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RESEARCH ARTICLE

Joint Optimized Operation of Electricity Spot and Reserve Markets Considering Bidding Strategies for Virtual Power Plants

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ABSTRACT As the reform of electricity marketization advances, the virtual power plant (VPP), as an emerging market participant, is being progressively incorporated into the trading scope of both the electricity spot market (ESM) and the reserve market (RM). Due to its flexible regulation capabilities, the bidding strategies of VPPs in the electricity market are complex and variable, presenting new challenges to the joint operation of power markets. In this context, first, based on the interactive game relationships among multiple market entities under the operating mechanisms of the spot and reserve markets, this paper designs a principal-follower game framework for transactions in these markets with the VPP as the main entity. Second, it constructs a two-level joint optimized bidding strategy model for VPP participation in the spot and reserve markets, where the inner layer is the VPP's optimized bidding strategy model aiming to maximize the total revenue from the spot and reserve markets; the outer layer is the spot and reserve market clearing model targeting the minimization of the total electricity purchasing cost for society. Finally, the simulation case analysis shows that the proposed method can achieve joint optimal operation of the electricity spot and reserve markets by considering the VPP bidding strategy, resulting in a 1.42% reduction in the total electricity purchase cost of the power market.

INDEX TERMS Virtual power plant, electricity spot market, reserve market, bi-level joint bidding strategy model, Stackelberg leader-follower game.

NOMENCLATURE

ABBREVIATIONS

VPP	Virtual Power Plant.
PV	Photovoltaic.
ESS	Energy Storage System.
ESM	Electricity Spot Market.
RM	Reserve Market.
ETC	Electricity Trading Center.
VPPO	Virtual Power Plant Operator.

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I. INTRODUCTION

A. MOTIVATION

Under the 'dual carbon' goals, various types of distributed energy resources, including distributed renewable energy, energy storage, and adjustable flexible loads, have been rapidly developing [1]. The grid integration of distributed energy resources benefits the economic and environmental performance of systems. However, their characteristics such as small capacities, diverse resource types, large scales, and dispersed locations pose significant challenges to the safe and stable operation of power systems [2], [3]. To effectively address these challenges, VPP, as an innovative distributed energy management technology, is gradually becoming an important component of the power market [4].

VPP integrates distributed generation resources, energy storage devices, controllable loads, etc., and utilizes advanced information technology and intelligent algorithms to achieve efficient coordination and optimized management of distributed energy resources [5]. This new management model not only enhances the utilization efficiency of distributed energy but also enables effective participation in the diversified operations of the power market [6], [7]. Although there has been preliminary research on the bidding strategies for VPPs participating in the power market, these studies are still insufficient. In particular, the strategies for VPPs participating in certain integrated markets remain underexplored. Moreover, the impact of VPP integration on the joint operation of the electricity spot market and reserve market currently lacks in-depth research and methods.

B. LITERATURE REVIEW

In recent years, with the deepening of power market reforms, the commercial operation models of VPPs are also continuously being explored and developed [8]. VPPs can participate in different markets based on the progress of market reforms, thereby gaining profits from multiple angles. Currently, the application scenarios for the commercial operation of VPPs mainly focus on peak regulation auxiliary services [9]. For regions that have implemented spot markets and allow virtual power plants to enter the market, VPPs can choose to participate in the spot market, as well as peak regulation and frequency modulation auxiliary service markets [10]. Their market bidding strategies have become a hot topic of research among many scholars. Document [11] considers the uncertainty of wind power output and the game relationship between multiple entities, proposing a bidding game method for multiple VPPs participating in the day-ahead market based on non-cooperative game theory and robust optimization concepts. Document [12], based on stochastic programming theory, proposes a multi-stage bidding strategy model for its participation in the day-ahead energy market, intraday demand response trading market, and real-time energy market. Document [13] comprehensively considers the uncertainty of wind power output and the volatility of market prices, proposing a VPP bidding model for simultaneous participation in the day-ahead spot market and real-time spot market. Document [14], under the dual settlement mechanism of the spot market and deviation assessment, proposes a VPP bidding model considering incentive-based demand response participation. Document [15], through a detailed analysis of the trading mechanisms of the spot market, models the risk costs for VPPs in the spot market, and establishes a VPP bidding model based on Stackelberg game theory. However, the aforementioned studies mainly focus on formulating bidding strategies for VPPs participating in single spot markets, without considering the scenario of joint operations across multiple markets.

Research on bidding strategies for VPPs participating simultaneously in multiple markets, such as the spot market and ancillary service markets, is still in its early stages. Document [16] starting from the retail market perspective, proposes a two-stage, bilevel stochastic bidding strategy model for VPPs engaging in both the spot and frequency regulation joint markets, enhancing the economic benefits of each entity by leveraging the complementarity of small-scale participants' output. Document [17] introduces a bidding strategy for VPPs participating in the day-ahead spot market and the day-ahead ancillary services market, and proposes a profit function for VPPs in the day-ahead ancillary services market based on the theory of information gap decision making. Document [18] constructs a two-stage, bilevel bidding strategy model for multi-entity interactive games under the joint operation mechanism of electricity-carbon markets. Document [19] presents a robust optimization strategy for day-ahead energy-frequency regulation joint market bidding, taking into account demand response and the frequency regulation performance index of VPPs. Document [20] proposes an optimal bidding strategy for VPPs participating simultaneously in the spot market and the frequency regulation ancillary service market. By introducing bidirectional long short-term memory networks, it accurately predicts the internal resources and information of VPPs, enabling precise bidding in both the spot market and the frequency regulation ancillary service market. The literature on VPP participation in power markets primarily focuses on bidding strategies in the spot-frequency regulation and spot-load balancing markets. A considerable amount of work has been devoted to exploring how optimization algorithms can enhance VPPs'

TABLE 1. Comparison between this work and existing works.

