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# Dynamic Pricing and Energy Management of Virtual Power Plant Based on Source-Charge Uncertainty

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## Abstract

*With the intermittent, random and volatile distributed renewable energy mass influx into the grid and power market, the power system will face greater challenges. As a small energy autonomous system that integrates distributed generation, energy storage and load, virtual power plant connects the power market and end users, and it is also an important subject of power market reform. Its operating efficiency directly determines the effectiveness of market reform. However, virtual power plant faces the market risk of double uncertainty of internal renewable energy output and load demand during operation, so it needs to optimize the market behavior to protect its own interests. Therefore, the paper takes virtual power plant as the research object, and discusses the dynamic pricing strategy of virtual power plant considering the double uncertainty of source and charge and real-time market linkage from the aspects of theoretical analysis, modeling construction and simulation analysis, to provide reference for decision pricing of virtual power plant and formulation of electricity market reform policy.*

**Keywords:** *Dynamic Pricing, Master-Slave Game, Virtual Power Plant, Distributed Renewable Energy, Stored Energy.*

## Introduction

With increasingly serious environmental and energy crisis, energy conservation and emission reduction, improvement of energy efficiency and effective use of renewable energy have become research hotspots in the field of power system [1,2,3]. Due to the rapidly development of renewable energy generation, a single power system transaction can't meet the increasingly complex energy demand, and the traditional unified pricing can't cope with the flexible power market environment [4,5,6]. In recent years, virtual power plant (VPP) has gradually become a new main body in the power market. Through the effective integration of renewable energy into the grid, the purpose of reducing operating costs, improving energy utilization and power supply reliability can be achieved [7,8].

With the continuous development of distributed energy and emerging technologies, VPPs have become the research focus of power market. Some scholars have obtained a new model through the classification and in-depth analysis of the VPP model, which has greater applicability in the types of power market in which VPPs participate [9]. This work classifies and deeply analyzes the latest research on VPPs. The results show that there is greater diversity in the power market in which VPPs participate, and there are still challenges in this research area. Erphan introduces the latest progress of existing VPP projects, and points out the considerations, necessary frameworks, regulations and policies to realize the next generation of VPPs, which can provide reference for researchers and practitioners in the field of VPPs [10]. Wang puts forward a VPP-P2H scheduling strategy based on random bargaining game, which realizes fair profit distribution through Nash bargaining mechanism [11]. Hu puts forward a two-stage double-level bidding scheduling model to study the strategic behavior of VPPs as price decision makers [12]. Yang puts forward the VPP bidding strategy considering carbon-electricity integrated transaction in the auxiliary service market [13]. In reference [14], considering the influence of the opening of the electricity selling side on the demand-side resources participating in the electricity market, the bidding strategy of VPPs considering the demand response in the environment of the opening of electricity selling side is put forward. In reference [15], considering the uncertainty of renewable energy output and market price, a new two-stage robust Stackellberg game is proposed to solve the energy management problem of aggregate prosumers. Baringo

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discussed the pricing decision of VPPs by constructing a stochastic bilevel programming model, and verifies that VPPs can increase their profits by acting as price makers in the energy and reserve markets [16]. Most of the existing literature focuses on the internal bidding strategy and energy management of VPPs, but does not fully consider the influence of external factors on VPPs.

At present, some scholars have studied the market behavior of VPPs participating in peak regulation. Regarding the coordination and cooperation between VPP and external market and internal members, the external and internal coordination bidding strategy of VPP is proposed [17]. Considering the participation of multiple VPPs in the peaking behavior of the power market, a trading strategy based on dynamic pricing and market clearing was proposed [18]. Aiming at the information transmission phenomenon of distribution network and VPP, a distributed transaction model based on the combination of target cascade method is proposed [19]. The distribution network containing VPP power supply is modeled and analyzed, and a PSO-DE optimization algorithm is proposed to solve it [20]. He proposes a privacy-protecting distributed learning method to determine the dynamic electricity price of intelligent electric vehicles to maximize the profit of the energy system [21]. By establishing dynamic electricity price model to guide users to use electricity reasonably, energy visualization of users and power companies can be realized [22]. Based on the power transaction problem among multiple microgrids on the distribution side, a cooperative game model of multi-microgrid bargaining transaction is constructed [23]. Based on the internal power demand of microgrid system, a dynamic Stackelberg game model is constructed [24]. Most of the existing literatures only consider the influence of VPP on the safe operation of distribution network side, and do not fully consider the influence of distribution network operator (DNO) and VPP energy pricing. The price is the key factor of the market, the implementation of a reasonable energy price scheme can balance the benefits of multiple players in the power market. It can be seen that there have been a lot of studies on the game between DNOs and VPPs, but few studies on price setting and collaborative optimization of energy management.

In summary, considering different scenarios, a game optimization model between DNOs and VPPs is established to study the interaction between DNOs' dynamic pricing and VPP operation strategy, so as to realize energy management of VPPs. The optimization algorithm based on the Kriging meta-model is used to replace the internal energy management model of the VPP in solution process, and the particle swarm optimization algorithm is used to search for excellent sampling points and update and revise the Kriging model to avoid the complicated calculation of the lower game model and improve the optimization efficiency [25,26]. Finally, an example is given to verify the effectiveness of model and proposed algorithm.

Studying the pricing mechanism of VPPs under different business models can fill the academic gap in the study of pricing mechanism under different business models, and provide a feasible solution to solve the pricing mechanism of VPPs under different business models. In this paper, a master and slave game model is constructed, and the validity of the pricing mechanism and model is verified through practical calculation, which provides a theoretical basis for power generation enterprises to choose strategies when participating in market competition, and also provides a solid theoretical basis for the development of VPP pricing mechanism.

The remaining part of study is as follows: In the second part, the game model of energy management is constructed. In the third part, the construction of master-slave game model. In the fourth part, parameter hypothesis and simulation results are analyzed. In the fifth part, summary and limitations of this study.

*Energy Management Game Model*

In order to maximize their own interests, in the unit time, the internal power generation and electricity consumption of VPP will not necessarily balance, if the power surplus is called "VPP for sale", and the power shortage is called "VPP for purchase". Based on this, this paper proposes the trading mechanism between DNOs and VPPs as shown in Figure 1, including three basic subjects: power trading institutions, DNOs and VPPs. The VPP is mainly composed of four parts: wind power plant, photovoltaic power generation, energy storage and flexible load. The DNO sets the buying and selling price, and the VPP sells the excess electricity to DNO according to the selling price, while the VPP purchases the shortage electricity

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from the DNO according to the buying price. According to the interaction of the VPP, the DNO trades the on-grid price (the electricity price purchased by the DNO from the power trading institution) and the grid price (the electricity price sold by the DNO to the power trading institution) with the power market, and uses the difference between the two to obtain income.

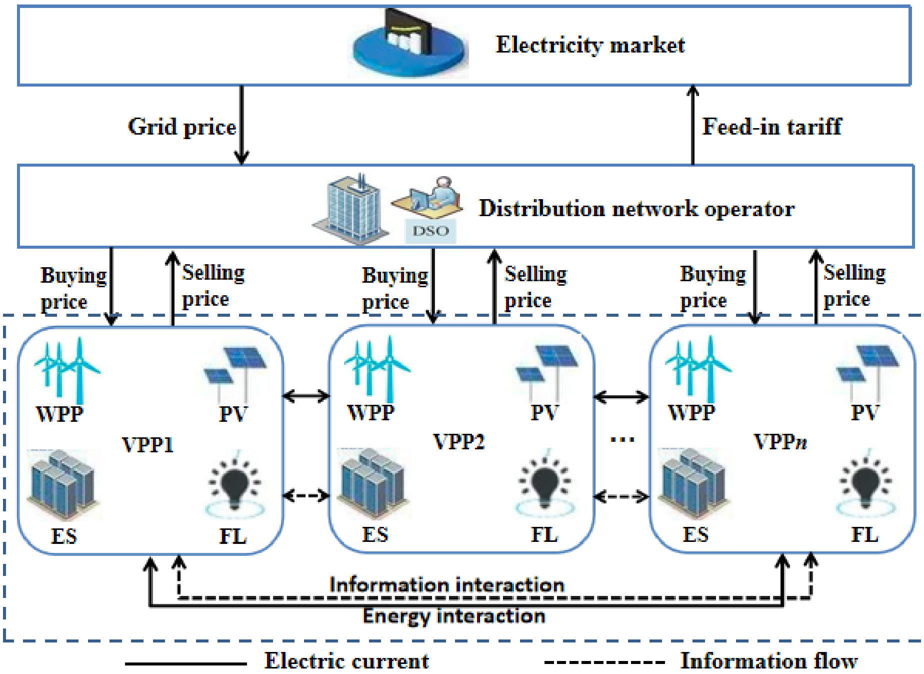


**Figure 1. Transaction Relationship Mechanism Diagram.**

Since DNOs and VPPs have different positions and investment and operation subjects, the paper regards DNOs and owners of VPPs as game participants, and constructs game block diagram as shown in Figure 2. Among them, the DNO acts as the leader, summarizes the buying and selling electricity reported by each VPP, combines the on-grid price and the grid price, considers the price response behavior of VPP, and sets the transaction price for each VPP with the goal of maximizing its own income. Each VPP acts as a follower, receives the transaction price set by the DNO, rationally arranges the internal distributed energy output, and sets the electricity traded with the operator with the goal of minimizing the operating cost. The sequential game between the leader and the follower constitutes the Stackelberg game, and the non-cooperative game is formed by the simultaneous decision among the VPPs.

