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A Two-Layer Interactive Mechanism for Peer-to-Peer Energy Trading Among Virtual Power Plants

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Abstract: This paper addresses decentralized energy trading among virtual power plants (VPPs) and proposes a peer-to-peer (P2P) mechanism, including two interactive layers: on the bottom layer, each VPP schedules/reschedules its internal distributed energy resources (DERs); and on the top layer, VPPs negotiate with each other on the trade price and quantity. The bottom-layer scheduling provides initial conditions for the top-layer negotiation, and the feedback of top-layer negotiation affects the bottom-layer rescheduling. The local scheduling/rescheduling of a VPP is formulated as a stochastic optimization problem, which takes into account the uncertainties of wind and photovoltaic power by using the scenarios-based method. In order to describe the capability of a seller VPP to generate more energy than the scheduled result, the concept of power generation potential is introduced and then considered during order initialization. The multidimensional willingness bidding strategy (MWBS) is modified and applied to the price bidding process of P2P negotiation. A 14-VPP case is studied by performing numerous computational experiments. The optimal scheduling model is effective and flexible to deal with VPPs with various configurations of DERs. The parallel price bidding with MWBS is adaptive to market situations and efficient due to its rapid convergence. It is revealed that VPPs can obtain higher profit by participating in P2P energy trading than from traditional centralized trading, and the proposed mechanism of two-layer "interactivity" can further increase VPPs' benefits compared to its "forward" counterpart. The impacts of VPP configuration and VPP number are also studied. It is demonstrated that the proposed mechanism is applicable to most cases where VPPs manage some controllable DERs.

Keywords: peer-to-peer energy trading; virtual power plant; two-layer interactive; local scheduling; distributed energy source; power generation potential

1. Introduction

In recent years, distributed energy resources (DERs) have attracted worldwide attention due to their simplicity, flexibility, and capability in exploiting renewable energy. However, large-scale penetration of small-capacity DERs raises great challenges for the operation of power grids because of the inherent uncertainties of DERs. The virtual power plant (VPP) is an effective solution to this problem. A VPP integrates and coordinates various DERs, including wind turbines (WTs), photovoltaics (PVs), micro gas turbine (MTs), energy storage systems (ESs), interruptible loads, etc. [1]. Although the outputs of internal DERs may be intermittent and highly uncertain, the overall behavior of a VPP is more deterministic. Thus, from the perspective of a power grid, each VPP is an entity whose output is predictable and controllable. A number of VPP projects have been launched in Europe, the United States, and China due to the effectiveness in integrating DERs [2–5].

As a rational player in the electricity market, a VPP attempts to maximize profit by optimally scheduling internal DERs. VPPs are energy sellers if they have surplus quantity and are energy buyers if they have a shortage in quantity. In the traditional electricity market, energy is centrally traded, and the grid corporation (GridCo) plays a central and dominant role. GridCo gathers information for all VPPs, clears the market, and then buys electricity from energy producers and sells electricity to energy consumers.

The optimal scheduling of a VPP and centralized energy trading evolving VPPs are thoroughly investigated. Reference [6] studies the scheduling model of VPP integrating wind, photovoltaics, hydro power, and energy storages where GridCo balances the power bidding deviation and charges the VPP imbalance fee. Reference [7] presents a bi-objective dispatch model in terms of economic cost and power quality and applied a long short-term memory network to improve the accuracy of wind prediction. In reference [8], VPP participates in joint energy and regulation reserve markets, and the uncertainties are taken into account. The demand response (DR) can also be applied to the optimal scheduling of VPP. References [9,10] carry out economic analyses of the DR in some VPP cases. In references [11,12], a collaborative scheduling model of VPP based on typical scenarios is established, but the model needs a centralized dispatch center to gather information and control VPPs, which can only be applied to cases with a small number of VPPs. In reference [13], the method of the multiple agent system is applied to transform a complex centralized control problem into a series of distributed optimization problems, while safety, stability, and economic efficiency can be guaranteed. Reference [14] builds a bi-level coordination mechanism of multiple VPPs, where the game theory is applied to describe the behavior of VPPs, but energy transactions among VPPs are still centrally regulated. References [15,16] propose a hierarchical structure for optimally operating a multi-microgrid system, where a control center coordinates all microgrids after their local optimizations. Although the centralized trading mode theoretically achieves global optimization of the entire system, it suffers from many drawbacks, such as intensive data transmission, heavy computation, weak scalability, and high vulnerability in case of a trade center crash.

Emerging technologies, such as smart metering, high-speed telecommunication, and blockchain, are offering decentralized alternatives for energy trading among VPPs. In the decentralized electricity market, each VPP is a peer with equal rights, and VPPs with an energy surplus can directly trade with VPPs with an energy shortage through peer-to-peer (P2P) negotiations. GridCo is no longer the energy broker dominating the market, but the energy transporter according to the results of P2P trading, and the power reserve provider in cases of imbalance. P2P energy trading has many advantages over centralized trading on economy, efficiency, reliability, scalability, and robustness [17,18].

Generally, P2P energy trading adopts a multi-layer structure. References [19,20] divide the process of P2P energy trading into several interoperability layers: transaction, control, information, grid, etc.which decouple the original functions, such as energy trading, information exchange, and device control. Blockchain [21] has been the enabling technology for P2P energy trading in recent years. Reference [22] presents a secure energy trading system called "energy blockchain" that uses a credit-based architecture to support fast and frequent energy trading. Reference [23] proposes a decentralized scheduling method of microgrids based on blockchain and P2P energy trading, and the power flow constraints are taken into account.

The strategy of price bidding is a crucial problem in P2P negotiation. Classical automated bidding strategies include zero intelligence, zero intelligence plus, and adaptive aggressiveness strategies [24,25], which are used in the continuous double auction market. Based on these strategies, reference [26] improves the adaptive aggressive bidding strategy and utilizes a blockchain technology called "color coins", thereby enabling traders to dynamically adjust their bidding strategies according to market information. Reference [27] uses the support vector machine algorithm to forecast the price and then determine its own bidding. With a knapsack approximation algorithm, reference [28] presents a mechanism of market clearing to maximize the economic surplus. However, the strategy of continuous double auction only considers the price of buyers and sellers, ignoring other preferences of traders, such as expected trading quantity, physical location, power flow, and environmental awareness. References [29,30] design an adaptive algorithm of price bidding for P2P energy trading and apply multidimensional willingness to quantify the dynamic attitude changes of traders in bidding. References [31–33] provide a new perspective on P2P trading by using a two-sided market approach. Considering the benefits of all players, reference [31] solves two problems: how each buyer selects sellers for and how transaction prices are decided. In reference [32], an innovative method considering network intermediation is proposed to promote the economy. Reference [33] discusses the network neutrality regulations of the Internet in the context of a two-sided market model and verifies that network neutrality regulation can be warranted by setting rational parameters, even if some competition is present.

To the best of the authors' knowledge, most of the existing work assumes that there is solely a forward path from local scheduling to P2P negotiation, i.e., the results of local scheduling setup the initial conditions of P2P negotiation, and the results of P2P negotiation do not affect local scheduling. However, it is revealed that some DERs may not be sufficiently utilized in the first round of local scheduling due to the lack of market information. Since the hierarchical collaborative scheduling model with central control institutions [15,16] can fully exploit these power generation potentials, we believe that it is reasonable for each VPP to respond to the results of P2P negotiation and to reschedule the internal DERs (i.e., local rescheduling), so that the power generation potential in each VPP is fully exploited. As a result, this paper deals with power generation potential as an element of the tradable quantity in P2P negotiation, considering that VPPs with an energy surplus may be able to provide more power than the results of local scheduling.

In this paper, VPPs involved in transactions build a decentralized trading platform, which can be treated as a two-sided market, where energy surplus and shortage are traded among VPPs in a P2P fashion. The changes of the supply–demand relationship have a tremendous impact on the bidding strategy. Hence, the multi-dimensional willingness bidding strategy (MWBS), an adaptive algorithm proposed in reference [30], is modified in this paper. MWBS quantifies the dynamic attitude changes of traders, based on the global supply–demand relationship, matching degree of bidding quantity, time pressure, and other factors. In this paper, due to the power generation potential, we focus on the modification of global supply–demand relationship and matching degree of bidding quantity.

The contributions of this paper are summarized as follows.

(1) The two-layer structure of a multi-VPP power system is constructed. On the bottom layer, VPP coordinates the internal DERs and performs local scheduling. On the top layer, there is a two-sided market, where energy surplus and shortage are traded among VPPs in a P2P fashion.
(2) The interactive mechanism between two layers is proposed. The local scheduling results on the bottom layer and the matched order results on the top layer can affect each other. The power generation potentials are taken into account
(3) A VPP day-ahead local scheduling model is established, where uncertainties of wind and solar power are described by typical scenarios with probability information.
(4) The MWBS, an adaptive algorithm of price bidding, is modified and applied to P2P negotiation. The prices are iteratively adjusted and negotiated among VPPs.

The remainder of this paper is organized as follows. Section 2 outlines the structure of a multi-VPP system and presents the process of P2P energy trading as a flow of trade order processing. Section 3 establishes the local scheduling/rescheduling model of a VPP. Section 4 concentrates on the strategy of bidding price in the stage of P2P negotiation. Section 5 performs a case study and analyzes the computational results. Finally, we draw the conclusions of the whole paper in Section 6.

2. Mechanism of P2P Energy Trading

2.1. Structure of a Multi-VPP System

A multi-VPP system for P2P energy trading can be presented by a hierarchical structure consisting of two interactive layers: the intra-VPP layer on the bottom and the inter-VPP layer on the top, as shown in Figure 1.

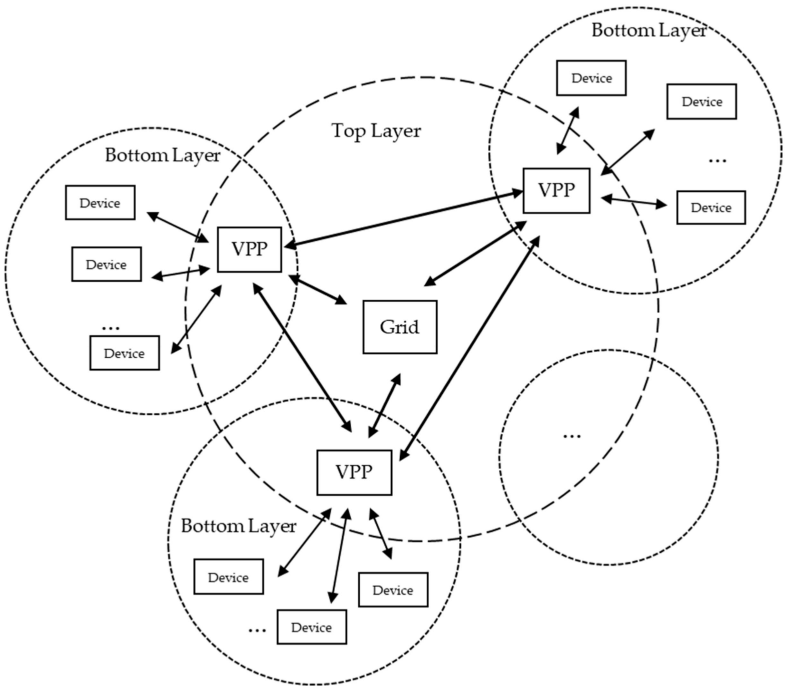


Figure 1. Schematic diagram of the peer-to-peer (P2P) energy trading mechanism involving two interactive layers.

