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A cooperative Stackelberg game based energy management considering price discrimination and risk assessment☆

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ABSTRACT

This paper presents a bi-level energy management framework that can help the retail market to coordinate peer-to-peer (P2P) energy trading among multiple prosumers. To this end, the interaction process is formulated as a cooperative Stackelberg game model, where a retailer acts as the leader that determines price discrimination for various prosumers, with the goal of maximizing the social welfare. On the other hand, prosumers act as followers and react to the leader's decision in a cooperative manner. Based on a general Nash bargaining scheme, prosumers participate in P2P energy trading to share their idle energy resource with neighbors while allocating the cooperative revenue based on their contribution. Considering the uncertainty of renewable energy, a stochastic programming approach with Conditional Value at Risk (CVaR) is employed to characterize the expected losses by the retailer. The hierarchic energy interaction is formulated as a nonlinear bi-level programming model, a two-phase approach is proposed to address the formulation with a power function in the lower-level. By using Karush-Kuhn-Tucker conditions, a bi-level model is transformed into an equivalent single-level mixed-integer linear programming problem in first phase. Furthermore, the second phase completes the market clearing and determines the payments of the prosumers according to the scheduling results. Numerical cases are performed to demonstrate the effectiveness of the proposed model.

1. Introduction

1.1. Background and motivation

The deployment of distributed energy resources (DER) and energy storage systems allows traditional consumers to become prosumers. Prosumers with these infrastructures have capacity to manage their generation and consumption. Given the feed-in-tariff, prosumers can trade energy with the distribution network (DN) to maintain the dynamic balance of supply and demand [1]. It also provides flexibility and reliability for energy market with prosumers, and improves the social benefit of overall system[2]. However, the presence of intermittent DER introduces challenges for power system to meet the balance [3]. To reduce the disturbance to the grid, a proper energy management technology is necessary to enable prosumers to share energy resources in a local area.

Peer-to-peer (P2P) energy trading (ET), as a new measure, is suitable for interaction among prosumers [4]. Recently, there are plentiful studies related to energy management, especially models and structures of the P2P ET [5,6]. Considering the autonomous prosumers in retail electricity market, it is critical to view a grid-connected energy management from a decentralized perspective [7]. With a decentralized management structure, a retailer delegates daily operations authority to prosumers rather than limiting it. Meanwhile, prosumers in this structure may have their decision and conflicts of interest. Considering the distinct behaviors of the participators, these prosumers governed by a retailer may constitute a leader-follower structure. Stackelberg game can effectively depict the leader-follower relationship where a retailer chooses the strategy prior to the decisions made by the prosumers. Given the guidance (usually price signals) from the retailer, prosumers with direct ET negotiate with each other to react to the prices.

Participators, including the retailer and prosumers, will profit from P2P ET. However, several challenges exist in designing an incentive scheme for energy collaboration. For retailer, it is desirable that a proper interactive scheme can motivate prosumers to actively participate in the

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Nomenclature

Indices

i	index of prosumers
t	index of hours
w	index of scenarios

Sets

$\mathcal{N}$	set of prosumers
Ω	set of wind generation scenarios
$\mathcal{T}$	set of time intervals

Parameters

$P_{load}^{i,\ t}$	total load in prosumer *i* at time slot t (MW)
$P_{Gen}^{i,\ t,\ w}$	generation output at time slot t (MW)
$P_{Ps,i}^{\max}$	limitation of selling power to the main grid (MW)
$P_{Pb,i}^{\max}$	limitation of purchasing power from the main grid (MW)
$P_{Ec,i}^{\max}$	maximum charging power of battery in prosumer *i* (MW)
$P_{Ed,i}^{\max}$	maximum discharging power of battery in prosumer *i* (MW)
$SOC_i^{\min}$	minimum limitation of state of charge of a battery in prosumer *i* (%)
$SOC_i^{\max}$	maximum limitation of state of charge of a battery in prosumer *i* (%)
Cap^i	capacity of a battery in prosumer *i* (MW)
SOC_{ini}^i	minimum limitation of state of charge of a battery in prosumer *i* (%)
η_{Ec}^i	charging efficiency of a battery in prosumer *i*
η_{Ed}^i	discharging efficiency of a battery in prosumer *i*
c_E^i	degradation cost of a battery in prosumer *i* (CNY/MW)
$\pi^{i,w}$	probability of occurrence of wind generation scenario
γ	confidence level
β	weighting factor
μ_{Db}^t	price that the retailer purchases energy from main grid (CNY/MW)
μ_{Ds}^t	price that the retailer sells energy to main grid (CNY/MW)