Comparison	[11]	[12]	[13]	[14]	[15]	[16]	[17]	[18]	[19]	[20]	This work
Single Electricity Market	✓	✓	✓	✓	✓	✗	✗	✓	✗	✗	✗
Spot and Peak Regulation Markets	✗	✗	✗	✗	✗	✗	✓	✗	✗	✗	✗
Spot and Frequency Regulation Markets	✗	✗	✗	✗	✗	✓	✗	✗	✓	✓	✗
Spot and Reserve Markets	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓
Considering VPP	✓	✗	✓	✓	✓	✓	✓	✗	✓	✓	✓
Not Considering VPP	✗	✓	✗	✗	✗	✗	✗	✓	✗	✗	✗

competitiveness and economic benefits in these specific markets. However, research on effective bidding strategies for VPPs in the spot and reserve markets is relatively scarce. Furthermore, while some studies have attempted to analyze the operational challenges faced by VPPs under different market conditions, few have systematically proposed optimized operational strategies for VPPs from the perspective of the market operator.

C. CONTRIBUTIONS AND PAPER ORGANIZATIONS

To summarize, this paper considers the impact of VPPs integrating into the power market, and under this scenario, conducts a study on the joint optimized operation methods for the electricity spot and reserve markets. The comparison between the proposed method and other methods is shown in Table 1 First, we analyze the interactive game relationships among multiple entities under the operating mechanisms of the spot and reserve markets, designing a principal-follower game framework for transactions in which the VPP is the main entity. Second, we construct a two-layer joint optimized bidding strategy model for the VPP under the spot and reserve market conditions. The inner layer aims to maximize the total revenue of the VPP in the spot and reserve markets, determining the optimal bidding strategy for the VPP's participation in these markets. The lower layer targets the minimization of the total electricity purchase cost for society, performing the clearing of the spot and reserve markets. Finally, the effectiveness and rationality of the proposed two-layer model are validated through case study analysis.

II. ELECTRICITY MARKET TRADING PROCESSES CONSIDERING INTEGRATION OF VPPS

A. COMPOSITION STRUCTURE AND PRINCIPLES OF VPPS

A VPP typically comprises various types and capacities of distributed energy resources. The VPP considered in this paper consists of distributed wind turbines, distributed PV, ESS, and flexible loads. Distributed power sources within a VPP are significantly influenced by natural meteorological factors and have a high degree of uncertainty in their output. However, internal ESS can mitigate the fluctuation of output from wind and solar units, thereby enhancing the overall controllability of the VPP and improving scheduling flexibility. Flexible loads can reduce or increase load, thus adjusting consumption behavior [21].

The control modes of a VPP can be categorized into centralized control, centralized-decentralized control, and fully decentralized control. The VPP defined in this paper adopts a centralized control mode, where a central control unit—the control coordination center—unifies the control of all power sources, ESS, and loads within the VPP. It also facilitates the exchange of energy and information with the power market managed by external system operators through the control coordination center. The specific structure of the VPP is illustrated in Fig. 1.

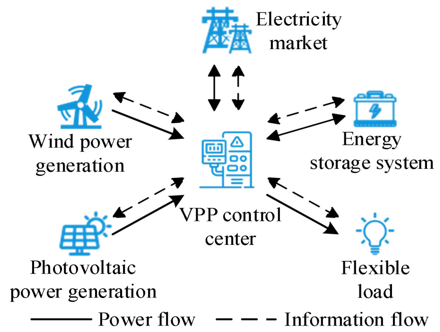


FIGURE 1. Structure of VPP.

B. ELECTRICITY MARKET TRADING PROCESSES UNDER THE CONTEXT OF MASS ENTITY ACCESS

As one of the typical massive entities, when a VPP participates in the electricity market trading, the trading period spans from 12:00 on the bidding day (D-1 day) until 12:00 on the following day (D day), consisting of a total of 24 periods, each lasting 1 hour [22], [23]. The specific process is as shown in Fig. 2.

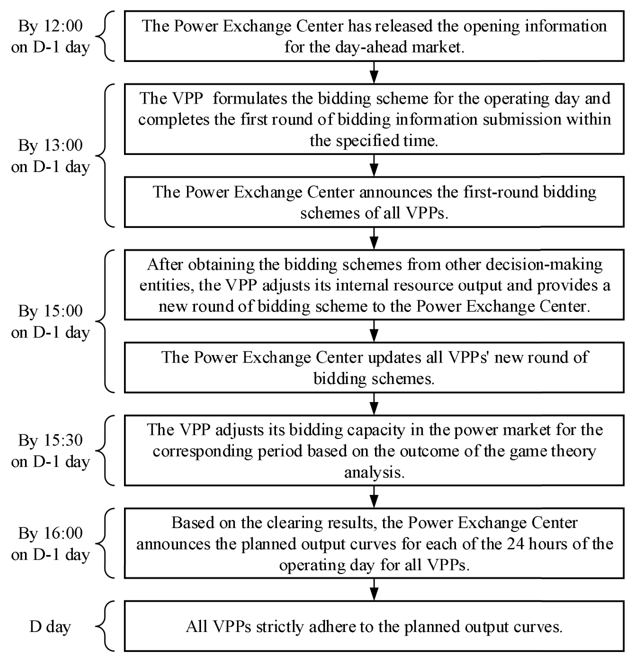


FIGURE 2. Flowchart of the electricity market trading process.

1) Before 12:00 on the bidding day, the power trading center publishes the opening information for the day-ahead market, including the load demand of the electricity market, the upper and lower limits of the bidding price, and other relevant information.

2) By 13:00 on the bidding day, each VPP shall, based on available market information and historical bidding strategies of competitors, formulate its bidding plan for the operation day with the objective of maximizing operational revenue.

This involves the optimal integration of resources to complete the first round of bidding information submission within the stipulated time frame. The submission must encompass the VPP's bidding price and volume in the energy market. Prior to the commencement of the subsequent phase, the ETC will disclose the initial bidding plans of all participating VPPs.

3) Prior to 15:00 on the bidding day, upon receipt of other decision-making entities' bidding strategies, each VPP retains the autonomy to adjust its internal resource output in alignment with its own interests. Consequently, they may iteratively submit updated bidding strategies to the ETC. Upon receiving a new round of bids from all VPPs, the ETC promptly discloses these on the online trading platform. This allows each VPP to engage in iterative bidding, based on the real-time market information released, until the conclusion of this stage.

