteristics of EVs and the PLR mechanism of the power system was analyzed, and the basic framework of a virtual power plant with EVs participating in the auxiliary service market was developed. Second, the economic efficiency and PLR effect of EVs participating in the PLR of thermal power units were analyzed based on the cost-benefit analysis method. The main findings of this study are as follows:

1. From an economic perspective, with virtual power plants as the carrier, the participation of EVs in deep PLR not only has significant economic benefits but can also effectively reduce the PLR cost of the system. Moreover, EV users can benefit through the income from the distribution of PLR and compensation from PLR discharge, thereby reducing the energy cost of users. As the primary operator, the virtual power plant can also improve its economic income.
2. From the perspective of the PLR effect, the participation of EVs in the PLR of the power system can increase the valley load and reduce the peak load, promote renewable energy generation and consumption, and ensure the safe, reliable, and stable operation of the power grid. Therefore, the participation of virtual power plants with EVs in the auxiliary service market for deep PLR is conducive to the successful and regular interactions between EV users and the power system. With the rapid development of the EV industry, this type of operation mode is increasingly valuable for promotion and application.

Finally, we proposed an operation mode of EVs to participate in the auxiliary service market for deep PLR with a virtual power plant as the carrier. The limitation of this model is that when investigating the participation of EV users in the PLR auxiliary service, the perspective of the EV users was considered in reducing the energy consumption cost, and not in the battery life degradation problem of EV batteries with the increasing number of charging and discharging cycles. With the advancement of technology, the improvement of compensation mechanisms, the development of external markets, and the problems, such as the low response degree of EV users and the quantification of

degradation cost of batteries, can be considered in future studies.

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CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

ORCID

Keke Wang  <https://orcid.org/0000-0002-4599-1464>

Gejirifu De  <https://orcid.org/0000-0002-2443-3113>

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