A Stackelberg Game Model for Photovoltaic and Energy Storage Charging Station participates in the Electrical Spot Market

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ABSTRACT The increasing integration of photovoltaic generation, energy storage, and electric vehicle charging infrastructure introduces new challenges for coordinated operation in grid-interactive energy systems. This study develops a bi-level Stackelberg game framework for photovoltaic-energy storage charging stations (PECS) participating simultaneously in day-ahead electricity and frequency-regulation ancillary service markets. A pre-clearing-based decision mechanism is introduced to coordinate interactions between charging stations and electric vehicle aggregators, enabling adaptive adjustment of charging demand, photovoltaic output, energy-storage scheduling, and market bidding strategies. The charging station operator acts as the leader by optimizing electricity pricing and multi-market participation strategies, while electric vehicles act as followers that dynamically respond to pricing signals to minimize charging costs. The resulting bi-level optimization problem is transformed into a mixed-integer linear programming formulation through Karush–Kuhn–Tucker conditions and solved efficiently. Three representative charging-station configurations with different photovoltaic-storage capacities and load characteristics are investigated. Simulation results demonstrate that the proposed framework improves charging coordination, enhances photovoltaic-energy storage utilization, increases revenues from electricity and frequency-regulation services, and strengthens system flexibility under varying market conditions. By establishing a coordinated decision architecture for distributed energy resources and demand-side response, the proposed method provides an engineering-oriented approach for adaptive energy scheduling, regulation-signal-responsive operation, and intelligent management of grid-connected energy systems.

INDEX TERMS distributed energy resources, frequency regulation, demand response, Stackelberg game

I. INTRODUCTION

WITH the increasing openness of the electricity market, various new market entities—such as energy storage systems, distributed generation, virtual power plants (VPPs), and load aggregators—are participating in trading. Tailoring market participation strategies to the specific energy consumption profiles of diverse manufacturing processes is crucial for the rational allocation and efficient utilization of energy resources across the industry.

Ref [1] proposed a non-cooperative game-based method for multiple VPPs participating in the day-ahead electricity market, aggregating diverse distributed energy resources to achieve optimal clearing schemes. Ref [2] established a bi-level model for energy storage resources participating in spot energy and frequency regulation markets, improving economic benefits through strategic bidding. Ref [3] developed a day-ahead frequency regulation ancillary service market model incorporating large-scale wind power, significantly reducing the frequency regulation costs of wind power systems. Ref [4] proposed a two-stage stochastic programming model for day-ahead and real-time markets, considering wind power uncertainty and incentive-based demand response participation. Ref [5] studied cooperative operation and electricity-carbon coupled trading in multi-microgrid systems under uncertainty, accounting for electricity price fluctuations in the power market.

Photovoltaic and energy storage charging stations (PECS), equipped with both PV and energy storage systems, can supply EV loads through both grid purchases and on-site generation. Due to their energy storage capabilities, PECS can participate in demand response programs [6-8], performing peak shaving and valley filling to smooth load fluctuations and achieve orderly EV charging/discharging [9-11]. Ref [12] established a Stackelberg game-based bi-level optimization model to study the optimal economic dispatch of EVs in islanded PECS. Ref [13] proposed aggregating EV loads, PV, and battery storage into a unified form through charging stations, using analytical target cascading to iteratively solve the optimal power flow in distribution networks, thereby obtaining optimal operational strategies.

While PECS can participate in electricity market trading with surplus energy, balancing EV load demands and market bidding requires further research. Ref [14] considered carbon emissions in PECS operation, optimizing both economic and environmental performance while meeting load demands. Ref [15] developed a stochastic chance-constrained economic dispatch model for PECS, achieving grid-friendly interaction while considering distribution network regulation pressures. Ref [16] proposed a multi-objective optimization crossover problem for Plug-in Hybrid Electric Vehicles (PHEVs) , particularly considering the penetration rate of plug-in electric vehicles in dynamic economic/emission dispatch.

To further explore this topic, this paper investigates the participation of PECS clusters serving large-scale production bases in energy and frequency regulation ancillary service markets from the operator's perspective. A Stackelberg game-based competition model is constructed between PECS and EVs in the day-ahead spot market. Leveraging the pre-clearing phase of the day-ahead market, the power exchange conducts joint pre-clearing for energy and frequency regulation markets at time T1 and publishes the clearing prices to PECS. As the upper-level leader, PECS determines the EV selling price based on the clearing price while optimizing PV and storage generation, maximizing its revenue. The lower-level EVs adjust their electricity purchases to minimize charging costs. After reaching equilibrium, PECS finalizes its optimal energy bids and frequency regulation capacity/mileage for the formal market clearing at T2. Finally, simulations under two different scenarios demonstrate the economic benefits of PECS participating in the electricity market through game-theoretic approaches.

II. THE CLEARING PROCESS OF PECS IN THE JOINT ELECTRIC ENERGY-AUXILIARY SERVICE MARKET

This study considers that multiple PECS participate in the day-ahead electric energy and FR auxiliary service market at the same time. In practical electricity market transactions, the pre-clearing price is an indicative signal rather than a binding constraint, which is consistent with the setting in this study. The pre-clearing price is only used as a forward-looking reference benchmark for the initial game between PECS and EVs, and does not determine the final transaction price and market bidding strategy of PECS. During the transaction cycle, PECS needs to meet the EV load through PV and ES in the station. When the output of the equipment in the station is not enough to meet the EV load, it needs to purchase electricity from the electric energy market. When the equipment in the station meets the EV load, there is a surplus of electricity to participate in the electric energy market and FR auxiliary service market. According to the timeline, during the information submitting period of $\Delta t1$, the PECS submits the purchase and sale of electricity in the energy market as well as FR capacity and FR mileage in the FR auxiliary service market. At time of T1, the power trading center collects the declaration information of various market participants to jointly pre-clear the electric energy market and the auxiliary service market, and announces that winning bid electricity and clearing electricity price to PECS. If the formal clearing price deviates from the pre-clearing price in the subsequent formal market clearing stage (T2), the PECS can dynamically adjust its operational decision variables (including EV charging price, PV and ES output) based on the latest formal clearing price, and the EV aggregators will synchronously adjust the charging load allocation according to the updated EV charging price. This flexible adjustment mechanism ensures that the Stackelberg game between PECS and EVs can quickly adapt to the price deviation and maintain the game equilibrium. At the time between T1 and $\Delta t2$, PECS can adjust the combination of EV load and unit output with reference to the pre-clearing price and the winning bid. Then quotes again in the electric energy market and auxiliary service market during the next information declaration period of $\Delta t2$. At time of T2, it participates in the joint market again to complete formal clearing so that maximize its own income in the whole process of trading. The transaction time flow chart of PECS participating in the electricity Energy-FR auxiliary service market is shown in Figure 1:

As shown in Figure 1, after pre-clearing at the time of T1, PECS adjusts the output of the equipment in the station through the Stackelberg game with EV according to the market clearing electricity price, so as to maximize the operating income in the process of market participation.