4) By 15:30 on the bidding day, if by the end of the previous period no VPP can benefit from unilaterally altering its bidding strategy, then the ETC proceeds with market clearing based on the outcome of the game theory dynamics in the market. Should the bidding rounds reach their upper limit before the end of the previous period and there are still VPPs wishing to submit new bidding proposals, the ETC will not accommodate such requests. Instead, it will allocate the total load demand of the market proportionally among the VPPs according to their maximum bidding capacities. Subsequently, each VPP is required to promptly readjust its bidding capacity for the corresponding period in the peak shaving market on this basis.

5) Prior to 16:00 on the bidding day, the ETC, based on the clearing outcomes from both the electricity market, releases the scheduled power output profiles for each of the 24 operational periods for every VPP for the running day.

6) During the operational day (D-day), each VPP is mandated to adhere rigorously to the scheduled power output profile as previously communicated.

III. GAME ANALYSIS OF THE SPOT AND RESERVE MARKETS

A. INTERACTIONS AND GAME RELATIONSHIPS AMONG DIVERSE MARKET PARTICIPANTS

The strategic interactions and game relationships among diverse market entities in the spot and reserve markets are illustrated in Fig. 3. VPPs and conventional power plants can concurrently engage as market participants in transactions within both the spot and reserve markets. Market players not only submit bids for electricity volume and price in the spot market but also declare their reserve capacity and corresponding reserve prices in the RM. In formulating their optimal bidding strategies, market members take into account the bids of their competitors as well as the system operator's response to the strategies reported by all market entities. The system operator, in turn, utilizes security-constrained unit commitment and secure economic dispatch programs for optimization calculations. This process is based on information submitted by market members along with the operational boundary conditions of the power grid, leading to the clearing of the day-ahead market transactions. This paper primarily focuses on the optimal bidding strategies employed by VPPs in the spot and reserve markets, where the bidding strategies of VPPs significantly influence the optimization operational decisions made by the system operator. Under this scenario, the game process between the VPP and the system operator can be conceptualized as a Stackelberg leader-follower game, with the VPP assuming the role of the leader in decision-making, and the system operator acting as the follower.

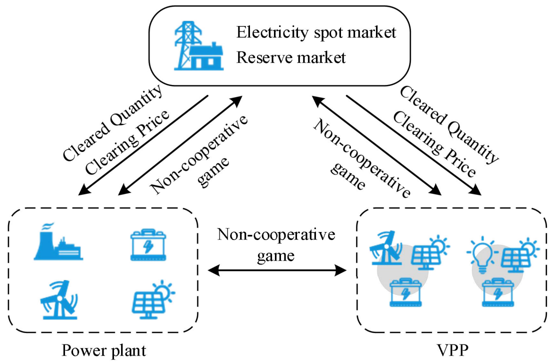


FIGURE 3. Game interaction of multi-market players in spot and reserve market.

B. THE STRATEGIC LEADER-FOLLOWER FRAMEWORK FOR INTERACTIONS IN SPOT AND RESERVE MARKET EXCHANGES

The leader-follower game framework for spot and reserve market transactions is illustrated in Fig. 4. The inner model of the game framework centers on the VPP as the subject of study, establishing a joint bidding model with the VPP as the primary bidder. The outer model represents the clearing model for the day-ahead spot market and reserve market under a centralized bidding trading mechanism.

In the inner model, the VPP, acting as the leader, aims to maximize its own profit as the objective function for the day-ahead joint bidding. In contrast, the system operator, positioned as the follower in the outer model, targets the minimization of the total electricity procurement cost for society as the objective function, which leads to the formation of the clearing results for all market participants.

IV. VPP'S JOINT OPTIMIZED BIDDING STRATEGY MODEL FOR PARTICIPATION IN THE SPOT AND RESERVE MARKETS

A. INNER LAYER VPP COLLABORATIVE OPTIMIZATION BIDDING STRATEGY MODEL

1) OBJECTIVE FUNCTION

The inner layer model is the VPP collaborative optimization bidding strategy model. Due to the spatial coupling and mutual exclusion between the ESM and the RM, joint

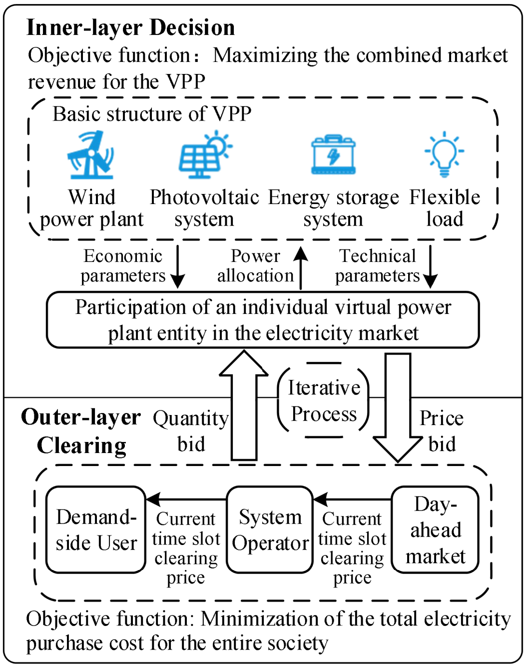


FIGURE 4. **Leader-follower game framework for spot and reserve market transactions.**

optimization of the spot and reserve markets becomes a crucial means to achieve optimal allocation of VPP resources. The inner model aims to maximize the total revenue of the VPP in the spot and reserve markets, with the specific formula as shown below.

$$\max R_{vpp}^{net} = \sum_{t=1}^{T} \begin{pmatrix} R_{vpp,t}^{em} - R_{vpp,t}^{srm} - C_{vpp,t}^{w} \\ -C_{vpp,t}^{pv} - C_{vpp,t}^{ess} - C_{vpp,t}^{fl} \end{pmatrix} \tag{1}$$

where P_{vpp}^{net} (yuan) is the net income that the VPP obtains from the energy and reserve markets; $P_{vpp,t}^{em}$ (yuan) and $P_{vpp,t}^{srm}$ (yuan) are the revenues that the VPP achieves in the spot market and the reserve market at time t; $C_{vpp,t}^{w}$ (yuan), $C_{vpp,t}^{pv}$ (yuan) and $C_{vpp,t}^{ess}$ (yuan) are the generation costs of wind power, PV, and energy storage within the VPP at time t. $C_{vpp,t}^{ct}$ (yuan) and $C_{vpp,t}^{tr}$ (yuan) are the economic loss costs of flexible loads inside the VPP.

