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Hybrid Game Trading Mechanism for Virtual Power Plant Based on Main-Side Consortium Blockchains

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Abstract: With the rapid development and technological innovation in the energy market, peer-to-peer (P2P) energy trading, as a decentralised and efficient trading model, has been widely studied and practically applied. However, in P2P energy transactions involving multiple prosumers, there are challenges such as information asymmetry, trust issues, and transaction transparency. To address these challenges, blockchain technology, as a distributed ledger technology, provides solutions. In this paper, we propose a blockchain technology-based prosumer–virtual power plant (VPP) two-tier interactive energy management framework to assist P2P energy transactions between multiple prosumers. In this framework, the virtual power plant acts as a leader and sets differentiated tariffs for different prosumers to equal the distribution of social welfare. The various prosumers act as followers and respond to the leader's decisions in a cooperative manner. Blockchain's immutability and transparency enable prosumers to participate in P2P energy trading with greater trust, share idle energy, and share revenues based on contribution. In addition, given the uncertainty of renewable energy, this paper employs a stochastic planning approach with conditional value at risk (CVaR) to describe the expected loss of VPP. Ultimately, as verified by the arithmetic simulation, the blockchain co-governance transaction model effectively supports energy coordination and optimization of complementarities while ensuring the utility of each transaction node. This model promotes the application of renewable energy in local consumption, while facilitating the innovation and sustainable development of the energy market.

Keywords: energy system; blockchain; VPP; hybrid game; P2P transaction; energy market

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1. Introduction

The deployment of renewable energy and energy storage systems in the context of national dual-carbon targets has transformed a large number of traditional consumers into prosumers. Prosumers can be motivated to join virtual power plants based on the characteristics of their energy output and geographic location [1]. The aggregation of prosumers in virtual power plants is an important means to awaken the vast amount of distributed resources (DERs) in the market [2].

Currently, much research has been achieved in the area of virtual power plants and the prosumer game. The virtual power plant coordinates and controls distributed energy sources with advanced energy management technologies to share local resources in order to promote efficient resource utilisation and sustainable development within the alliance, and to increase its own profitability. Under this management framework, the virtual power plant delegates day-to-day operations to prosumers rather than restricting their operational decisions. Under this structure, virtual power plants may make different decisions and may have conflicts of interest with prosumers. Therefore, a leader–follower structure is presented between the virtual power plant and the prosumers. The Stackelberg game is used to describe the relationship between the leader and the follower, where the operator develops a strategy before the producer and consumer make a decision. Guided by the operator's price signals, the prosumers who trade energy are directly negotiated with and respond to the price. In reference [3], a master–slave game model is developed to set reasonable electricity sales prices to guide EV charging to the grid, with virtual power plants as leaders and EVs as followers. In reference [4], based on the Stackelberg game, a two-tier bidding model of a virtual power plant is established, in which the distributed power sources and loads inside the virtual power plant act as independent subjects, bidding for the sale and purchase of electricity from the virtual power plant respectively. Reference [5] proposed a VPP market trading model based on a non-cooperative game model, in which the operator dominates the market and forms a Stackelberg game relationship with other participants. This model promotes the local consumption of clean energy and reduces transmission losses through tariff guidance and power sharing. Reference [6] proposed a non-cooperative game-based energy trading approach for multiple virtual power plants. The coordination and control model of public buildings is incorporated into the scheduling framework of VPPs, and a non-cooperative game model is established to explore the game relationship between power selling companies in the P2P trading process.

For virtual power plants, an appropriate incentive programme needs to be constructed to encourage prosumers to actively participate in energy management while meeting their own interests. However, for prosumers, a scheme needs to be designed to enable them to respond to retail price fluctuations in a cooperative manner. In exploring cooperative games between prosumers, market designs based on cooperative games have been proposed to encourage direct P2P energy trading. Under a fixed purchase and sale price, prosumers can directly share unused energy resources in the region and distribute revenues on a contractual or contribution basis. However, the limitation of these studies is that prosumers can only act as price takers, passively accepting price decisions from upstream agents. In order to realise a two-tier interaction, reference [7] proposes a co-operative Stackelberg game model to accommodate the participation of prosumers in energy management through a suitable form of alliance. In reference [8], for prosumers in a fixed coalition, a cooperative game based on the Nash bargaining theory is more suitable for modelling negotiations between prosumers. Considering the multiple contributions of users, the P2P energy trading problem is formulated as a general Nash game problem, introducing the concept of bargaining power [9].

The above literature mainly adopts game theory to analyse the decision-making and benefits of market players, which provides a theoretical basis for the bidding of virtual power plants and the design of market mechanisms. However, in actual aggregation transactions, prosumers lack the right to speak and choose in many cases, which triggers a series of trust issues, including information opacity and excessive third-party power. At the same time, differences in information acquisition capacity and weak ability to predict power among prosumers, coupled with problems of asymmetric and non-transparent transaction information in the market, make it difficult to successfully realise a multi-actor game based on information sharing. In addition, ensuring that market players are subject to regulation, privacy protection, and secure information interactions in a non-trusted environment are key elements in guaranteeing the efficient operation of the market trading mechanism and the virtual power plant operation model. However, the existing centralised management model can hardly meet the above needs. Blockchain technology, with its decentralised and data-immutable characteristics, provides a solution for virtual power plants to aggregate prosumers to participate in electricity market transactions.

Blockchain is essentially a distributed shared database that consists of cryptographic blocks linked in chronological order [10]. Each block consists of two parts: the block body and the block header [11]. This organisation gives blockchain technology several unique features, including decentralisation, openness and transparency, security, and smart contracts [12]. The virtual power plant transaction model based on blockchain technology includes two main aspects. On the one hand, blockchain technology builds an open and transparent trading platform for multi-virtual power plants, and each virtual power plant uploads information such as tariffs and electricity to the blockchain, which incentivises virtual power plants to reduce costs, promotes market competition, and results in a more reasonable and fairer distribution of resources. On the other hand, P2P transactions are realised between prosumers within the VPP, and the consensus mechanism of blockchain technology ensures that the information is open and transparent, and flexible transactions and automatic settlements are realised between the VPP and prosumers through smart contracts. The continuous development of blockchain technology brings more justice and security to P2P transactions.

VPP aggregation prosumers can trade energy with distribution networks (DNs) to maintain the balance of supply and demand [13]. It can also provide flexibility and reliability to the energy market and improve the social benefits of the whole system [14]. However, although renewable energy sources are abundant, they suffer from unevenness in temporal and spatial distribution, intermittency, and volatility. Stochastic programming is viewed as one of the effective methods of dealing with uncertainty, and the conditional value at risk (CVaR) is incorporated into the objective function to quantify the expected losses that may result from the uncertainty of distributed resources. However, current research lacks the consideration of co-operation factors between prosumers, thus failing to adequately reflect their impacts. Therefore, virtual power plants should make trade-offs between social welfare and risk levels in order to develop tariff requirements for different prosumers and to coordinate energy trading.

To this end, this paper focuses on the layered interaction model of virtual power plant and blockchain trusted transaction technology, aiming to establish a blockchain technology-based prosumer–virtual power plant two-layer interaction energy management framework. Firstly, the blockchain node model and decision-making model of virtual power plants and consumers are established; the incentive mechanism is designed by combining the Stackelberg game model between virtual power plants and prosumers with the cooperative game process between consumers and producers; and the blockchain platform is used for the writing and deployment of smart contracts. Finally, an example analysis is carried out to verify the feasibility of the model.

2. Main-Side Consortium Blockchain Governance Structure and Node Deployment

2.1. Main-Side Consortium Blockchain Governance Structure

The Main–side chain structure diagram is shown in Figure 1. On the main chain, virtual power plants with access conditions are allowed to become nodes of the main chain and thus participate in energy and service transactions. These nodes are the basis for both acting as agents for prosumers to fulfil the functions of market bidding, order confirmation, fund flow, information enquiry, etc., as well as for the distributed database to perform multi-point parallel bookkeeping duties. This main chain builds a virtual power plant trading platform in which energy and service transactions take place. The virtual power plant nodes earn revenue by acting as agents for prosumers in energy transactions through adaptive pricing strategies, as compensation for their provision of the trading platform and agent services.