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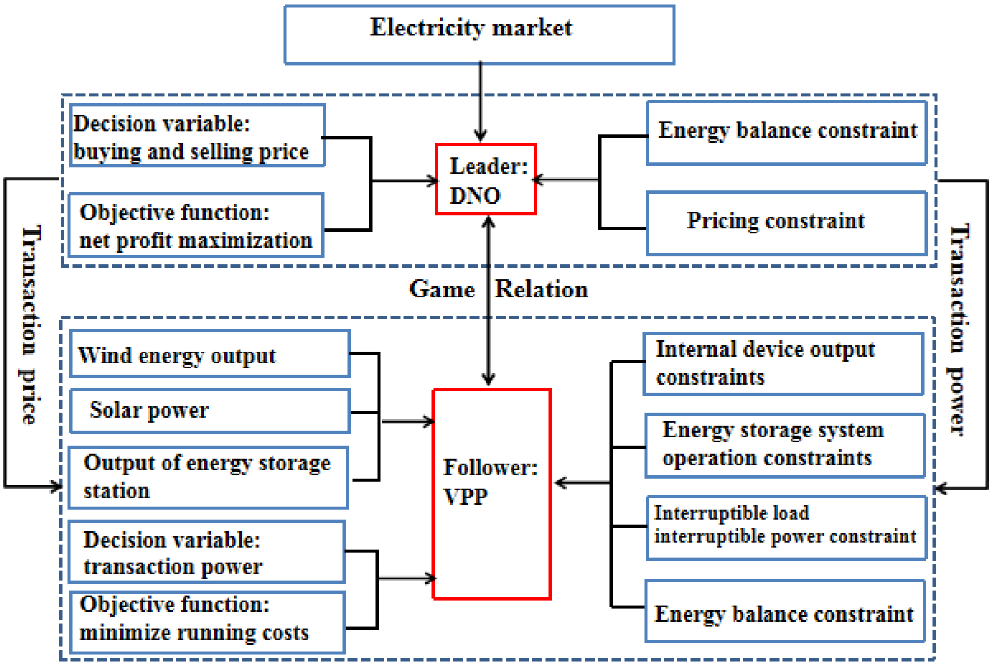


**Figure 2. Game Frame Structure Diagram.**

The energy game in this paper consists of two stages: pricing and quantification, which have a sequence and influence each other. The DNO (a leader) has the priority to decide; The VPP (a follower) makes the best response according to the leader's pricing strategy, and the leader can update its strategy again by considering the best response of the follower to obtain the maximum economic benefit.

Pricing stage: the upper level DNO sets the buying and selling price for the VPP according to the electricity transaction of the VPP, with the goal of maximizing economic benefits. The VPP with sufficient electricity sells excess electricity to the DNO according to the established sale price, while the VPP with insufficient electricity buys the shortage electricity from the DNO according to the purchase price.

Quantitative stage: The lower-level VPP determines the optimal output plan with the goal of minimizing the operating cost and trades electricity with the DNO, so the optimal decision of the lower-level can be regarded as a function of the upper-level decision variables.

*Construction Of Game Model*

The transaction power of VPP affects the income of DNOs and the price optimization strategy. Within the scope of electricity price constraint, the larger the difference of electricity price set by the DNO, the larger the transaction power of the VPP, the greater the income of the DNO. In addition, the response behavior of VPP to electricity price also affects the profit of DNOs. The higher the purchase price, the smaller the purchase power of VPP. The smaller the selling price, the smaller the selling power of the VPP, resulting in a smaller transaction power of the VPP. Therefore, there is an interest game between DNOs and VPPs.

The DNO is a leader, and the VPP is a follower. Both of them aim to maximize the net profit and minimize the operating cost respectively to develop the optimization strategy space. In the scheduling process, from the perspective of the leader, the DNO summarizes the electricity transaction situation reported by each VPP, and then combines the electricity price situation of the power trading institution to develop a reasonable price optimization strategy space. From the follower's point of view, the VPP receives the electricity price set by the DNO, reasonably arranges the internal distributed generation output and conducts electricity transaction with the DNO to minimize the operating cost.

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When we consider the game between one VPP and the DNO, we ignore the influence of other VPPs. In this case, a master-slave game model is constructed.

*One Master and One Slave Dno Game Model*

The objective function of the DNO is

$$\max C^{\mathrm{DNO}} = \max \sum_{t=1}^{24} \left( \lambda_t^{\mathrm{W,s}} P_t^{\mathrm{DNO,s}} - \lambda_t^{\mathrm{W,b}} P_t^{\mathrm{DNO,b}} + \lambda_t^{\mathrm{D,b}} P_t^{\mathrm{VPP,b}} - \lambda_t^{\mathrm{D,s}} P_t^{\mathrm{VPP,s}} \right) \tag{1}$$

Where, $C^{\mathrm{DNO}}$ is the net profit of the DNO. $\lambda_t^{\mathrm{W,s}}$ and $\lambda_t^{\mathrm{W,b}}$ are respectively the on-grid price and the grid price of the electricity market during the $t$ period. $\lambda_t^{\mathrm{D,b}}$ and $\lambda_t^{\mathrm{D,s}}$ are the purchase price and sale price formulated by DNOs for VPPs in the $t$ period, respectively. $P_t^{\mathrm{DNO,s}}$ and $P_t^{\mathrm{DNO,b}}$ are the sales and purchase of electricity from the power market by DNOs in the $t$ period respectively. $P_t^{\mathrm{VPP,b}}$ and $P_t^{\mathrm{VPP,s}}$ represent respectively the purchased and sold electricity from the VPP to the DNO during the period $t$.

(1)Electricity price constraint: In order to avoid the reluctance of VPP to conduct transactions with DNOs when considering the market price and maximizing their own interests, the purchase price of the DNO's strategy should not exceed the grid price in the power market, and the sale price should not be less than the on-grid price in the power market. The price constraint is as follows.

$$\lambda_t^{\mathrm{W,s}} \le \lambda_t^{\mathrm{D,s}} \le \lambda_t^{\mathrm{D,b}} \le \lambda_t^{\mathrm{W,b}} \tag{2}$$

Purchase and sale power constraints

$$P_t^{\mathrm{DNO}} = P_t^{\mathrm{VPP,b}} - P_t^{\mathrm{VPP,s}} \tag{3a}$$

$$P_t^{\mathrm{DNO,b}} = \begin{cases} 0, & P_t^{\mathrm{DNO}} < 0 \\ P_t^{\mathrm{DNO}}, & P_t^{\mathrm{DNO}} \ge 0 \end{cases} \tag{3b}$$

$$P_t^{\mathrm{DNO,s}} = \begin{cases} 0, & P_t^{\mathrm{DNO}} \ge 0 \\ -P_t^{\mathrm{DNO}}, & P_t^{\mathrm{DNO}} < 0 \end{cases} \tag{3c}$$

Where, $P_t^{\mathrm{DNO}}$ is the total electricity traded between the DNO and the power market. If $P_t^{\mathrm{DNO}}$ is greater than 0, it means that the DNO buys electricity from the power market. If it is less than 0, it means that the DNO has sold electricity to the electricity market.

