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A Two-Layer Peer-To-Peer Energy Sharing Model for Virtual Power Plants Based on Demand-Side Management (CEN2023)

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ABSTRACT

As a transitional layer between the electricity market and prosumers, Virtual Power Plants (VPPs) can effectively integrate distributed resources of prosumers to participate in the electricity market to improve the energy economy for prosumers. This study aggregates distributed resources such as photovoltaics, energy storage, and flexible loads into a VPP within the same community microgrid. A two-layer peer-to-peer (P2P) energy sharing model within and among VPPs is established to consume PV power and construct a stable power supply system. At the VPP-layer, a comprehensive energy management model is created to optimize the scheduling of flexible loads to achieve optimal energy economic performance of the community. At the market-layer, a VPP bidding model is established to organize P2P energy sharing among VPPs. The VPP-layer scheduling provides initial information for the market-layer to participate in energy sharing, and energy sharing results of the market-layer are fed back to the VPP-layer as boundary conditions for re-scheduling. The energy economy analysis of the proposed system shows that the community's cost is reduced by participating in P2P sharing, and the two-layer interactive mechanism can further reduce the community's cost by increasing the quantity of shared energy in the P2P market, achieving dual technological and economic benefits.

Keywords: peer-to-peer energy sharing, virtual power plant, demand-side management, PV community

NONMENCLATURE

Abbreviations	
CDA	Continuous Double Auction
DER	Distributed Energy Resource
FIT	Feed-in Tariff
P2P	Peer-to-peer
VPP	Virtual Power Plant
Symbols	
$P_{buy,grid}$	Power bought from the grid
$P_{buy,P2P}$	Power bought through P2P sharing
P_{ch}	Battery charging power
P_{dis}	Battery discharging power
P_{load}	Load demand
P_{loss}	Power loss
P_{PV}	PV power
$P_{sell,grid}$	Power sold to the grid
$P_{sell,P2P}$	Power sold through P2P sharing

1. INTRODUCTION

With the rapid development of distributed energy, the proportion of prosumers with the ability to generate and consume electricity in the distribution network is gradually increasing [1, 2]. Virtual power plants (VPPs) can effectively aggregate distributed energy resources (DERs) of prosumers, including photovoltaic (PV), energy storage systems (ESS), and flexible loads. Existing literature has studied the management of distributed energy resources within VPPs and the participation of VPPs in various electricity markets [4-6]. Ref [7-9] utilized various heuristic algorithms for aggregation and operational optimization of distributed resources within VPPs to maximize technical or economic benefits. Several studies have investigated the advantages and challenges of VPP participation in various types of electricity markets such as the day-ahead market [10, 11] and ancillary services market [12, 13].

Peer-to-peer (P2P) energy sharing provides a decentralized alternative for energy trading between VPPs, reducing transaction security risks and processing

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times brought by centralized energy management and market trading. However, there is still a lack of research on P2P energy sharing among VPPs. Meanwhile, there is a lack of information interaction between P2P sharing results and energy scheduling within VPPs, which affects access to technical and economic benefits. Therefore, this study considers aggregating PV, battery, and flexible loads in communities into VPPs, and a two-layer interactive model is established for P2P energy sharing among VPPs. The main contributions of this study are as follows:

（1）A two-layer P2P energy sharing model for VPPs is constructed. The local scheduling results of the VPP-layer and the energy sharing results of the market-layer interact with each other, improving the techno-economic benefits of the PV community through iterative optimization.

（2）An energy management model is established at the VPP-layer to organize the dispatch optimization and sharing of distributed energy by the VPP operator to achieve the optimal energy economic performance of the community.

（3）At the market-layer, an autonomous bidding model for VPPs is established, and the continuous double auction (CDA) mechanism is used to guarantee VPPs' autonomy to participate in the market.

2. SYSTEM DESCRIPTION

2.1 Two-layer interaction model

In this study, a two-layer interaction model based on P2P energy sharing for VPPs is established, including VPP-layer and market-layer, as shown in Fig. 1.