In order to ensure the security and reliability of energy transactions, the main chain is in the form of a coalition chain. Therefore, the nodes involved in the transaction need a certain communication capability and reputation base. To meet this requirement, agent nodes of grid companies and VPP operators are deployed in the main chain. Among them, the VPP operator not only needs to configure the virtual trading agent of prosumers (used to simulate the external market environment, and the volume of transactions it makes with internal prosumers in the virtual power plant is equivalent to the volume of transactions made between prosumers and the external market), but also needs to perform some functions of the VPP management agent, such as the authentication of the identity of the uplinked producer and consumer nodes and the adjustment of the transaction orders after security calibration. At the same time, the power grid node realises energy transactions with the virtual power plant, and also needs to supervise the power transactions of the virtual power plant, provide security checking services, provide data support for the centralised regulation of the power system, and assist the VPP operator in the authentication of the consumer–producer nodes. The main chain mainly serves to record the power transaction information between the VPP operator and the power grid company; it records these data in the distributed ledger. By utilising the tamper-proof nature of blockchain technology, it ensures the authenticity and reliability of the data relating to the flow of funds and electricity, which fundamentally eliminates the possibility of fraudulent operations in the financial management process. This guarantee mechanism effectively simplifies the financial management process of the power system and achieves a more efficient operation.

As for the side chain, it is used to manage the energy interactions between the prosumers aggregated by the virtual power plant. These consumer–producer agents can act as main side chain anchor nodes to manage the lower-level energy interaction process by establishing side chains. The governance structure of the side chain can be private or federated, depending on the needs of the prosumer business model. The side chain enables the updating of the current transaction tariff and the availability of electricity.

Each side chain not only records the transaction information alongside the prosumer to whom it belongs, but also backs up the transaction information generated on the main chain in order to achieve reverse supervision of the market behaviour of the prosumer operator. Each distributed resource entity is equipped with at least one measurement device, such as a smart meter, as a light node of the side chain. These nodes not only have basic measurement and communication functions, but also need certain power prediction and market proxy capabilities to regularly upload data to the blockchain. Unlike consensus nodes and light nodes in traditional alliance chains, the management scope of the main side chain forms a data barrier. Distributed resources or users in the side chain can only access the transaction information of the participating subjects in this side chain and the agent's transaction information in the main chain, which has a higher level of privacy protection. In addition, each side chain can adopt different consensus mechanisms and smart contracts according to the demand to meet the diversity of business models of different market agents in virtual power plants.

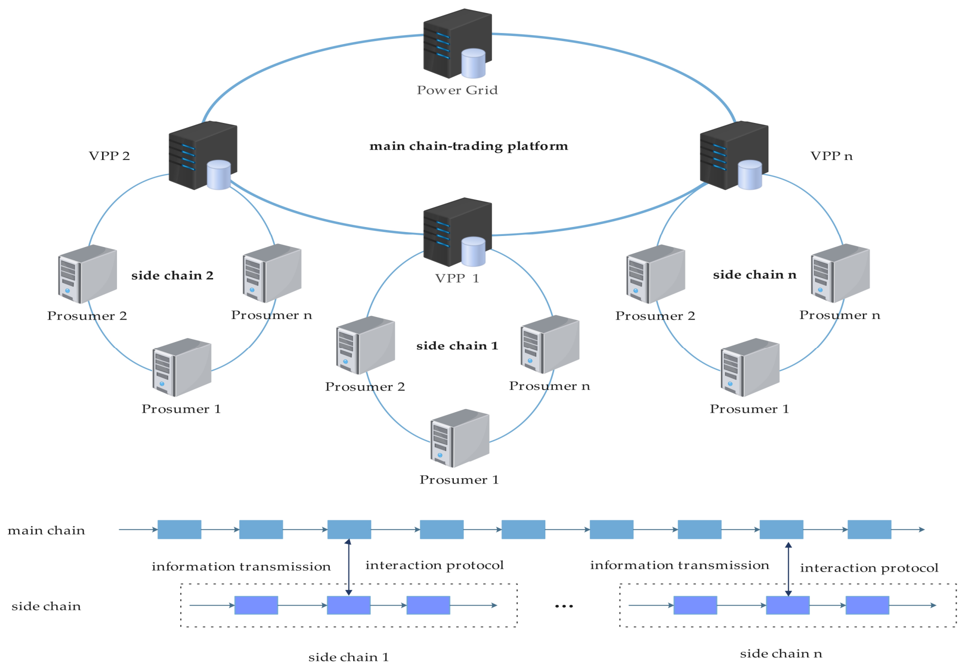


Figure 1. Main–side chain node structure diagram.

2.2. Virtual Power Plant and Prosumer Blockchain Node Model

2.2.1. Virtual Power Plant Node Model

The VPP plays the role of a coordinator and is responsible for managing the balance of energy supply and demand between prosumers. When there is an imbalance between supply and demand between prosumers, the VPP needs to trade energy with the distribution network (DN) to ensure stable system operation.

Virtual power plants need to set the price at which energy is traded with prosumers. Typically, the sale price is set below the purchase price to encourage prosumers to adjust their intrinsic energy use independently and to interact directly with other prosumers, thus reducing their dependence on the larger grid. This price differential can be used as an incentive for prosumers to provide additional energy when there is a shortage of energy or to inject excess energy into the system when there is an excess supply of energy. The virtual power plant node needs to consider the time-of-day tariff of the grid, the energy output and energy demand of each producer and consumer, and the operational constraints, and adjust the amount of energy traded with the larger grid according to the market supply and demand in order to maximise the market benefits. The decision-making model of the virtual power plant is as follows:

$$\max_{\mu_{Pb}^{i,t},\mu_{Ps}^{i,t},p_{Pb}^{i,t,w},p_{Ps}^{i,t,w}} \sum_{w\in\Phi_w}\sum_{t=1}^{T}\sum_{i=1}^{N}\pi^{i,w}((\mu_{Ds}^{t}P_{Ps}^{i,t,w}+\mu_{Pb}^{i,t}P_{Pb}^{i,t,w})-(\mu_{Db}^{t}P_{Pb}^{i,t,w}+\mu_{Ps}^{i,t}P_{Ps}^{i,t,w}))+\beta\sum_{i=1}^{N}\left[\zeta^{i}-\frac{1}{1-\gamma}\sum_{w\in\Phi_w}\pi^{i,w}\eta^{i,w}\right] \quad (1)$$

Constraints:

$$\mu_{Pb}^{t,\min}\leqslant\mu_{Pb}^{i,t}\leqslant\mu_{Pb}^{t,\max},\forall i\in N,\forall t\in T \quad (2)$$

$$\mu_{Ps}^{t,\min}\leqslant\mu_{Ps}^{i,t}\leqslant\mu_{Ps}^{t,\max},\forall i\in N,\forall t\in T \quad (3)$$

$$\frac{\sum_{t}^{T}\mu_{Pb}^{i,t}}{T}\leq\mu_{Pb,ave}^{i,t},\forall i\in N \quad (4)$$

$$\frac{\sum_{t}^{T}\mu_{Ps}^{i,t}}{T}\geq\mu_{Ps,ave}^{i,t},\forall i\in N \quad (5)$$

$$\zeta^{i}-\sum_{t=1}^{T}\left[(\mu_{Ds}^{t}P_{Ps}^{i,t,w}+\mu_{Pb}^{i,t}P_{Pb}^{i,t,w})-(\mu_{Db}^{t}P_{Pb}^{i,t,w}+\mu_{Ps}^{i,t}P_{Ps}^{i,t,w})\right]\leqslant\eta^{i,w},\forall i\in N,\forall w\in W \quad (6)$$

where $\mu_{Pb}^{i,t}, \mu_{Ps}^{i,t}$ is the transaction price from the virtual power plant to prosumer i at moment t; $P_{Pb}^{i,t,w}, P_{Ps}^{i,t,w}$ is the amount of electricity produced and consumed by prosumer i in transaction with the virtual power plant under scenario w at moment t; $\mu_{Ds}^{t}, \mu_{Db}^{t}$ is the time-of-day tariff between the power grid and the virtual power plant at moment t; and $\pi^{i,w}$ is the probability of occurrence of the uncertain scenario for wind power.