III. ARCHITECTURE OF STACKELBERG GAME BETWEEN PECS AND EV

In the energy market and auxiliary service market, the power trading center declares the clearing price and winning bid to all market participants after clearing. PECS adjusts the EV charging price according to the clearing price and winning bid considering its own profits, and the objection function is profit maximization, that is, the higher the EV charging price to EV, the more profit. The EV aggregator adjusts the charging capacity according to the charging price. On the premise of meeting the basic load demand in the system, reduce the amount of electricity purchased when the price is high, and the objection function is the minimum charging cost, that is, the lower the charging price from the charging station, the smaller the cost. There is a competition of interests between them, which constitutes a non-cooperative game relationship. Among them, PECS will announce the charging price information in advance, and then EV aggregators will adjust the purchase of electricity according to the electricity price, and then feedback the purchased electricity to PECS, which will affect the pricing and output of PECS. Therefore, with PECS as the leader, EV as the follower builds a Stackelberg game model. The two parties engage in iterative strategic interactions until equilibrium is achieved. The master and slave game relationship between PECS and

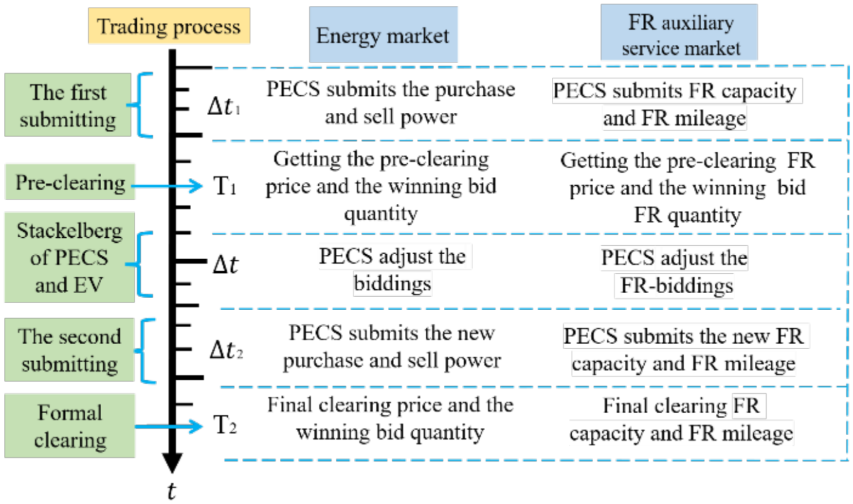

FIGURE 1. Timeline of PECS participates in the day-ahead electricity Energy-FR auxiliary service market

EV is shown in Figure 2:

A. UPPER-LEVEL MODEL OF PECS

1) Objection Function

The revenue from the price difference between PECS's power sales to EVs and power purchase is a comprehensive energy price difference based on the joint operation of on-site PV, ES and grid power purchase. The core source of this price difference profit is the on-site PV power generation of PECS (with zero power purchase cost), and grid power purchase is only a supplementary energy source for meeting peak EV load demand, whose price difference is restricted by the regulatory upper limit.

According to the different types of electricity market participation, the revenue sources of the upper PECS are divided into two parts. The first is the income in the electric energy market: PECS can earn income from the price difference, buying electricity at a low price from the current spot market, and then selling it to EV at a high price. Furthermore, it can also directly sell electricity power to the energy market to earn trading revenue. The second is the income in the market of FR auxiliary services: providing FR capacity and FR mileage[17]. The objection function corresponding to the total benefit of operation can be expressed as follows:

$$\max F_j = C_j^{\mathrm{PE}}(t) + C_j^{\mathrm{AS}}(t) - C_j^{\mathrm{PV}}(t) - C_j^{\mathrm{Batt}}(t) \quad (1)$$

$$\begin{aligned}
C_j^{\mathrm{PE}}(t) &= C_j^{\mathrm{EV},b}(t) + C_j^{\mathrm{Grid},b}(t),\\
C_j^{\mathrm{EV},b}(t) &= \lambda^{\mathrm{PECS},s}(t)\cdot P_j^{\mathrm{EV},b}(t) - \lambda^{\mathrm{PE}}(t)\cdot P_j^{\mathrm{PECS},b}(t),\\
C_j^{\mathrm{Grid},b}(t) &= \lambda^{\mathrm{PE}}(t)\cdot P_j^{\mathrm{PECS},s}(t),\\
C_j^{\mathrm{AS}}(t) &= C_j^{\mathrm{cap}}(t) + C_j^{\mathrm{mil}}(t),\\
C_j^{\mathrm{mil}}(t) &= \lambda^{\mathrm{AS},mil}(t)\cdot P_j^{\mathrm{mil}}(t),\\
C_j^{\mathrm{PV}}(t) &= \sum_{t=1}^{24}\left[\eta_{pv}\cdot P_j^{\mathrm{PV}}(t)\right],\\
C_j^{\mathrm{Batt}}(t) &= \sum_{t=1}^{24}\left[\eta_{\mathrm{Batt}}\cdot\left(P_{ch}^{\mathrm{Batt}}(t) + P_{dis}^{\mathrm{Batt}}(t)\right)\right].\\
C_j^{\mathrm{cap}}(t) &= \lambda^{\mathrm{AS},cap}(t)\cdot P_j^{\mathrm{cap}}(t) \quad (2)
\end{aligned}$$

where F_j is the total revenue of PECS j from the electricity market. $C_j^{\mathrm{PE}}(t)$ is the revenue of PECS from the day-ahead energy market at time t. $C_j^{\mathrm{AS}}(t)$ represents the revenue of PECS from the ancillary service market; $C_j^{\mathrm{PV}}(t)$ represents the PV operation and maintenance cost of PECS j at time t. $C_j^{\mathrm{Batt}}(t)$ represents the ES operation and maintenance cost of PECS j at time t. $C_j^{\mathrm{EV},b}(t)$ represents the selling revenue of PECS j from EV at time t. $\lambda^{\mathrm{PECS},s}(t)$ is the selling price of PECS j at time t. $P_j^{\mathrm{EV},b}(t)$ is the purchasing power of EV from PECS j at time t. $\lambda^{\mathrm{PE}}(t)$ is day-ahead energy market electricity price at time t. $P_j^{\mathrm{PECS},b}(t)$ is the purchasing power of PECS j in energy market at time t. $C_j^{\mathrm{Grid},b}(t)$ represents the selling revenue of PECS j from EV at time t. $P_j^{\mathrm{PECS},s}(t)$ is the selling power of PECS j in energy market at time t. η^{pv} is the PV operation and maintenance coefficient. $P_j^{\mathrm{PV}}(t)$ is the PV power at time t; η^{Batt} is the ES operation and maintenance c oefficient. $P_{ch}^{\mathrm{Batt}}(t)$ and $P_{dis}^{\mathrm{Batt}}(t)$ are the rated charging a nd discharging power of ES.