a: REVENUE FROM THE SPOT MARKET

In the spot market, entities submit their power-price curves, and the market clearing price determines the winning bid for the generating units. The specific revenue for the VPP in the spot market is shown in.

$$R_{vpp,t}^{em} = \sum_{n=1}^{N} P_{vpp,n,t}^{em} \cdot Q_{vpp,n,t}^{em} \tag{2}$$

where $R_{vpp,t}^{em}$ (yuan) is the revenue of the VPP in the spot market at time t; $Q_{vpp,n,t}^{em}$ (MWh) and $P_{vpp,n,t}^{em}$ (yuan/MWh) are the cleared volume and cleared price, for the VPP in the spot market; N is the maximum number of power-price segments allowed to be declared in the spot market.

b: REVENUE FROM THE RESERVE MARKET

In the reserve market, market participants submit bids for reserve capacity and corresponding prices; the market clearing price is determined as the winning price for the power units. The revenue for the VPP in the reserve market is shown in.

$$R_{vpp,t}^{srm} = P_{vpp,t}^{srm} \cdot Q_{vpp,t}^{srm} \tag{3}$$

where $R_{vpp,t}^{srm}$ (yuan) is the revenue of the VPP in the reserve market at time t; $Q_{vpp,t}^{srm}$ (MWh) and $P_{vpp,t}^{srm}$ (yuan/MWh) are the cleared volume and cleared price for the VPP in the reserve market.

c: GENERATION COST OF DISTRIBUTED ENERGY RESOURCES

A VPP encompasses distributed energy resources such as wind power and PV, whose generation costs include both the actual output costs of the units and the costs associated with curtailed wind and solar power. The specific formula is shown in.

$$C_{vpp,t}^{de} = \sigma_w \cdot P_{vpp,t}^{w} + \sigma_{pv} \cdot P_{vpp,t}^{pv} - \lambda_{ae} \cdot P_{vpp,t}^{ae} \tag{4}$$

where $C_{vpp,t}^{de}$ (yuan) is the generation cost of distributed energy resources within the VPP; $P_{vpp,t}^{w}$ (MW) and $P_{vpp,t}^{pv}$ (MW) are the actual outputs of wind power and photovoltaics, at time t; σ_w and σ_{pv} are the cost coefficients for wind and photovoltaic power; $P_{vpp,t}^{ae}$ (MW) is the curtailed power amount of distributed resources; λ_{ae} is the cost coefficient for curtailed power.

d: COST OF ENERGY STORAGE OPERATION

Given the charge-discharge characteristics of ESS, their generation cost is represented by the charging and discharging cost of the units. The specific formula is shown in.

$$C_{vpp,t}^{ess} = \left(\mu \cdot P_{vpp,t}^{ess+} + (1-\mu) \cdot P_{vpp,t}^{ess-}\right) \cdot \omega_{ess} \tag{5}$$

where $C_{vpp,t}^{ess}$ (yuan) is the generation cost of energy storage within the VPP; $P_{vpp,t}^{ess+}$ (MW) and $P_{vpp,t}^{ess-}$ (MW) are the charge-discharge amounts of the energy storage at time t; w_{ess} is the charge-discharge cost coefficient of the energy storage; μ is a binary variable (0-1 variable).

e: ECONOMIC LOSS COST OF FLEXIBLE LOAD

Flexible load, acting as a modulatable demand, participates in the reserve market competition. During peak electricity consumption periods, it interrupts or shifts part of its load to gain market revenue, which simultaneously incurs certain economic losses to the users. The specific formula is shown in.

$$C_{vpp,t}^{fl} = \varepsilon_c \cdot P_{vpp,t}^{cut} + \varepsilon_s \cdot P_{vpp,t}^{shf} \tag{6}$$

where $C_{vpp,t}^{fl}$ (yuan) is the generation cost associated with the energy storage within the VPP; $P_{vpp,t}^{cut}$ (MW) and $P_{vpp,t}^{shf}$ (MW) are the interruptible and shiftable load volumes, at time t; ε_c

and ε_s are the cost coefficients for interruptible and shiftable loads.

2) CONSTRAINTS

a: VPP INTERNAL POWER BALANCE CONSTRAINT

$$P^{em}_{vpp,t} + P^{srm}_{vpp,t} = P^{w}_{vpp,t} + P^{pv}_{vpp,t} + P^{ess^-}_{vpp,t} + P^{cut}_{vpp,t} + P^{shf}_{vpp,t} \tag{7}$$

b: OUTPUT CONSTRAINTS OF DISTRIBUTED ENERGY RESOURCES

$$\begin{cases} P^{w,mix}_{vpp} \le P^{w}_{vpp,t} + P^{w,ess}_{vpp,t} \le P^{w,\max}_{vpp} \\ P^{pv,mix}_{vpp} \le P^{pv}_{vpp,t} + P^{pv,ess}_{vpp,t} \le P^{pv,\max}_{vpp} \end{cases} \tag{8}$$

where $P^{w,\max}_{vpp}$ (MW) and $P^{w,mix}_{vpp}$ (MW) are the maximum and minimum power outputs of wind energy; $P^{pv,\max}_{vpp}$ (MW) and $P^{w,\max}_{vpp,t}$ (MW) are the maximum and minimum power outputs of photovoltaic energy; $P^{w,ess}_{vpp,t}$ (MW) and $P^{pv,ess}_{vpp,t}$ (MW) denote the amount of electric energy transferred from wind and photovoltaic sources to the energy storage unit at time t.

c: ENERGY STORAGE OUTPUT CONSTRAINTS

$$\begin{cases} P^{ess^+}_{vpp,t} \le S^{ess,cr^+}_{vpp} \\ P^{ess^-}_{vpp,t} \le S^{ess,cr^-}_{vpp} \\ V^{ess}_{vpp,t} = V^{ess}_{vpp,t-1} + \mu \cdot \xi_{ess^+} \cdot P^{ess^+}_{vpp,t} - (1-\mu)\xi_{ess^-} \cdot P^{ess-}_{vpp,t} \\ P^{ess-}_{vpp,t} = P^{em,ess-}_{vpp,t} + P^{srm,ess-}_{vpp,t} \\ 0 \le V^{ess}_{vpp,t} \le V^{ess,\max}_{vpp} \end{cases} \tag{9}$$

where S^{ess,cr^+}_{vpp} (MW) and S^{ess,cr^-}_{vpp} (MW) are the charging and discharging rates of the energy storage; $V^{ess}_{vpp,t}$ is the state of charge of the energy storage at time t; ξ_{ess^+} (%) and ξ_{ess^-} (%) are the charging and discharging efficiencies of the energy storage; $P^{em,ess-}_{vpp,t}$ (MW) and $P^{srm,ess-}_{vpp,t}$ (MW) are the energy discharged from the storage into the spot market and the reserve market.