Variables

$C_{Non}^{i,w}$	operation cost of prosumer *i* without ET (CNY)
$C_O^{i,w}$	operation cost of prosumer *i* with ET (CNY)
$Ce_{Pay}^{i,w}$	net payment of prosumer *i* for ET among prosumers (CNY)
$P_{Pb}^{i,t,w}$	prosumer *i* purchases power from the main grid (MW)
$P_{Ps}^{i,t,w}$	prosumer *i* sells power to the main grid (MW)
$P_{Ec}^{i,t,w}$	charging power of a battery in prosumer *i* at time slot t (MW)
$P_{Ed}^{i,t,w}$	discharging power of a battery in prosumer *i* at time slot t (MW)
$SOC^{i,t,w}$	state of charge of a battery in prosumer *i* at time slot t (%)
$P_{trading}^{i,t,w}$	prosumer *i* sells power to prosumer *j* at time slot t
$\mu_{Pb}^{i,t}$	price that prosumer *i* purchases energy from the retailer (CNY/MW)
$\mu_{Ps}^{i,t}$	price that prosumer *i* sells energy to the retailer (CNY/MW)
ζ^i	auxiliary variable related to prosumer i and used to calculate the CVaR (CNY), and the optimal value ζ^{i*} is VaR
$\eta^{i,w}$	auxiliary variable related to prosumer *i* and scenario *w* and used to calculate the CVaR (CNY)
λ^*	Lagrange multiplier associated with the lower-level constraints (CNY)
$\mathcal{T}C_{Operation}^w$	cost of energy scheduling (CNY)
$\mathcal{T}C_{Benefits}^w$	economic benefits of cooperation (CNY)

management programs while satisfying their own interests. For prosumers, it is crucial to design a scheme to react to the retail prices in a cooperative manner. Besides, considering the uncertainty caused by DER, risk assessment should be merged into the energy management to address the stochastic nature in the decision-making procedure. Consequently, to address the aforementioned problems, an energy management strategy is required to effectively guide and motivate energy transactions under uncertainty.

1.2. Literature review

There are several efforts in literatures to solve the first challenge associated with the retail price. In the leader-follower structure, the price and the quantity of electricity are always set as interactive variables. Two effective measurements, including market bidding and dynamic pricing, are used for determining the price and coordinating the ET. As for the former group, prosumers are classified as sellers or buyers. Under fixed roles, the bidding is implemented among them [8–10]. Specifically, sellers, as the leader, determine the price while buyers react and change their operation strategies [8,11]. In contrast, sellers announce their available energy to buyers and buyers give the best price they want to pay [9,10]. As a prosumer is an entity who installs renewable energy and load internally, it consumes power while producing it. Depending on the net power profile, a prosumer may behave as a seller or a buyer during a daily time. Thus, since the roles of participators are predetermined, market bidding cannot fully capture the flexibility of prosumers which may waste idle resources and increase unnecessary costs. To make prosumers own equal privilege to participate in P2P ET, a trading platform is used as an auctioneer to determine the auction price and energy amount for buyers and sellers [12].

A dynamical pricing model is another method to coordinate energy management. Stackelberg game is utilized for modeling the pricing schemes between a governor and multiple participators. In order to maximize the benefit of both provider and users, a provider determines the prices to motivate users to adjust the energy consumption plan [13]. A price-sensitivity model develops dynamic energy prices to facilitate power exchange of multiple Microgrids in the regional DN [14]. Furthermore, an operator determines prices to coordinate the energy sharing process among prosumers and match the deviations of internal net energy [15]. For the load management problems in a facility, a price is presented to induce less energy consumption during high electricity prices [16]. Nevertheless, an important similarity in these pricing schemes is that the transaction price is same for each participator, which is not attractive for participators, especially for the one who is sensitive to price [17].

Price discrimination refers to the practice in which a seller charges buyers different prices for the same quality and quantity of a product [18]. Different prices are provided for customers to encourage consumers to participate in energy management [19]. Furthermore, price discrimination is employed to incentivize energy trading [20]. The model in [19,20] takes the point that there is no interaction among the end users. Nevertheless, the impact of price incentives on energy transaction is weakened with the emergence of P2P ET because prosumers may directly communicate with each other. Recent investigation shows that direct ET among prosumers will attract them to procure energy from neighbors, which reduces the effect of prosumers' behavior on DN [21]. Thus, the effectiveness of price discrimination needs further considered in energy management.