3.2 One master and one slave VPP energy management model

The objective function of the VPP is

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$$\min f^{\mathrm{VPP}} = \min\left(C_t^{\mathrm{VPP}} + C_{m,t}^{\mathrm{ES}} + C_{m,t}^{\mathrm{DER}} + C_{m,t}^{FL}\right) \tag{4}$$

The objective function involves a number of costs, including power purchase cost $C_{i,t}^{\mathrm{VPP}}$, energy storage system operating cost $C_{m,t}^{\mathrm{ES}}$, wind generator set operating cost $C_{m,t}^{\mathrm{DER}}$ and flexible load cost $C_{m,t}^{\mathrm{FL}}$ on the demand side. $m \in M$ , $M$ is the quantity of distributed generation included in the VPP.

The specific expression of the various costs is as follows.

$$C_t^{\mathrm{VPP}} = \lambda_t^{\mathrm{D,b}} P_t^{\mathrm{VPP,b}} - \lambda_t^{\mathrm{D,s}} P_t^{\mathrm{VPP,s}} \tag{5a}$$

$$C_{m,t}^{\mathrm{ES}} = \theta_m^{\mathrm{ES}} \left(P_{m,t}^{\mathrm{ES}}\right)^2 \tag{5b}$$

$$C_{m,t}^{\mathrm{DER}} = a_m P_{m,t}^{\mathrm{W}} + b_m P_{m,t}^{\mathrm{PV}} \tag{5c}$$

$$C_{m,t}^{\mathrm{FL}} = \omega_m^{\mathrm{FL}} P_{m,t}^{\mathrm{FL}} \tag{5d}$$

Where, $\theta_m^{\mathrm{ES}}$ is the scheduling cost factor of energy storage; $P_{m,t}^{\mathrm{ES}}$ is the charge and discharge power of the energy storage, $P_{m,t}^{\mathrm{ES}}$ greater than zero means discharge, less than zero means charging; $a_m$ is the operating cost factor of the wind turbine, $P_{m,t}^{\mathrm{W}}$ is the output power of the wind turbine; $b_m$ is the operating cost factor of the photovoltaic generator set, and $P_{m,t}^{\mathrm{PV}}$ is the output power of the photovoltaic generator set. $\omega_m^{\mathrm{FL}}$ is the compensation price of the flexible load on the demand side, and $P_{m,t}^{\mathrm{FL}}$ is the interrupt power of the flexible load on the demand side.

*Power Constraint Of VPP*

$$P_t^{\mathrm{VPP}} = P_t^{\mathrm{VPP,b}} - P_t^{\mathrm{VPP,s}} \tag{6a}$$

$$0 \le P_t^{\mathrm{VPP,b}} \le (1-\alpha_t) P_{\max}^{\mathrm{VPP}} \tag{6b}$$

$$0 \le P_t^{\mathrm{VPP,s}} \le \alpha_t P_{\max}^{\mathrm{VPP}} \tag{6c}$$

Where, $P_t^{\mathrm{VPP}}$ is the transaction electricity between VPP and DNO; $\alpha_t$ is a Boolean variable. When the value is 1, it means that the VPP sells electricity to the DNO at time $t$; when the value is 0, it means that the VPP buys electricity from the DNO at time $t$. $P_{\max}^{\mathrm{VPP}}$ is the maximum amount of electricity traded between VPP and DNO.

*Power Balance Constraints*

$$P_t^{\mathrm{VPP}} + \sum_{m\in M}\left(P_{m,t}^{\mathrm{ES}} + P_{m,t}^{\mathrm{W}} + P_{m,t}^{\mathrm{PV}} + P_{m,t}^{\mathrm{FL}}\right) = \sum_{m\in M} P_{m,t}^{\mathrm{LD}} \tag{7}$$

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Where $P_{m,t}^{\mathrm{LD}}$ is the predicted value of the load at time $t$.

*Internal Power Constraints*

$$P_{m,\min}^{\mathrm{ES}} \le P_{m,t}^{\mathrm{ES}} \le P_{m,\max}^{\mathrm{ES}} \tag{8a}$$

$$R_{m,t}^{\mathrm{ES}} = R_{m,t-1}^{\mathrm{ES}} - \frac{\Delta t}{E_{m,\max}} P_{m,t}^{\mathrm{ES}} \tag{8b}$$

$$R_{m,\min}^{\mathrm{ES}} \le R_{m,t}^{\mathrm{ES}} \le R_{m,\max}^{\mathrm{ES}} \tag{8c}$$

$$0 \le P_{m,t}^{\mathrm{W}} \le P_{m,t,\max}^{\mathrm{W}} \tag{8d}$$

$$0 \le P_{m,t}^{\mathrm{PV}} \le P_{m,t,\max}^{\mathrm{PV}} \tag{8e}$$

$$0 \le P_{m,t}^{\mathrm{FL}} \le P_{m,t,\max}^{\mathrm{FL}} \tag{8f}$$

Where, $P_{m,\max}^{\mathrm{ES}}$ and $P_{m,\min}^{\mathrm{ES}}$ are the upper and lower limits of the energy storage charging and discharging power respectively; $R_{m,t}^{\mathrm{ES}}$ is the charged state of energy storage at time $t$; $E_{m,\max}$ is the maximum energy capacity of energy storage; $R_{m,\max}^{\mathrm{ES}}$ and $R_{m,\min}^{\mathrm{ES}}$ are the upper and lower limits of the state of charge respectively, where the related constraints of energy storage ignore loss. $P_{m,t,\max}^{\mathrm{W}}$ and $P_{m,t,\max}^{\mathrm{PV}}$ are respectively the maximum output power of wind turbine and photovoltaic generator set at time $t$; $P_{m,t,\max}^{\mathrm{FL}}$ is the maximum interruption of the flexible load.

When we consider the game between multiple VPPs and DNO, in this case we construct a master-many-slave game model.

*One Master and Multi-Slaves DNO Game Model*

The game strategy of the leader is to collect the transaction electricity of the VPP during the optimal scheduling period, consider the electricity price of the power trading institution and the price response of the VPP side, and then make transactions with the power trading institution according to the on-grid electricity price and the grid electricity price, in order to maximize economic benefits. Make use of the difference between the two profit to maximize the purpose of trading net profit.

The objective function of the DNO is

$$\max C^{\mathrm{DNO}} = \max \sum_{t=1}^{24} \left( \lambda_t^{\mathrm{W,s}} P_t^{\mathrm{DNO,s}} - \lambda_t^{\mathrm{W,b}} P_t^{\mathrm{DNO,b}} + \lambda_t^{\mathrm{D,b}} \sum_{i=1}^{n} P_{i,t}^{\mathrm{VPP,b}} - \lambda_t^{\mathrm{D,s}} \sum_{i=1}^{n} P_{i,t}^{\mathrm{VPP,s}} \right) \tag{9}$$

Where, $C^{\mathrm{DNO}}$ is the net profit of the DNO. $\lambda_t^{\mathrm{W,s}}$ and $\lambda_t^{\mathrm{W,b}}$ are respectively the on-grid price and the grid price of the electricity market during the $t$ period. $\lambda_t^{\mathrm{D,b}}$ and $\lambda_t^{\mathrm{D,s}}$ are the purchase price and sale price formulated by DNOs for VPPs in the $t$ period, respectively. $P_t^{\mathrm{DNO,s}}$ and $P_t^{\mathrm{DNO,b}}$ are the sales and purchase

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of electricity from the power market by DNOs in the $t$ period respectively. $P_{i,t}^{\mathrm{VPP,b}}$ and $P_{i,t}^{\mathrm{VPP,s}}$ are respectively the $i$ VPP in the $t$ period to purchase and sell electricity from the DNO. The $n$ indicates the number of VPPs.

The solution of DNO optimization model needs to ensure the power balance among VPPs and ensure that VPPs choose to trade with DNOs, so the following constraints need to be met.