d: FLEXIBLE LOAD DISPATCH CONSTRAINTS

$$\begin{cases} 0 \le P^{cut}_{vpp,t} \le \sigma_c \cdot P^{load}_{vpp,t} \\ 0 \le P^{shf}_{vpp,t} \le \sigma_s \cdot P^{load}_{vpp,t} \end{cases} \tag{10}$$

where $P^{load}_{vpp,t}$ (MW) is the amount of flexible load at time t; σ_c (%) and σ_s (%) are the proportions of interruptible load and shiftable load.

B. OUTER-LEVEL MODEL FOR THE JOINT CLEARING OF THE DAY-AHEAD AND RESERVE MARKETS

1) OBJECTIVE FUNCTION

The outer layer model is the day-ahead and reserve market clearing model, where the system operator, based on the demand status of each market and the bidding information from market participants, conducts the day-ahead market clearing under the conditions that supply-demand balance and various unit safety constraints are met. The objective function of the outer layer model aims to minimize the total electricity procurement cost for the entire society, and the specific formula is shown in.

$$\min R_{soc} = \sum_{t=1}^{T}(R^{em}_{vpp,t} + R^{srm}_{vpp,t}) + \sum_{t=1}^{T}\sum_{m=1}^{M}(P^{srm}_{m,t} \cdot Q^{srm}_{m,t} + \sum_{n=1}^{N} P^{em}_{m,n,t} \cdot Q^{em}_{m,n,t}) \tag{11}$$

where $P^{em}_{m,n,t}$ (MWh) and $Q^{em}_{m,n,t}$ (yuan/MWh) are the cleared electricity volume and clearing price of conventional units in the energy market; $P^{srm}_{m,t}$ (MW) and $Q^{srm}_{m,t}$ (yuan/MWh) are the cleared electricity volume and clearing price of conventional units in the reserve market; M is the number of conventional units.

2) CONSTRAINTS

a: REAL-TIME MARKET POWER BALANCE CONSTRAINT

$$P^{em}_{soc,t} = P^{em}_{vpp,t} + \sum_{m=1}^{M} P^{em}_{m,n,t} \tag{12}$$

where $P^{em}_{soc,t}$ (MW) is the system's real-time demand at time t.

b: RESERVE MARKET CAPACITY BALANCE CONSTRAINT

$$P^{srm}_{soc,t} = P^{srm}_{vpp,t} + \sum_{m=1}^{M} P^{srm}_{m,n,t} \tag{13}$$

where $P^{srm}_{soc,t}$ (MW) is the system's reserve requirement at time t.

c: CONVENTIONAL UNIT OUTPUT CONSTRAINT

$$P^{\min}_{m} \le \sum_{n=1}^{N} P^{em}_{m,n,t} + P^{srm}_{m,t} \le P^{\max}_{m} \tag{14}$$

where $P^{\max}_{m}$ (MW) and $P^{\min}_{m}$ (MW) are the maximum and minimum output of conventional unit m.

C. SOLUTION METHOD

The solution process for the bi-level optimization model proposed in this paper is illustrated in Fig. 5.

Firstly, the latest market information from external markets and the output data of wind power, PV, and energy storage systems are collected. These raw data, after preprocessing, will be used for subsequent analysis. Then, based on the preprocessed data, a bidding strategy aimed at maximizing the revenue of the VPP is formulated. To more accurately simulate the market environment, Latin hypercube sampling technology is employed to generate a series of typical bidding scenarios for competitors [24]. Subsequently, through scenario reduction techniques, the most representative competitor bidding scenarios r are selected from these.

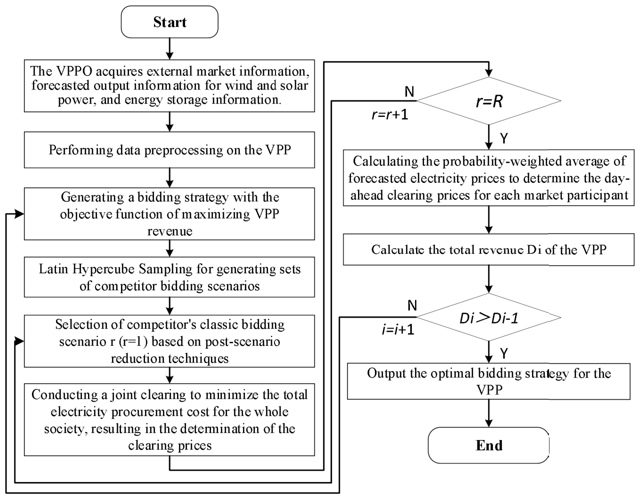


FIGURE 5. Model solving flowchart.

On this basis, the electricity trading center, aiming to minimize the overall electricity purchasing cost of society, implements a joint clearing procedure for the main market and ancillary service market to determine the clearing prices for all market participants. It is worth noting that under different bidding scenarios, the adjustment of the bidding strategies of the VPP and other traditional generating units will influence the final clearing results of the system operator through a dynamic interaction process, thereby affecting the objective function. As the strategies of all participants in the bidding process continue to optimize and adjust, when the bidding strategies of all market participants no longer change, it indicates that they have reached their optimal revenue state, i.e., a Nash equilibrium within the market has been achieved. At this point, the system operator confirms that both the inner and outer decision-making processes have reached a stable state, officially ends the interactive decision-making process, and announces the final clearing results.