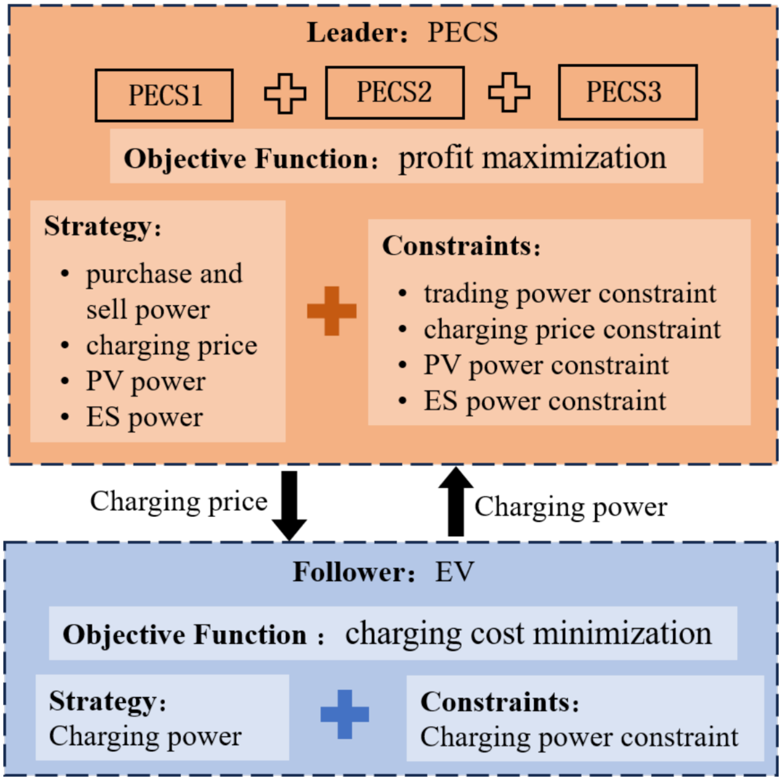

FIGURE 2. Framework of Stackelberg game model Between PECS and EV

2) Upper-Level Constraints

1. purchasing and selling power constraints

$$\begin{aligned} &P_j^{\text{Grid}}(t) = P_j^{\text{PECS},b}(t) - P_j^{\text{PECS},s}(t), \\ &\left|P_j^{\text{Grid}}(t)\right| \le P_{\text{Grid},j}^{\max}(t), \\ &\quad 0 \le P_j^{\text{PECS},b}(t) \le \sigma_1(t) \cdot P_{\text{Grid},j}^{\max}(t), \\ &\quad 0 \le P_j^{\text{PECS},s}(t) \le [1-\sigma_1(t)] \cdot P_{\text{Grid},j}^{\max}(t). \end{aligned} \tag{3}$$

The maximum purchase and sale power values of each PECS are different in different units at different times in the energy market, and all conform to the constraints: $P_j^{\text{Grid}}(t)$ is the purchasing and selling power of PECS j at time t. $P_{\text{Grid},j}^{\max}(t)$ is the maximum of purchasing and selling power of PECS j with Power trading center at time t. $\sigma_1(t)$ is a state variable of 0-1 at time t, and the constrained ES can not be in the state of charge and discharge at the same time.

2. FR capacity and FR mileage constraints FR capacity is a reserved potential for PECS to provide frequency regulation (FR) ancillary services, with no real-time power flow and thus not involved in the real-time power balance calculation. FR mileage refers to the actual dispatched active power for FR response, which generates real-time power flow and needs to be included in the power balance calculation. The range of FR capacity and FR mileage need to meet the following basic constraints, respectively:

$$\begin{aligned} &0 \le P_j^{\text{cap}}(t) \le P_j^{\text{cap,max}}(t), \\ &0 \le P_j^{\text{mil}}(t) \le \beta_0 P_j^{\text{cap,max}}(t). \end{aligned} \tag{4}$$

In the formula, $P_j^{\text{cap,max}}(t)$ is the maximum FR capacity of PECS j at time t. β_0 is the FR mileage factor.

3. EV charging price constrains The selling price set by PECS is affected by the clearing price of the electricity market. PECS sets the selling price with EV on the basis of considering a certain profit [18]. In order to make a profit, the selling price of PECS takes the pre-clearing price of the electric energy market before t time as the reference lower limit, which can be dynamically revised according to the formal clearing price at the T2 stage to adapt to the market price deviation. At the same time, taking into account the charging wishes of EV users, it is necessary to set an upper limit of selling price:

$$\lambda^{PE}(t) \le \lambda^{PECS,s}(t) \le \beta_1 \lambda^{PE}(t) \tag{5}$$

where β_1 is the coefficient of the price range.

4. PV power constraint

$$0 \le P_j^{PV}(t) \le P_j^{PV,\max}(t)$$

where $P_j^{PV,\max}(t)$ is the maximum PV output of PECS j at time t.

5. ES capacity constraints The power value of the ES charging and discharging at any time in the PECS can not exceed the maximum actual charging and discharging power of the ES equipment, and the state of the ESB is unique

during scheduling period, that is, it cannot be charged and discharged at the same time:

$$0 \le P_{ch}^{\text{Batt}}(t) \le \sigma_2(t) \cdot P_{ch}^{\text{Batt,max}}(t),$$
$$0 \le P_{dis}^{\text{Batt}}(t) \le [1-\sigma_2(t)] \cdot P_{dis}^{\text{Batt,max}}(t).$$

$P_{ch}^{\text{Batt,max}}(t)$ and $P_{dis}^{\text{Batt,max}}(t)$ are the maximum rated charging and discharging power of ES; $\sigma_2(t)$ is binary variable at time t to prevent ES from charging and discharging at the same time.

In addition, the battery capacity and SOC should be restricted accordingly. In the research, the work period of ES is set into 24h. The last SOC is equal to the initial SOC:

$$SE(t) = SE(t-1) + \frac{\eta^{ch} P_{ch}^{\text{Batt}}(t)\Delta t}{P_m^{\text{Batt}}} - \frac{P_{dis}^{\text{Batt}}(t)\Delta t}{\eta^{dis} P_m^{\text{Batt}}},$$
$$SE^{\min} \le SE(t) \le SE^{\max},$$
$$\eta^{ch} \sum_{t=1}^{24} P_{ch}^{\text{Batt}}(t) - \eta^{dis} \sum_{t=1}^{24} P_{dis}^{\text{Batt}}(t) = 0.$$

where $SE(t)$ is initial SOC of the battery at time t, η^{ch} and η^{dis} are charging and discharging efficiency of ES, P_m^{Batt} is the total capacity of ES, $SE^{\min}$ and $SE^{\max}$ are th e lower and upper limits of the battery SOC,

Equation (8) ensures the SOC at the last scheduling period is equal to the initial SOC.

6. The power balance constraint in PECS It should be noted that all decision variables of PECS (including charging price, PV/ES output, market bidding volume, and the allocation of FR capacity/FR mileage) and EV aggregators (including charging power, transferable/reducible load allocation) are flexible and adjustable. When the market price deviates, the flexible adjustment of the above variables can ensure that the objection functions of both parties are still optimized, and the game equilibrium is maintained without breaking the original constraint system. During the operation of PECS, the total input power (PV output, energy storage output, grid purchase power) must be equal to the total output power (EV charging power, energy market selling power, actual FR mileage power) at any time. The real-time power balance equation is given by:

$$P_j^{\text{PV}}(t) + P_{dis}^{\text{Batt}}(t) + P_j^{\text{PECS},b}(t) = P_j^{\text{EV},b}(t) + P_j^{\text{PECS},s}(t) + P_j^{\text{mil}}(t)$$

where the left side of the equation represents the total input power of PECS j at time t (PV on-site generation + energy storage discharge + grid purchase), and the right side represents the total output power (EV charging load + energy market selling power + actual FR mileage response power). Only the actually dispatched FR mileage power is included in the equation, which conforms to the physical connotation of real-time power flow balance.

B. LOWER-LEVEL MODULE OF PECS

1) Lower-Level Objection Function

The lower-level objection function is charging cost minimization, which can be described as:

$$\min F_j^{\text{EV}} = \lambda_j^{\text{PECS},s}(t) \cdot \left[P_j^{\text{Base}}(t) + \sigma_3(t) P_j^{\text{Dec}}(t) + P_j^{\text{Trans}}(t)\right].$$

where F_j^{EV} is the EV charging cost in PECS j. $\lambda_j^{\text{PECS},s}(t)$ is the charging price of PECS j at time t. The EV load is classified into three types: basic load $P_j^{\text{Base}}(t)$, power-transferable load $P_j^{\text{Trans}}(t)$, and power-reducible load $P_j^{\text{Dec}}(t)$; the sum of the three parts is the total charging capacity of EV in PECS j. $\sigma_3(t)$ is binary variable to represent whether the EV load can be reduced at time t. Notably, for the industrial PECS serving parks, the power-reducible load is strictly defined for the EVs undertaking non-core logistics tasks and only activated during the off-peak production periods of manufacturing. It does not involve the EVs responsible for the core production logistics of parks, thus avoiding any disruption to the normal manufacturing process.