Electricity price constraint: In order to avoid the reluctance of VPPs to conduct transactions with DNOs when considering the market price and maximizing their own interests, the purchase price of the DNO's strategy should not exceed the grid price in the power market, and the sale price should not be less than the on-grid price in the power market. The price constraint is as follows.

$$\lambda_t^{\mathrm{W,s}} \le \lambda_t^{\mathrm{D,s}} \le \lambda_t^{\mathrm{D,b}} \le \lambda_t^{\mathrm{W,b}} \tag{10}$$

Purchase and sale power constraints: purchase and sale power constraints are as follows.

$$P_t^{\mathrm{DNO}} = \sum_{i=1}^{n} \left( P_{i,t}^{\mathrm{VPP,b}} - P_{i,t}^{\mathrm{VPP,s}} \right) \tag{11a}$$

$$P_t^{\mathrm{DNO,b}} = \begin{cases} 0 \quad , & P_t^{\mathrm{DNO}} < 0 \\ P_t^{\mathrm{DNO}}, & P_t^{\mathrm{DNO}} \ge 0 \end{cases} \tag{11b}$$

$$P_t^{\mathrm{DNO,s}} = \begin{cases} 0 \quad , & P_t^{\mathrm{DNO}} \ge 0 \\ -P_t^{\mathrm{DNO}}, & P_t^{\mathrm{DNO}} < 0 \end{cases} \tag{11c}$$

Where, $P_t^{\mathrm{DNO}}$ is the total electricity traded between the DNO and the power market. If $P_t^{\mathrm{DNO}}$ is greater than 0, it means that the DNO buys electricity from the power market. If it is less than 0, it means that the DNO has sold electricity to the electricity market.

*One Master and Multi-Slaves VPP Energy Management Model*

The follower takes buying and selling power and distributed energy resources of each period as the strategy to play the game. After receiving the purchase and sale price set by the DNO, the internal distributed generation output is rationally arranged to achieve the purpose of minimizing the operation cost.

The objective function involves a number of costs, including power purchase cost $C_{i,t}^{\mathrm{VPP}}$, energy storage system operating cost $C_{m,t}^{\mathrm{ES}}$, wind generator set operating cost $C_{m,t}^{\mathrm{DER}}$ and flexible load cost $C_{m,t}^{\mathrm{FL}}$ on the demand side. $m \in M$, $M$ is the quantity of distributed generation included in the $i$ VPP, and the expression

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is as follows.

$$\min f_i^{\mathrm{VPP}} = \min\left(C_{i,t}^{\mathrm{VPP}} + C_{m,t}^{\mathrm{ES}} + C_{m,t}^{\mathrm{DER}} + C_{m,t}^{FL}\right) \tag{12}$$

The specific expression of the various costs is as follows.

$$C_{i,t}^{\mathrm{VPP}} = \sum_{i=1}^{24}\left(\lambda_t^{\mathrm{D,b}} P_{i,t}^{\mathrm{VPP,b}} - \lambda_t^{\mathrm{D,s}} P_{i,t}^{\mathrm{VPP,s}}\right) \tag{13a}$$

$$C_{m,t}^{\mathrm{ES}} = \theta_m^{\mathrm{ES}}\left(P_{m,t}^{\mathrm{ES}}\right)^2 \tag{13b}$$

$$C_{m,t}^{\mathrm{DER}} = a_m P_{m,t}^{\mathrm{W}} + b_m P_{m,t}^{\mathrm{PV}} \tag{13c}$$

$$C_{m,t}^{\mathrm{FL}} = \omega_m^{\mathrm{FL}} P_{m,t}^{\mathrm{FL}} \tag{13d}$$

Where, $\theta_m^{\mathrm{ES}}$ is the scheduling cost factor of energy storage; $P_{m,t}^{\mathrm{ES}}$ is the charge and discharge power of the energy storage, $P_{m,t}^{\mathrm{ES}}$ greater than zero means discharge, less than zero means charging; $a_m$ is the operating cost factor of the wind turbine, $P_{m,t}^{\mathrm{W}}$ is the output power of the wind turbine; $b_m$ is the operating cost factor of the photovoltaic generator set, and $P_{m,t}^{\mathrm{PV}}$ is the output power of the photovoltaic generator set. $\omega_m^{\mathrm{FL}}$ is the compensation price of the flexible load on the demand side, and $P_{m,t}^{\mathrm{FL}}$ is the interrupt power of the flexible load on the demand side.

When the VPP responds to the price set by the DNO, it needs to consider the operation constraints of itself and the grid, which are as follows.

*Power Constraint Of VPP*

$$P_{i,t}^{\mathrm{VPP}} = P_{i,t}^{\mathrm{VPP,b}} - P_{i,t}^{\mathrm{VPP,s}} \tag{14a}$$

$$0 \le P_{i,t}^{\mathrm{VPP,b}} \le \left(1-\alpha_{i,t}\right) P_{i,\max}^{\mathrm{VPP}} \tag{14b}$$

$$0 \le P_{i,t}^{\mathrm{VPP,s}} \le \alpha_{i,t} P_{i,\max}^{\mathrm{VPP}} \tag{14c}$$

Where, $P_{i,t}^{\mathrm{VPP}}$ is the transaction electricity between the $i$ VPP and the DNO; $\alpha_{i,t}$ is a Boolean variable. When the value is 1, it means that the $i$ VPP sells electricity to the DNO at time $t$; when the value is 0, it means that the $i$ VPP buys electricity from the DNO at time $t$. $P_{i,\max}^{\mathrm{VPP}}$ is the maximum amount of electricity traded between the $i$ VPP and the DNO.

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*Power Balance Constraints*

$$P_{i,t}^{\mathrm{VPP}} + \sum_{m\in M}\left(P_{m,t}^{\mathrm{ES}} + P_{m,t}^{\mathrm{W}} + P_{m,t}^{\mathrm{PV}} + P_{m,t}^{\mathrm{FL}}\right) = \sum_{m\in M} P_{m,t}^{\mathrm{LD}} \quad (15)$$

Where $P_{m,t}^{\mathrm{LD}}$ is the predicted value of the load at time $t$.

*Internal Power Constraints*

$$P_{m,\min}^{\mathrm{ES}} \le P_{m,t}^{\mathrm{ES}} \le P_{m,\max}^{\mathrm{ES}} \quad (16a)$$

$$R_{m,t}^{\mathrm{ES}} = R_{m,t-1}^{\mathrm{ES}} - \frac{\Delta t}{E_{m,\max}} P_{m,t}^{\mathrm{ES}} \quad (16b)$$

$$R_{m,\min}^{\mathrm{ES}} \le R_{m,t}^{\mathrm{ES}} \le R_{m,\max}^{\mathrm{ES}} \quad (16c)$$

$$0 \le P_{m,t}^{\mathrm{W}} \le P_{m,t,\max}^{\mathrm{W}} \quad (16d)$$

$$0 \le P_{m,t}^{\mathrm{PV}} \le P_{m,t,\max}^{\mathrm{PV}} \quad (16e)$$

$$0 \le P_{m,t}^{\mathrm{FL}} \le P_{m,t,\max}^{\mathrm{FL}} \quad (16f)$$

Where, $P_{m,\max}^{\mathrm{ES}}$ and $P_{m,\min}^{\mathrm{ES}}$ are the upper and lower limits of the energy storage charging and discharging power respectively; $R_{m,t}^{\mathrm{ES}}$ is the charged state of energy storage at time $t$; $E_{m,\max}$ is the maximum energy capacity of energy storage; $R_{m,\max}^{\mathrm{ES}}$ and $R_{m,\min}^{\mathrm{ES}}$ are the upper and lower limits of the state of charge respectively, where the related constraints of energy storage ignore loss. $P_{m,t,\max}^{\mathrm{W}}$ and $P_{m,t,\max}^{\mathrm{PV}}$ are respectively the maximum output power of wind turbine and photovoltaic generator set at time $t$; $P_{m,t,\max}^{\mathrm{FL}}$ is the maximum interruption of the flexible load.

*Example Analysis*

*One Master and One Slave Game Parameter Setting*

Assume that the VPP contains three producers, one flexible load and one energy storage device. Among them, the first producer is the residential type, the second producer is the commercial type, and the power generation resources owned by the residential type and the commercial type are distributed photovoltaic units, with the power of 4.3MW and 3.2MW respectively. The third producer is industrial and has a distributed wind turbine with a power of 5.1MW. In the actual operation of the VPP, the load of the prosumer is a rigid load, and the fluctuation of the prediction deviation is small. The predicted values of each prosumer and the flexible load are shown in Figure 3. The maximum allowable fluctuation deviation of flexible load power, wind power output and photovoltaic output can be set according to the previous historical forecast deviation. In this paper, the fluctuation deviation of flexible load power, wind power and photovoltaic output is considered to be 10%, 10% and 15% of the forecast respectively [27]. The wind and wind output of each prosumer is shown in Figure 4.