The objective function (1) consists of two parts: the first part is the VPP's expected revenue, the revenue that the virtual power plant receives from the sale of electricity to the prosumer and the grid minus the virtual power plant's expenditure on the purchase of electricity from the prosumer and the grid. The second component is the result of the trade-off between expected revenue and risk, which is realised by multiplying the conditional value at risk (CVaR) by the weighting parameter β. The magnitude of the β-value has an impact on risk appetite, with larger β-values indicating a stronger risk aversion preference. The VPP may choose a lower β-value in order to increase their revenues and reduce expected costs. In contrast, conservative operators are more likely to choose a larger β value to strengthen the risk aversion weighting.

Constraints (2) and (3) serve to limit the transaction prices of prosumers to a specific interval. In order to constrain the VPP's influence in the market, constraints (4) to (5) set the average daily price to define the upper and lower limits of the retail price. Constraint (6) aims to characterise the impact of the β-value on returns by calculating the conditional value at risk (CVaR). This constraint reveals the role of the β-value in return forecasting.

2.2.2. Prosumer Node Model

According to the dynamic pricing strategy of the virtual power plant, prosumers with energy production capacity have two options: one is to interact with other prosumers directly, and the other is to trade energy through the operator. In terms of energy interaction, prosumers are able to utilise distributed resources and loads to achieve mutual benefits for both parties through direct interaction. The Nash game is adopted here to study the process of direct energy interaction. In the Nash game, each producer and consumer makes decisions independently and cooperates with other prosumers to share idle resources, thus maximising the overall benefits. In addition, the Nash game encourages direct energy interactions between prosumers to distribute the revenue based on their respective contributions. The prosumers respond to the energy transactions with the operator, given a known price. The following is the objective function of the prosumers:

$$P_{Pb}^{i,t,w}, P_{Ps}^{i,t,w} \in arg\max(C_{Non}^{i,w}(\chi_{Non}^{i,w}) - (C_{Tra}^{i,w}(\chi_{Tra}^{i,w}) + Ce_{Pay}^{i,w}))^{\alpha_i^w} \tag{7}$$

$$C_{Non}^{i,w}(\chi_{Non}^{i,w}) = \sum_{t=1}^{T}\left[\mu_{Pb}^{i,t}P_{Pb}^{i,t,w} - \mu_{Ps}^{i,t}P_{Ps}^{i,t,w} + c_E^i(P_{Ec}^{i,t,w} + P_{Ed}^{i,t,w})\right], \forall i \in N, \forall w \in W \tag{8}$$

$$C_{Tra}^{i,w}(\chi_{Tra}^{i,w}) = \sum_{t=1}^{T}\left[\mu_{Pb}^{i,t}P_{Pb}^{i,t,w} - \mu_{Ps}^{i,t}P_{Ps}^{i,t,w} + c_E^i(P_{Ec}^{i,t,w} + P_{Ed}^{i,t,w})\right], \forall i \in N, \forall w \in W \tag{9}$$

Constraints:

$$P_{Pb}^{i,t,w} + P_{Gen}^{i,t,w} + P_{Ed}^{i,t,w} + P_{trading}^{i,t,w} = P_{Ps}^{i,t,w} + P_{load}^{i,t} + P_{Ec}^{i,t,w} : \lambda_{pro}^{i,t,w}, \forall i \in N, \forall t \in T, \forall w \in W \tag{10}$$

$$\sum_{i=1}^{N} P_{trading}^{i,t,w} = 0 : \lambda_{trading}^{t,w}, \forall t \in T, \forall w \in W \tag{11}$$

$$0 \leqslant P_{Pb}^{i,t,w} \leqslant P_{Pb,i}^{\max} : \lambda_{Pb}^{i,t,w}, \forall i \in N, \forall t \in T, \forall w \in W \tag{12}$$

$$0 \leqslant P_{Ps}^{i,t,w} \leqslant P_{Ps,i}^{\max} : \lambda_{Ps}^{i,t,w}, \forall i \in N, \forall t \in T, \forall w \in W \tag{13}$$

$$0 \leqslant P_{Ec}^{i,t,w} \leqslant P_{Ec,i}^{max} : \lambda_{Ec}^{i,t,w}, \forall i \in N, \forall t \in T, \forall w \in W \tag{14}$$

$$0 \leqslant P_{Ed}^{i,t,w} \leqslant P_{Ed,i}^{max} : \lambda_{Ed}^{i,t,w}, \forall i \in N, \forall t \in T, \forall w \in W \tag{15}$$

$$SOC_i^{min} \leqslant SOC^{i,t,w} \leqslant SOC_i^{max} : \overline{\lambda_{SOC}^{i,t,w}}, \underline{\lambda_{SOC}^{i,t,w}}, \forall i \in N, \forall t \in T, \forall w \in W \tag{16}$$

$$SOC^{i,1,w}Cap^i = SOC_{\text{int}}^i Cap^i + \eta_{Ec}^i P_{Ec}^{i,1,w} - \frac{1}{\eta_{Ed}^i P_{Ed}^{i,1,w}} : \lambda_{SOC1}^{i,1,w}, \forall i \in N, \forall w \in W \tag{17}$$

$$SOC^{i,t,w}Cap^i = SOC^{i,t-1,w}Cap^i + \eta_{Ec}^i P_{Ec}^{i,t,w} - \frac{1}{\eta_{Ed}^i P_{Ed}^{i,t,w}} : \lambda_{SOC1}^{i,t,w}, \forall i \in N, \forall t \in T, \forall w \in W \tag{18}$$

$$SOC^{i,24,w} = SOC_{exp}^i : \lambda_{SOC2}^{i,w}, \forall i \in N, \forall w \in W \tag{19}$$

$$\alpha_i^w = \frac{\sum_t P_{trading}^{i,t,w}}{\sum_i \sum_t P_{trading}^{i,t,w}}, \forall i \in N, \forall t \in T \quad (20)$$

$$\chi_{Non}^{i,\mathbf{w}} = [P_{Pb}^{i,t,w}, P_{Ps}^{i,t,w}, P_{Ec}^{i,t,w}, P_{Ed}^{i,t,w}, SOC^{i,t,w}] \quad (21)$$

$$\chi_{Tra}^{i,\mathbf{w}} = [P_{Pb}^{i,t,w}, P_{Ps}^{i,t,w}, P_{Ec}^{i,t,w}, P_{Ed}^{i,t,w}, SOC^{i,t,w}, P_{trading}^{i,t,w}] \quad (22)$$

where: $C_{Non}^{i,w}$ is the operating cost of prosumer i without energy interaction with other producers under scenario w; $C_{Tra}^{i,w}$ is the operating cost of prosumer i after energy interaction with other producers under scenario w; $Ce_{Pay}^{i,w}$ is the cost of energy interaction of prosumer i under scenario w; $P_{Ec}^{i,t,w}, P_{Ed}^{i,t,w}$ are the charging and discharging power of prosumer i in scenario w at time t; and c_E^i is the cost coefficient of charging and discharging of prosumer i. (The difference between (8) and (9) is whether the constraint function considers energy sharing).

Constraint (10) ensures the power balance of the prosumers in each scenario at each moment in time, and constraint (11) ensures that the sum of the output powers of the prosumers with surplus energy is equal to the sum of the input powers of the remaining prosumers. The energy trading between the virtual power plant and the generators and consumers is limited by constraints (12) and (13). Constraints (14) and (15) define the charging and discharging limits, while constraint (16) limits the maximum and minimum states of the battery. Battery storage changes according to energy balance constraint (17) at t = 1 and energy balance constraint (18) when using the equation. The expected state of charge (SOC) at t = 24 should satisfy constraint (19); α_i^w is the bargaining power of prosumer i under scenario w. Energy balance constraint (17) is energy balance constraint (18) at t = 1 and energy balance constraint (19) at t = 24. $\chi_{Non}^{i,\mathbf{w}}, \chi_{Tra}^{i,\mathbf{w}}$ are the decision vectors of prosumer i with and without participation in P2P energy sharing.