On the bottom layer (intra-VPP), each VPP independently performs the local scheduling/rescheduling of internal DERs based on the estimated or forecast states. In this paper, the DERs of a VPP include load (L), WT, PV, MT, ES, and DR. The outputs of the first three DERs are predictable, and the outputs of the last three are controllable. In addition, this paper uses interruptible load to achieve DR, with which the VPP can control some internal demand. It is assumed that all internal DERs of a VPP are fully cooperative, although they may belong to different stakeholders. Thus, a VPP has the complete authority to schedule the internal DERs to maximize its overall profit. The local scheduling/rescheduling results of a VPP determine its role in P2P energy trading.

On the top layer (inter-VPP), all VPPs participate in the P2P energy trading, and each VPP is a peer in this market. VPPs with energy shortage and with energy surplus behave as buyers and sellers, respectively. The trade prices are negotiated among multiple peers (buyers or sellers) in parallel. A P2P trade order is successfully matched if the trade price is agreed upon by the two peers. GridCo has three responsibilities: 1) check (and tailor, if necessary) matched P2P orders to ensure system safety, 2) transmit energy according to matched P2P orders, 3) provide a power reserve for unmatched P2P orders to balance the energy shortage or surplus.

From the perspective of the electricity market, the bottom-layer (re)schedulings of different VPPs are performed in parallel, and the top-layer negotiation among peer VPPs is fully decentralized, and all trade orders are matched in a P2P manner; there is neither a trade center nor an exchange hub. However, the centralized role of GridCo cannot be removed based on the physical constraints and technical requirements of the power system.

2.2. Process of P2P Energy Trading

The trade order plays a crucial role in P2P energy trading among VPPs. As illustrated in Figure 2, the process of P2P energy trading is flow of trade order processing, which consists of five stages, as follows.

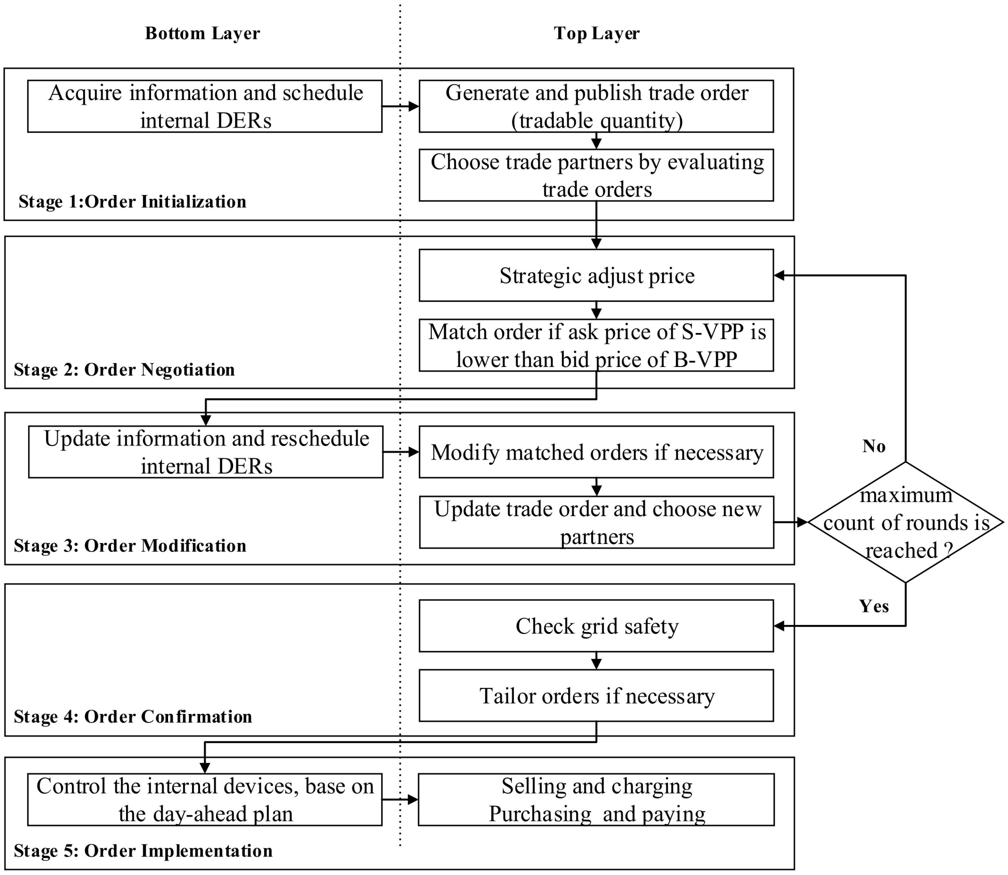


Figure 2. Five-stage trade order processing of P2P energy trading. VPP, virtual power plant; DER, distributed energy resource.

Stage 1: Order initialization. On the bottom layer, each VPP independently acquires multi-source information (weather forecast, market conditions, price signal, status of internal DERs, etc.) and derives the optimal scheduling of local DERs. The local scheduling results for each VPP determine its role on the top layer: VPPs with energy surplus/shortage are sellers/buyers in the P2P market, which are respectively denoted by S-VPP and B-VPP.

Considering the local scheduling results and the power generation potential, each VPP determines the tradable quantity. This information is published in the P2P market. Each B-VPP submits trade requests to multiple seller-VPPs (at most three in this paper), according to its own preference. Each S-VPP chooses its trade partners by evaluating the trade requests. The trade order of a VPP indicates the tradable quantity, the ask/bid price, and the trade partners. The format of the trade order is shown in Figure 3.

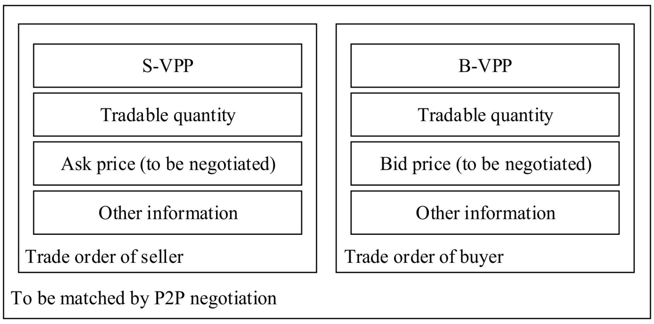


Figure 3. Format of trade order in P2P energy trading.

Stage 2: Order negotiation. Each S/B-VPP evaluates the market conditions and applies sophisticated strategies to adjust the ask/bid price in parallel. Generally, S-VPPs reduce their ask prices and B-VPPs raise their bid prices. At this stage, the ask price of an S-VPP can be different for different trade partners. A trade order is successfully matched if the ask price of an S-VPP is no higher than the bid price of one trade partner. The tradable quantity is updated when a trade order is successfully matched.

In a round of P2P negotiations, the preceding procedure is repeated until no more trade orders can be matched for most $\overline{r}$ runs.

Stage 3: Order modification. The results of order matching on the top layer are utilized as the feedback for a VPP to reschedule the internal DERs of the VPP on the bottom layer. Since the tradable quantity of an S-VPP includes its power generation potential, which may be overestimated, the result of rescheduling may not be able to fully satisfy orders matched in Stage 2. Hence, some trade orders may be modified, and each S-VPP preferentially satisfies orders with a higher price to obtain a greater benefit.

After rescheduling, VPPs that still have a tradable quantity regenerate the trade order and reselect trade partners by considering the unmatched tradable quantity and the power generation potential (the process is similar to order initialization). Then, go back to Stage 2 for a new round of order negotiations. The trade orders in previous rounds will not be changed.

This procedure is unconditionally repeated for $\overline{R}$ rounds.

Stage 4: Order Confirmation. GridCo is responsible for the system safety check by examining the power flows, nodal voltage deviations, etc. Some orders will be tailored, and the output of relevant VPPs will be clamped in the case of congestion management [34]. The confirmed trade orders are to be committed.

Stage 5: Order Implementation. According to the already confirmed trade orders, S-VPPs produce and sell energy, and B-VPPs purchase and consume energy. Further, considering the uncertainty of DERs, VPPs should maintain their actual outputs as scheduled by regulating internal DERs. GridCo monitors the actual output of each VPP and charges VPPs for providing the services of energy transmission and power reserve.

In this paper, we assume that the P2P energy trading is hourly and day-ahead. Hence, the first four stages of the trade order processing are repeated for each hour of a day, and all the P2P trade orders in 24 hours should be accomplished before 00:00 on the running day, and Stage 5 is carried out every hour of the running day. In the following sections, we focus on Stages 1–3 and perform investigations in detail. Due to space limitations, Stages 4 and 5 are not considered in this paper.

3. Model of Local (re)Scheduling on Bottom Layer

On the bottom layer, each VPP optimally schedules internal DERs by compromising multi-source information. The results of local scheduling and rescheduling are used for trade order initialization (Stage 1) and modification (Stage 3), respectively.

3.1. Local Scheduling for Order Initialization

It is nontrivial for a VPP to schedule internal DERs due to the uncertainties of renewable energy (wind, photovoltaics, etc.). Generally, the forecast error follows a normal distribution with a zero mean [35]. In this paper, we adopt a scenario-based method to describe the uncertainties of WTs and PVs. Thousands of scenarios of wind and photovoltaic power are randomly generated by using the Monte-Carlo simulation, and then a set of typical scenarios $\mathbb{S}$ is obtained by using a clustering algorithm [15,36]. A VPP schedules internal DERs by compromising all typical scenarios in $\mathbb{S}$.

3.1.1. Objective

The objective of VPP is to maximize the profits via the optimal scheduling of internal DERs in various scenarios:

$$\max F_n = \max \sum_{t \in \mathbb{T}} \sum_{s \in \mathbb{S}}]\rho_n^s \left(W_{n,t} + V_{n,t}^s - K_{n,t}^s \right) \tag{1}$$

where F, W, V, and K are the profit, revenue of energy trading, penalty of nonscheduled output, and operation costs of a VPP, respectively. $]\rho$ is the probability of a scenario. n, t, and s, as subscripts and superscripts for variable X, indicate that X belongs to VPP$_n$ at time unit t under scenario s.

Since the local scheduling of internal DERs is the first step of P2P trading, VPPs have no knowledge about the P2P negotiation results. It is sensible for a VPP to consider the worst case, that no order can be matched, and it can only trade with GridCo. The revenue is

$$W_{n,t} = C_{\text{FIT},t} \cdot Q_{\text{sur},n,t} - C_{\text{RTP},t} \cdot Q_{\text{short},n,t} \tag{2}$$

$$g(x) = \max(x, 0) \tag{3}$$

$$Q_{\text{sur},n,t} = g(P_{n,t} \cdot \Delta t) \tag{4}$$

$$Q_{\text{short},n,t} = g(-P_{n,t} \cdot \Delta t) \tag{5}$$

where C_{RTP} and C_{FIT} are the real-time price (RTP) and feed-in tariff (FIT) of the energy trading with GridCo, respectively. $g(x)$ is a "valley-fill" function that only converts negative numbers to zero, and Q_{sur} and Q_{short} are the energy surplus and shortage of a VPP, respectively. P_n is the scheduled net output of VPP$_n$. $P_{n,t} > 0$ implies that VPP$_n$ has an energy surplus and plays the role of a seller in P2P energy trading; $P_{n,t} < 0$ implies that VPP$_n$ has an energy shortage and plays the role of the buyer in P2P energy trading.

The actual net output of a VPP in scenario s is the algebraic sum of the output of internal DERs:

$$P_{n,t}^s = P_{\text{WT},n,t}^s + P_{\text{PV},n,t}^s + P_{\text{MT},n,t}^s + P_{\text{ES},n,t}^s + P_{\text{DR},n,t}^s + P_{\text{L},n,t} \tag{6}$$

where the subscripts "WT", "PV", "MT", "ES", "DR", and "L" indicate that the output power is associated with wind turbines, photovoltaics, micro gas turbines, energy storage systems, demand responses, and load demand, respectively. Notice that $P_{\text{ES}} > 0$ if ES is discharging, and $P_{\text{ES}} < 0$ if ES is charging, and generally $P_{\text{L}} < 0$.