2) Lower-Level Constraints

1. EV charging capacity constraint

$$0 \le P_j^{\text{EV},b}(t) = P_j^{\text{Base}}(t) + \sigma_3(t) P_j^{\text{Dec}}(t) + P_j^{\text{Trans}}(t) \le P_j^{\text{EV,max}}(t)$$

where $P_j^{\text{EV},b}(t)$ is the total EV charging power in PECS j at time t. $P_j^{\text{EV,max}}(t)$ is the EV maximum charging power in PECS j at time t.

2. EV power-reducible capacity and power-reducible times constraints

$$0 \le P_j^{\text{Dec}}(t) \le \beta_2 P_j^{\text{Base}}(t), \qquad 0 \le \sum_{t=1}^{24} \sigma_3(t) \le \beta_3$$

where β_2 represents the proportion of power-reducible load in the basic load. β_3 represents the power-reducible times in a complete simulation cycle. The 8% proportion of power-reducible load is a moderate setting adapted to the rigid operation of industrial parks, and the limited reduction times further avoid frequent load adjustment, which ensures the main charging demand of industrial EVs is fully satisfied.

3. power-transferable load capacity constraint

$$P_j^{\text{Trans}}(t) \le \beta_4 P_j^{\text{Base}}(t)$$

where β_4 represents the proportion of power-transferable load in the basic load.

C. SOLUTION OF THE BI-LEVEL STACKELBERG GAME

In the Stackelberg Game, the upper-level of PECS objection function is linear and the decision variable contains 0-1 variable, which belongs to mixed integer linear programming problem solving. The lower-level EV objection function has quadratic term, and the decision variable also contains 0-1 variable, which belongs to mixed integer nonlinear programming. Therefore the PECS operation optimization model can be converted into the constraints of the EV charging strategy model by the KKT conditions, then converting the bi-level problem into a single-level problem[19]. The KKT conditions of upper-level PECS is given as:

$$
\begin{aligned}
L_v = \sum_{t=1}^{24} \Big(& \lambda^{PECS,s}(t) \cdot P_j^{EV,b}(t) - \lambda^{PE}(t) \cdot P_j^{PECS,b}(t) \\
& + \lambda^{PE}(t) \cdot P_j^{PECS,s}(t) + \lambda^{AS,cap}(t) \cdot P_j^{cap}(t) + \lambda^{AS,mil}(t) \cdot P_j^{mil}(t) \\
& - \eta^{pv} \cdot P_j^{PV}(t) - \eta^{Batt} \cdot \left(P_{Batt}^{ch}(t) + P_{Batt}^{dis}(t) \right) \Big) + \omega_{\min}^{Grid,b}(t) \left(0 - P_j^{PECS,b}(t) \right) \\
& + \omega_{\max}^{Grid,b}(t) \left(P_j^{PECS,b}(t) - \sigma_1(t) P_{Grid,j}^{\max}(t) \right) + \omega_{\min}^{Grid,s}(t) \left(0 - P_j^{PECS,s}(t) \right) \\
& + \omega_{\max}^{Grid,s}(t) \left(P_j^{PECS,s}(t) - (1-\sigma_1(t)) P_{Grid,j}^{\max}(t) \right) \\
& + \omega_{\min}^{mil}(t) \left(0 - P_j^{mil}(t) \right) + \omega_{\max}^{mil}(t) \left(P_j^{mil}(t) - \beta_1 P_j^{cap,\max}(t) \right) \\
& + \omega_{\min}^{cap}(t) \left(0 - P_j^{cap}(t) \right) + \omega_{\max}^{cap}(t) \left(P_j^{cap}(t) - P_j^{cap,\max}(t) \right) \\
& + \omega_{\min}^{price,s}(t) \left(\lambda^{PE}(t) - \lambda^{PECS,s}(t) \right) \\
& + \omega_{\max}^{price,s}(t) \left(\lambda^{PECS,s}(t) - \beta_1 \lambda^{PE}(t) \right) \\
& + \omega_{\min}^{PV}(t) \left(0 - P_j^{PV}(t) \right) + \omega_{\max}^{PV}(t) \left(P_j^{PV}(t) - P_{PV,j}^{\max}(t) \right) \\
& + \omega_{\min}^{Batt,ch}(t) \left(0 - P_{Batt}^{ch}(t) \right) \\
& + \omega_{\max}^{Batt,ch}(t) \left(P_{Batt}^{ch}(t) - \sigma_2(t) P_{Batt}^{ch,\max}(t) \right) \\
& + \omega_{\min}^{Batt,dis}(t) \left(0 - P_{Batt}^{dis}(t) \right) \\
& + \omega_{\max}^{Batt,dis}(t) \left(P_{Batt}^{dis}(t) - (1-\sigma_2(t)) P_{Batt}^{dis,\max}(t) \right) \\
& + \omega_{\min}^{SE}(t) \left(SE^{\min} - SE(t) \right) + \omega_{\max}^{SE}(t) \left(SE(t) - SE^{\max} \right) \\
& + v^{SE}(t) \left(SE(t) - SE(t-1) - \left(\eta^{ch} P_{Batt}^{ch}(t) - \frac{1}{\eta^{dis}} P_{Batt}^{dis}(t) \right) \frac{\Delta t}{P_{Batt}^{m}} \right) \\
& + v^{Batt}(t) \left(\eta^{ch} \sum_{t=1}^{24} P_{Batt}^{ch}(t) - \frac{1}{\eta^{dis}} \sum_{t=1}^{24} P_{Batt}^{dis}(t) \right) \\
& + v^{Bal}(t) \left(P_j^{PV}(t) + P_{Batt}^{dis}(t) + P_j^{PECS,b}(t) - P_j^{EV,b}(t) - P_j^{PECS,s}(t) - P_j^{cap}(t) - P_j^{mil}(t) \right)
\end{aligned}
$$

where $\omega_{\min}^{Grid,b}(t), \omega_{\max}^{Grid,b}(t), \omega_{\min}^{Grid,s}(t), \omega_{\max}^{Grid,s}(t), \omega_{\min}^{cap}(t), \omega_{\max}^{cap}(t), \omega_{\min}^{mil}(t), \omega_{\max}^{mil}(t), \omega_{\max}^{price,s}(t)$, $\omega_{\min}^{PV}(t), \omega_{\max}^{PV}(t), \omega_{\min}^{Batt,ch}(t), \omega_{\max}^{Batt,ch}(t), \omega_{\min}^{Batt,dis}(t), \omega_{\max}^{Batt,dis}(t), \omega_{\min}^{SE}(t), \omega_{\max}^{SE}(t), v^{SE}(t), v^{Batt}(t), v^{Bal}(t)$ are the Lagrange multipliers of equality and inequality constraints.