To solve the second challenge, cooperative game based market designs are proposed to incentivize direct ET among prosumers

[10,22–26]. Given the fixed prices from upstream wholesale market/supplier, participators directly share idle energy in a local area and allocate the revenues according to a contract [22] or their contribution [23]. A limitation of these designs is that participators, as price takers, passively accept the strategic decisions determined by upstream agents. To achieve the interaction between two levels, Stackelberg game is extensively used for designing energy management schemes [10,24]. However, a noncooperative Stackelberg game can not obtain system optimum due to the competition of bi-level model and the selfishness of the leader [25]. A cooperative Stackelberg game model is proposed to engage prosumers in energy management in the form of a suitable coalition [21]. For prosumers in a fixed coalition, Nash bargaining theory based cooperative game is more suitable for modeling the negotiation among prosumers [27]. Considering the various contributions of prosumers, P2P ET problem is formulated as a general Nash game (GNB) problem with a notion of bargaining power [23,26]. In this paper, a cooperative Stackelberg game is used to deal with the price-based coordination between the retailer and prosumers. An incentive mechanism integrated GNB theory promotes direct ET among prosumers to react to the prices. Meanwhile, the effect of cooperation on price discrimination requires further consideration.

The intermittent energy shortage or surplus caused by the stochastic nature of DER is neglected in the aforementioned work, which may cause fluctuation in the power system [28]. Stochastic programming is one of the promise methods to deal with uncertainty [29,30]. As an effective measure, Conditional Value at Risk (CVaR) is merged in the objective function to quantify the expected losses caused by the uncertainty of DER [31,32]. Nevertheless, these studies ignore the cooperation of prosumers where the impact among prosumers is not fully captured. In this regard, a retailer integrates the social welfare and risk level to determine price discrimination and coordinate the energy transaction process.

1.3. Motivations and contributions

Taking into account the above challenges, this paper aims to address the interaction problem between a retailer and cooperative prosumers. To this end, the interaction problem is formulated as a cooperative Stackelberg game model. The retailer, as a leader, provides price discrimination to engage prosumers in energy management and maximize the social welfare. Prosumers, as followers, cooperate with each other to share idle energy resources and react to the prices. In addition, the potential risk caused by uncertainty of DER is considered to improve the practicality of the model. To summarize, the main contributions are as follows.

- A cooperative Stackelberg game model is proposed for energy transaction between a retailer and multiple prosumers while satisfying their own interests. This model integrates P2P ET in grid-connected systems which allows prosumers to purchase energy from neighbors rather than the retailer alone.
- The retailer, as a leader, makes a tradeoff between expected profits and CVaR. Specifically, the social welfare and stochastic nature are considered simultaneously from the perspective of the leader to determine price discrimination. It is beneficial to measure the overall risk level and maximize the social welfare.
- Given the retail prices, the P2P ET scheme is established via a GNB game to capture prosumers' reaction. This scheme incentivizes energy sharing and ensures fair benefits allocation which enhances prosumers' response ability. Meanwhile, the mutual effect between cooperative prosumers and CVaR is explored to mitigate the risks of uncertainty.

The rest paper is organized as follows: The problem description of energy management is given in Section 2; In Section 3, we describe the bi-level stochastic programming framework of prosumers and the

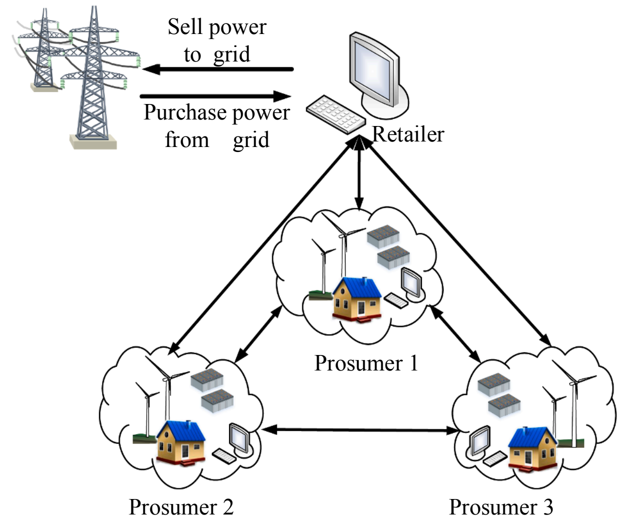


Fig. 1. A system with interconnected prosumers.

system model; The solution method is presented in Section 4; Case studies and results analysis are discussed in Section 5; Finally, Section 6 concludes this paper.