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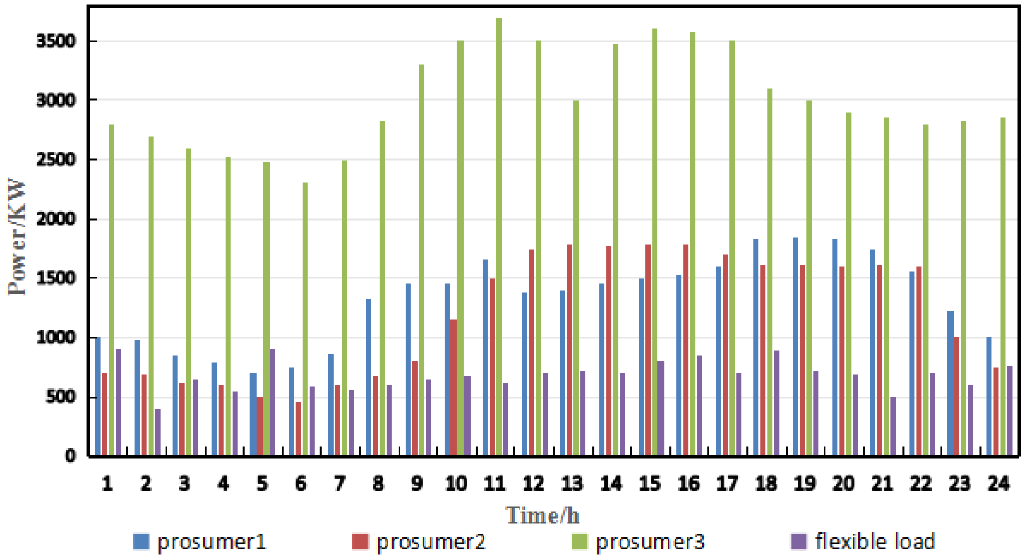


**Figure 3. Forecasts Of ProsumersaAnd Flexible Load.**

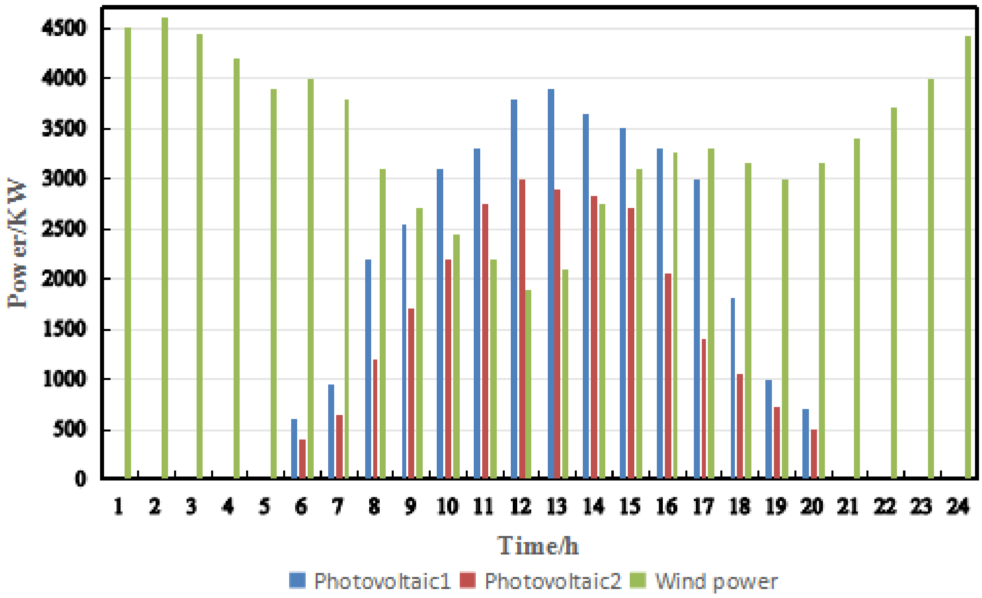


**Figure 4. Wind And Solar Power Generation**

The basic operating parameters of the VPP are shown in Table 1. The levelized kwh cost in 2020 is 0.57 yuan /kwh [28]. The purchasing price of nodes in the electricity market is shown in Table 2. The selling price in the electricity market is the average price of onshore wind power and photovoltaic online, then the purchasing and selling price in the real-time market can be obtained, and its change is shown in Figure 5.

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**Table 1. Operation Parameters Of VPP**

| Content | Parameter | Numerical value | Source |
|---|---|---|---|
| Flexible load | $P_{m,t}^{FL,pf}$ | $10\%P_{m,t}^{FL,e}$ | CEC,2013 |
| | $P_{m,t}^{FL,vf}$ | $10\%P_{m,t}^{FL,e}$ | |
| | $P_{m,t}^{FL,max}$ | $110\%P_{m,t}^{FL,e}$ | |
| | $P_{m,t}^{FL,min}$ | $90\%P_{m,t}^{FL,e}$ | |
| Photovoltaic | $P_{m,t}^{PV,max}$ | $115\%P_{m,t}^{PV,e}$ | CEC,2013 |
| | $P_{m,t}^{PV,min}$ | $85\%P_{m,t}^{PV,e}$ | |
| Wind power | $P_{m,t}^{W,max}$ | $110\%P_{m,t}^{W,e}$ | Fan,2022 |
| | $P_{m,t}^{W,min}$ | $90\%P_{m,t}^{W,e}$ | |
| Energy storage system parameters | $P_{m,max}^{ES}$ | 2000 kW | Liu,2023<br>Liu,2018 |
| | $E_{max}^{ES}$ | 4000 kwh | |
| | $E_{min}^{ES}$ | 500 kwh | |
| | $E_{0}^{ES}$ | 500 kwh | |
| | $\eta_{ch}/\eta_{dis}$ | 0.95 | |
| Interactive power of DNO | $P_{max}^{DNO}$ | 1500kw | Liu,2018 |

**Table 2. Electricity Market Node Purchase Price**

| Time | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Price(yuan/kwh) | 0.4148 | 0.3931 | 0.3875 | 0.3856 | 0.3900 | 0.4062 | 0.4664 | 0.5442 |
| Time | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
| Price(yuan/kwh) | 0.5836 | 0.5718 | 0.5432 | 0.5324 | 0.5321 | 0.5122 | 0.5066 | 0.5028 |
| Time | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 |
| Price(yuan/kwh) | 0.4933 | 0.5168 | 0.5572 | 0.5651 | 0.5442 | 0.5258 | 0.4911 | 0.4278 |

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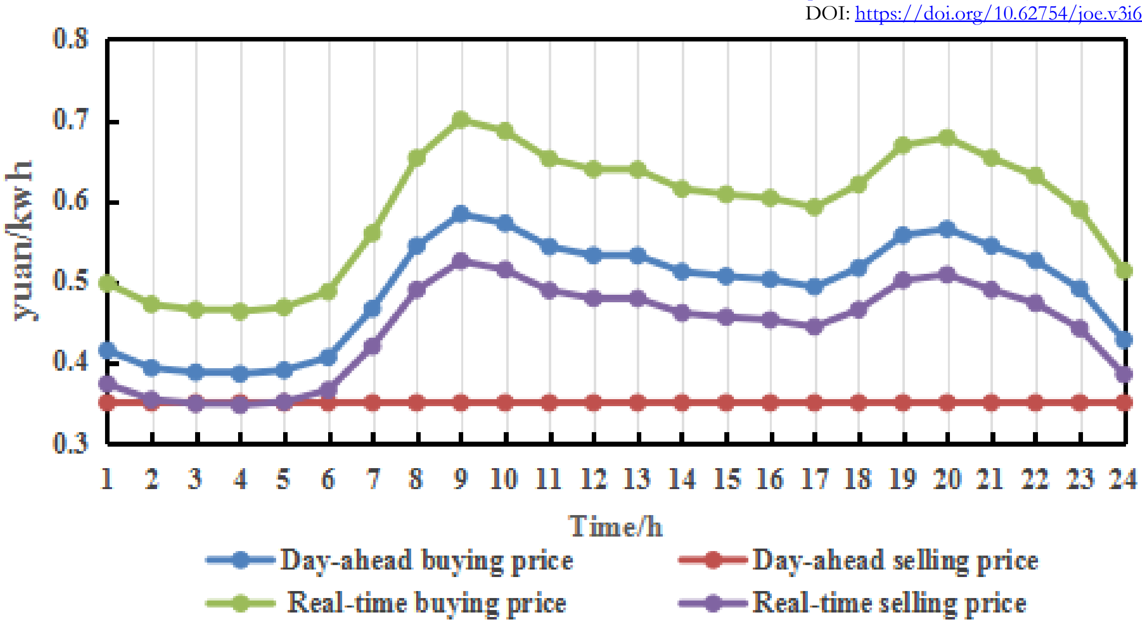


**Figure 5. Node Prices in The Electricity Market**

Analysis of simulation results of one master and one slave game

The VPP is affected by many uncertain factors, so it will have a great impact on the operating state of the system and market behavior. On the energy supply side, the output of distributed power sources such as wind power and photovoltaic is characterized by randomness, intermittency and fluctuation. On the demand side of load, due to the influence of external factors such as energy price, user scheduling plan and energy use mode, the terminal demand side also has strong uncertainty. In order to better fit the realistic scene, this part mainly considers the scene with moderate source load uncertainty. That is, the photovoltaic output reaches the minimum value of the forecast interval in the 6 periods of 9:00-14:00 and 15:00-16:00, and the wind power output reaches the minimum value of the forecast interval in the 5 periods of 22:00-3:00.