Due to the inherent uncertainties of internal DERs, the net outputs of VPP under various scenarios tend to deviate from the scheduled result:

$$\Delta P_{n,t}^s = \left(P_{n,t}^s - P_{n,t} \right) \tag{7}$$

GridCo provides power reserves to compensate for deviations, and VPPs are economically penalized for such nonscheduled output. The penalty for a VPP is to sell its overproduced energy to GridCo at lower price, or to buy the under-produced energy from GridCo at higher price:

$$V_{n,t}^s = C_{\text{FIT},t} \left(1 - \alpha^+ \right) g\left(\Delta P_{n,t}^s \Delta t \right) - C_{\text{RTP},t} (1 + \alpha^-) g\left(-\Delta P_{n,t}^s \Delta t \right) \tag{8}$$

where α^{+}, α^{-} are pre-set penalty coefficients for positive and negative deviation, respectively. The surplus power ($\Delta P^{s}_{n,t} > 0$) is sold to GridCo at a price under FIT. The unsatisfied demand ($\Delta P^{s}_{n,t} < 0$) is bought from GridCo at a price higher than RTP.

The total cost of a VPP includes the economic cost of enabling DR, the fuel cost of MT, and the operating cost:

$$K^{s}_{n,t} = a_{\mathrm{DR},n}(P^{s}_{\mathrm{DR},n,t}\Delta t)^{2} + b_{\mathrm{DR},n}\left(P^{s}_{\mathrm{DR},n,t}\Delta t\right) + a_{\mathrm{MT},n}(P^{s}_{\mathrm{MT},n,t}\Delta t)^{2} + b_{\mathrm{MT},n}\left(P^{s}_{\mathrm{MT},n,t}\Delta t\right) + c_{n} \tag{9}$$

where a, b, c are coefficients of the quadratic cost functions.

3.1.2. Constraints

In order to ensure the safety of the power system, the output of each VPP under any scenario should be limited:

$$\underline{P}_{n,t} \leq P^{s}_{n,t} \leq \overline{P}_{n,t} \tag{10}$$

Each DER has output limits, as follows:

$$0 \leq P^{s}_{\mathrm{Z},n,t} \leq \overline{P}^{s}_{\mathrm{Z},n,t} \tag{11}$$

$$\underline{\Delta P^{s}}_{\mathrm{Z},n,t} \leq P^{s}_{\mathrm{Z},n,t+1} - P^{s}_{\mathrm{Z},n,t} \leq \Delta\overline{P}^{s}_{\mathrm{Z},n,t} \tag{12}$$

where $Z \in \{\mathrm{WT}, \mathrm{PV}, \mathrm{MT}, \mathrm{ES}, \mathrm{DR}\}$. Notice that the output limits of MT, ES, and DR are invariant with scenarios.

The state-of-charge (SOC) and the efficiency of ES during the charge/discharge process are both taken into account:

$$SOC^{s}_{n,t} = SOC^{s}_{n,t-1} + \eta_{\mathrm{ch}} g\left(-P^{s}_{\mathrm{ES},n,t}\Delta t\right) - \frac{1}{\eta_{\mathrm{dis}}} g\left(P^{s}_{\mathrm{ES},n,t}\Delta t\right) \tag{13}$$

$$SOC^{s}_{n,24} = SOC_{n,0} \tag{14}$$

$$0 \leq SOC^{s}_{n,t} \leq \overline{SOC}_{n} \tag{15}$$

where η_{ch} and η_{dis} are the efficiency during the charge and discharge processes.

Since the impact of DR on a consumer's life is expected to be minimized, the proportion of the DR of the total load should be limited for both one single hour and two continuous hours:

$$\frac{P^{s}_{\mathrm{DR},n,t}}{P_{L,n,t}} \leq \overline{\xi}_{n} \tag{16}$$

$$0 \leq \frac{P^{s}_{\mathrm{DR},n,t}}{P_{L,n,t}} + \frac{P^{s}_{\mathrm{DR},n,t+1}}{P_{L,n,t+1}} \leq \overline{\xi}^{\mathrm{cn}}_{n} \tag{17}$$

where $\overline{\xi}_{n}$ and $\overline{\xi}^{\mathrm{cn}}_{n}$ are the relevant upper limits.

3.1.3. Power Generation Potential

Based on the scheduled net output, which is the result of local scheduling, each VPP can determine the initial tradable quantity for subsequent P2P negotiation. For a B-VPP (indexed by i), its tradable quantity is equal to the scheduled net output since it is of the top priority to satisfy the internal demand.

$$\hat{Q}_{i,t} = Q_{\mathrm{short},i,t} = g(-P_{i,t} \cdot \Delta t)\ \forall i \in \mathbb{N}_{B} \tag{18}$$

On the contrary, the net output of an S-VPP (indexed by j) can be higher than the scheduled output due to the power generation potential:

$$\hat{Q}_{j,t} \geq Q_{\text{sur},j,t} = g\left(P_{j,t} \cdot \Delta t\right) \; \forall j \in \mathbb{N}_S \tag{19}$$

Indeed, the tradable quantity of S-VPP$_j$ assumes that all DERs provide the maximum outputs:

$$\hat{Q}_{j,t} = \left[\sum_{s \in \mathbb{S}}]\rho_j^s \left[\overline{P}^s_{\text{WT},j,t} + \overline{P}^s_{\text{PV},j,t}\right] + \overline{P}_{\text{MT},j,t} + \overline{P}_{\text{ES},j,t} + \overline{P}_{\text{DR},j,t} + P_{\text{L},j,t}\right] \Delta t \; \forall j \in \mathbb{N}_S \tag{20}$$

In this paper, each B-VPP can submit requests to at most three S-VPPs for P2P trading, based on the transmission distance.

3.2. Local Rescheduling for Order Modification

3.2.1. Formulation of Matched Orders

As mentioned in Section 2.2, the stages of order negotiation and modification are unconditionally repeated for $\overline{R}$ rounds. In each round, since the local rescheduling is after the P2P order matching, all the matched orders of this round and the previous rounds can affect the rescheduling results.

For B-VPP$_i$, the newly matched orders in round R are denoted by

$$\left\{\left(C^{[R]}_{j\to i,t}, Q^{[R]}_{j\to i,t}\right)\middle| j \in \mathbb{N}^{[R]}_{S,i,t}\right\} \tag{21}$$

and for S-VPP$_j$, the newly matched orders in round R are denoted by

$$\left\{\left(C^{[R]}_{j\to i,t}, Q^{[R]}_{j\to i,t}\right)\middle| i \in \mathbb{N}^{[R]}_{B,j,t}\right\} \tag{22}$$

where $\mathbb{N}_{S,i}$ and $\mathbb{N}_{B,j}$ are the sets of P2P trade partners, with whom B-VPP$_i$ and S-VPP$_j$ trade energy, respectively. $C_{j\to i,t}$ and $Q_{j\to i,t}$ are the trade prices and traded quantity between S-VPP$_j$ and B-VPP$_i$. $[R]$ as a superscript indicates that the variable is associated with the R^{th} round of P2P negotiation.

3.2.2. Formulation of Matched Orders After Modification

Since the tradable quantity of an S-VPP includes the power generation potential, which may be overestimated, the result of rescheduling may not be able to fully satisfy the orders matched in Stage 2. Hence, some trade orders may be modified.

For B-VPP$_i$, the newly modified orders in round R are denoted by

$$\left\{\left(C^{[R]}_{j\to i,t}, q^{[R]}_{j\to i,t}\right)\middle| j \in \mathbb{N}^{[R]}_{S,i,t}\right\} \tag{23}$$

and all orders till round R are

$$te_R\left\{\left(C^{[R]}_{j\to i,t}, q^{[R]}_{j\to i,t}\right)\middle| j \in \mathbb{N}^{[R]}_{S,i,t}\right\}. \tag{24}$$

For S-VPP$_j$, the newly modified orders in round R are denoted by

$$\left\{\left(C^{[R]}_{j\to i,t}, q^{[R]}_{j\to i,t}\right)\middle| i \in \mathbb{N}^{[R]}_{B,j,t}\right\} \tag{25}$$

and all orders till round R are

$$te_R\left\{\left(C^{[R]}_{j\to i,t}, q^{[R]}_{j\to i,t}\right)\middle| i \in \mathbb{N}^{[R]}_{B,j,t}\right\} \tag{26}$$

where $q_{j\rightarrow i,t}^{[R]}$ is the traded quantity between S-VPP$_j$ and B-VPP$_i$ in the modified orders, which can be determined by the process of rescheduling in round R.

3.2.3. Update of Revenue

The objective of local rescheduling is still to maximize the profit and has a similar expression as Formula (1). However, the revenue from energy trading is slightly different, since the results of the P2P order matching are taken into account.

The revenue of a VPP includes the revenue from trading with GridCo and the revenue derived from P2P trading. The P2P trading can reduce the amount of energy sold/bought to/from GridCo, which should be considered when calculating the revenue of trading with GridCo. The P2P trading revenue is the sum of the accumulated revenue of previous rounds and the newly-added revenue of round R. Because of its power generation potential, S-VPP may modify some matched orders, i.e., S-VPPs determine $q_{j\rightarrow i,t}^{[R]}$ in matched orders after modification. Since local rescheduling is complemented independently by each VPP, B-VPP cannot gain the modified result immediately, and can only utilize the quantity $Q_{j\rightarrow n,t}^{[R]}$ in matched orders when rescheduling its internal DERs. The revenue of a VPP can be formulated as follows:

$$\begin{aligned} W_{n,t} \quad &= C_{\mathrm{FIT},t}\cdot\left[Q_{\mathrm{sur},n,t}-g\left[q_{n,t}^{[R-1]}\right]-\sum_{i\in\mathbb{N}_{B,n,t}^{[R]}} q_{n\rightarrow i,t}^{[R]}\right] \\ &-C_{\mathrm{RTP},t}\cdot\left[Q_{\mathrm{short},n,t}-g\left[-q_{n,t}^{[R-1]}\right]-\sum_{j\in\mathbb{N}_{S,n,t}^{[R]}} Q_{j\rightarrow n,t}^{[R]}\right] \\ &+H_{n,t}^{[R-1]}+\Delta\hat{H}_{n,t}^{[R]} \end{aligned} \tag{27}$$

$$\Delta\hat{H}_{n,t}^{[R]}=\sum_{i\in\mathbb{N}_{B,n,t}^{[R]}} q_{n\rightarrow i,t}^{[R]}\cdot\left(C_{n\rightarrow i,t}^{[R]}-C_{n\otimes i}\right)-\sum_{j\in\mathbb{N}_{S,n,t}^{[R]}} Q_{j\rightarrow n,t}^{[R]}\cdot C_{j\rightarrow n,t}^{[R]} \tag{28}$$

where $H_{n,t}^{[R-1]}$ is the accumulated P2P trading revenue of previous rounds, $\Delta\hat{H}_{n,t}^{[R]}$ the estimated newly-added revenue of round R. $q_{n,t}^{[R-1]}$ is the accumulated traded quantity of previous rounds, $q_{n,t}^{[R-1]} > 0$ implies that VPP$_n$ plays the role of seller in P2P energy trading, and $q_{n,t}^{[R-1]} < 0$ implies that VPP$_n$ plays the role of seller in P2P energy trading. $C_{i\otimes j}$ is the transmission tariff between VPP$_i$ and VPP$_j$, and it is assumed that the seller pays the transmission service in P2P energy trading.

In round R, $q_{n\rightarrow i,t}^{[R]}$, $Q_{\mathrm{sur},n,t}$, $Q_{\mathrm{short},n,t}$ are decision variables. $H_{n,t}^{[R-1]}$, $q_{n,t}^{[R-1]}$ have already been calculated in the previous round.