3. Designing a Two-Tier Energy Trading Mechanism for VPP–Prosumer Based on Main-Side Consortium Blockchain Structure

A hybrid game-based two-tier energy management framework for VPP-Prosumer is shown in Figure 2. The time-of-day tariff set by the power grid node is used as a benchmark in the main chain, which is transmitted to the side chain through the main chain, providing a reference basis for the hybrid gaming operation. On the side chain, the virtual power plant and the prosumers engage in a strategic game based on the game model, which takes into account time-of-day tariffs, energy supply and demand, and other factors in order to achieve a trading equilibrium solution. The results of the game will guide the VPP node to trade energy with the power grid node in the main chain to achieve an efficient flow of energy.

3.1. Design of Side Chain Smart Contracts

The smart contract in the transaction process proposed in this paper is used to guide adaptive pricing between the virtual power plant and different prosumers on the side chain and the decision-making of energy sharing between prosumers, thus simplifying the transaction process and improving the rationality of each subject. Based on the time-sharing tariff of the power grid on the main chain, the purchase and sale tariffs and power volumes of the VPP to the prosumers on the side chain and the energy-sharing power volumes between the prosumer nodes are calculated by the smart contract. In this process, the smart contract operation process includes three phases: the node access phase, hybrid gaming phase, and power tariff clearing phase. The node access stage mainly completes the authentication of the identity of the subjects on the side chain; the hybrid game stage completes the decision-making and information interaction of the subjects; and the power tariff clearing stage completes the delivery and clearing of the power tariff.

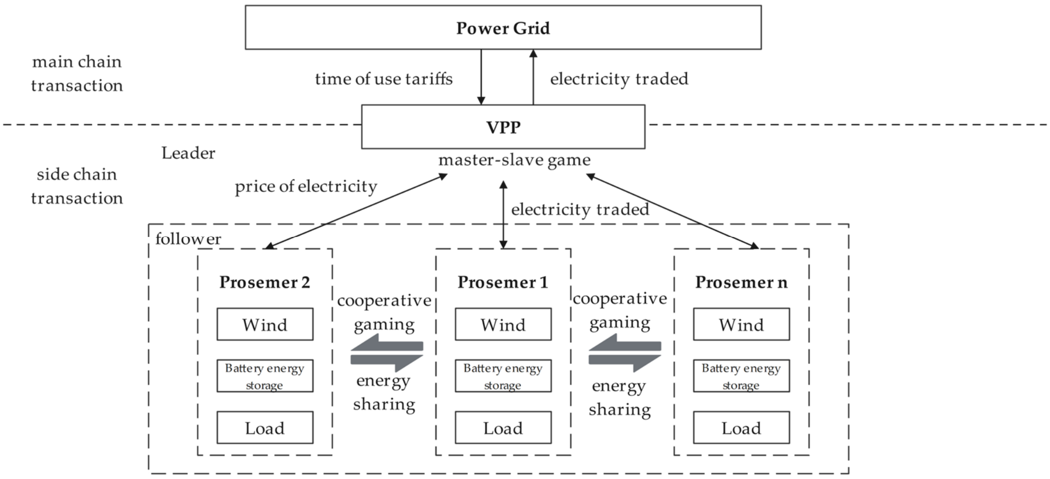


Figure 2. A hybrid game-based two-tier energy management framework for VPP–Prosumer.

Since objective function (7) is a power function, objective function (7) is decomposed into two sub-problems using the Nash negotiation theory: the operating cost minimisation problem (23) and the bargaining problem (24). Then, according to the volume of electric energy transactions between prosumers, the cooperative benefit distribution is achieved based on the Nash negotiation theory. Finally, the price of electricity traded between prosumers is obtained.

$$F^{w}_{Operation} = \min \sum_{i}^{N} C^{i,w}_{Tra}(\boldsymbol{x}^{\boldsymbol{i,w}}_{Tra}) \tag{23}$$

$$F^{w}_{Benefits} = \max \prod_{i}^{N} \left(\eta^{i,w,*} - Ce^{i,w}_{Pay} \right)^{a^{w}_{i}} \tag{24}$$

Style: $\eta^{i,w,*} = C^{i,w}_{Non}(x^{i,w}_{Non}) - C^{i,w}_{Tra}(x^{i,w}_{Tra})$

First, using the KKT condition, the lower objective function and constraints are composed of Lagrange multipliers as constraints in the upper layer, which transforms the two-layer model into a one-layer model. Next, since $\mu^{i,t}_{Pb}P^{i,t,w}_{Pb}, \mu^{i,t}_{Ps}P^{i,t,w}_{Ps}$ in the upper layer objective function are obtained by multiplying two decision variables in the lower layer model, the term is non-linear. Therefore, the strong duality theorem is applied to linearise it with the first-order optimality condition in the KKT condition.

(1) The hybrid game model is first rearranged into a compact form, denoted as:

$$\min F^{w}_{Operation} = \sum_{j=1}^{N_{\text{var}}} \left(f_j X(j) \right) \tag{25}$$

Constraints:

$$\begin{cases} \sum\limits_{n=1}^{N_{eq}} \sum\limits_{j=1}^{N_{\text{var}}} \left(a_{n,j} X(j) \right) \leqslant b_n \\ \sum\limits_{m=1}^{N_{eq}} \sum\limits_{j=1}^{N_{\text{var}}} \left(c_{m,j} X(j) \right) = d_m \end{cases} \tag{26}$$

where N_{var} is the number of decision variables in the lower model; f_j is the coefficient of the decision variable in the objective function; $X(j)$ is the set of decision variables in the model, and $X(j) = \chi^{i,\mathbf{w}}_{Tra} = [P^{i,t,w}_{Pb}, P^{i,t,w}_{Ps}, P^{i,t,w}_{Ec}, P^{i,t,w}_{Ed}, SOC^{i,t,w}, P^{i,t,w}_{trading}]$; $a_{n,j}, c_{m,j}$ is the coefficient of the decision variable in the inequality and equation constraints; b_n, d_m are the constant terms in the inequality and equation constraints; $\mathrm{N}_{ineq}, \mathrm{N}_{eq}$ are the numbers of inequality and equation constraints.

(2) Establish Lagrange function L of the lower model and $\nabla L = 0$ at the optimal solution point. Transform the model using the KKT condition:

$$\nabla L = \frac{\partial L}{\partial X(j)} = f_j + \sum_{n=1}^{N_{ineq}} \mu_n a_{n,j} + \sum_{m=1}^{N_{eq}} \lambda_m c_{m,j} = 0 \tag{27}$$

$$\sum_{j=1}^{N_{\mathrm{var}}} \left(c_{m,j} X(j)\right) - d_m = 0 \tag{28}$$

$$\sum_{j=1}^{N_{\mathrm{var}}} \left(a_{n,j} X(j)\right) - b_n \leqslant 0 \tag{29}$$

$$\mu_n \left[\sum_{j=1}^{N_{\mathrm{var}}} \left(a_{n,j} X(j)\right) - b_n \right] = 0 \tag{30}$$

where μ_n, λ_m are the introduced Lagrange operators, corresponding to the inequality constraint and the equality constrain. The specific equation is appended in Appendix A.

Since Equation (30) is a bilinear term, it is linearised using the large M method.

$$\begin{cases} 0 \le \mu_n \le \mathrm{M}\delta_n \\ 0 \le \sum_{j=1}^{N_{\mathrm{var}}} \left(a_{n,j} X(j)\right) - b_n \le \mathrm{M}(1 - \delta_n) \end{cases} \tag{31}$$

where M is the constant introduced by the large M method with a sufficiently large value and δ_n is the binary variable introduced by the large M method.