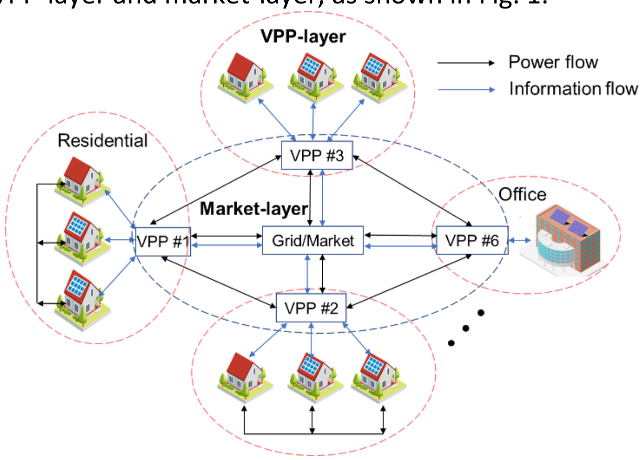

Fig. 1 Two-layer interaction model of P2P energy sharing for VPP

The VPP aggregates and controls distributed resources including PV, flexible loads (such as shiftable loads like washing machines and adjustable loads like air conditioners), and energy storage systems in PV communities of residential and office types. Under the time-of-use tariff mechanism, the VPP operator organizes P2P energy sharing within the VPP and designs optimal flexible load scheduling for users to minimize total costs. At the market-layer, a P2P energy sharing market based on the CDA mechanism is established among VPPs. VPP operators provide the market with the electricity and price to be traded, and the market matches the energy sharing contract based on the offer information. Moreover, P2P energy sharing among VPPs can utilize the complementary load profiles of different building types to further consume PV power and reduce electricity costs.

2.2 Two-layer interaction mechanism

The two-layer interaction mechanism based on P2P energy sharing is shown in Fig. 2, where the VPP-layer and the market-layer can optimize their respective behaviors through information interaction.

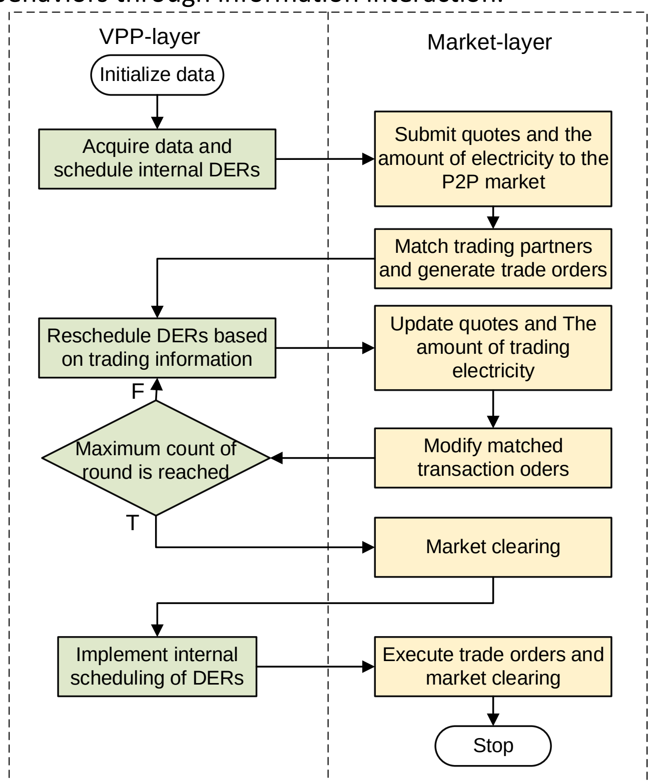

Fig. 2 Flowchart of the two-layer interaction mechanism between VPP-layer and market-layer

Initially, the VPP operator obtains the initial electricity price and load demand to schedule the internal flexible loads to minimize the total electricity cost and generate the electricity demand or supply information of the entire VPP. The electricity price between households and VPP operators is the retail electricity price and the feed-in tariff (FIT). The VPP operator quotes the transaction price and quantity to the market based on the internal electricity demand or supply information. The market matches energy sharing orders among VPPs through the CDA mechanism, where the price of the order is between the FIT and the retail tariff to benefit both buyers and sellers. The energy sharing information is fed back to the VPP-layer, which then re-plans the scheduling of internal flexible loads and generates new energy supply and demand information to be sent to the market-layer. The VPPs in the market-layer re-match the transaction based on the modified energy supply and demand information, resulting in new transaction prices and quantities, and feeding back to the VPP-layer. After multiple iterations until reaching the maximum iteration times, the market is cleared and the electricity demand or supply that failed to be matched is met by the utility grid.