2. Problem description

As shown in Fig. 1, we consider an energy management problem with a retailer and a set of prosumers. Generally, the problem is formulated as a Stackelberg game model, where two types of participators are identified, namely the leader (retailer) and followers (prosumers). As an intermediary, the retailer has the priority to determine the price to promote energy transaction between the main grid and prosumers. Supported by the main grid, each prosumer, comprised of wind generation, battery and loads, interacts with one another to maintain the supply and demand balance. In the proposed model, stochastic programming approach is adopted to tackle the uncertainty, where the uncertainty of generation output is captured by discrete scenarios.

The retailer makes decisions to assist the DN for achieving the reliable operation and reducing the disturbance, such as those associated with prices setting. As prosumers are also rational and selfish, participation in energy management largely depends on their willingness. In contrast to uniform price, the retailer provides price discrimination technique to make the prosumers an integral part of energy management. To account for the uncertainty, a decision making model is proposed for a retailer to control the overall risk level from a global perspective by leveraging CVaR [33].

After observing the retailer's decision, prosumers negotiate with each other to react to the retail prices as an aggregation. To this end,

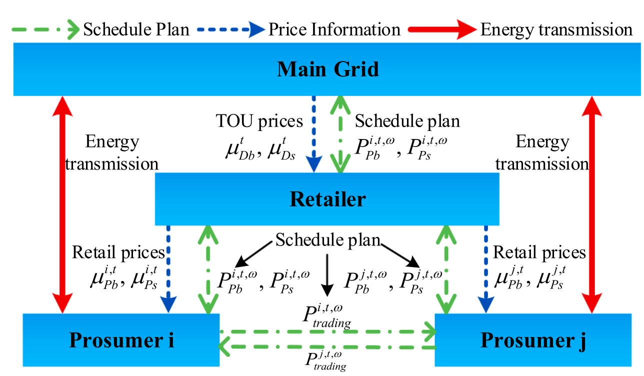


Fig. 2. The flow of energy transaction in energy management.

prosumers' responses are captured via a GNB game considering the impact of retail prices on prosumer's decisions. They make the optimal operation strategy for maximizing the total profits and allocate the benefits according to their respective contributions. The GNB based incentive scheme promotes direct ET among prosumers to meet the supply-demand balance under uncertainty. Based on this, this paper studies the procedure of a retailer's decision making and the response of prosumers considering the uncertainty.

3. System model

As shown in Fig. 2, a cooperative Stackelberg game is developed to study the energy transaction procedure. According to feed-in-tariff (μ_{Db}^t, μ_{Ds}^t), the retailer enjoys priority in the decision-making process to maximize the social welfare and control the overall risk level. To better respond to the decision, cooperative prosumers react to the retail prices (μ_{Pb}^t, μ_{Ps}^t) rationally to pursue the profits. To guarantee fairness, the cooperative revenue is allocated based on the respective contribution. The optimality of such an energy management problem is defined by the Nash equilibrium [34]. And then, the schedule plan is executed in which the energy is transmitted through the main grid.

3.1. Leader's strategy

A retailer, as a coordinator, is obligated to conduct the management of prosumers. In particular, the retailer is required to trade energy with DN to balance the supply and demand of prosumers when the internal mismatch occurs. According to the feed-in-tariff, the transaction prices between the retailer and prosumers are set by the retailer to coordinate the management. Generally, the sale price is lower than the purchase price to encourage prosumers to schedule inner energy, and further reduce the impact on the DN. The goal of retailer is to maximize the social welfare while controlling the risk level to account for the uncertainty. The decision model of the leader is formulated as follows.

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

s.t.

$$\mu_{Pb}^{t,\min}\leqslant\mu_{Pb}^{i,t}\leqslant\mu_{Pb}^{t,\max},\forall i\in\mathcal{N},\forall t\in\mathcal{T} \tag{2}$$

$$\mu_{Ps}^{t,\min}\leqslant\mu_{Ps}^{i,t}\leqslant\mu_{Ps}^{t,\max},\forall i\in\mathcal{N},\forall t\in\mathcal{T} \tag{3}$$

$$\sum_{t}^{\mathcal{T}}\mu_{Pb}^{i,t}/T\leqslant\mu_{Pb,ave}^{i,t},\forall i\in\mathcal{N} \tag{4}$$

$$\sum_{t}^{\mathcal{T}}\mu_{Ps}^{i,t}/T\geqslant\mu_{Ps,ave}^{i,t},\forall i\in\mathcal{N} \tag{5}$$

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

The objective function (1) comprises two terms: 1) the expected revenue of the retailer (expected revenue from selling to prosumers minus the expected cost of purchasing from DN); and 2) the tradeoff between expected revenue and risk (the CVaR multiplied by the weighting parameter β). The larger value of β means the greater preference for risk aversion. To obtain the higher revenue, a retailer may select a lower value of β to reduce the expected cost. In contrast, a conservative retailer prefers to choose a larger value of β to increase the weight of risk-aversion.