The first order condition is as followed:

$$
P_i^{\mathrm{EV},b}(t) + \omega_{\mathrm{price},s}^{\min}(t) - \beta_1 \omega_{\mathrm{price},s}^{\max}(t) = 0 \tag{6}
$$

$$
\begin{aligned}
-\lambda^{\mathrm{PE}}(t) - \omega_{\mathrm{Grid},b}^{\max}(t) + \omega_{\mathrm{Grid},b}^{\min}(t) + v_{\mathrm{Bal}}(t) = 0, \\
\lambda^{\mathrm{PE}}(t) - \omega_{\mathrm{Grid},s}^{\max}(t) + \omega_{\mathrm{Grid},s}^{\min}(t) - v_{\mathrm{Bal}}(t) = 0, \\
\lambda^{\mathrm{AS},cap}(t) - \omega_{\mathrm{cap}}^{\min}(t) + \omega_{\mathrm{cap}}^{\max}(t) - v_{\mathrm{Bal}}(t) = 0, \\
\lambda^{\mathrm{AS},mil}(t) - \omega_{\mathrm{mil}}^{\min}(t) + \omega_{\mathrm{mil}}^{\max}(t) - v_{\mathrm{Bal}}(t) = 0, \\
-\eta_{pv} - \omega_{\mathrm{PV}}^{\min}(t) + \omega_{\mathrm{PV}}^{\max}(t) = 0, \\
-\eta_{\mathrm{Batt}} - \omega_{\mathrm{Batt},ch}^{\max}(t) + \omega_{\mathrm{Batt},ch}^{\min}(t) - \eta_{ch} v_{\mathrm{SOC}}(t) + \eta_{ch} v_{\mathrm{Batt}}(t) - v_{\mathrm{Bal}}(t) = 0, \\
-\eta_{\mathrm{Batt}} - \omega_{\mathrm{Batt},dis}^{\max}(t) + \omega_{\mathrm{Batt},dis}^{\min}(t) + \frac{v_{\mathrm{SOC}}(t)}{\eta_{dis}} - \frac{v_{\mathrm{Batt}}(t)}{\eta_{dis}} + v_{\mathrm{Bal}}(t) = 0, \\
-\omega_{\mathrm{SE}}^{\min}(t) + \omega_{\mathrm{SE}}^{\max}(t) + v_{\mathrm{SE}}(t) = 0.
\end{aligned}
$$

Complementary slackness is given as:

$$
\begin{aligned}
& 0 \le \omega_{\mathrm{Grid},b}^{\min}(t) \perp P_j^{\mathrm{PECS},b}(t) \ge 0, \\
& 0 \le \omega_{\mathrm{Grid},b}^{\max}(t) \perp \sigma_1(t) P_{\mathrm{Grid},j}^{\max}(t) - P_j^{\mathrm{PECS},b}(t) \ge 0, \\
& 0 \le \omega_{\mathrm{Grid},s}^{\min}(t) \perp P_j^{\mathrm{PECS},s}(t) \ge 0, \\
& 0 \le \omega_{\mathrm{Grid},s}^{\max}(t) \perp (1-\sigma_1(t)) P_{\mathrm{Grid},j}^{\max}(t) - P_j^{\mathrm{PECS},s}(t) \ge 0, \\
& 0 \le \omega_{\mathrm{cap}}^{\min}(t) \perp P_j^{\mathrm{cap}}(t) \ge 0, \\
& 0 \le \omega_{\mathrm{cap}}^{\max}(t) \perp P_j^{\mathrm{cap,max}}(t) - P_j^{\mathrm{cap}}(t) \ge 0, \\
& 0 \le \omega_{\mathrm{mil}}^{\min}(t) \perp P_j^{\mathrm{mil}}(t) \ge 0, \\
& 0 \le \omega_{\mathrm{mil}}^{\max}(t) \perp \beta_1 P_j^{\mathrm{cap,max}}(t) - P_j^{\mathrm{mil}}(t) \ge 0, \\
& 0 \le \omega_{\mathrm{price},s}^{\min}(t) \perp \lambda^{\mathrm{PECS},s}(t) - \lambda^{\mathrm{PE}}(t) \ge 0, \\
& 0 \le \omega_{\mathrm{price},s}^{\max}(t) \perp \beta_1 \lambda^{\mathrm{PE},s}(t) - \lambda^{\mathrm{PECS},s}(t) \ge 0, \\
& 0 \le \omega_{\mathrm{PV}}^{\min}(t) \perp P_j^{\mathrm{PV}}(t) \ge 0, \\
& 0 \le \omega_{\mathrm{PV}}^{\max}(t) \perp P_{\mathrm{PV},j}^{\max}(t) - P_j^{\mathrm{PV}}(t) \ge 0, \\
& 0 \le \omega_{\mathrm{Batt},ch}^{\max}(t) \perp \sigma_2(t) P_{ch}^{\mathrm{Batt,max}}(t) - P_{ch}^{\mathrm{Batt}}(t) \ge 0, \\
& 0 \le \omega_{\mathrm{Batt},ch}^{\min}(t) \perp P_{ch}^{\mathrm{Batt}}(t) \ge 0, \\
& 0 \le \omega_{\mathrm{Batt},dis}^{\min}(t) \perp P_{dis}^{\mathrm{Batt}}(t) \ge 0, \\
& 0 \le \omega_{\mathrm{Batt},dis}^{\max}(t) \perp (1-\sigma_2(t)) P_{dis}^{\mathrm{Batt,max}}(t) - P_{dis}^{\mathrm{Batt}}(t) \ge 0, \\
& 0 \le \omega_{\mathrm{SE}}^{\min}(t) \perp SE(t) - SE^{\min} \ge 0, \\
& 0 \le \omega_{\mathrm{SE}}^{\max}(t) \perp SE^{\max} - SE(t) \ge 0, \\
& 0 \le \omega_{\mathrm{Grid},b}^{\min}(t) \perp P_i^{b}(t) \ge 0, \\
& 0 \le \omega_{\mathrm{Grid},b}^{\max}(t) \perp P_{\mathrm{Grid},i}^{\max}(t) - P_i^{b}(t) \ge 0, \\
& 0 \le \omega_{\mathrm{Grid},s}^{\min}(t) \perp P_i^{s}(t) \ge 0, \\
& 0 \le \omega_{\mathrm{Grid},s}^{\max}(t) \perp P_{\mathrm{Grid},i}^{\max}(t) - P_i^{s}(t) \ge 0.
\end{aligned}
$$

Equation (18) shows that complementary slackness conditions are still nonlinear and non-convex, which can be linearized by following method.

Taking $\omega_{\mathrm{price},s}^{\min}(t)$ and $\lambda^{\mathrm{PECS},s}(t)$ two variables as example, showing The Big-M method:

$$
\begin{aligned}
& 0 \le \omega_{\mathrm{price},s}^{\min}(t) \perp \lambda^{\mathrm{PECS},s}(t) - \lambda^{\mathrm{PE}}(t) \ge 0, \\
& 0 \le \lambda^{\mathrm{PECS},s}(t) - \lambda^{\mathrm{PE}}(t) \le M \cdot \phi_{\min}(t), \\
& 0 \le \omega_{\mathrm{price},s}^{\min}(t) \le M \cdot (1 - \phi_{\min}(t)), \quad \phi_{\min}(t) \in \{0,1\}.
\end{aligned}
$$

where M is sufficiently large constant. $\phi_{\min}(t)$ is a binary variable. The bi-level optimization model has been converted to a mixed integer linear programming problem, which can be solved by a commercial solver. Even if a finite round of re-game is conducted due to the deviation of formal clearing price, the re-game model can still be linearized and solved by the above KKT conditions and Big-M method, which ensures the consistency of the solution method.

IV. CASE SIMULATION

A. SCENARIO DESCRIPTION AND PARAMETERS DEFINITION

The upper layer of the model built in this case is PECS group, and three types charging stations PECS1, PECS2 and PECS3 are set up with different scene respectively:

PECS1 is the type of PECS in the industrial area.

PECS2 is the type of PECS in the residential areas.

PECS3 is the type of PECS in the commercial area.

The three charging stations are respectively equipped with photovoltaic of different capacity, energy storage equipment, as well as the upper limit of the purchase and sale of electricity in the electric energy market, in order to verify the economy of PECS when the equipment operates with different output. The regulatory upper limit of the price difference Δ p is set to 0.25 CNY/kWh which is in line with the actual price supervision rules for charging stations in the electricity market.