V. CASE STUDIES

A. BASIC DATA

This study uses a VPP consisting of wind turbines, photovoltaic units, energy storage units, and flexible loads, along with five conventional generating units, as a case for analysis. Day-ahead scheduling is adopted, with a dispatch interval of 1 hour and a dispatch cycle of T = 24 hours. Based on the general pattern of load fluctuations, we may set the declaration period for the reserve market to be from 11:00 to 14:00 and from 18:00 to 21:00, with the system reserve demand being 10% of the system's maximum daily load. The total system load and the predicted output curves of the power sources within the VPP are shown in Fig. 6. The output parameters and cost coefficients of each power source within the VPP are presented in Table 2. The relevant information on conventional units participating in the electricity market is shown in Table 3.

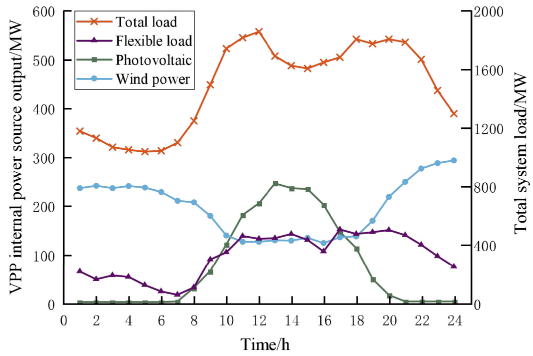


FIGURE 6. System total load and the predicted output curve of internal power sources within the VPP.

TABLE 2. Output parameters and cost coefficients of individual power sources within the VPP.

Parameter	Value
Maximum energy storage capacity (MWh)	100
Initial energy storage level (MWh)	0
Energy storage charging efficiency	0.9
Energy storage discharging efficiency	0.95
Energy storage cost coefficient	185
Wind energy cost coefficient	135
Photovoltaic cost coefficient	120

TABLE 3. Relevant information on conventional units participating in the electricity market.

Unit	Spot market price ceiling			Reserve market price ceiling (yuan)	Output constraint		
	First tier (yuan)	Second tier (yuan)	Third tier (yuan)		First tier (MW)	Second tier (MW)	Third tier (MW)
Unit C	130	215	270	180	[180, 205]	(205, 290]	(290, 350]
Unit D	135	225	270	185	[175, 200]	(200, 290]	(290, 350]
Unit E	135	220	275	185	[175, 200]	(200, 285]	(285, 350]
Unit F	140	220	280	190	[175, 195]	(195, 300]	(300, 350]
Unit G	130	225	275	180	[180, 205]	(205, 290]	(290, 350]

B. VPP OPTIMAL SCHEDULING RESULTS AND BEST BIDDING ANALYSIS

Through the model presented in this paper, the internal optimized scheduling results for the VPP can be obtained as shown in Fig. 7, with specific data presented in Table 4. The optimal bids of the VPP in various markets are presented in Table 5.

As can be seen from Fig. 7, the VPP employs efficient strategies to optimize the allocation and scheduling of its internal resources. During the early morning hours from 1:00 AM to 5:00 AM when the load is relatively low, the VPP

TABLE 4. Internal optimization results of the VPP.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Energy storage charging (MW)	-25	-25	-25	-25	-11	0	0	0	0	-8	0	0	-25	-25	-25	-25	-11	0	0	0	0	0	0	0
Energy storage - spot market (MW)	0	0	0	0	0	0	0	0	7	0	0	0	0	0	0	0	0	1	33	17	0	0	0	0
Energy storage - reserve market (MW)	0	0	0	0	0	0	0	0	0	0	42	56	0	0	0	0	0	18	13	15	0	0	0	0
Interruptible load - reserve market (MW)	0	0	0	0	0	0	0	0	0	0	17	17	17	0	0	0	0	18	18	19	18	0	0	0
Shiftable load - reserve market (MW)	0	0	0	0	0	0	0	0	0	0	9	9	9	0	0	0	0	9	10	10	9	0	0	0
Photovoltaic - spot market (MW)	2	2	2	2	2	2	3	31	65	120	181	205	246	236	234	202	146	113	49	16	3	3	3	3
Wind power - spot market (MW)	170	148	148	148	148	148	147	207	179	131	121	124	5	15	17	49	105	137	169	218	249	248	248	248

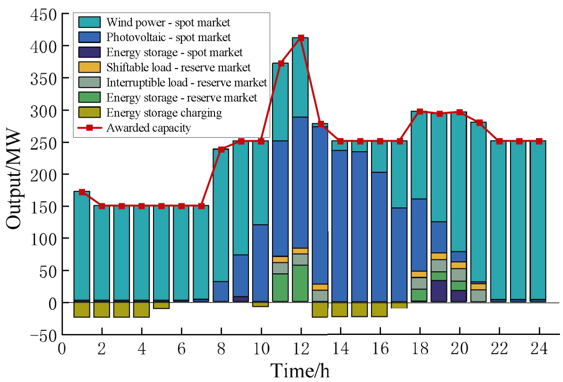


FIGURE 7. VPP internal optimization results.

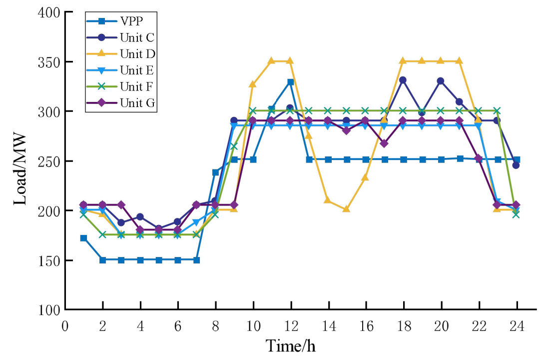


FIGURE 8. Spot market clearing results.

TABLE 5. The optimal bidding strategy of the VPP in each market.

Market type	Market bidding		
Spot Market	First tier	Output (MW)	[150,170]
		Bid (yuan/MWh)	150
	Second tier	Output (MW)	[171,251]
		Bid (yuan/MWh)	215
	Third tier	Output (MW)	[252,330]
		Bid (yuan/MWh)	275
Reserve Market	/	Bid (yuan/MWh)	185

takes full advantage of this opportunity to charge its ESS. Conversely, during peak load periods in the morning from 9:00 AM to 12:00 PM and in the evening from 6:00 PM to 9:00 PM, the role of the storage systems shifts as they discharge power to the grid. Owing to the distinctive capabilities of the ESS, the VPP is enabled to concurrently engage in both spot and reserve markets. Through judicious sizing of storage capacities, a portion thereof can be cleared in the spot market, while the majority is allocated to the reserve market. By capitalizing on the differential revenues between the two markets, the VPP achieves maximization of its aggregate profits.