(3) Based on the strong duality theorem [15] (the optimal value of the original problem is equal to the optimal value of the dual problem), the bilinear term in the objective function can be expressed in the form of the neutral term of the objective function and the Lagrange operator as:

$$\mu_{Pb}^{i,t} P_{Pb}^{i,t,w} - \mu_{Ps}^{i,t} P_{Ps}^{i,t,w} = -c_E^i (P_{Ec}^{i,t,w} + P_{Ed}^{i,t,w}) + \sum_{n=1}^{\mathrm{N}_{ineq}} (b_n \mu_n) + \sum_{m=1}^{\mathrm{N}_{eq}} (d_m \lambda_m) \tag{32}$$

By substituting Equation (32) into Equation (1), the original two-layer problem with bilinear terms has been converted to a standard single-layer mixed-integer linear programming problem.

$$\begin{gathered} \max \sum_{w \in \Phi_w} \sum_{t=1}^{T} \sum_{i=1}^{N} \pi^{i,w} (\mu_{Ds}^t P_{Ps}^{i,t,w} - \mu_{Db}^t P_{Pb}^{i,t,w} - c_E^i (P_{Ec}^{i,t,w} + P_{Ed}^{i,t,w})) \\ + \sum_{n=1}^{\mathrm{N}_{ineq}} (b_n \mu_n) + \sum_{m=1}^{\mathrm{N}_{eq}} (d_m \lambda_m) + \beta \sum_{i=1}^{N} \left[\zeta^i - \frac{1}{1-\gamma} \sum_{w=1}^{\Omega} \pi^{i,w} \eta^{i,w} \right] \end{gathered} \tag{33}$$

Rewrite bargaining problem (24) as:

$$F_{Benefits}^{w} = \min \sum_{i=1}^{N} -\alpha_i^w log\left(\eta^{i,w,*} - Ce_{Pay}^{i,w}\right), \forall w \in W \tag{34}$$

Constraints:

$$\sum_{i} \alpha_i^w = 1, \forall i \in N, \forall w \in W \tag{35}$$

$$C_{Tra}^{i,w}(x_{Tra}^{i,w}) + Ce_{Pay}^{i,w} \leqslant C_{Non}^{i,w}(x_{Non}^{i,w}), \forall i \in N, \forall w \in W \tag{36}$$

$$\sum_i Ce_{Pay}^{i,w} = 0, \forall i \in N, \forall w \in W \tag{37}$$

This paper establishes a two-layer energy management framework for VPP-Prosumer based on hybrid game in the construction of side chain. There are two layers; the upper layer is the master–slave game between the virtual power plant and the prosumer, and the lower layer is the cooperative game between the prosumers. Therefore, the two-layer optimisation model is transformed into a single-layer mixed-integer linear (33) model by converting the lower-layer optimisation model into the constraints of the upper-layer planning model through the KKT condition, linearising the complementary relaxation conditions through the large M method, and rewriting the bilinear product as a linear expression through the strong duality theorem, and then the lower-layer cooperative game (34) model is solved based on the solving results. Side chain transaction flowchart is shown in Figure 3.

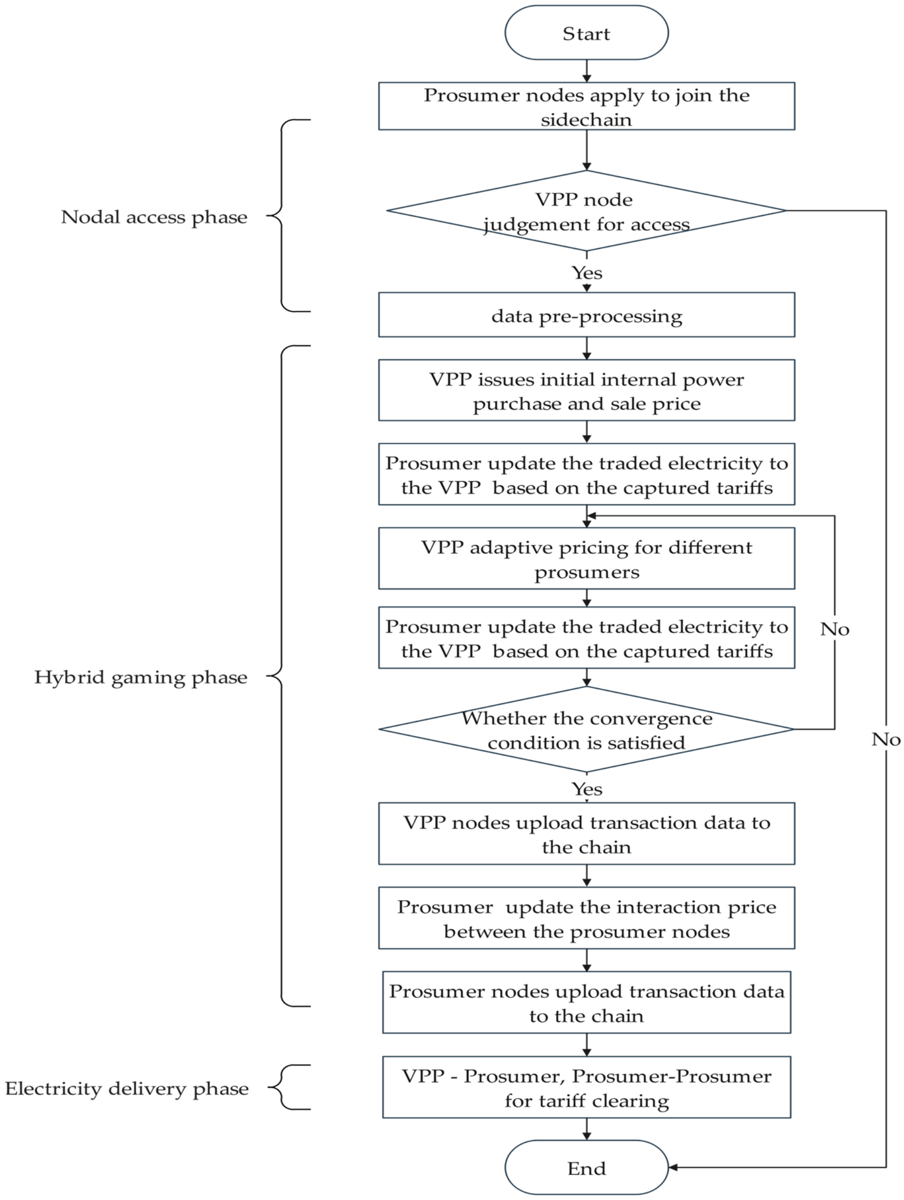


Figure 3. Side chain transaction flowchart.

3.2. Main Chain Transaction Process Design

The main chain transaction flowchart is shown in Figure 4, and the main steps include:

Step 1: The VPP node applies to join the main chain, and the access conditions of the VPP node are reviewed by the power grid node;

Step 2: The power grid node broadcasts the time-of-use tariff information, which is read by each VPP and thus passed to the side chain for hybrid gaming decisions between the VPP and the prosumers in the side chain;

Step 3: The VPP nodes declare the trading hours and trading power with the power grid node on the main chain based on the results of the side chain hybrid game;

Step 4: The VPP and the power grid node make the actual power and electricity deliveries in accordance with the negotiated trading hours and trading volumes.