2.3 Power balance modeling

Depending on whether the VPP buys or sells PV power in the P2P market, the VPP is divided into buyer VPP (b-VPP) and seller VPP (s-VPP). The power balance equation of b-VPP is shown in Eq.(1):

$$\begin{aligned} &P_{PV}(t)+P_{dis}(t)+P_{buy,P2P}(t)+P_{buy,grid}(t) \\ &=P_{load}(t)+P_{loss}(t), \forall b-VPP \end{aligned} \tag{1}$$

where the left side of this equation represents the power supply, including PV power, battery discharging and power bought from the P2P market and grid. The total power consumption is on the right side, including load demand and power loss.

Similarly, the power balance equation of s-VPP is shown in Eq.(2):

$$\begin{aligned} P_{PV}(t)=P_{load}(t)+P_{sell,P2P}(t)+P_{sell,grid}(t) \\ +P_{ch}(t)+P_{loss}(t), \forall s-VPP \end{aligned} \tag{2}$$

On the left of this equation, only PV power is available as energy supply, while the energy consumption includes load demand, electricity sold to the P2P market and grid, battery charging and power loss.

3. RESULTS AND DISCUSSIONS

This study simulates a P2P energy sharing market as a case study consisting of six PV communities in Shenzhen, including five residential communities and one office building, named VPP #1 - VPP #6. Three comparison modes are proposed, including the VPP mode, the VPP+P2P mode, and the two-layer interaction mode. In the first mode, VPPs independently control the internal load operation without P2P energy sharing among them. In the second mode, there is P2P energy sharing between VPPs but no information interaction between the VPP-layer and the market-layer, while in the third mode, information can be interacted between the two layers.

Fig. 3 shows the total cost of electricity for each VPP under the three modes. Since P2P sharing enables VPP to trade electricity at a price between the FIT and the retail tariff, its implementation reduces the total cost of electricity for each VPP by 4%-22% compared to the VPP mode. On this basis, through the two-layer interaction, the VPPs adjust their internal flexible load dispatch according to the market trading information. This allows the seller VPP to sell power when the trading price is high and the buyer VPP to buy power when the trading price is low. Thus, buyers and sellers participate in the P2P market and obtain financial benefits. The two-layer interaction reduces the cost of VPPs by 2%-9%.

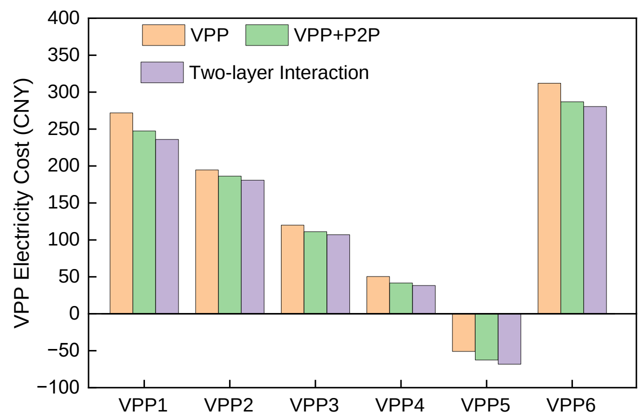

Fig. 3 Electricity cost of each VPP under the three modes

To investigate the impact of two-layer interaction on P2P energy sharing among VPPs, Fig. 4 shows the electricity purchased through P2P sharing before and after the implementation of two-layer interaction, represented by VPP #1.

In the two-layer interaction mode, the P2P energy sharing information within the market-layer is used as a signal for internal flexible load dispatching. Flexible loads are scheduled to operate in periods when P2P energy sharing price is low, thus allowing VPP #1 to purchase more PV power at low price to meet high load demand. Compared to the mode without two-layer interaction, VPP #1 purchases more PV power from other VPPs at a lower price than the retail price through P2P sharing from 8:00-14:00 and 15:00-16:00. For VPP #1, the power purchased through P2P sharing increases from 108.5 kWh to 116.8 kWh.