C. ANALYSIS OF JOINT OPTIMIZED CLEARING IN SPOT AND RESERVE MARKETS

When the VPP adopts the aforementioned bidding strategy to participate in the joint spot and reserve market, the results of the integrated optimized operation in both markets, obtained using the model proposed in this paper, are illustrated in Fig. 8 and Fig. 9. The clearing outcomes for all market participants are presented in Tables 6 and 7.

From Fig. 8, it can be seen that in the spot market, conventional generating units are the primary source of energy supply. However, the VPP demonstrates a notably significant energy supply capability during the period from 10:00 to 13:00, mainly due to the excellent light conditions at noon, which enable PV power generation to produce higher output power. In contrast, during the nighttime hours from 0:00 to 8:00, the energy supply from the VPP is significantly reduced. This phenomenon is attributed to the lower electricity demand at night and the lack of sunlight, which prevents the PV components in the VPP from generating power, thus only providing limited energy. These observations highlight the complementary roles of different energy types at various times of the day and how reasonable scheduling can maximize the utilization potential of renewable energy sources.

According to the data in Table 6, it can be seen that the VPP's winning capacity in the spot market is 5456.15 MW, accounting for 15.33% of the total capacity of the spot

TABLE 6. The clearing results for each market participant in the spot market.

Time	VPP (MW)	Unit C (MW)	Unit D (MW)	Unit E (MW)	Unit F (MW)	Unit G (MW)
1	172	205	200	200	195	205
2	150	205	195	200	175	205
3	150	187	175	175	175	205
4	150	193	175	175	175	180
5	150	181	175	175	175	180
6	150	188	175	175	175	180
7	150	205	175	188	175	205
8	238	209	200	200	195	205
9	251	290	200	285	264	205
10	251	290	326	285	300	290
11	302	290	350	285	300	290
12	329.15	302.85	350	285	300	290
13	251	290	274	285	300	290
14	251	290	209	285	300	290
15	251	290	200	285	300	280
16	251	290	232	285	300	290
17	251	290	290	285	300	267
18	251	331	350	285	300	290
19	251	298	350	285	300	290
20	251	330	350	285	300	290
21	252	309	350	285	300	290
22	251	290	290	285	300	252
23	251	290	200	209	300	205
24	251	245	200	200	195	205
Total	5456.15	6288.85	5991	5887	6099	5879

market on that day. This figure is 572.82 MW lower than the average winning capacity of conventional generating units. This characteristic of the VPP primarily stems from its power generation system composition—comprising diverse distributed power sources such as wind, solar, and energy storage devices. Compared to traditional generating units, the power output of the VPP is more random, intermittent, and fluctuating. Therefore, when participating in market bidding, the VPP needs to consider the differences in power output across different time periods more meticulously.

Furthermore, compared to conventional generating units, the VPP typically has higher costs in terms of power generation and operation, which is also reflected in its bidding prices in the spot market. Higher costs mean that the VPP is at a disadvantage in price competition, thereby affecting its competitiveness in the spot market and leading to a relatively lower winning capacity.

From Fig. 9, it can be seen that the winning capacities of market participants in the reserve market exhibit significantly greater fluctuations compared to the spot market. This is because the reserve market primarily handles short-term power supply and demand balance and serves as a supplementary mechanism to the spot market. During the market clearing process, the system operator first ensures that the demand in the spot market is met; after the spot market clearing is completed, the remaining capacity of generating units is allocated to the reserve market. This process leads

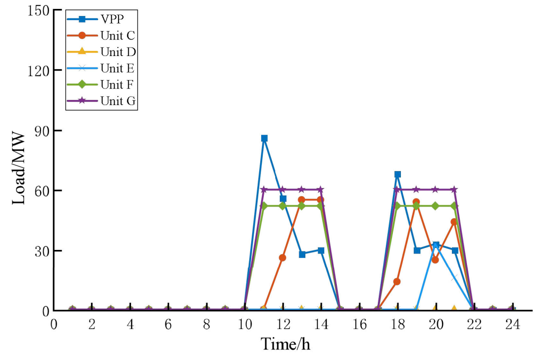
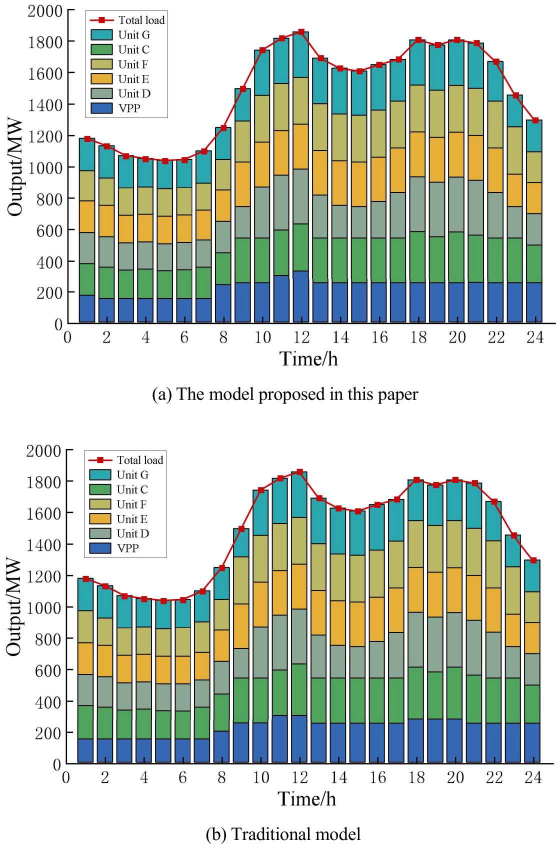


FIGURE 9. Reserve market clearing results.

TABLE 7. The clearing results for each market participant in the reserve market.