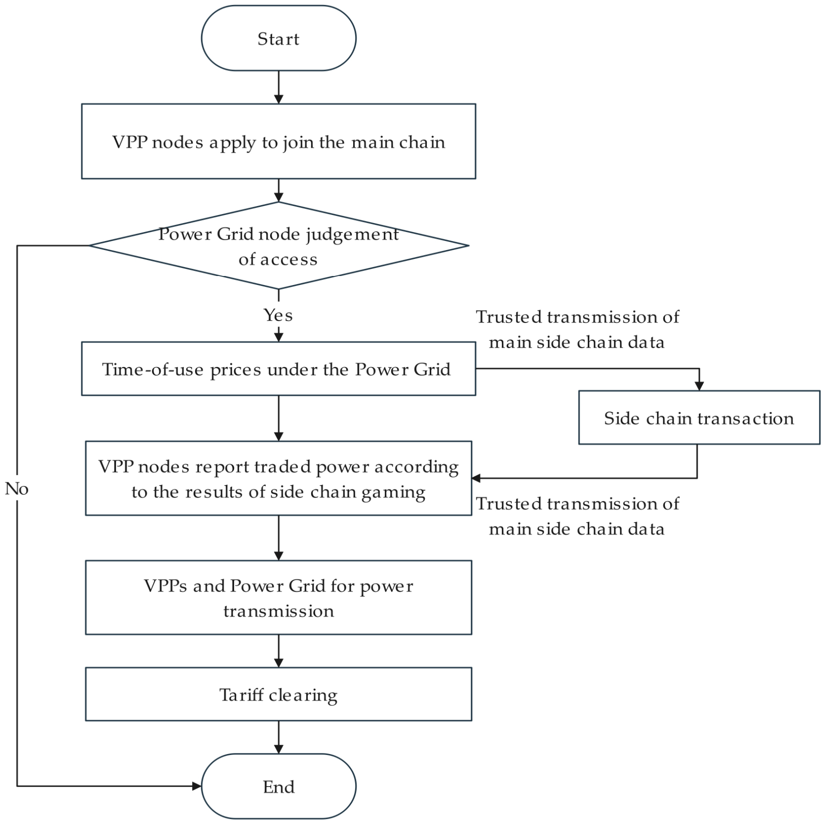


Figure 4. Main chain transaction flowchart.

3.3. Block Data Structure Design

The underlying block structure contains the block header and the block body. After a transaction is completed, the block is generated in the main chain by the power grid node, and in the side chain by the VPP node. The block body contains the transaction process and the result of the day, in which the time of all completed transactions, the amount of electricity traded, and the subject of the transaction are recorded in the transaction result of the day. The block header contains the Merkel root with fixed length after the Hash calculation, and the block data structure is shown in Figure 5. The block can ensure the high efficiency and credibility of each node's gaming process while storing the data, which can help the multi-governance transaction mode to operate efficiently in the long term.

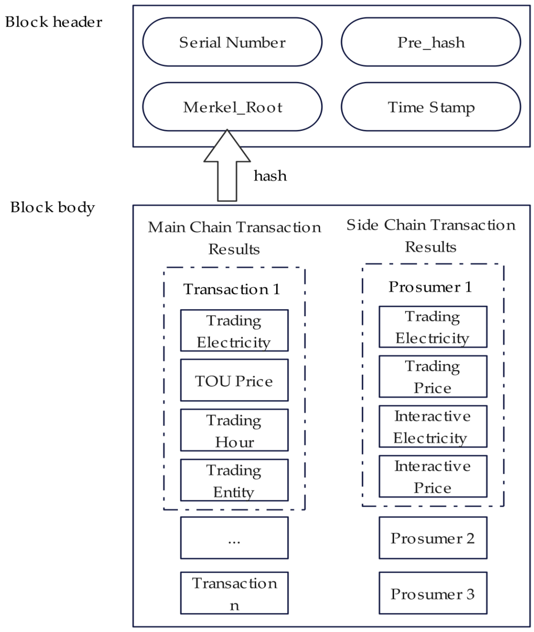


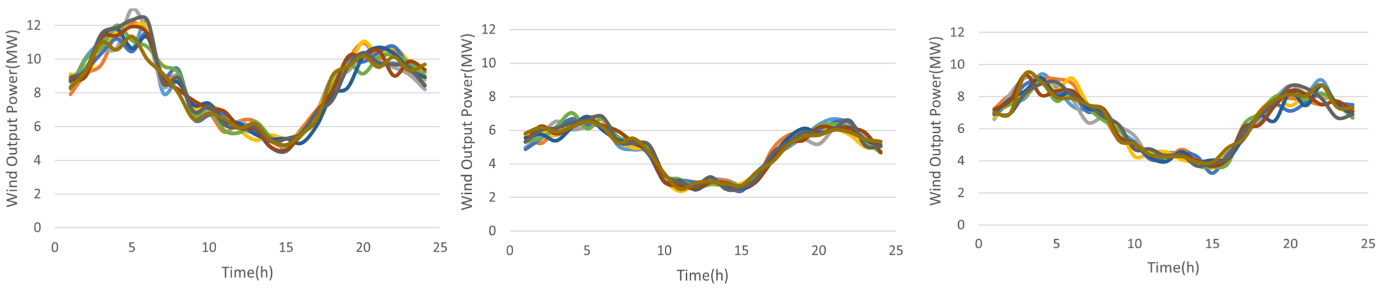
Figure 5. Block data structure diagram.

4. Example Analysis

In this paper, we deploy Hyperchain, an alliance chain platform, and Hypervision, a monitoring platform. In order to improve the reusability and compatibility of smart contracts, HyperEVM is used, which is a smart contract specification that is fully compatible with Ethereum, uses Solidity as the smart contract development language, and uses the optimised Ethereum virtual machine EVM as the underlying layer.

4.1. Calculation Parameters

The case study in this paper considers the blockchain technology-based virtual power plant trading problem for three prosumers. Wind power generation is characterised by a high degree of intermittency and uncertainty, posing a challenge to energy management. In order to simulate the realistic conditions of wind power generation, 10,000 scenarios are randomly generated by Monte Carlo simulation method and the scenario reduction is performed by improved K-means algorithm. Figure 6a–c show the wind output power for prosumers 1, 2, and 3. Figure 7 shows the time-of-use prices between the VPP and the power grid. See reference [16] for other parameters.



(**a**) Prosumer 1 (**b**) Prosumer 2 (**c**) Prosumer 3

Figure 6. Wind output power by prosumer. (**a**) Wind output power by prosumer 1. (**b**) Wind output power by prosumer 2. (**c**) Wind output power by prosumer 3.

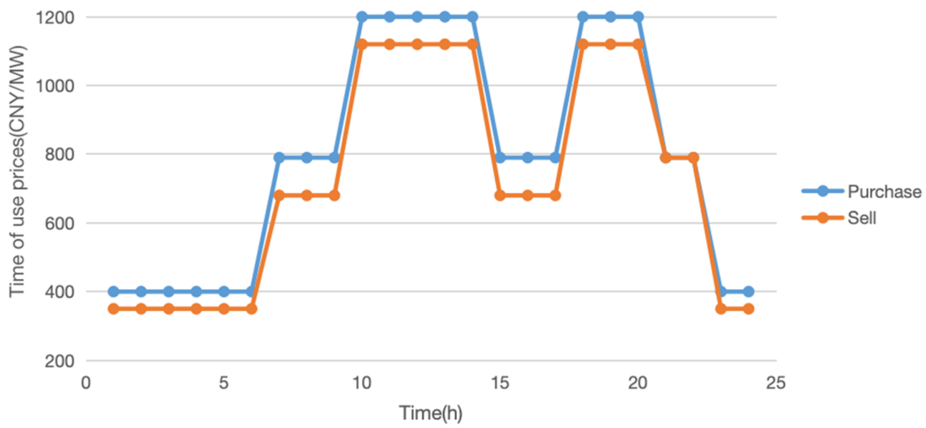
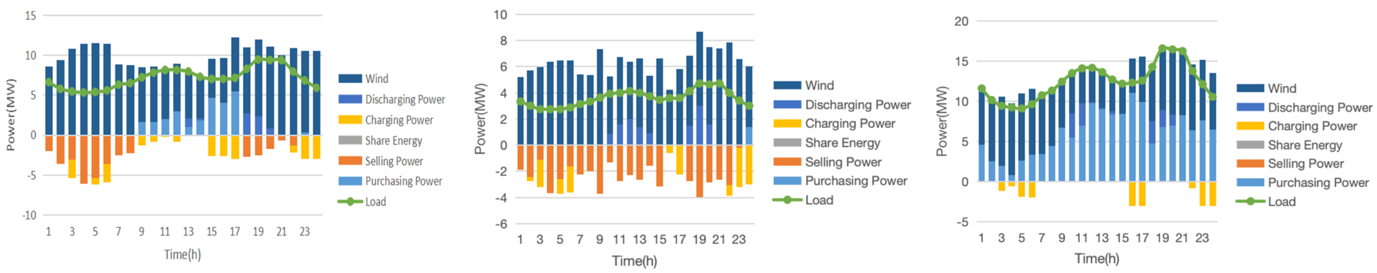


Figure 7. Time-of-use prices.