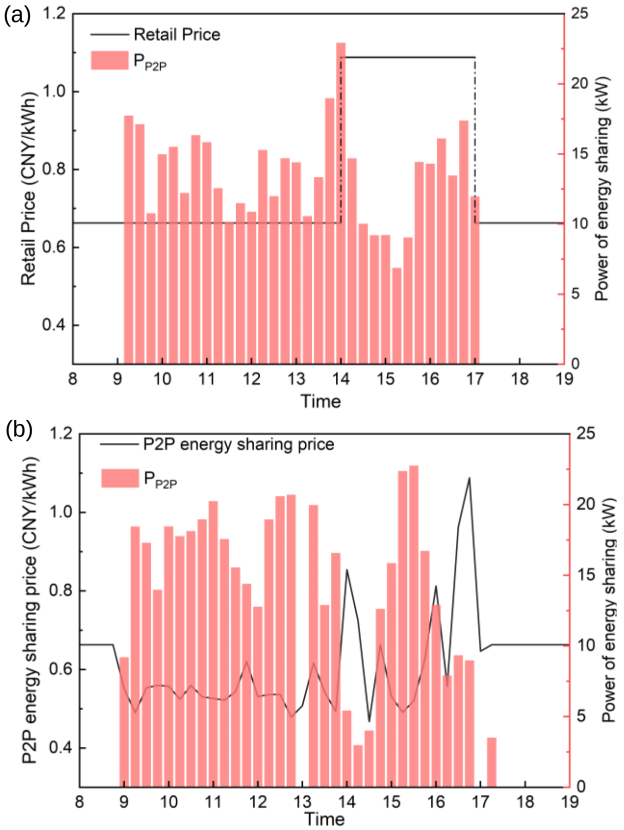

Fig. 4 Power purchased by VPP #1 through P2P sharing (a) VPP+P2P mode (b) Two-layer interaction mode

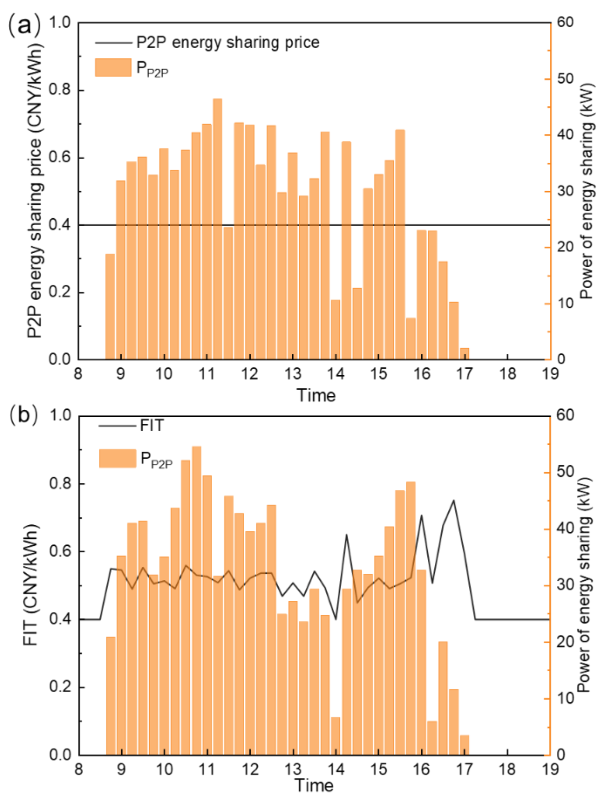

Fig. 5 Power sold by VPP #5 through P2P sharing (a) VPP+P2P mode (b) Two-layer interaction mode

shows VPP #5 as a representative of selling energy through P2P sharing. With the two-layer interaction, the transaction information in market-layer is used as a signal to influence the flexible load dispatch of VPP-layer. In this case, some flexible loads within VPP #5 are dispatched to operate at moments when P2P energy sharing price is low, allowing more power to be sold in the P2P market at a high price. For example, during 10:00-12:00 and 15:00-16:00, compared to the mode of P2P+VPP, VPP #5 sells more PV power at a higher price than FIT and obtains higher revenue. The power sold by VPP #5 through P2P increases from 257.5 kWh to 281.3 kWh.