After local rescheduling, B-VPPs can gain information on modified orders, i.e., $q_{n\rightarrow i,t}^{[R]}$ has been determined. Then, $\Delta H_{n,t}^{[R]}$, $H_{n,t}^{[R]}$, $q_{n,t}^{[R]}$, $\hat{Q}_{n,t}^{[R+1]}$ can be calculated, which will be used in the next round (R+1).

The actual newly-added revenue from P2P trading can be calculated:

$$\Delta H_{n,t}^{[R]}=\sum_{i\in\mathbb{N}_{B,n,t}^{[R]}} q_{n\rightarrow i,t}^{[R]}\cdot\left(C_{n\rightarrow i,t}^{[R]}-C_{n\otimes i}\right)-\sum_{j\in\mathbb{N}_{S,n,t}^{[R]}} q_{j\rightarrow n,t}^{[R]}\cdot C_{j\rightarrow n,t}^{[R]} \tag{29}$$

The accumulated revenue from P2P trading can be updated in round R:

$$H_{n,t}^{[R]}=H_{n,t}^{[R-1]}+\Delta H_{n,t}^{[R]} \tag{30}$$

$$H_{n,t}^{[0]}=0 \tag{31}$$

The accumulated traded quantity can be updated in round *R:*

$$q_{n,t}^{[R]} = q_{n,t}^{[R-1]} + \sum_{i \in \mathbb{N}_{B,n,t}^{[R]}} q_{n \to i,t}^{[R]} - \sum_{j \in \mathbb{N}_{S,n,t}^{[R]}} q_{j \to n,t}^{[R]} \tag{32}$$

$$q_{n,t}^{[0]} = 0 \,. \tag{33}$$

The tradable quantity of VPP_n is also updated in round *R:*

$$\hat{Q}_{n,t}^{[R+1]} = \hat{Q}_{n,t} - \left| q_{n,t}^{[R]} \right| \tag{34}$$

3.2.4. Constraints

There is little difference between the constraints of this stage and those of Stage 1 (local scheduling), except for some differences in the results of P2P energy trading.

The total quantity of the already-matched order and the newly-added orders cannot exceed the tradable quantity. If VPP_n is an S-VPP, the sold energy in the P2P market cannot exceed the energy surplus:

$$g\left(q_{n,t}^{[R-1]}\right) + \sum_{i \in \mathbb{N}_{B,n,t}^{[R]}} q_{n \to i,t}^{[R]} \leq Q_{\mathrm{sur},n,t}^{[R]} \tag{35}$$

and if VPP_n is a B-VPP, the bought energy in the P2P market cannot exceed the energy shortage:

$$g\left(-q_{n,t}^{[R-1]}\right) + \sum_{j \in \mathbb{N}_{S,n,t}^{[R]}} Q_{j \to n,t}^{[R]} \leq Q_{\mathrm{short},n,t}^{[R]} \,. \tag{36}$$

Since an S-VPP may over-estimate the initial tradable quantity due to its power generation potential, the total quantity of energy sold to other VPPs at this stage may be less than those in the matched orders:

$$0 \leq q_{j \to i,t} \leq Q_{j \to i,t} \tag{37}$$

Formula (37) indicates that if there is an infeasible gap between $q_{j \to i,t}$ and $Q_{j \to i,t}$, the related orders will be modified and the quantity will be reduced to $q_{j \to i,t}$. The unfeasible gap can be bought from GridCo or other VPPs in the next round.

4. Strategy of Price Bidding on the Top Layer

4.1. Initial Price and Iterative Bidding

In each round of P2P negotiation (Stage 2), the trade prices are iteratively negotiated for $\bar{r}$ runs between each seller–buyer pair, in which an S-VPP and a B-VPP, respectively, adjust the ask price and the bid price by applying the MWBS. A trade order is successfully matched if a seller–buyer pair reaches an agreement on the trade price.

As shown in Figure 4, B-VPPs and S-VPPs, respectively, adjust the bid and ask prices in each bidding run (indexed by r). Before the deadline ($r \leq \bar{r}$), a trade order is successfully matched if the B-VPP's bid price exceeds S-VPP's ask price, and the bid price is adopted as the trade price of the matched order. As a result, the tradable quantity in the unmatched orders is immediately updated. This procedure ends if there is no matchable order or the deadline is reached ($r > \bar{r}$).

In P2P energy trading, S-VPPs may sell energy to B-VPPs at prices higher than FIT, and B-VPPs may buy energy from S-VPPs at prices lower than RTP. Due to the differences between FIT and RTP, both S-VPPs and B-VPPs can benefit from participating in P2P energy trading.

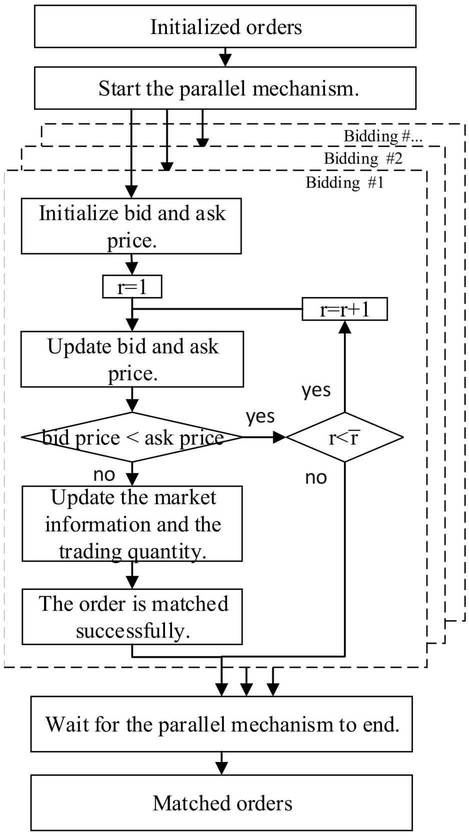


Figure 4. Price bidding for P2P order matching.

Denote the initial bid price by $C_i^{\text{bid}:[0]}$. On one hand, B-VPPs tend to set the bid prices as low as possible to maximize profits. On the other hand, the bid prices cannot be lower than FIT, otherwise S-VPPs would rather trade with GridCo, and the P2P trading would become infeasible. Hence the initial bid price is set as follows:

$$C_i^{\text{bid}:[0]} = C_{\text{FIT}} + \mu \tag{38}$$

where μ is a pre-set small random number.

In the r^{th} run of bidding, a B-VPP adjusts its bid price by applying MWBS:

$$C_i^{\text{bid: }[r]} = C_i^{\text{bid: }[r-1]} + WN_i^{[r]} \tag{39}$$

Similarly, the initial ask price of an S-VPP is

$$C_j^{\text{ask}:[0]} = C_{\text{RTP}} - \mu \tag{40}$$

and the ask price is adjusted as follows:

$$C_j^{\text{ask: }[r]} = C_j^{\text{ask: }[r-1]} - WN_j^{[r]} \tag{41}$$

WN in (39) and (41) is the adjustment factor, which takes "multidimensional willingness" into account:

$$WN_{n,t}^{[r]} = SDR_{n,t} \times \left(MD_{n,t}^{[r]} + TP_{n,t}^{[r]}\right) \times HTR_{n,t} \times CB_{n,t}^{[r]} \tag{42}$$

where $SDR_{n,t}$, $MD_{n,t}^{[r]}$, $TP_{n,t}^{[r]}$, $HTR_{n,t}$, and $CB_{n,t}^{[r]}$ denote the global supply–demand relationship, the matching degree of bidding quantity, time pressure, historical trade records, and counter behavior to the bidding price, respectively. Interested readers may refer to [30] for more details about Formulas (38)–(42). We focus on the modification of $SDR_{n,t}$ and $MD_{n,t}^{[r]}$ in this paper.

4.2. Discussion of Multidimensional Willingness

4.2.1. Global Supply–Demand Relationship

The global supply–demand relationship from the perspective of a B-VPP is

$$SDR_{i,t} = \begin{cases} 1-\psi, & \text{if} Q_{\Sigma B,t} < Q_{\Sigma S,t} \\ 1, & \text{if} Q_{\Sigma S,t} \leq Q_{\Sigma B,t} \leq \overline{Q}_{\Sigma S,t} \\ 1+\psi, & \text{otherwise} \end{cases} \quad \forall i \in \mathbb{N}_B \tag{43}$$

where $Q_{\Sigma B,t} = \sum_{i\in\mathbb{N}_B} Q_{\text{short},i,t}$, $Q_{\Sigma S,t} = \sum_{j\in\mathbb{N}_S} Q_{\text{sur},j,t}$, $\overline{Q}_{\Sigma S,t} = \sum_{j\in\mathbb{N}_S} \hat{Q}_{j,t}$, and ψ are predefined small positive numbers. In case of an oversupply, i.e., $Q_{\Sigma B,t} < Q_{\Sigma S,t}$, the trade willingness of B-VPPs is weakened. In the case of an abundant supply, i.e., $Q_{\Sigma S,t} \leq Q_{\Sigma B,t} \leq \overline{Q}_{\Sigma S,t}$, B-VPPs' demands can be satisfied by considering the power generation potentials of S-VPPs. Otherwise, the demand is globally undersupplied and the trade willingness of the B-VPPs becomes much stronger.

Similarly, the *SDR* from the perspective of an S-VPP is

$$SDR_{j,t} = \begin{cases} 1+\psi, & \text{if} Q_{\Sigma B,t} < Q_{\Sigma S,t} \\ 1, & \text{if} Q_{\Sigma S,t} \leq Q_{\Sigma B,t} \leq \overline{Q}_{\Sigma S,t} \\ 1-\psi, & \text{otherwise} \end{cases}, \forall j \in \mathbb{N}_S \tag{44}$$

4.2.2. Matching Degree of Bidding Quantity

The matching degree of bidding quantity indicates the supply–demand relationship between a VPP and its three trade partners, which can be formulated as follows:

$$MD_n^{[r]} = \exp\left(1 - \left|\frac{Q_n^{\text{pn}:[r]}}{Q_{n,t}^{\text{ep}:[r]}}\right|\right) \tag{45}$$

where $Q_{n,t}^{\text{ep}:[r]}$ is the expected trade quantity of VPP$_n$, and $Q_n^{\text{pn}:[r]}$ is the sum of trade quantities of partners at run r. In the case of $Q_n^{\text{ep}} < Q_n^{\text{pn}}$, the expected quantity can be traded, the willingness is weakened ($MD_n < 1$), and the VPPs tend to "wait for" more favorable trade prices. On the contrary, in the case of $Q_n^{\text{ep}} > Q_n^{\text{pn}}$, the expected quantity seems to be untraded, the willingness becomes strong ($MD_n > 1$), and VPPs try to reach agreements as soon as possible.

From the perspective of a B-VPP, the expected trade quantity is just the tradable quantity. However, its partners' (S-VPPs') power generation potential is not completely reliable, so the degree of optimism on potential can be utilized to determine Q_n^{pn}, which can be formulated as follows:

$$Q_{i,t}^{\text{ep}:[r]} = \hat{Q}_{i,t}^{[r]} \tag{46}$$

$$Q_i^{\text{pn}:[r]} = \sum_{j\in\mathbb{N}_{S,n,t}} \left[\tau_i \hat{Q}_{j,t}^{[r]} + [1-\tau_i] Q_{\text{sur},j,t}^{[r]}\right] \tag{47}$$

where τ_n is a pre-set number, τ_n presents the degree of optimism on the power generation potential, and $\tau_n \in [0,1]$. If $\tau_n = 0$, only the scheduled part is considered, and if $\tau_n = 1$, the VPP believes that the power generation potential is fully realizable. $\hat{Q}_{j,t}^{[r]}$ and $Q_{\text{sur},j,t}^{[r]}$ are the estimated tradable quantity and scheduled energy surplus in run r, which can be updated dynamically if some orders are matched.