The specific parameters are shown in Table 1.

TABLE 1. The maximum value of equipment in PECS

Parameter	PECS1	PECS2	PECS3
PV	150	100	100
ES	150	50	100
Grid	200	150	150

The PV operation and maintenance cost coefficient η^{pv} is 0.023 yuan/kWh; the ES operation and maintenance cost coefficient η^{Batt} is 0.050 yuan/kWh; the battery charge and discharge efficiency η^{ch} and η^{dis} are 0.95; the upper limit o f electricity price β_1 is 1.15; the proportion of power-r educible load in base load β_2 is 8%; the maximum number of load reduction that can be reduced within 24 hours is β_3 ; the proportion of transferable load in base load β_4 is 10%. In order to verify the stability of the game equilibrium under price deviation, the formal clearing price is set to deviate from the pre-clearing price by 20% and 40% based on the PJM market pricing data, and the other simulation parameters are completely consistent with the above settings to ensure the comparability of the results.

B. SIMULATION RESULT ANALYSIS

In order to verify the effectiveness of the model, two cases are set up to simulate and compare:

Case 1: PECS and EV do not go through the Stackelberg game, but directly participate in the clearing of electricity energy and FR auxiliary service market.

Case 2: PECS is pre-cleared in advance in the day-ahead market, and then optimize finally participates in the formal clearing through the Stackelberg game.

1) Analysis of Electricity Price and Equipment Output Optimization Result

In case1, PECS1, PECS2 and PECS3 do not play the Stackelberg game with EV, and the formulation of the selling price is only limited by the upper limit of the clearing price. Each charging station sets the upper limit of the clearing price in order to achieve the maximum profit. In case 2, the game pricing of PECS and EV needs to take into account the profit of EV, and the determination of selling price is also affected by the feedback of

EV charging capacity. In the final game equilibrium, PECS formulates the selling price curve as shown in Figure 3, and the operation strategies of PECS1, PECS2 and PECS3 after game optimization are shown in Figure 4.

It can be seen from Figure 3 that during the period of 0-6, the selling price of PECS1, PECS2 and PECS3 is higher than the market clearing price. This is because the capacity of PECS photovoltaic and energy storage equipment is insufficient, and each PECS buys electricity from the spot market to supply EV load. In order to ensure the profit of electricity sale, the selling price is set slightly higher than the clearing price. After 8 periods of time, with the increase of photovoltaic output, the selling price of PECS begins to be lower than the clearing price, and the decrease of PECS1 price is the most obvious, because PECS1, as an optical storage charging station in the industrial area, is equipped with more photovoltaic and energy storage, so it relies on the equipment in the station to meet the EV load, and its dependence on power purchase is lower, and the electricity price is more flexible; in the 18-21 period, it is mainly energy storage, and the selling price of PECS1 is lower.

Figure 4 shows the adjustment of PECS photovoltaic and energy storage output and market trading electricity, as well as the adjustment of EV charging quantity after the game between PECS and EV. Compared with the photovoltaic energy storage value of PECS in strategy 1, the PECS in strategy 2 increases the photovoltaic output in the period from 10:00 to 13:00 when the clearing price is higher, and shifts the main charging period of energy storage to the low price period, and increases the storage and discharge in the high price period, which can not only reduce the amount of electricity purchased in the electric energy market when the electricity price is high, save the cost of purchasing electricity, but also increase the profit of FR in the FR auxiliary service market. For the adjustment of the EV charging load, it can be seen from Figure 4 that after the master-slave game, the EV charging load reduces the charge at the electricity price peak at 10:00 and 16:00, but the effect is not obvious, because first, PECS1 belongs to the industrial zone charging station, which can reduce the load capacity is smaller, and the EV load volatility is reduced mainly through the translation of the peak charging load, and all the load reduction behaviors in the simulation are concentrated in the off-peak production periods of the park with no impact on the core production logistics. Second, the photovoltaic output of PECS1 configuration is mainly concentrated in the period from 10:00 to 16:00, so it is necessary to increase the consumption of new energy equipment in order to reduce the operating cost, so the load transferred to other time periods is less. In contrast, PECS2 effectively reduces the peak value of EV in the morning and evening, because as a residential charging station, users have higher charging flexibility, more load dispatching and load reduction, and better charging order.

2) Transaction Situation of PECS in Energy-FR Auxiliary Service Market

Electricity energy market and FR auxiliary service market clearing electricity price base data refer to American PJM market pricing [20] as shown in Figure 5. The overall electricity trading situation of the PECS group in the electric