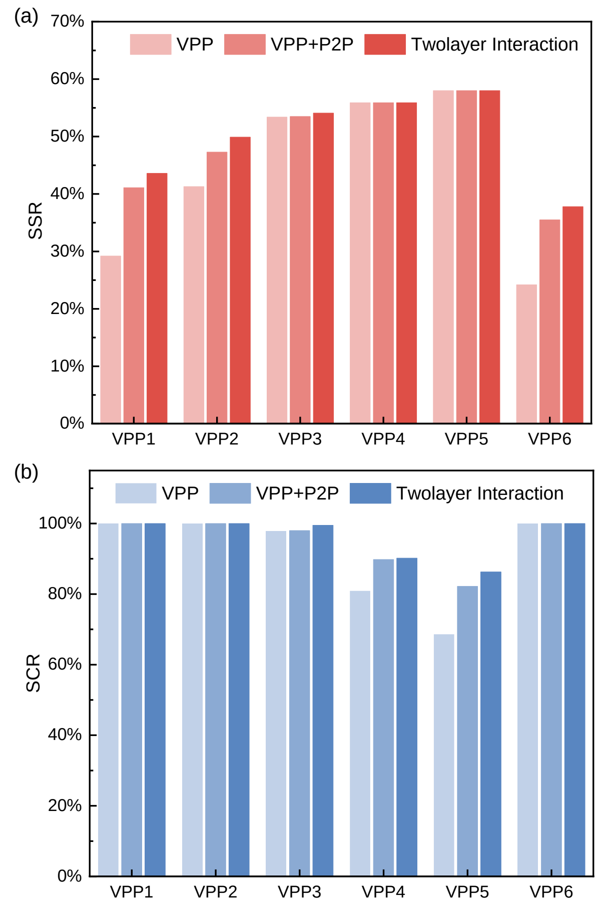

Fig. 6 The SSR and SCR of each VPP in three modes

To measure the impact of P2P sharing and the two-layer interaction mechanism on the energy supply and demand of the VPPs, Fig. 6 shows the self-consumption rate (SCR) and self-sufficiency rate (SSR) of each VPP under the three modes. In communities with low PV penetration (e.g., VPP #1 and VPP #2), the PV power is fully consumed and the SCR is 100%. In communities with high PV penetration (e.g., VPP #4 and VPP #5), the PV power is quite high and cannot be completely consumed within the community, resulting in less than 100% of SCR. Through P2P energy sharing among VPPs, the VPPs with high PV penetration can sell excess PV generation to other VPPs, thus increasing their SCR and the SSR of other VPPs. For example, the SSR of VPP #1 increases from 29.2% to 40.8%, an increase of 43.5%, while the SCR of VPP #5 increases from 68.6% to 82.2%, an increase of 19.8%.

In the two-layer interaction mode, a 5% increase in SCR is achieved by VPP #5 by adjusting the flexible load dispatch to enable more PV power to participate in energy sharing. Similarly, the two-layer interaction allows the buyer VPP to adjust flexible loads to operate at times when the market's energy supply is sufficient, further increasing the SCR of VPP #1 from 41.2% to 44.5%.

4. CONCLUSIONS

In this study, VPPs are used to achieve aggregated control of distributed resources, and a two-layer interaction model for VPPs based on P2P energy sharing is constructed from the perspective of energy economics, which could enhance the technical and economic benefits of the PV community.

Due to the different PV penetration rates and the differences in load profiles of different building types, VPPs can consume lots of PV power by sharing excess PV generation in the P2P market. As a result, the techno-economic benefits of VPPs are improved, including reducing the cost of VPPs by 4-22% and increasing the SCR and SSR by up to 40%. Moreover, with the two-layer interaction mechanism, the VPP operator adjusts its internal flexible load dispatching to sell or buy more PV power in the P2P energy sharing market based on the trading information. Thus, the techno-economic performance of VPPs is further enhanced, with electricity cost savings of 2%-9% for VPPs and approximately 5% increase for SSR and SCR.

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DECLARATION OF INTEREST STATEMENT

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

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