From the perspective of an S-VPP, the expected trade quantity is affected by the degree of optimism on the power generation potential. Its partners' (B-VPP) tradable quantity is reliable, which can be formulated as followed:

$$Q_{j,t}^{\mathrm{ep}:[r]} = \tau_j \hat{Q}_{j,t}^{[r]} + \left(1-\tau_j\right) Q_{\mathrm{sur},j,t}^{[r]} \quad (48)$$

$$Q_j^{\mathrm{pn}:[r]} = \sum_{i \in \mathbb{N}_{B,j,t}} \hat{Q}_{i,t}^{[r]} \quad (49)$$

5. Case Study

5.1. Case Description and Simulation Setup

A case of 14 VPPs is used to validate the proposed two-layer interactive mechanism of P2P energy trading. The nominal parameters of the internal DERs of each VPP are exhibited in Table 1 (the output of WT and PV is the maximum output of original 24-hour data). For each VPP, 20 typical scenarios of wind/photovoltaic power are generated by using the Monte-Carlo method. Without a loss of generality, the 20 scenarios of wind/photovoltaic power in VPP_1 are shown in Figure 5.

Table 1. Nominal parameters of internal DERs in VPPs (kW).

VPP	Wind Turbine	Photovoltaic	Load	Micro Gas Turbine	Energy Storage System (Capacity)
1	1280	535	−1126	500	±100 (400 kWh)
2	950	220	−883	0	±100 (400 kWh)
3	1480	0	−1412	0	0
4	1330	0	−672	400	±100 (400 kWh)
5	1550	0	0	0	±100 (400 kWh)
6	0	1262	0	0	±100 (400 kWh)
7	1120	0	−1412	500	0
8	1260	0	−853	300	±100 (400 kWh)
9	0	892	0	0	0
10	590	0	0	300	±100 (400 kWh)
11	1530	0	−1210	0	±100 (400 kWh)
12	0	461	0	500	0
13	0	335	−1122	0	±100 (400 kWh)
14	0	318	−855	0	±100 (400 kWh)

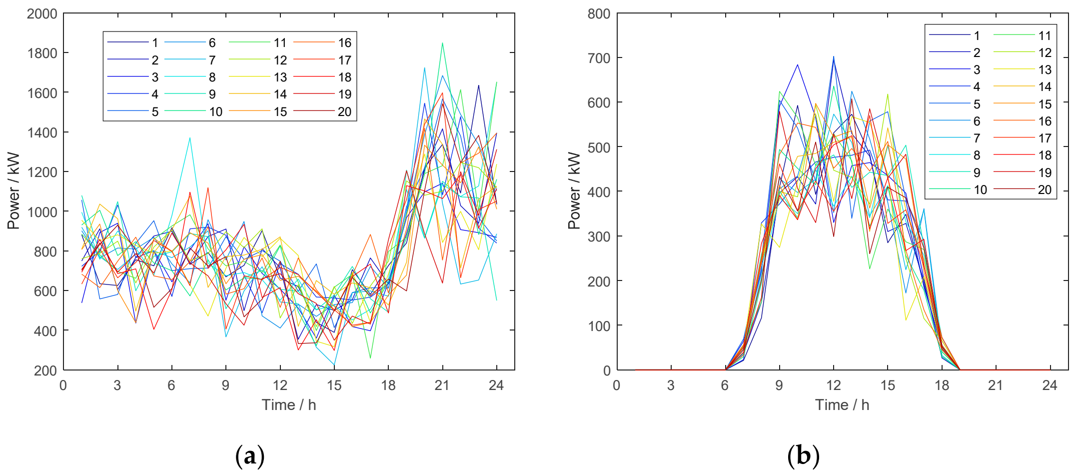


Figure 5. Twenty typical scenarios of wind/photovoltaic power in VPP_1: (**a**) wind power; (**b**) photovoltaic power.

In the day-ahead market, both RTP and FIT adopt the time-of-use (TOU) pricing strategy see (Table 2).

Table 2. Real-time price (RTP) and feed-in tariff (FIT) in the day-ahead market.

Period	FIT (CNY/kWh)	RTP (CNY/kWh)
7:00–22:00	0.40	0.75
22:00–7:00(D+1)	0.28	0.63

The pre-set penalty coefficients are $\alpha^{+} = 0.4$ and $\alpha^{-} = 0.1$. GridCo charges VPPs for the transmission service at the tariff 0.0015 CNY/(kWh·km), and the distance matrixes of the VPPs are given in Table 3.

Table 3. Distance matrix of the 14 VPPs in the case (km).

Dst	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	0	9.6	11.4	36.7	38.2	39.2	21.3	13.9	39.7	40	40.5	26	40.7	32.8
2	9.6	0	12.7	37.9	39.3	40.6	23.3	12.4	40.6	41.2	41.6	27.8	42.1	34.3
3	11.4	12.7	0	38.6	39.9	40.8	7.1	14.9	41	41.7	42	28.7	42.7	34.9
4	36.7	37.9	38.6	0	10.4	44.5	30.4	39.7	14.3	15.6	45.6	33.6	46	39.3
5	38.2	39.3	39.9	10.4	0	45.7	31.8	41.1	17.7	18.8	46.7	35.1	47.2	40.5
6	39.2	40.6	40.8	44.5	45.7	0	33.2	29.4	46.7	47.2	9.6	36.2	11.6	41.6
7	21.3	23.3	7.1	30.4	31.8	33.2	0	26	33.2	33.9	34.3	15	35	25.2
8	13.9	12.4	14.9	39.7	41.1	29.4	26	0	42.1	42.7	43	30.1	43.9	36.1
9	39.7	40.6	41	14.3	17.7	46.7	33.2	42.1	0	18	47.7	36.4	48.1	41.7
10	40	41.2	41.7	15.6	18.8	47.2	33.9	42.7	18	0	48.1	37	48.6	42.1
11	40.5	41.6	42	45.6	46.7	9.6	34.3	43	47.7	48.1	0	37.4	12	42.9
12	26	27.8	28.7	33.6	35.1	36.2	15	30.1	36.4	37	37.4	0	38	29.3
13	40.7	42.1	42.7	46	47.2	11.6	35	43.9	48.1	48.6	12	38	0	43
14	32.8	34.3	34.9	39.3	40.5	41.6	25.2	36.1	41.7	42.1	42.9	29.3	43	0

The formulation presented in this paper was implemented with MATLAB, and the local (re)scheduling was solved by using the IBM ILOG CPLEX Optimization Studio (CPLEX). All computations are done on an Intel (R) Core (TM) i7-7700 @ 3.6GHz with 8 GB DDR3 RAM.

5.2. Results and Analysis

5.2.1. Analysis of Local Scheduling Results

Through local scheduling, each VPP coordinates the internal DERs and determines the initial trade order for the subsequent P2P negotiation. The local scheduling of a VPP is done to maximize profits. In this case, 14 VPPs independently perform the local scheduling. Due to space limitations, we take VPP_1, VPP_6, and VPP_7 as examples and demonstrate the scheduled results in Figure 6 Notice that the profile of wind/photovoltaic power is one of 20 scenarios, and the load agrees with the predictions.

VPP_1 is an S-VPP of high controllability since it has an energy surplus in most of the time units and manages abundant controllable DERs. During local scheduling, it is assumed that the energy surplus can only be sold to GridCo at FIT. The high FIT (7:00–22:00) attracts VPP_1 to increase the output close to the maximum. During the low FIT period (0:00–8:00), VPP_1 maintains its MT at a low output and charges its ES, so as to enlarge the power generation potential for the high FIT period.

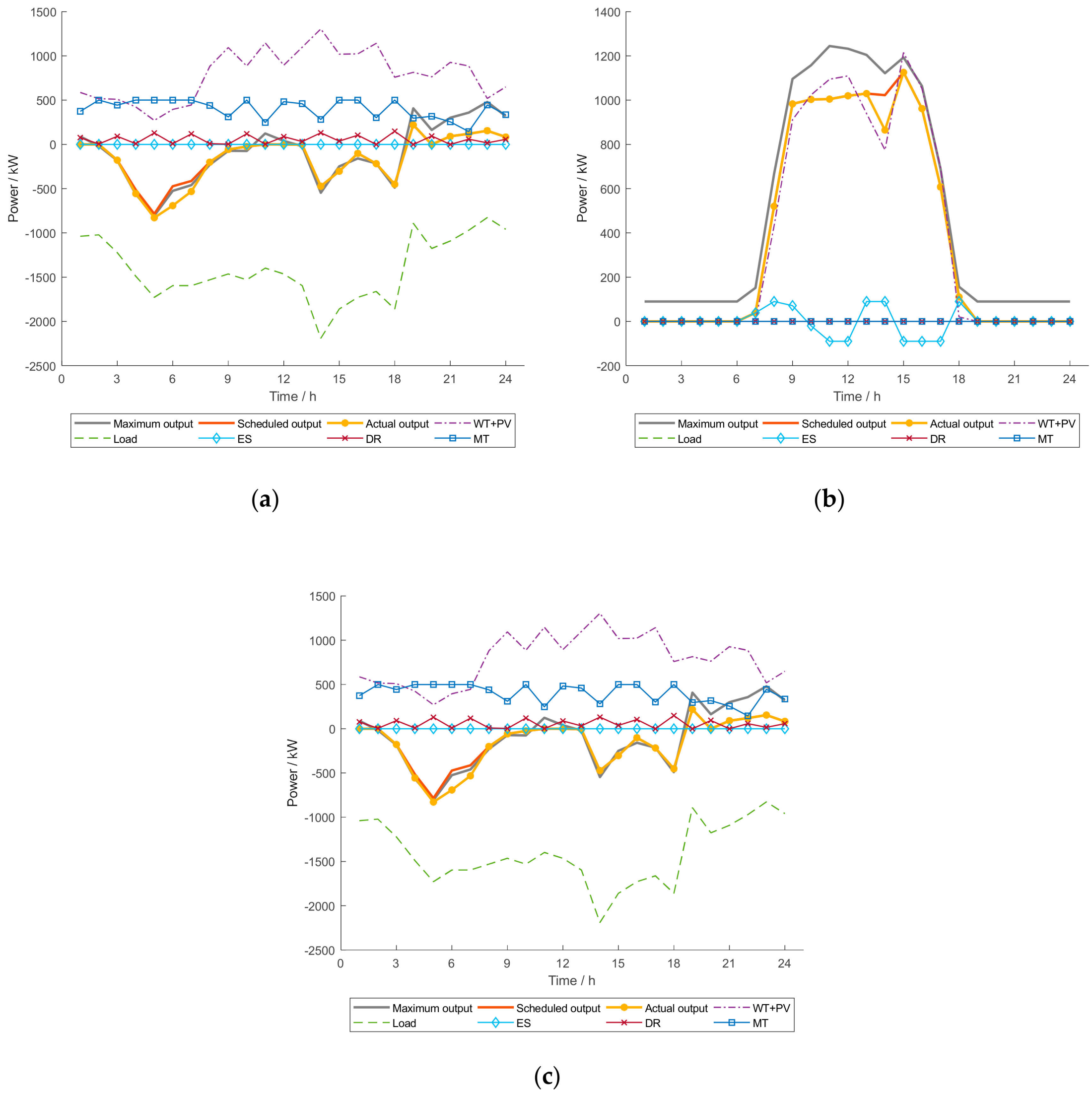


Figure 6. Local scheduling results of VPPs: (**a**) VPP_1; (**b**) VPP_6; (**c**) VPP_7.

VPP_6 only has PV and ES as internal DERs. Although PV is relatively uncontrollable, the capability of ES to shift energy still provides some power generation potential for trading.