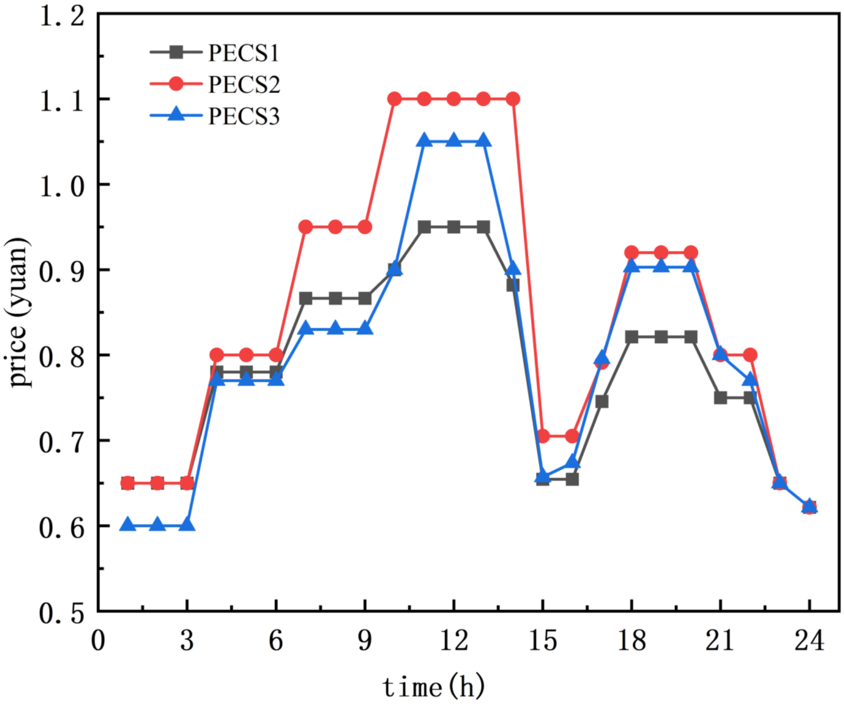

FIGURE 3. Diagram of PECS1 PECS2 and PECS3 electricity price in Strategy 2

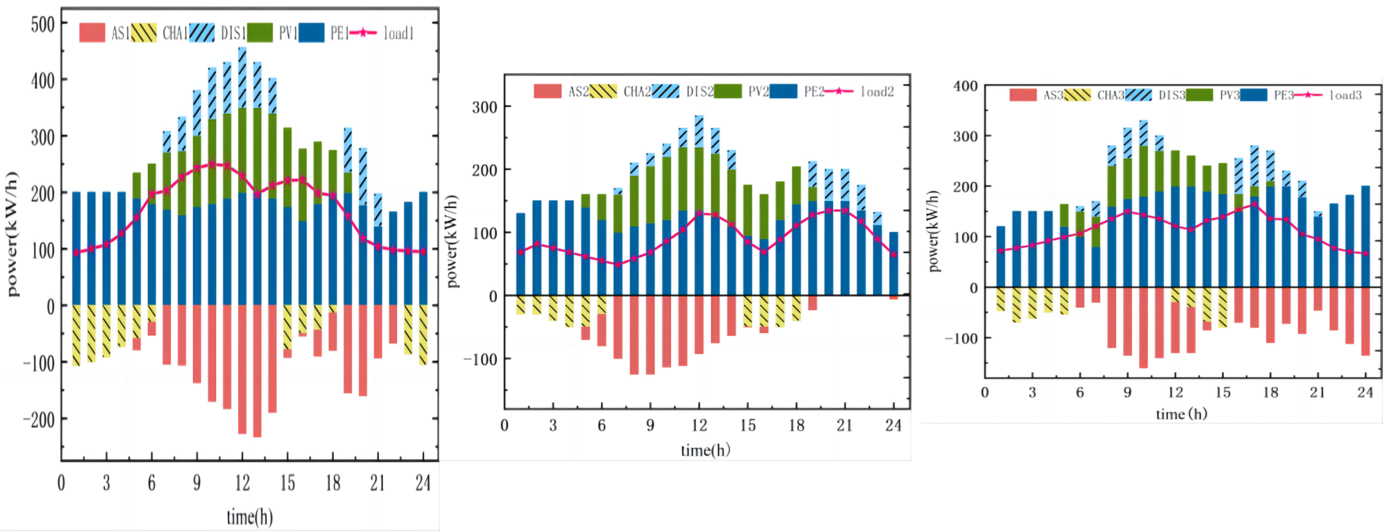

FIGURE 4. PECS-Optimized Operational Strategy Diagram

energy market and auxiliary service market is shown in Figure 6, where the positive value of electricity indicates that PECS has won the bid in the electricity market, and the negative value indicates the actual response of electricity in the FR auxiliary service market.

In Figure 6, PECS purchases electricity from the electricity market and participates in the FR mileage declaration of the FR auxiliary service market in several periods. This is because in the clearing price of the two markets in Figure 5, even in the peak period of 10-13 of the electricity price in the energy market, the clearing price corresponding to the FR mileage and FR capacity is still higher than that in

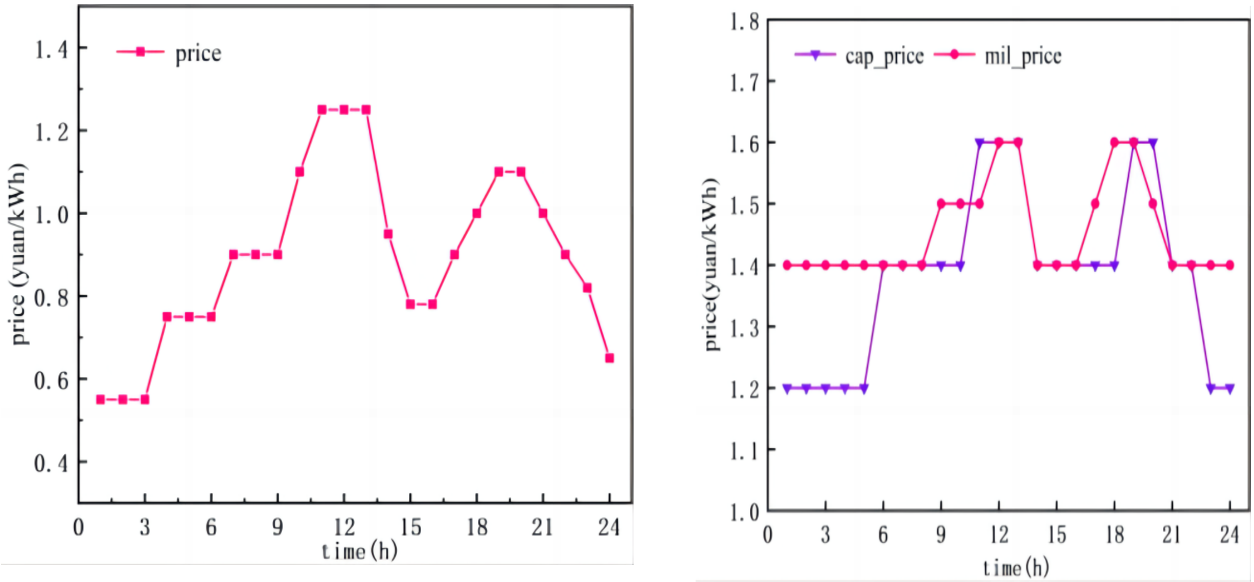

FIGURE 5. Energy-FR auxiliary service market clearing price

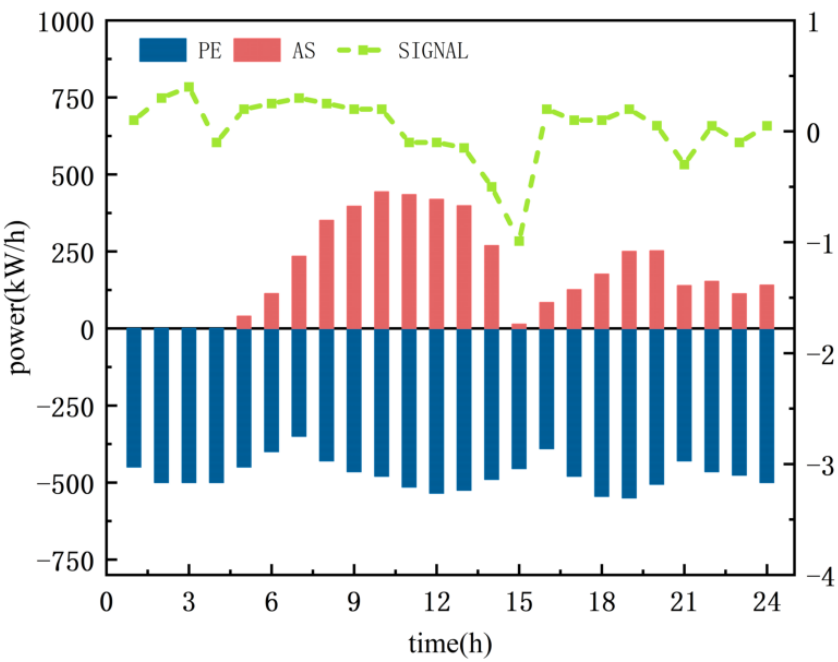

FIGURE 6. Energy-FR auxiliary service market cleared biding volume

the electricity market, so PECS in order to increase revenue, under the premise of satisfying the EV load. Will purchase electricity from the electric energy market and participate in the FR mileage response in the auxiliary service market.

3) PECS Profitability Analysis

The operating income results of each market subject under strategy 1 and 2 are shown in Table 2, the EV game result value is the charging cost, and the PECS running result value represents the actual income.

As can be seen from the data in Table 2, after the game between PECS and EV, the charging cost of EV decreases and the operating income of PECS increases. Among them, the reduction of EV cost mainly reduces the PECS electricity purchase price through the game, and reasonably allocates

TABLE 2. The cost value of each market subject before and after the Stackelberg

Participant	Strategy1	Strategy2
EV1	16.663	13.362
EV2	9.615	8.066
EV3	7.360	6.719
PECS1	4.265	4.667
PECS2	3.038	3.615
PECS3	3.338	3.871

the electricity purchased in different periods to avoid the peak electricity price as much as possible. On the one hand, the increase of PECS operating income depends on the sufficient dispatching of photovoltaic, energy storage equipment to generate and store electricity in the station, reducing the cost of purchasing electricity from the electricity market; on the other hand, under the premise of meeting the EV load, PECS group participates in the FR auxiliary service market and obtains auxiliary service benefits by providing FR mileage and FR capacity. In addition, it can be seen from the data that PECS and EV, as both sides of the game, achieve the maximum profit when they reach the equilibrium solution of the game, but the optimization results show that the increase ratio of the three PECS benefits is not the same, in which PECS1 has more EV load, in contrast, its income increase percentage is the lowest, while the corresponding EV load cost reduction ratio under PECS1 is the highest. It shows that through the game between PECS and EV, although the overall income of PECS increases and the overall charging cost of EV decreases, the one who benefits more from both sides is EV.