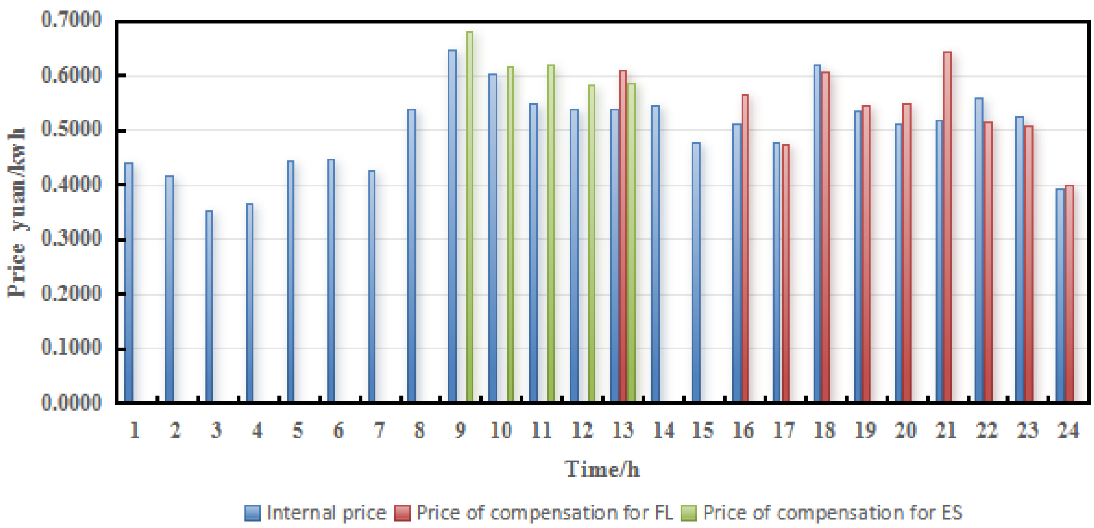


**Figure 6. Internal Pricing Of VPP**

Figure 6 shows the internal pricing under natural source load uncertainty. It can be seen that during the 5 time periods from 9:00-13:00, the VPP invokes the energy of the energy storage system. The VPP should first satisfy the energy balance among the prosumers, then call the energy supplement of the energy storage

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when the energy is insufficient, and finally dispatch the flexible load to respond to the demand.

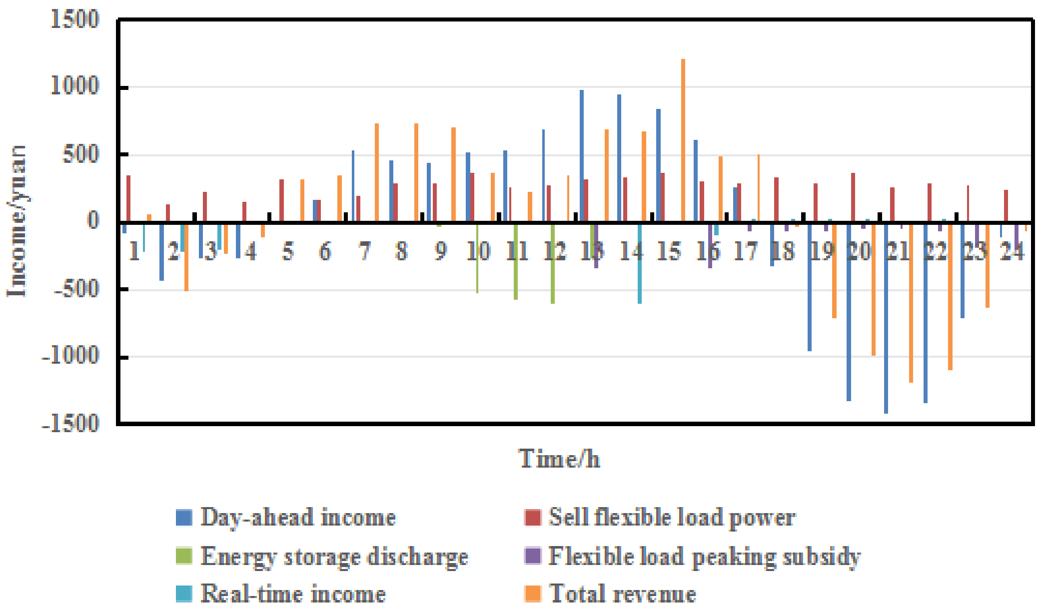


**Figure 7. Income Of Different Entities**

Figure 7 shows that flexible load participates in demand response. If the VPP does not dispatch flexible load, its income will decrease and the number of power purchase from the DNO will increase, which is not conducive to the stability of the regional power system. At the same time, the flexible load participated in the peak regulation and carried out the load interruption, so the benefit of peak regulation was obtained. In addition, the flexible load purchases electricity from the VPP, and because the internal purchase and sale price set by the VPP is lower than the retail price of the DNO, the cost of the flexible load is reduced.

The VPP through the internal and external collaborative optimization in the more wind power output period have obtained a certain income, of which 7:00-17:00 income is relatively high, is the peak period of photovoltaic power generation. Due to the uncertainty of wind power, the revenue of VPPs decreases from 0:00-1:00. 2:00-4:00 Wind power is sufficient and the load demand is less, and its income is negative. Due to the low power purchase price at this time, the VPP needs to buy a part of the electricity for storage charging. The revenue is particularly high from 13:00-15:00, because there is not only sufficient photovoltaic output during this period, but also relatively high electricity selling prices in the internal market, and the two factors of power generation capacity and price promote the high profits of VPPs.

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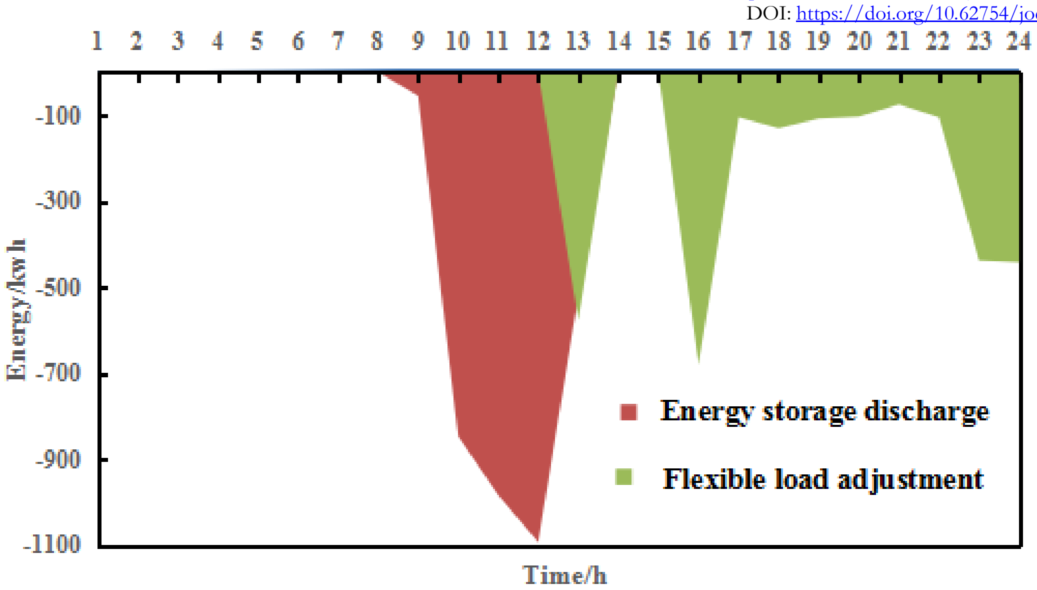


**Figure 8. Adjustment Of Flexible Load And Energy Storage Resources**

As can be seen from Figure 8, when the source load is uncertain, the energy storage mainly discharges during the peak power consumption period from 9:00-13:00, and the flexible load begins to participate in the demand response due to the increase of the load demand power from 16:00-22:00. In addition, a comprehensive comparison of Figure 8 and Figure 6 shows that the scheduling of energy storage and flexible load is positively correlated with internal pricing. When the VPP needs to schedule higher energy storage or flexible load, a higher compensation price will be set for the corresponding energy storage or flexible load. At the same time, higher internal buying (selling) prices will be set to promote the transfer of energy between prosumers.