VPP_7 mainly plays the role of B-VPP in a day due to the large internal demand and lack of power generation. From 0:00 to 8:00, the outputs of WT and MT are close to the upper limits needed to satisfy the large demand, which is very different from the results of VPP_1, and the unsatisfied demand can only be bought from GridCo at a high RTP. Further, the scheduled output of VPP_7 is always consistent with the maximum curve, i.e., this B-VPP has little room to adjust the tradable quantity in the subsequent P2P negotiation.

The scheduled output of a VPP is derived by compromising various scenarios. Due to the uncertainties of internal DERs, the actual output of a VPP inevitably deviates from the scheduled output. In each VPP, the controllable DERs, such as MT, ES, and DR, are utilized to reduce such deviation. For example, VPP_1 can easily handle most deviations because of the abundant capacities of MT and DR. As for VPP_6, it is difficult to eliminate the deviations by using the limited ES. Further, VPP_7 has no ES, and its internal MT is mainly used to meet the internal demand. The high dependency on DR leads to a volatile profile for DR.

5.2.2. Analysis of Parallel Price Bidding Process in P2P Negotiation

Figure 7 shows the price bidding processes of four typical buyer–seller pairs in the P2P negotiation. In Figure 7a, neither the buyer (VPP_2) nor seller (VPP_{10}) has a strong trade willingness, so the deadline is reached and no order is matched. In Figure 7b, the trade price converges to a low level since the trade willingness of the seller (VPP_8) is stronger than that of the buyer (VPP_3). In Figure 7c, the buyer (VPP_3) matches the order with other sellers, and its tradable quantity is partly sold. The willingness of the seller (VPP_5) significantly increases due to the shrink of the tradable quantity of the buyer (VPP_3). In Figure 7d, the price bidding process between VPP_3 and VPP_{10} is terminated before the end since one of them successfully becomes order matched with another partner, and the tradable quantity becomes cleared.

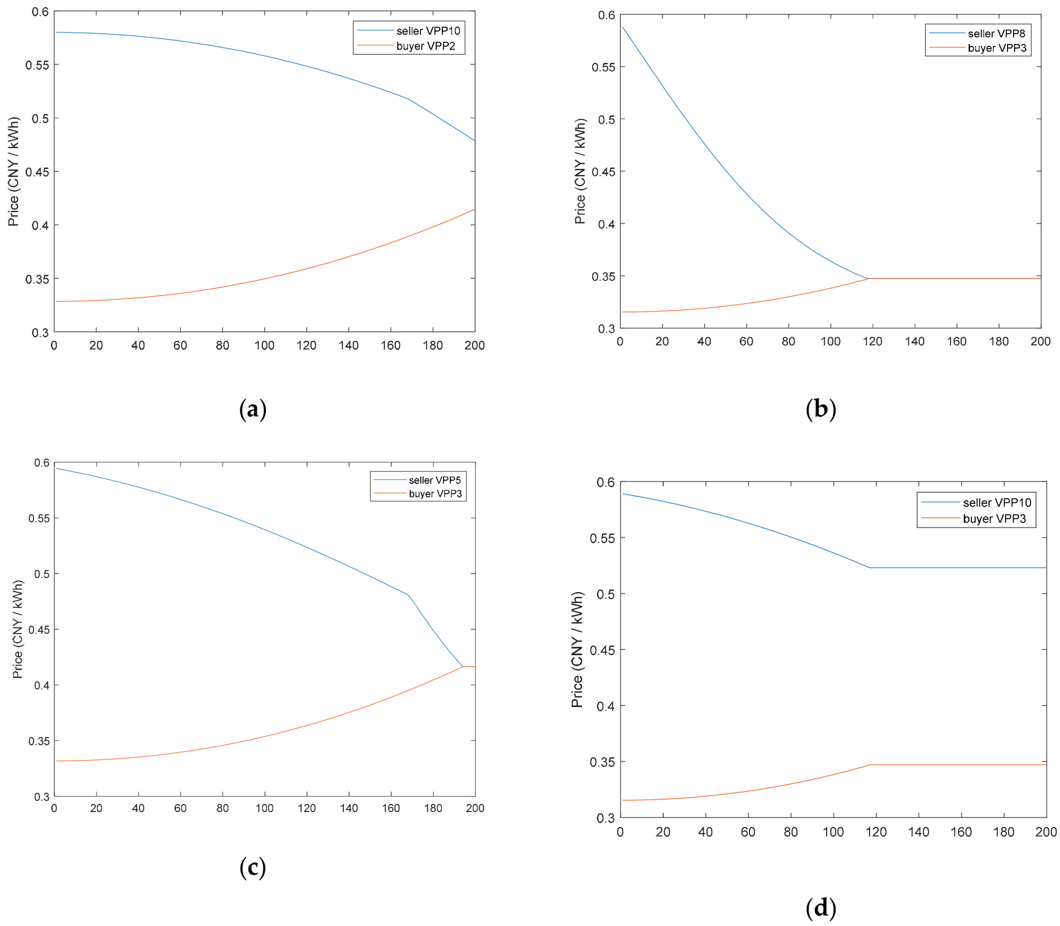


Figure 7. Price bidding process in the first round of P2P negotiation ($R = 1$): (**a**) VPP_2 vs. VPP_{10}, $t = 1$; (**b**) VPP_3 vs. VPP_8, $t = 2$; (**c**) VPP_3 vs. VPP_5, $t = 1$; (**d**) VPP_3 vs. VPP_{10}, $t = 2$.

5.2.3. Analysis of Matched Orders

Figure 8 shows the overall market supply and demand relationship and P2P trade prices varying with time. Globally speaking, the system is significantly oversupplied, and the P2P trade prices are low from 8:00 to 16:00. The system is significantly undersupplied and the P2P trade prices are high from 16:00 to 21:00. The system is “critically supplied” during other hours of the day, since the total scheduled output of the B-VPPs is higher than that of the S-VPPs but can be satisfied by considering the power generation potential of the S-VPPs.

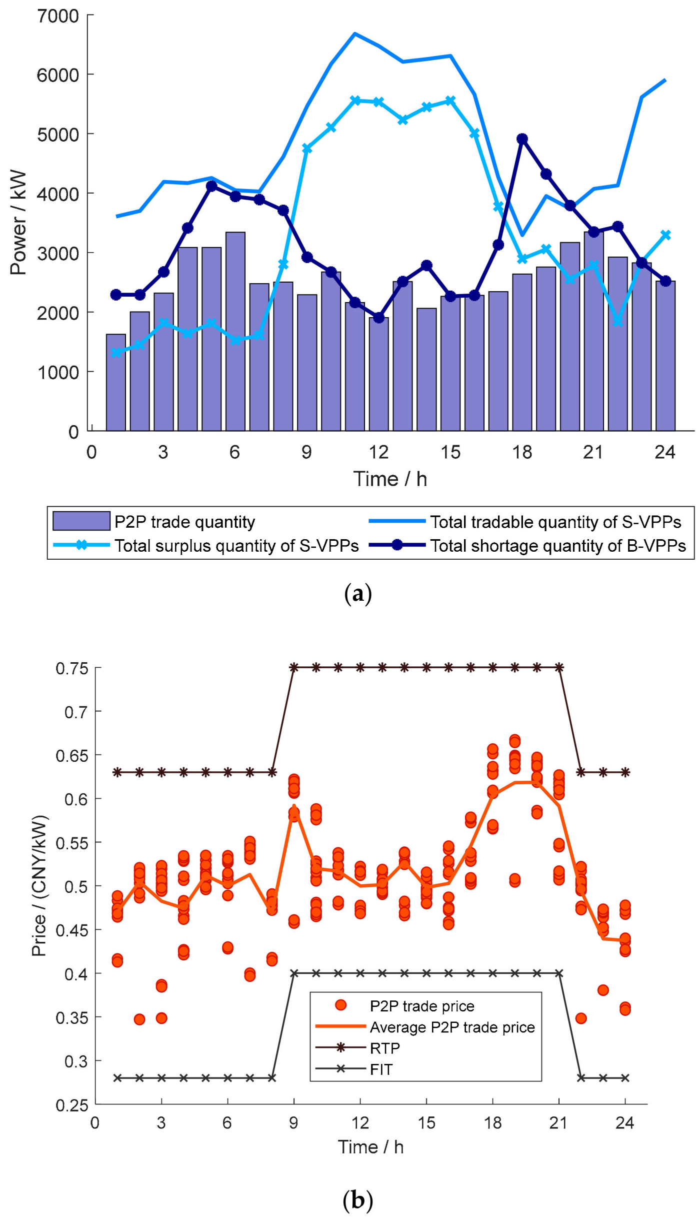


Figure 8. (**a**) Various quantities varying with time; (**b**) trade prices of matched orders in the first round of P2P negotiation (R = 1).

As shown in Figure 8a, the system is "critically supplied" during the third hour (02:00–02:59). Table 4 presents detailed information of the matched orders in the third hour and first round of P2P negotiations (t = 3, R = 1).

In Order #1, the buyer is VPP_3 and the seller is VPP_8. The trade willingness of VPP_3 is weak since it can buy from three S-VPPs to satisfy its small shortage quantity. On the contrary, VPP_8 is eager to get its orders matched as quickly as possible due to its large surplus quantity. As a result, the trade price between VPP_3 and VPP_8 converges to a low level. Similarly, in Order #2, VPP_7 and VPP_{10} also reach a low price in the P2P negotiations. Despite the low scheduled output, VPP_{10} has a large power generation potential, so its willingness is also strong. Considering its large shortage quantity, it is necessary for VPP_{13} to buy from multiple S-VPPs. Thus, three orders (#4, #5, #6) are successfully matched, and their trade prices are all high.

Table 4. Details of the matched orders in $t = 3$ and $R = 1$.

Order#.	B-VPP	S-VPP	Shortage Quantity (kWh)	Surplus Quantity (kWh)	Tradable Quantity (kWh)	Quantity in Matched Order (kWh)	Quantity in Modified Order (kWh)	Trade Price (CNY/kWh)
1	3	8	168	710	964	168	168	0.348
2	7	10	178	292	666	178	178	0.384
3	11	5	586	254	381	229	162	0.494
4	13	1	1099	312	718	718	581	0.498
5	13	2	1099	101	275	275	165	0.519
6	13	5	1099	254	381	107	107	0.509
7	14	4	642	147	596	596	580	0.503
8	14	5	642	254	381	46	46	0.494

In addition, Table 4 also shows the P2P trade quantity after order modification. Only a few trade orders are modified. If an S-VPP is required to modify the matched orders, it preferentially satisfies the orders with higher prices to maximize profits. For example, VPP_5 sells electricity to VPP_{11}, VPP_{13}, and VPP_{14}. VPP_5 preferentially satisfies the other two VPPs rather than VPP_{11} due to its lower price.

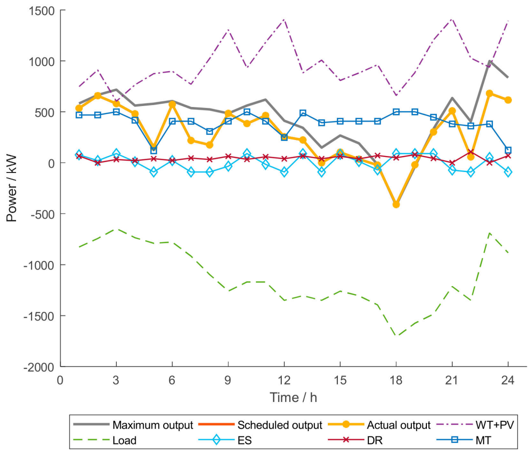
5.2.4. Analysis of Local Rescheduling Results

This subsection investigates the effectiveness and impact of rescheduling, which considers the results of order matching in P2P negotiation. VPP_1, VPP_6, and VPP_7 are again taken as examples, and the changes in the output and P2P trade quantity after rescheduling are shown in Figure 9b–d. Figure 9a shows the result of the local rescheduling of VPP_1.