4.2. Programme Comparison

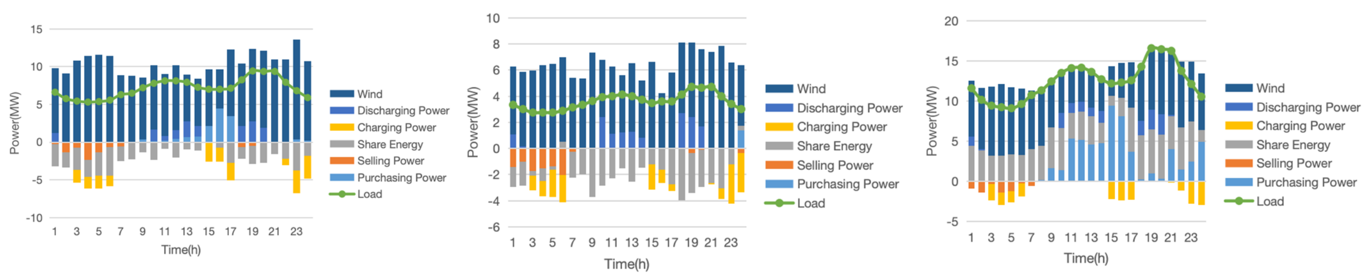
In order to verify the feasibility and effectiveness of the method proposed in this paper, the method proposed in this paper (Scheme I) is compared with the scheme that only considers a VPP and prosumer master–slave game without considering energy sharing between prosumers (Scheme II).

The electric power balance curve is shown in Figures 8 and 9. From the figures, it can be seen that the upper and lower energies are balanced, where the positive values are the wind output, storage discharge power, and purchasing power, and the negative values are the storage charging power, selling power, and load, and the amount of P2P energy sharing is greater than zero for receiving energy and less than zero for transmitting energy.



(**a**) Prosumer 1 (**b**) Prosumer 2 (**c**) Prosumer 3

Figure 8. Results of trading without P2P energy sharing under smart contract.



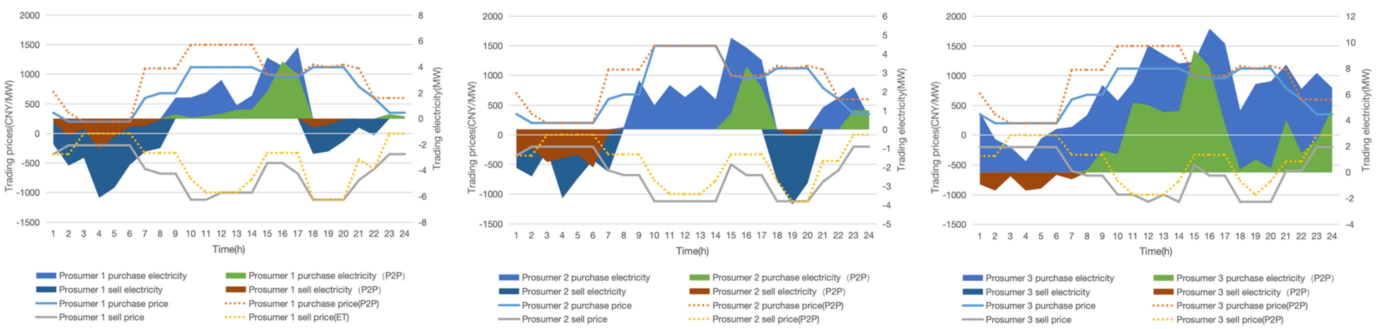
(**a**) Prosumer 1 (**b**) Prosumer 2 (**c**) Prosumer 3

Figure 9. Results of trading with P2P energy sharing under smart contract.

The electric power situation obtained by using Scheme II is shown in Figure 8. For prosumer 1 in the 1:00–8:00 and 18:00–22:00 time periods, the wind power output is larger, the electric load is low. Prosumer 1 will sell the remaining wind power to the virtual power plant to sell electricity to obtain revenue and the remaining power will be stored by the energy storage equipment. During the 9:00–17:00 period, the electric load is high and the wind power is not enough to support the electricity demand of prosumer 1, so they purchase electricity from the virtual power plant. During the 23:00–24:00 period, the price of electricity is low, so they purchase electricity from the virtual power plant and use it for the storage of energy storage equipment. Prosumer 2 achieves the peak and valley arbitrage of energy storage equipment by charging the energy storage equipment when the price of electricity is low and discharging it when the price of electricity is high. Prosumer 3 has a large electrical load and needs to purchase a large amount of electricity from the virtual power plant to satisfy the electrical load and store it for the energy storage device when the price of electricity is low.

The electric power situation obtained by using Scheme I is shown in Figure 9. Compared with Figure 8, it can be seen that in the case of smaller loads and wind output at a high level, electricity trading between the prosumer and the virtual power plant changes. In this case, it is no longer limited to the sale of electricity from the prosumer to the virtual power plant, but a new possibility arises, where P2P electricity trading can take place between the prosumers. This means that energy-rich prosumers have the opportunity to provide electricity to energy-poor prosumers, thus achieving energy sharing and mutual aid within the system. This mutual energy assistance not only reduces the cost of power trading, but also helps to improve the sustainability of the energy system. This is because during peaks and valleys, mutualisation ensures smooth energy supply, reduces waste, and improves the efficiency of the entire system.

In Figure 10, it can be seen that the trading mechanism considering P2P trading energy sharing reduces the amount of energy produced and consumed by the prosumer interacting with the virtual power plant, and electricity trading among the prosumers is more attractive compared to electricity trading with the virtual power plant, especially during peak hours (10:00–14:00, 18:00–20:00). In Figure 11, prosumers try to minimise the total cost through energy sharing. Prosumers can satisfy the supply–demand balance and reduce their dependence on third parties of virtual power plants through proactive P2P trading of energy sharing. Prosumers are able to share energy with other prosumers instead of relying solely on the virtual power plant. As can be seen from the purchase and sale price curves, the purchase and sale prices of the virtual power plant to all three prosumers have increased after considering P2P transactions, because the prosumers prefer to trade among themselves, which leads to a decrease in the volume of transactions between the prosumers and the virtual power plant, and the virtual power plant can only ensure its interests by increasing the purchase and sale prices.



(**a**) Prosumer 1 (**b**) Prosumer 2 (**c**) Prosumer 3

Figure 10. Chart of results of trading with and without P2P energy sharing.

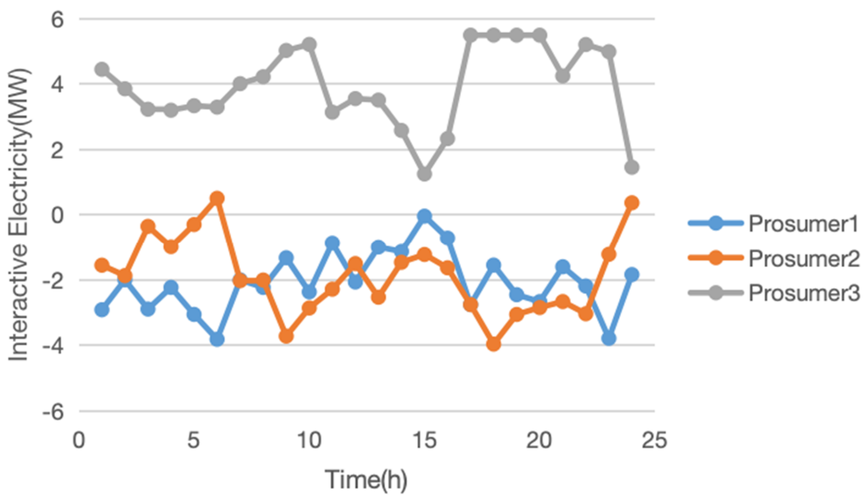


Figure 11. Prosumer interaction electricity.