4) Price Deviation Sensitivity Analysis

Based on the original simulation parameters, this section sets the formal clearing price with 20% and 40% positive deviation from the pre-clearing price (the most common price deviation scenario in the market) to verify the stability of the Stackelberg game equilibrium. The results show that even under the condition of price deviation, the PECS and EV can still reach the Nash equilibrium through flexible adjustment of decision variables, and the operating income of PECS and the charging cost of EV are still better than those in the nongame scenario (Case 1). The specific variation of PECS income and EV cost under different deviation rates is shown in Table 3.

TABLE 3. Sensitivity analysis results of formal clearing price deviation (Unit: 10,000 CNY)

Deviation rate	PECS1 income	PECS2 income	PECS3 income	EV1 cost	EV2 cost	EV3 cost
20% positive deviation	4.582	3.541	3.795	13.625	8.183	6.802
40% positive deviation	4.496	3.468	3.721	13.891	8.301	6.885

Note: The data in the table is the result of the game scenario (Case 2) under price deviation, and all values are still higher/lower than the non-game scenario (Case 1), which verifies the stability of the game equilibrium. With the increase of the positive deviation rate of the formal clearing price, the operating income of PECS shows a slight decline, and the charging cost of EV shows a slight increase, but the overall level is still better than the non-game scenario. This indicates that the Stackelberg game model proposed in this study has good robustness to the price deviation, and the game equilibrium can be effectively maintained through the flexible adjustment of decision variables.

5) Sensitivity Analysis of Key Parameters of β_0 and β_1

To verify the influence of the mileage factor β_0 and the price range coefficient β_1 on the Stackelberg game equilibrium, a sensitivity analysis with ±20% fluctuation of the two parameters' benchmark values is conducted in this section. Only the two core indicators (PECS operating income and EV charging cost) are selected for analysis, and the other simulation parameters are consistent with the original settings. The results are shown in Table 4.

TABLE 4. Sensitivity analysis results of β_0 and β_1 (Unit: 10,000 CNY, Change rate: %)

Parameter	Fluctuation	PECS1 income / Change rate	PECS2 income / Change rate	PECS3 income / Change rate	EV1 cost / Change rate	EV2 cost / Change rate	EV3 cost / Change rate
β_0	Benchmark	4.667 / -	3.615 / -	3.871 / -	13.362 / -	8.066 / -	6.719 / -
β_0	+20%	4.890 / +4.78%	3.796 / +5.01%	4.065 / +5.01%	13.201 / -1.21%	8.005 / -0.76%	6.680 / -0.58%
β_0	-20%	4.410 / -5.51%	3.424 / -5.28%	3.668 / -5.24%	13.510 / +1.11%	8.120 / +0.67%	6.756 / +0.55%
β_1	Benchmark	4.667 / -	3.615 / -	3.871 / -	13.362 / -	8.006 / -	6.719 / -
β_1	+20%	4.759 / +1.97%	3.678 / +2.00%	3.950 / +2.04%	13.489 / +0.95%	8.145 / +0.98%	6.785 / +0.58%
β_1	-20%	4.575 / -1.97%	3.543 / -2.00%	3.792 / -2.04%	13.235 / -0.95%	7.987 / -0.98%	6.653 / -0.58%

It can be seen from Table 3 that the mileage factor β_0 has a certain impact on the game equilibrium: the increase of β_0 improves the income of PECS from frequency regulation ancillary services, which makes the game equilibrium tilt to PECS, leading to a slight increase in PECS income and a small decrease in EV charging cost; the decrease of β_0 has the opposite effect, with the change rate of core indicators about 5%. The price range coefficient β_1 has a weak impact on the game equilibrium, with the change rate of core indicators only about 2%. This is because the model sets rigid upper and lower limit constraints on the EV charging price, which effectively avoids the excessive fluctuation of the charging price caused by the change of β_1 , and reflects the good stability of the model's price setting mechanism.

In summary, within the range of ±20% reasonable fluctuation of β_0 and β_1 , the core indicators of the game equilibrium do not change significantly, which proves that the Stackelberg game model proposed in this paper has good robustness to the key parameters. The research conclusions are not affected by the small fluctuation of the above parameters, which further improves the engineering applicability of the model.

V. CONCLUSION

Focusing on the participation of PECS in day-ahead energy and frequency regulation markets within integrated industrial parks, this paper establishes a two-level optimization model based on a master-slave game between PECS and electric vehicles. This approach optimizes the power exchange between renewable energy storage and the fluctuating electric loads of machinery. The pre-clearing price in this study is set as an indicative reference signal, which isconsistent with the actual operation rules of the e lectricitymarket, and the flexible adjustment mechanism of t he modelensures the stability of the game equilibrium when theformal clearing price deviates. Through the co mparativeanalysis of the two strategies, the following concl usions are drawn: the pre-release link is set up in the spo t market to determine the unit combination in advance an d issue thepre-clearing price to each market subject. It i s beneficialfor each market subject to further fully dispatc h their ownpower generation and use electricity source s, so as toachieve a better allocation of resources. In this study, PECScarries on the master-slave game with EV acc ording to thepre-cleared electricity price, adjusts the equi pment outputand EV charging capacity in the station, a nd determinesthe declared electricity quantity in the day -ahead electricenergy market and FR auxiliary service m arket, so as tobetter allocate power resources and improv e the operatingincome of the station relying on on-site PV p ower generationand multi-market participation. By chargin g from PECS bygame, EV can adjust the purchase of ele ctricity accordingto the sales price set by PECS, reduc e the purchase ofelectricity at the peak of electricity pri ce, and effectivelyreduce charging expenses. From the as pect of power grid,it also realizes the orderly charging of EV and relievesthe pressure of power supply during peak hours, with thereducible load of industrial EVs in parks strictly limitedto non-core logistics and off-peak production periods toensure the rigidity of industrial produ ction scheduling. Whatthis paper realizes is that PECS par ticipates in the markettransaction model under the tradin g framework of the day-ahead spot market through a ga me with EV, but it doesnot involve the clearing model with shorter cycle in thereal-time market, especially th e clearing of FR capacityand FR mileage in the FR auxi liary service market, whichis more sensitive to the infor mation changes of markettraders in a short period of tim e, which has more researchsignificance. In addition, th e sensitivity analysis resultsshow that the proposed Stac kelberg game model has goodrobustness to the deviation o f formal clearing price, and canmaintain the game equilibriu m and the optimization effect ofmarket players' benefits thr ough the flexible adjustment ofdecision variables, which f urther improves the engineeringapplicability of the model.I t will be the next research point.

AUTHOR CONTRIBUTIONS

Conceptualization –Hongjie Tian, Haidong Chen, Yunfeng Zhang, Chunning He and Jisheng Zhang; methodology – Hongjie Tian, Haidong Chen, Chunning He and Jisheng Zhang; investigation – Hongjie Tian, Haidong Chen, Yunfeng Zhang, Chunning He and Jisheng Zhang; writing-original draft preparation – Hongjie Tian, Haidong Chen, Yunfeng Zhang, Chunning He and Jisheng Zhang. All authors have read and agreed to the published version of the manuscript.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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