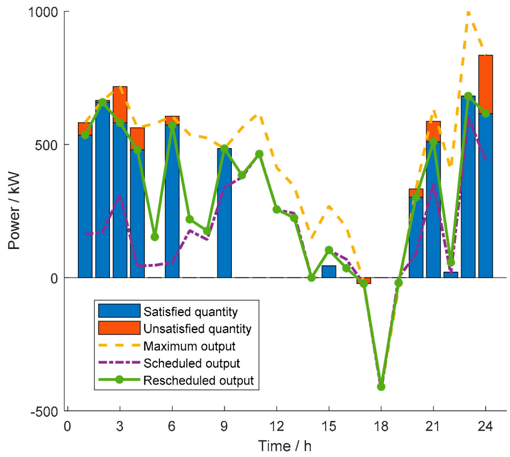
In P2P energy trading, VPP_1 and VPP_6 behave as energy sellers during most of the time. VPP_1 behaves as a seller and participates in P2P trading from 0:00 to 9:00 and from 20:00 to 24:00. PV can hardly generate electricity during these two periods, so there is little competition among the S-VPPs. Figure 9 illustrates that MT is the main force of VPP_1 in P2P trading, and its ES and DR are not very effective.

VPP_6 has only PV and ES as its internal DERs. The local rescheduling can shift the energy along the time axis. For example, the outputs in 8 h and 15 h are both reduced and shifted to 7 h to commit the matched order. After rescheduling, although the S-VPP may fail in fully committing matched orders, the uncommitted or modified proportion is minimized. In addition, once an S-VPP modifies its matched orders, it will be disqualified for the next round of P2P negotiation. This setting provides more opportunities for B-VPPs to become satisfied by trading with other S-VPPs.

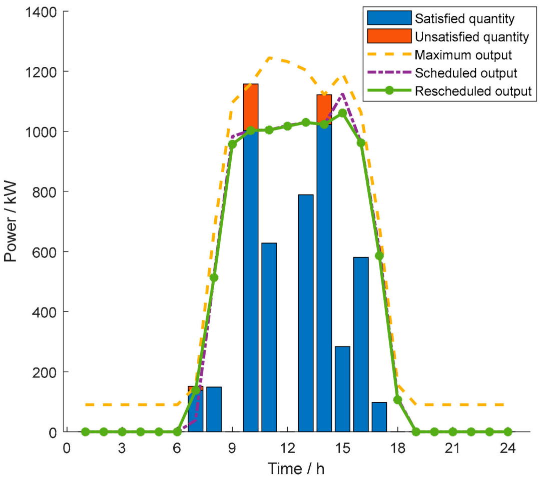
During most of the day, VPP_7 has an energy shortage and acts as a buyer in P2P trading. As shown in Figure 9, this rescheduling has little impact on the output of VPP_7. The trade quantities are almost invariant since they are mainly determined by the rescheduling results of other S-VPPs. It is revealed that only a small number of P2P orders of buyers can be affected by the order modification process.



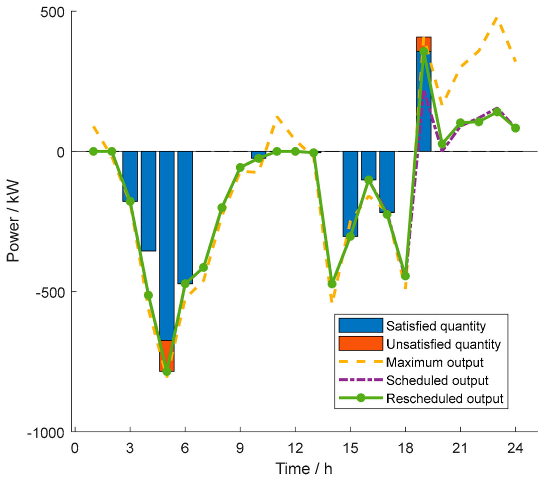
(**a**)



(**b**)



(**c**)



(**d**)

Figure 9. Changes in the output and P2P trade quantity of a VPP after rescheduling in the first round of negotiations ($R = 1$): (**a**) The detailed result of rescheduling VPP_1; (**b**) changes in the output and P2P trade quantity of VPP_1 after rescheduling; (**c**) changes in the output and P2P trade quantity of VPP_6 after rescheduling; (**d**) changes in the output and P2P trade quantity of VPP_7 after rescheduling.

5.2.5. Analysis on Quantity and Profit

After three rounds (i.e., $\overline{R} = 3$) of P2P negotiation (Stage 2) and order modification (Stage 3), the results of P2P trading in 1 hour are determined. Using the same method, we can derive the results of P2P trading in 24 hours of a day. Then the 24 h accumulated profit and trade quantity of each VPP can be calculated. Table 5 shows the profit, the trade quantity, the surplus quantity, etc. of the 14 VPPs. For ease of comparison, the results with and without P2P trading are all listed in Table 5.

It is revealed that all VPPs can obtain higher profits by participating in P2P trading. The total profit of the 14 VPPs increases by 22,964 CNY, and the average growth is 1640 CNY per VPP. The total output of VPPs increases by 14,386 kWh. A total of 92.9% of the VPPs' demands are satisfied through P2P trading.

Table 5. Twenty-four hour accumulated profit and trade quantity of each VPP without P2P and with P2P trading.

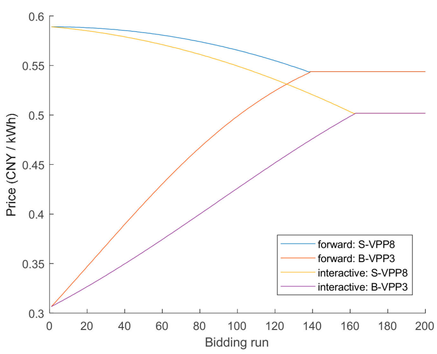
VPP	Profit Without P2P (CNY)	Profit With P2P (CNY)	Surplus Without P2P (kWh)	Surplus With P2P (kWh)	Quantity Sold in P2P (kWh)	Energy Shortage (kWh)	Quantity Bought in P2P (kWh)
1	−1974	−770	4462	8511	7137	444	22
2	−5225	−3641	1648	2023	1896	7428	6949
3	−7191	−5814	327	496	377	7046	6498
4	1060	2708	9472	13,036	9776	0	0
5	7236	9522	21,385	21,644	15,491	0	0
6	3392	4094	9427	9424	5728	0	0
7	−7052	−6104	667	1397	1045	4197	3791
8	−4131	−2706	4184	5109	4667	3275	3087
9	2064	2500	5852	6034	3467	0	0
10	2304	4510	12,754	15,219	11,965	0	0
11	−6301	−5013	158	300	210	8140	6810
12	632	1788	8841	10,370	7081	0	0
13	−17,327	−13,565	0	0	0	25,032	24,149
14	−12,873	−9929	0	0	0	18530	17,535
Total	−45,385	−22,421	79,177	93,563	68,842	74,092	68,842

5.3. Comparison and Discussion

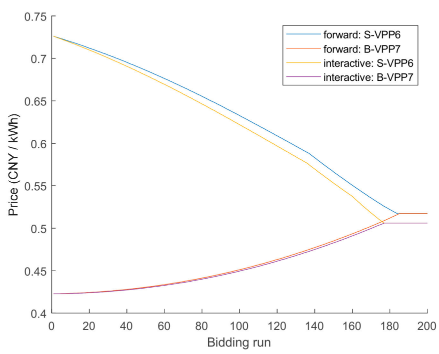
5.3.1. Advantages of the "Interactive" Mechanism

Both this paper and reference [30] address the P2P energy trading mechanism among multiple microgrids/VPPs and adopt the MWBS for price bidding. The work of this paper is based on the contributions of reference [30]. However, our proposal is featured as "interactive"; it takes the power generation potential into account and utilizes P2P negotiation results for the rescheduling of each VPP. On the contrary, the mechanism in reference [30] is simply "forward", which neglects power generation potential and does not perform rescheduling.

In Figure 10a, the trade price under the "forward" mechanism is higher than that under the "interactive" mechanism, because at $t = 6$, the total scheduled output of the B-VPPs is higher than that of the S-VPPs but can be satisfied by considering the power generation potential, which leads to a stronger willingness of the buyer and a weaker willingness of the seller under the "forward" mechanism.



(**a**)



(**b**)

Figure 10. The price bidding process of P2P negotiation under two different mechanisms ($R = 1$): (**a**) VPP_8 vs. VPP_3, $t = 1$; (**b**) VPP_6 vs. VPP_7, $t = 2$. Figure 10 shows the price bidding processes of two typical buyer–seller pairs in the P2P negotiation.

In Figure 10b, the "forward" and "interactive" mechanisms have similar results, because at $t = 12$, the system is significantly oversupplied and power generation potential has little impact on the trade price.

As shown in Figure 11, the "interactive" mechanism is superior to its "forward" counterpart in at least three aspects: a larger trade quantity (+40.1%), higher profit (+4521 CNY), and faster convergence.

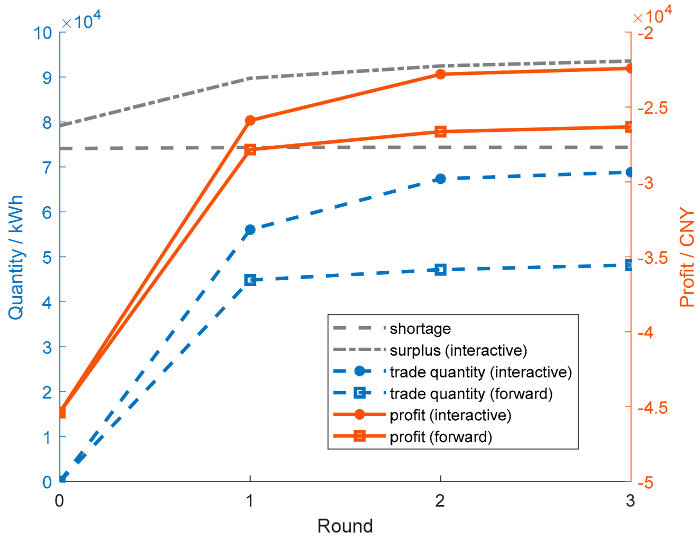


Figure 11. Comparison of the total trade quantities and total profits between two cases.

5.3.2. Impact of VPP Configuration

In order to investigate the impact of ES, DR, and MT on VPPs' profits, five different configurations of 14 VPPs are established, as follows:

(a) #1: all VPPs are as described in Table 1;
(b) #2: each VPP disables DR;
(c) #3: each VPP disables ES;
(d) #4: each VPP disables MT;
(e) #5: each VPP disables DR, ES, and MT.

Figure 12 shows the profit growth, which is equal to the difference between the profit with P2P and that without P2P in different configurations.

As shown in Figure 12, MT plays an important role, because MT is the main contributor of power generation potential. A comparison between #1 and #3 indicates that DR has little effect on the results. A comparison between #1 and #3 indicates that ES can provide some power generation potential and slightly increase profit. In #5, the mechanism proposed in this paper has no advantage. Therefore, the mechanism proposed in this paper is only applicable to cases where VPPs manage some controllable DERs.