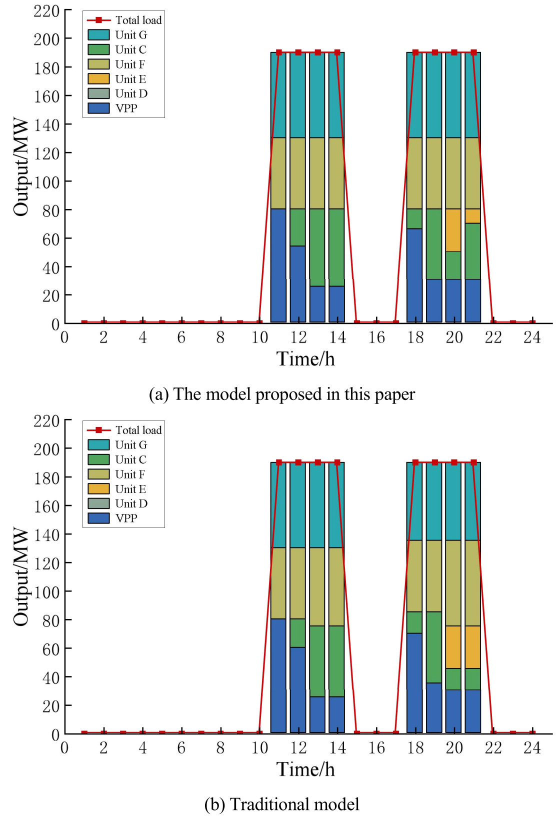
Time	VPP (MW)	Unit C (MW)	Unit D (MW)	Unit E (MW)	Unit F (MW)	Unit G (MW)
1	0	0	0	0	0	0
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	0	0	0	0	0	0
5	0	0	0	0	0	0
6	0	0	0	0	0	0
7	0	0	0	0	0	0
8	0	0	0	0	0	0
9	0	0	0	0	0	0
10	0	0	0	0	0	0
11	86	0	0	0	52	60
12	56	26	0	0	52	60
13	28	55	0	0	52	60
14	30	55	0	0	52	60
15	0	0	0	0	0	0
16	0	0	0	0	0	0
17	0	0	0	0	0	0
18	68	14	0	0	52	60
19	30	54	0	0	52	60
20	33	25	0	33	52	60
21	30	44	0	16	52	60
22	0	0	0	0	0	0
23	0	0	0	0	0	0
24	0	0	0	0	0	0
Total	361	273	0	49	416	480



(a) The model proposed in this paper

(b) Traditional model

FIGURE 10. Spot market clearing situation.



(a) The model proposed in this paper

(b) Traditional model

FIGURE 11. Reserve market clearing situation.

to larger fluctuations in the winning capacities in the reserve market.

Based on the data in Table 7, it is known that the VPP's winning capacity in the reserve market is 361 MW, accounting for 22.86% of the total reserve capacity on that day. Conventional generating units take on the primary role in the reserve market, while the VPP, due to its relatively smaller scale, has a lower winning capacity in the reserve market compared to conventional units. However, it is noteworthy that some conventional units provide a large amount of power in the spot market, limiting their available capacity in the reserve market. In such circumstances, the VPP can increase its profitability in the reserve market by raising its bidding price. This strategy not only helps improve the economic viability of the VPP but also enhances the flexibility and reliability of the power system, demonstrating the unique value of the VPP in the electricity market.

D. COMPARISON OF ELECTRICITY PURCHASE COSTS IN THE SPOT AND RESERVE MARKETS

To compare the differences in electricity purchase costs between the model proposed in this paper and the traditional model, the clearing situations of the spot market and the reserve market are shown in Fig. 10 and 11, respectively. The comparison of electricity purchase costs in the electricity market is presented in Table 8.

TABLE 8. Comparison of electricity purchase costs in the electricity market.

	Spot market electricity purchase cost (yuan)	Reserve market electricity purchase cost (yuan)	Total electricity purchase cost (yuan)
The model proposed in this paper	7348035	279500	7627535
Traditional model	7457810	279975	7737785

From the aforementioned clearing situations of the electricity market, it can be observed that the traditional market models have limitations in handling the interactions between market operators and market participants, failing to adequately consider the game-theoretic relationship between them. As a result, the market clearing outcomes under such models are not always optimal, leading to relatively higher electricity purchase costs in both the spot and reserve markets. In contrast, the bi-level game model proposed in this paper effectively addresses this issue. Through this model, market operators and participants can flexibly adjust their strategies based on changes in each other's behavior, thereby promoting the market to reach a more optimized clearing state. Specifically, after adopting the bi-level game model, the electricity purchase costs in the spot market and the reserve market were reduced by 1.47% and 0.17%, respectively, resulting in an overall decrease of 1.42% in the total electricity purchase cost.

VI. CONCLUSION

Based on the analysis of the interactive game-theoretic relationships among diversified market players, this paper investigates the joint operational optimization of the spot and reserve markets, taking into account the bidding strategies of the VPP. The specific conclusions derived from this research are as follows:

1) The joint optimization and operation method for the ESM and reserve market discussed in this article fully considers the game-theoretic competitive relationships between VPPs and other diverse market entities, achieving efficient market clearing in the electricity sector. This method achieves dual-layer optimization both internally and externally, ensuring that the VPP maximizes its revenue while also minimizing the total electricity purchase cost for society. Ultimately, compared to the traditional model, this approach reduces the electricity purchase costs in the spot market and the reserve market by 1.47% and 0.17%, respectively, leading to an overall reduction of 1.42% in the total electricity purchase cost.

2) When a VPP participates in the power market and competes with conventional power generation units, the traditional units often secure the majority of power volume shares in the spot market due to their advantages of stable output and ease of regulation. In contrast, as a new form of energy organization, the characteristics of the resource mix within a VPP make its output power more stochastic, intermittent, and volatile. This necessitates that during the bidding process in the spot market, a VPP must carefully consider variations in output power across different time periods, which to some extent limits its competitiveness in the spot market.

Additionally, the methodology proposed in this paper also has certain limitations. Specifically, the model constructed in this study assumes that market participants behave in a completely rational manner, whereas in reality, the market environment is fraught with uncertainty and information asymmetry is a common phenomenon. These factors are not fully considered in the model, which may lead to some deviation in the actual application process. To enhance the practicality and accuracy of the model, future research could attempt to incorporate more complex factors from real-world markets, such as participants' psychological expectations and market sentiment fluctuations, in order to achieve more realistic analysis results.

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