In Table 1, it can be seen that the total benefit of the proposed method Scheme I is increased by CNY 40,685.48 compared with Scheme II, which is because when considering the hybrid game, prosumers can achieve energy complementarity through P2P power sharing to increase the benefit of the prosumers. However, the total revenue of the virtual power plant decreases by CNY 29,042.94, simply because after considering the hybrid game, the dependence of each prosumer on the virtual power plant decreases and thus the revenue of the virtual power plant decreases as well. Prosumer 1's gain is reduced by CNY 33,610.97, prosumer 2's gain is reduced by CNY 61,996.92, and prosumer 3's gain is enhanced by CNY 236,293.37, which is due to the introduction of Nash negotiation, which distributes the cooperative gains according to the energy sharing of each prosumer in order to achieve a fair distribution of the cooperative gains. However, prosumer 1 and prosumer 2 share more wind power with other prosumers through P2P trading for energy sharing instead of selling power to virtual power plants. Prosumer 3 pays money to prosumer 1 and prosumer 2, while they export power to prosumer 3 through energy sharing, which realises P2P transactions and improves the efficiency of energy utilisation.

Table 1. Blockchain hybrid gaming transaction model revenue changes. (Negative sign means benefits).

(CNY)	Prosumer 1		Prosumer 2	Prosumer 3	Prosumer Total Cost	VPP Total Cost
Scheme I	Total Cost	−73,423.24	−161,492.03	1,202,360.19	967,444.92	−157,436.32
	(Interactive Cost)	−37,681.32	−73,634.19	111,315.51		
Scheme II	−39,812.27		−99,495.11	1,438,653.56	1,299,346.18	−186,479.26
Total	−33,610.97		−61,996.92	−236,293.37	−331,901.26	29,042.94

5. Conclusions

Nowadays, the traditional power market trading model relies on third-party trading institutions, while the trading model proposed in this paper realises P2P trading among prosumers, which corresponds to the spatially distributed characteristics of the aggregated prosumers in the virtual power plant. In the traditional transaction model, the transaction data are stored in a centralised server, which is not transparent, faces the risk of tampering, and cannot be traced back. However, blockchain ensures that transaction data are transparent, tamper-proof, and traceable through asymmetric encryption technology, data signature, and consensus mechanism, which can solve the above problems well.

In this paper, we propose a virtual power plant transaction mechanism based on main side consortium blockchains and a hybrid game transaction mechanism. Firstly, we derive a Stackelberg game theory model, assuming that the VPP is the leader and the prosumer is the follower. Conditional value at risk is incorporated into the model to describe the virtual power plant's attitude towards risk, and the virtual power plant makes a trade-off between revenue and risk and sets the purchase and sale prices for different producers and prosumers. Meanwhile, the nature of P2P energy transactions is investigated; the cooperation of consumers in P2P energy transactions improves the responsiveness to the purchase and sale price of electricity and effectively reduces the problems of information opacity and excessive power of third parties. In addition, cooperation and distribution of benefits between prosumers is achieved using the Nash negotiation game, which incentivises energy trading and ensures fairness in the distribution of benefits. The use of blockchain technology can help achieve information interaction in the trading game, and the trading parties can dynamically adjust their offers according to the market trading information. The main chain carries out electricity and energy trading in the centralised market between the virtual power plant and the power grid; the side chain carries out energy trading between the virtual power plant and the prosumers and encourages distributed trading among the prosumers. Furthermore, as our paper primarily centres around the design of a blockchain-based transaction model without delving deeply into the underlying mechanisms of energy blockchains, our future research endeavours will revolve around exploring consensus mechanisms capable of supporting extensive P2P transactions and refining the block data structure. This approach aims to facilitate the blockchain's application in the distributed transactions of virtual power plants.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Constraints:

1. Dual constraints:

$$\lambda_{pro}^{i,t,w} + \lambda_{Pb}^{i,t,w} \leqslant \mu_{Pb}^{i,t}, \forall i \in N, \forall t \in T, \forall w \in W$$

$$-\lambda_{pro}^{i,t,w} + \lambda_{Ps}^{i,t,w} \leqslant -\mu_{Ps}^{i,t}, \forall i \in N, \forall t \in T, \forall w \in W$$

$$\lambda_{pro}^{i,t,w} + \lambda_{trading}^{t,w} = 0, \forall i \in N, \forall t \in T, \forall w \in W$$

$$-\lambda_{pro}^{i,t,w} + \lambda_{Ec}^{i,t,w} - \lambda_{SOC1}^{i,t,w}\eta_{Ec}^{i} \leqslant c_{E}^{i}, \forall i \in N, \forall t \in T, \forall w \in W$$

$$\lambda_{pro}^{i,t,w} + \lambda_{Ed}^{i,t,w} + \frac{1}{\lambda_{SOC1}^{i,t,w}\eta_{Ed}^{i}} \leqslant c_{E}^{i}, \forall i \in N, \forall t \in T, \forall w \in W$$

$$\overline{\lambda_{SOC}^{i,t,w}} + \underline{\lambda_{SOC}^{i,t,w}} + \lambda_{SOC1}^{i,t,w}Cap^{i} - \lambda_{SOC1}^{i,t+1,w}Cap^{i} = 0, \forall i \in N, \forall t \in T, \forall w \in W$$

$$\overline{\lambda_{SOC}^{i,24,w}} + \underline{\lambda_{SOC}^{i,24,w}} + \lambda_{SOC1}^{i,24,w}Cap^{i} + \lambda_{SOC2}^{i,w} = 0, \forall i \in N, \forall w \in W$$

2. Complementary slackness constraints:

$$0 \geqslant \lambda_{Pb}^{i,t,w} \perp P_{Pb}^{i,t,w} - P_{Pb}^{\max} \leqslant 0, \forall i \in N, \forall t \in T, \forall w \in W$$

$$0 \geqslant \lambda_{Ps}^{i,t,w} \perp P_{Ps}^{i,t,w} - P_{Ps}^{\max} \leqslant 0, \forall i \in N, \forall t \in T, \forall w \in W$$

$$0 \geqslant \lambda_{Ec}^{i,t,w} \perp P_{Ec}^{i,t,w} - P_{Ec}^{\max} \leqslant 0, \forall i \in N, \forall t \in T, \forall w \in W$$

$$0 \geqslant \lambda_{Ed}^{i,t,w} \perp P_{Ed}^{i,t,w} - P_{Ed}^{\max} \leqslant 0, \forall i \in N, \forall t \in T, \forall w \in W$$

$$0 \geqslant \overline{\lambda_{SOC}^{i,t,w}} \perp SOC^{i,t,w} - SOC_i^{max} \leqslant 0, \forall i \in N, \forall t \in T, \forall w \in W$$

$$0 \leqslant \underline{\lambda_{SOC}^{i,t,w}} \perp SOC^{i,t,w} - SOC_i^{min} \geqslant 0, \forall i \in N, \forall t \in T, \forall w \in W$$

$$0 \leqslant P_{P_b}^{i,t,w} \perp \mu_{Pb}^{i,t,w} - \lambda_{pro}^{i,t,w} - \lambda_{Pb}^{i,t,w} \geqslant 0, \forall i \in N, \forall t \in T, \forall w \in W$$

$$0 \leqslant P_{P_s}^{i,t,w} \perp -\mu_{Ps}^{i,t,w} + \lambda_{pro}^{i,t,w} - \lambda_{Ps}^{i,t,w} \geqslant 0, \forall i \in N, \forall t \in T, \forall w \in W$$

$$0 \leqslant P_{Ec}^{i,t,w} \perp c_E^i + \lambda_{pro}^{i,t,w} - \lambda_{Ec}^{i,t,w} + \lambda_{SOC1}^{i,t,w} \eta_{Ec}^i \geqslant 0, \forall i \in N, \forall t \in T, \forall w \in W$$

$$0 \leqslant P_{Ed}^{i,t,w} \perp c_E^i - \lambda_{pro}^{i,t,w} - \lambda_{Ed}^{i,t,w} - \frac{1}{\lambda_{SOC1}^{i,t,w} \eta_{Ed}^i} \geqslant 0, \forall i \in N, \forall t \in T, \forall w \in W$$

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