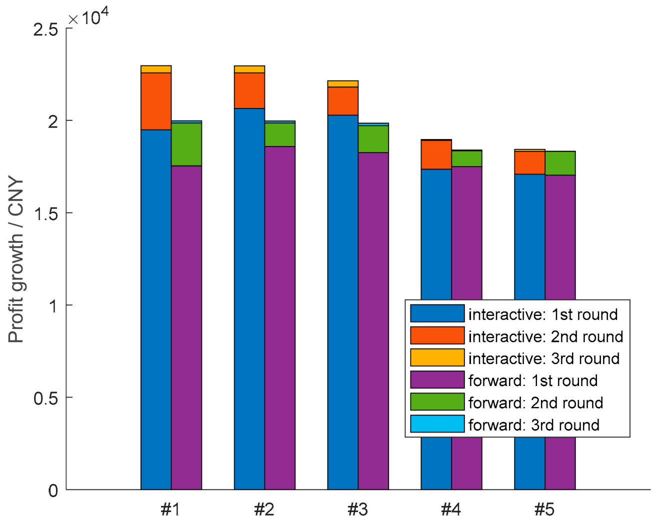


Figure 12. Profit growth in five different configurations of VPPs.

5.3.3. Impact of VPP Number

The generality and scalability of the proposed mechanism is examined by performing a sensitivity analysis on the number of VPPs. Six cases of different VPP numbers are generated and studied. For example, an x-VPP case is generated as follows:

Step 1: The 14 VPPs described in Table 1 are set as the dataset;
Step 2: Randomly select one VPP from the dataset;
Step 3: Repeat Step 2 x times to generate an x-VPP case;
Step 4: Compute the profit of this x-VPP case;
Step 5: Repeat Step 2–Step 4 5 times;
Step 6: Compute the average profit growth of each VPP, which is equal to the difference between the profit with P2P and that without P2P.

Figure 13 shows the average profit growth under different numbers of VPPs participating in P2P energy trading. These results demonstrate that the proposed mechanism is applicable to various numbers of VPPs. The average profit growth of VPPs is increasing, with an increasing number of VPPs. However, this trend gradually slows down. Moreover, the numbers of VPPs have little effect on the convergence efficiency.

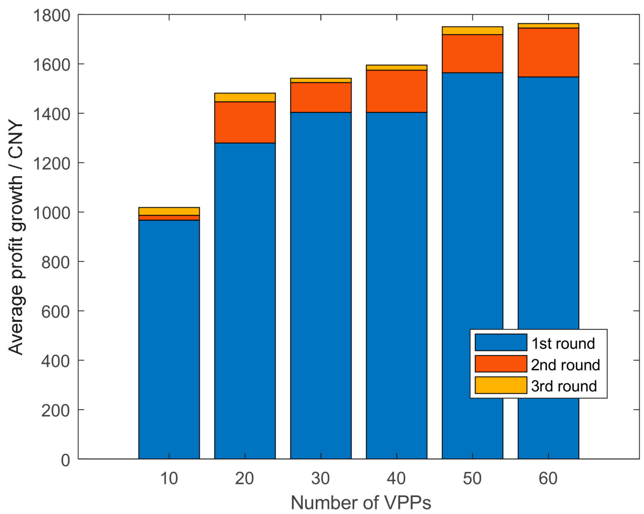


Figure 13. Average profit growth with different numbers of VPPs.

5.4. Potential Implementation

Blockchain has been recognized as a trending technology for decentralized P2P trading solutions. In this subsection, we discuss the potential implementation of the proposed mechanism by using the technology of blockchain.

Blockchain technology is essentially a distributed ledger where each block is equivalent to a page in the ledger. All information is recorded in an encrypted manner, and the blocks are connected in chronological order. A new block can be added to the blockchain only if all new information in the block is verified by most nodes. In this way, decentralized P2P trading can be realized, and information security is strengthened.

However, in this paper, information is updated frequently during P2P trading, especially in the negotiation stage. If a single public chain is still used, like in the bitcoin network, where each new piece of information needs to be propagated to most nodes, it will take a large amount of time to update the information. Therefore, as shown in Figure 14, this paper designed three kinds of chains.

(1) The VPP chain, composed of VPP internal DERs, is applied to internal management and local scheduling. Since VPP local scheduling is independent from the others, the VPP can choose whether to use the VPP chain to manage internal DERs.

(2) The negotiation chain, composed of a small number of VPPs, is applied to P2P negotiations in this paper. These chains can record all ask/bid prices. In this paper, VPPs match each other in the negotiation stage. If S-VPP and B-VPP are not in a negotiation chain, the buyer can temporarily use the seller's negotiation chain. Since, in this article, the seller can only select three objects for trading, the number of temporary members can be limited. Moreover, temporary members can be treated as supervisors in the negotiation chain.

(3) The global chain, composed of all VPPs and GridCo, records the results of the 5 stage P2P energy trading, which is written at a lower frequency in each stage and can be read at a higher frequency. Since the global chain contains all VPPs, it is not suitable for scenarios that require frequent updates. However, if there are only a few VPPs involved in P2P trading, it is a better choice to use the global chain directly, instead of the negotiation chain.

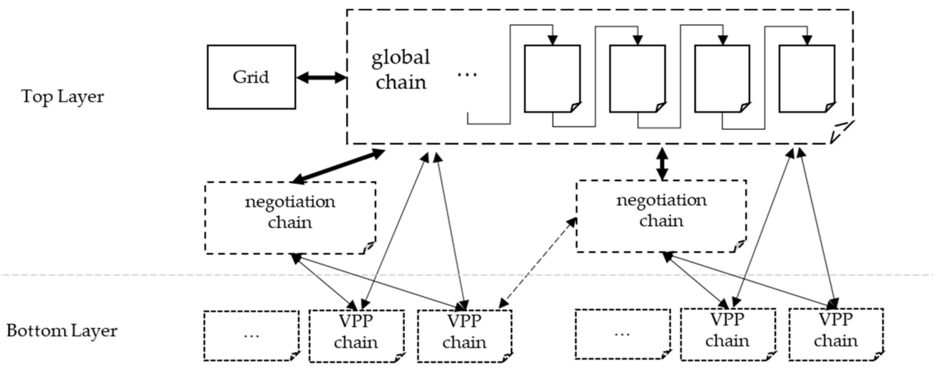


Figure 14. Schematic diagram of a potential implementation using blockchain.

6. Conclusions

This paper addresses decentralized energy trading among VPPs and proposes a peer-to-peer (P2P) mechanism with two interactive layers: On the bottom layer, each VPP schedules/reschedules its internal DERs, and on the top layer, VPPs negotiate with each other on the trade price and quantity. The interaction mechanism plays a key role in this paper: The bottom-layer scheduling provides the initial conditions for the top-layer negotiation, and the feedback of top-layer negotiation affects the bottom-layer rescheduling.

Thousands of scenarios are generated and then reduced to 20 to describe the uncertainties of wind and photovoltaic power. The local scheduling/rescheduling of a VPP is formulated as a stochastic optimization problem. The objective is to maximize profits, which requires consideration of revenue, penalties, and cost. Various physical and economic constraints are also taken into account.

The strategy of initial pricing is also presented. Based on the formulation of matched orders, we apply the multidimensional willingness bidding strategy (MWBS) to the iterative bidding process of P2P negotiation. Two factors, the supply–demand relationship (SDR) and matching degree (MD), are modified.

A numeric case of 14 VPPs is studied, in which each VPP has different internal DERs. The simulation results verify the effectiveness and flexibility of the optimal scheduling model in dealing with various VPPs. The parallel price bidding with MWBS is adaptive to market situations and efficient due to rapid convergence. It is revealed that VPPs can obtain higher profit by participating in P2P energy trading than in the traditional centralized trading, and the proposed mechanism of the two-layer "interactive" element can further increase the VPPs' benefits compared to the "forward" counterpart of "interactive". The impact of VPP configuration and the impact of the VPP number are studied as well, which verifies that the proposed mechanism can be applicable to most cases where VPPs manage some controllable DERs. Finally, this paper presents a potential implementation by using the technology of blockchain.

Author Contributions: Conceptualization, X.L., Z.X., and N.W.; methodology, X.L. and Z.X.; software, X.L.; supervision, Z.X. and W.X.; validation, X.L., Z.X., N.W., and M.F.; visualization, X.L.; writing—original draft, X.L.; writing—review and editing, X.L. and Z.X. All the authors have read and approved the final manuscript.

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Abbreviations

Abbreviations:	**Description:**
DER	distributed energy resource
P2P	peer-to-peer
VPP	virtual power plant, coordinator of internal DERs and player of P2P energy market
GridCo	grid corporation, service provider of transmission and power reserve
B-VPP	a VPP with energy shortage and plays the role of buyer in P2P energy trading
S-VPP	a VPP with energy surplus and plays the role of seller in P2P energy trading
MT	micro gas turbine
WT	wind turbine
PV	photovoltaic
ES	energy storage system
L	load demand
DR	demand response
FIT	feed-in tariff, the uniform price at which VPPs sell electricity to GridCo
RTP	real-time price, the uniform price at which VPPs buy electricity from GridCo
Variables:	**Description:**
$\mathbb{N}$	set of VPPs
$\mathbb{N}_B, \mathbb{N}_S$	set of B-VPPs, S-VPPs in P2P energy market
$\mathbb{N}_{S,i}, \mathbb{N}_{B,j}$	set of trade partners of B-VPP$_i$, S-VPP$_j$
$\mathbb{S}$	set of scenarios of wind and photovoltaic power
$\mathbb{T}$	set of time units
n	index of VPP, generally used as the subscript of a variable in this paper
i, j	index of B-VPP, S-VPP
s	index of scenario, generally used as the superscript of a variable in this paper
t	index of time unit of scheduling/rescheduling, generally used as the subscript of a variable in this paper $t = 1, \cdots, 24$

Δt	time unit of scheduling/rescheduling, $\Delta t = 1$ h in this paper
$]\rho_n^s$	probability of scenario s in VPP$_n$
F_n	profit of VPP$_n$
$W_{n,t}$	revenue of energy trading of VPP$_n$ at time unit t
$V_{n,t}^s$	penalty of nonscheduled output of VPP$_n$ at time unit t
$K_{n,t}^s$	total cost of VPP$_n$ at time unit t
$P_{Z,n,t}^s$	output of Z in VPP$_n$ at time unit t under scenario s, Z is a kind of DER, such as WT, PV, MT, ES, DR
$P_{n,t}$	scheduled output of VPP$_n$ at time unit t
$P_{n,t}^s$	net output of VPP$_n$ at time unit t under scenario s, algebraic sum of $P_{Z,n,t}^s$ in VPP$_n$
C_{RTP}	real-time price (RTP) at which VPPs buy energy from GridCo
C_{FIT}	feed-in tariff (FIT) at which VPPs sell energy to GridCo
SOC	state of charge of an energy storage system
$\eta_{\mathrm{ch}}, \eta_{\mathrm{dis}}$	efficiency of charge, discharge of an energy storage system
R	index of round of order negotiation and modification in the 5-stage P2P energy trading, generally used as the superscript of a variable in this paper, $R = 1, \cdots, \overline{R}$
r	index of bidding run in a single round of P2P negotiation, generally used as the superscript of a variable in this paper, $r = 1, \cdots, \overline{r}$
Q	results of local scheduling/rescheduling of a VPP
$Q_{\mathrm{sur}}, Q_{\mathrm{short}}$	energy surplus, shortage of a VPP
$\hat{Q}$	estimated tradable quantity of a VPP for P2P negotiation
$C_i^{\mathrm{bid}:[r]}$	bid price of B-VPP$_i$ in bidding run r
$C_j^{\mathrm{ask}:[r]}$	ask price of S-VPP$_j$ in bidding run r
$Q_{j \to i,t}$	traded quantity from S-VPP$_j$ to B-VPP$_i$ in a matched order
$C_{j \to i,t}$	trade price between S-VPP$_j$ and B-VPP$_i$ in a matched order
$q_{j \to i,t}$	traded quantity from S-VPP$_j$ to B-VPP$_i$ in a matched order after modification
$\underline{X}, \overline{X}$	minimum, maximum of a variable X

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