*One Master and Many Slaves Game Parameter Setting*

The example system built in this part takes the test system containing 3 VPPs as an example. Among them, each VPP consists of four parts: wind turbine, photovoltaic generator set, energy storage device and flexible load. This calculation is based on the 2018 power grid data in North China. The relevant parameters of the energy storage device are shown in Table 3. The maximum modulation rate and compensation electricity price of flexible load are 0.1 thousand yuan /MWh and 1.4 thousand yuan /MWh respectively, the operating cost coefficients of wind power and photovoltaic are 0.3 thousand yuan /MWh and 0.04 thousand yuan /MWh respectively, and the scheduling cost coefficient of energy storage is 0.083 thousand yuan /$(MWh)^2$.The output forecasting curves and load forecasting curves of wind power and photovoltaic units are shown in Figure 9 and Figure 10 respectively.

**Table 3. Parameters Of Energy Storage Device**

| VPP | $P_{min}^{ES}$ | $P_{max}^{ES}$ | $E_{max}$ | $R_{min}^{ES}$ | $R_{max}^{ES}$ |
|---|---|---|---|---|---|
| 1 | -0.7 | 0.7 | 1 | 0.15 | 0.85 |
| 2 | -0.7 | 0.7 | 1 | 0.15 | 0.85 |
| 3 | -1.4 | 1.4 | 2 | 0.15 | 0.85 |

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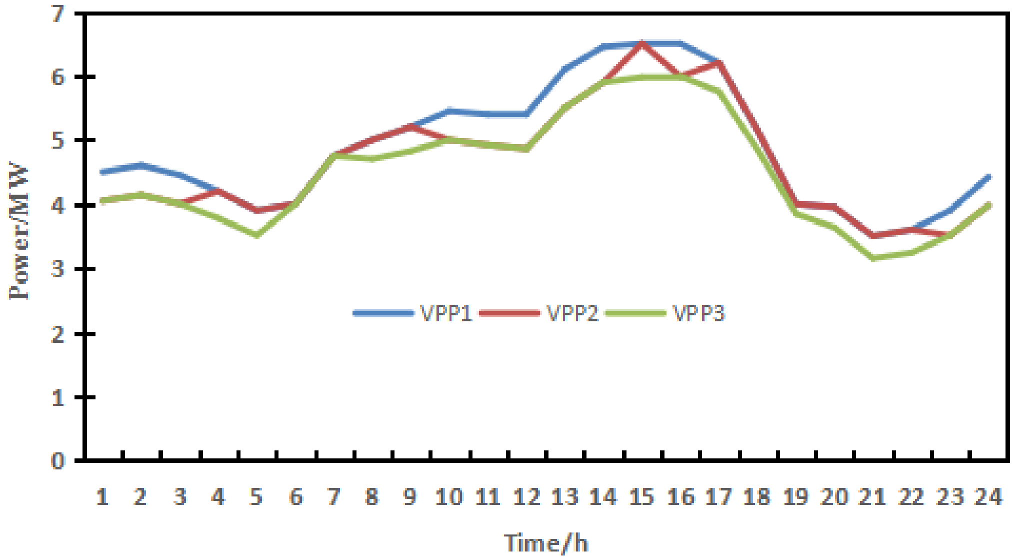


**Figure 9. Forecast Curve of Wind Power and Photovoltaic Units**

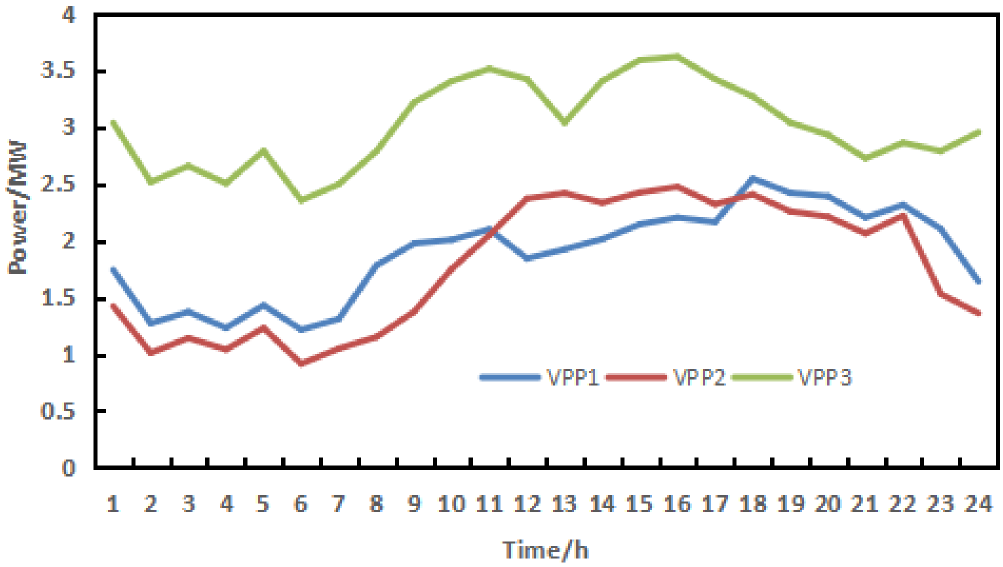


**Figure 10. Load Forecasting Curve**

*Analysis Of Simulation Results of One Master and Many Slaves Game*

In order to reflect the dynamic pricing strategy between DNO and multi-VPPs and the effectiveness of energy management, the following two strategies are set up in this part. Strategy 1 is that DNO do not adopt price optimization, and the purchase and sale price of power trading institutions is the transaction price between DNO and VPPs. Strategy 2 is for DNO to adopt the electricity price optimization strategy proposed in this paper, as shown in Figure 11.

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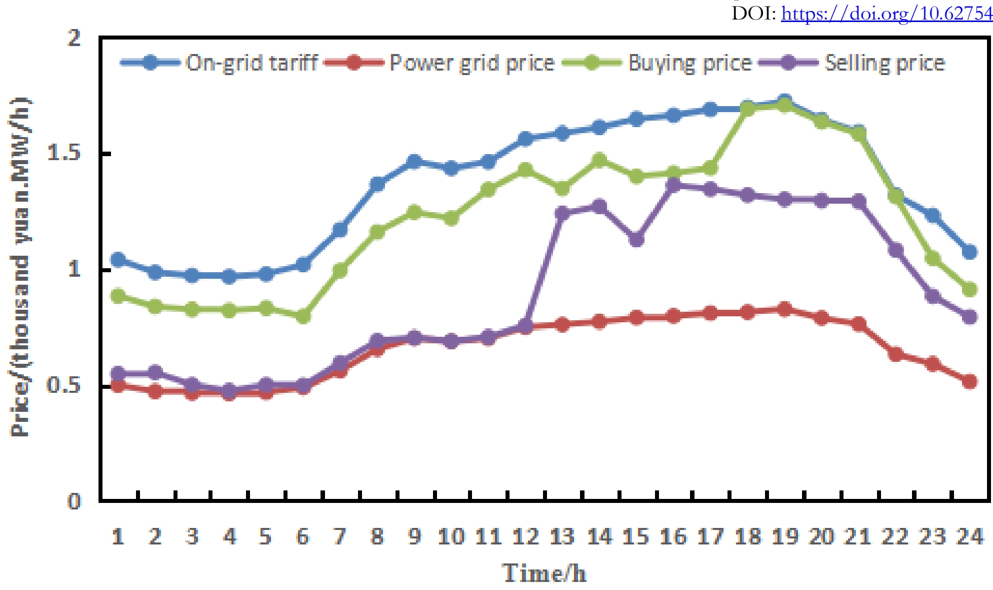


**Figure 11. Electricity Price Optimization Strategy**

Under the price optimization strategy proposed in this paper, the purchase and sale price formulated by the DNO is shown in Figure 12. As can be seen from the figure, the game maximizes the benefit of the leader and minimizes the cost of the follower. There are three cases of transaction power between vVPPs that are energy>0, energy=0 and energy<0, respectively, which are represented as electricity purchase from DNO between VPPs, internal supply and demand balance between VPPs, and electricity sales between VPPs to DNO.

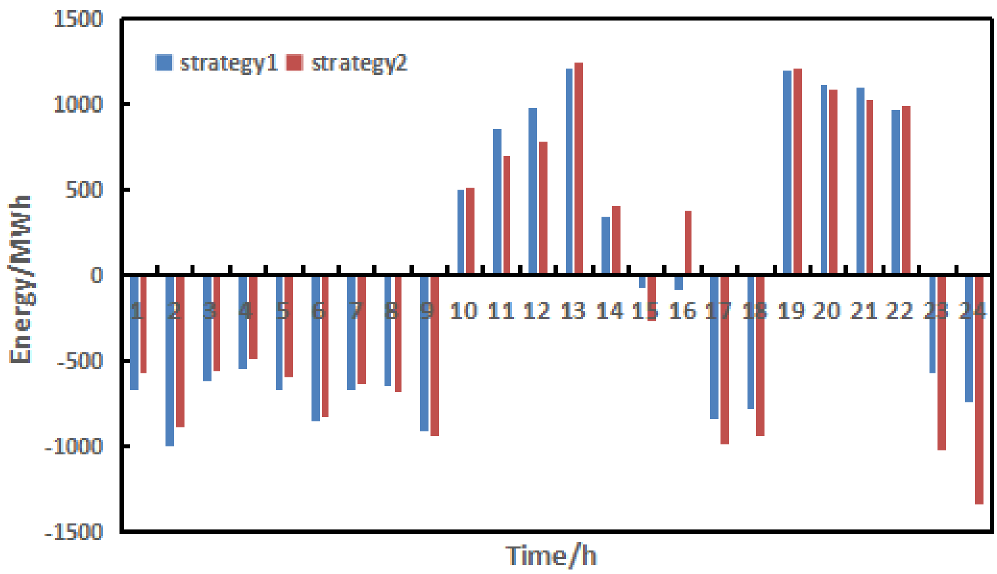


**Figure 12. Sum Of Power Buying and Selling by DNO And Vpps.**

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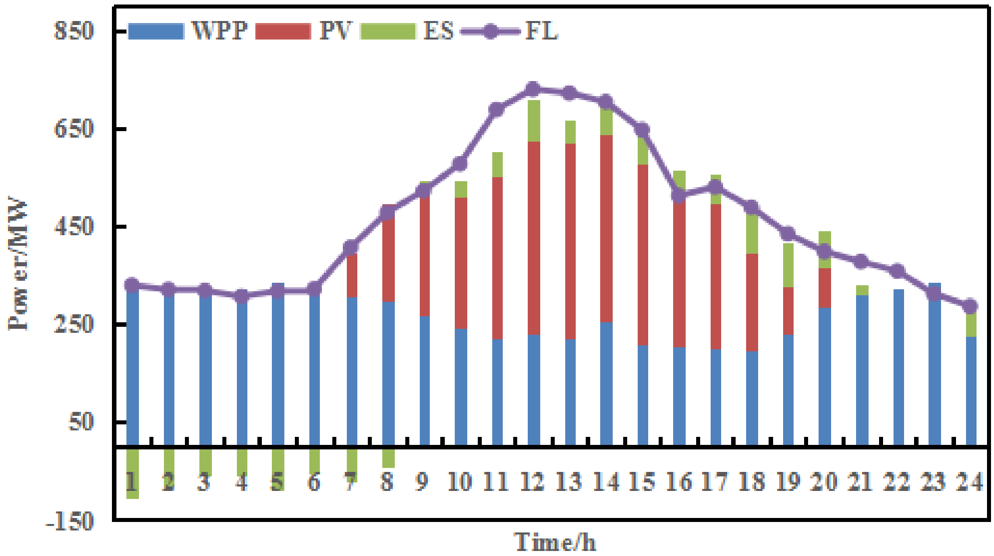


**Figure 13. System Output Under Strategy 1.**

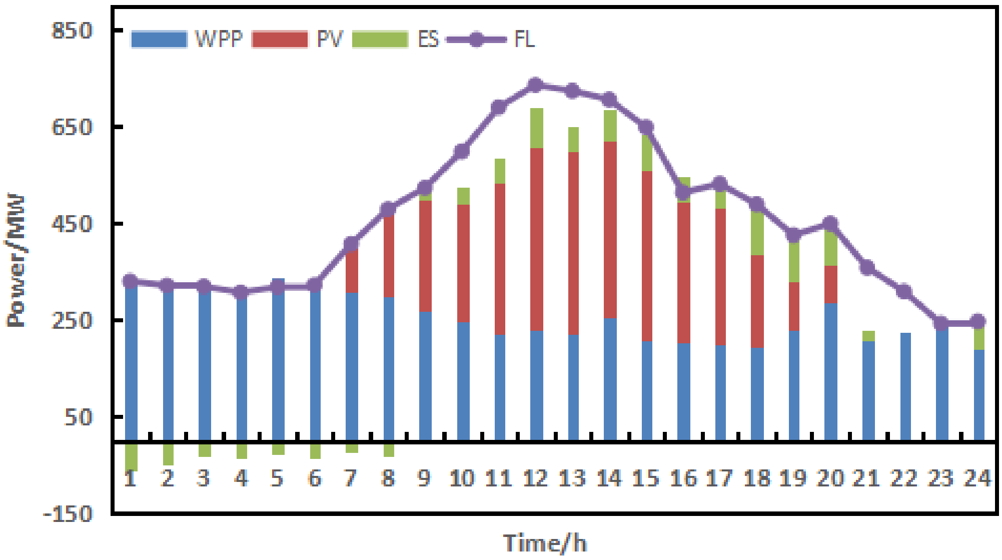


**Figure 14. System Output Under Strategy 2**

In combination with Figure 11-14, it can be seen that :(1) During the periods of 00:00-06:00 and 22:00-23:00, due to the low purchase price of strategy 1, the energy storage charging power increases, and the purchased power of the VPP increases at this time. (2) In the period of 07:00-11:00 and 17:00-21:00, the selling price and purchasing price of the two strategies are the same respectively, so the system output is basically the same. (3) During the period from 12:00-16:00, the electricity supply of solar power generation increases slightly, basically balancing the electricity demand, so the purchase and sale of electricity at this time reach a balance. (4) From 16:00-17:00, due to the high price of electricity sold at this time, the energy storage is in a discharge state, and the electricity sold by the VPP increases at this time. Therefore, through the electricity price optimization strategy, the VPP reasonably arranges the internal distributed power output plan to minimize the operating cost of the system.

In summary, the DNO and the VPP optimize the internal distributed power output of the virtual power plant system through the non-cooperative game behavior of one master and many slaves, which maximizes its own economic benefits and reduces the operating cost of the virtual power plant system. It can be seen

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that the proposed strategy has certain guiding significance.

## Conclusions

Considering the power supply pressure of the energy side of the VPP, a master-slave game model based on dynamic pricing is proposed in this paper. The DNO guides the rational internal power consumption of the VPP through the dynamic pricing strategy, and the VPP responds to the price by optimizing the internal energy output reasonably. The DNO can increase the purchase and sale electricity of VPP to maximize its own profit and reduce the total operation cost of VPP by formulating the purchase and sale price optimization strategy. The simulation results show that dynamic energy pricing can guide VPPs to purchase and sell electricity reasonably, which proves the effectiveness of the proposed strategy. At the same time, the impact of the proposed dynamic pricing strategy on DNOs and VPPs, in real life, due to the difference in distributed energy output between the summer typical day and the winter typical day, it is necessary to further modify the optimization model to improve economic benefits.

This paper only considers the dynamic pricing between VPPs and DNO, but with the further development of electricity market reform, flexible resources such as production, consumption and energy storage will have greater autonomy. In the future, the pricing situation of the game between VPPs can be considered to further optimize the market behavior of each subject and promote the full utilization of resources.

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