Constraints (2)–(3) bound the transaction prices provided to prosumers to be within the interval. To restrict the retailer's market power, constraints (4)–(5) set the daily average prices to impose the bound of the retail prices. During operation, the agreement is assumed to take effect for the retailer and prosumers. To depict the impact of the value β on the benefits, CVaR is computed by constraint (6).

3.2. Followers' response

In response to the retailer's strategy, prosumers, with energy producing capability, can participate in direct ET with neighbors and trade energy with the retailer. Prosumers exploit the DER and load to achieve mutual benefits through direct ET. GNB game, as a branch of cooperative game, will be used to study the process of direct ET interactions [27]. In the GNB game, prosumers autonomously make the decision and cooperate with neighbors to share idle energy (DRE or load) while maximizing the overall revenue. Meanwhile, it also incentivizes direct ET among prosumers and allocates the revenues according to their contributions [26].

Given the prices, the reaction of prosumers is captured by quantifying the energy trading with the retailer. The model under various scenarios is formulated as follows.

$$P_{Pb}^{i,t,w},P_{Ps}^{i,t,w}\in arg\left\{\max\prod_{i=1}^{\mathcal{N}}\left(C_{Non}^{i,w}(\boldsymbol{x}_{Non}^{i,w})-\left(C_{Tra}^{i,w}(\boldsymbol{x}_{Tra}^{i,w})+Ce_{Pay}^{i,w}\right)\right)^{\alpha_i^w}\right. \tag{7}$$

$$C_{Non}^{i,w}(\boldsymbol{x}_{Non}^{i,w})=\sum_{t=1}^{\mathcal{T}}\left[\mu_{Pb}^{i,t}P_{Pb}^{i,t,w}-\mu_{Ps}^{i,t}P_{Ps}^{i,t,w}+c_{E}^{i}(P_{Ec}^{i,t,w}+P_{Ed}^{i,t,w})\right],\forall i\in\mathcal{N},\forall w\in\Omega \tag{8}$$

$$C_{Tra}^{i,w}(\boldsymbol{x}_{Tra}^{i,w})=\sum_{t=1}^{\mathcal{T}}\left[\mu_{Pb}^{i,t}P_{Pb}^{i,t,w}-\mu_{Ps}^{i,t}P_{Ps}^{i,t,w}+c_{E}^{i}(P_{Ec}^{i,t,w}+P_{Ed}^{i,t,w})\right],\forall i\in\mathcal{N},\forall w\in\Omega \tag{9}$$

s.t.

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

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

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

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

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

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

$$SOC_{i}^{min}\leqslant SOC^{i,t,w}\leqslant SOC_{i}^{max}:\lambda_{SOC_{min}}^{i,t,w},\lambda_{SOC_{max}}^{i,t,w},\forall i\in\mathcal{N},\forall t\in\mathcal{T},\forall w\in\Omega \tag{16}$$

$$SOC^{i,1,w}Cap^{i} = SOC^{i}_{ini}Cap^{i} + \eta^{i}_{Ec}P^{i,1,w}_{Ec} - 1/\eta^{i}_{Ed}P^{i,1,w}_{Ed} : \lambda^{i,1,w}_{SOC1}, \forall\ i \in \mathcal{N}, \forall w \in \Omega \tag{17}$$

$$SOC^{i,t,w}Cap^{i} = SOC^{i,t-1,w}Cap^{i} + \eta^{i}_{Ec}P^{i,t,w}_{Ec} - 1/\eta^{i}_{Ed}P^{i,t,w}_{Ed} : \lambda^{i,t,w}_{SOC1}, \forall i \in \mathcal{N}, \forall t \in \mathcal{T}, \forall w \in \Omega \tag{18}$$

$$SOC^{i,24,w} = SOC^{i}_{exp} : \lambda^{i,w}_{SOC2}, \forall i \in \mathcal{N}, \forall w \in \Omega \tag{19}$$

$$\sum_{i}\alpha^{w}_{i} = 1, \forall i \in \mathcal{N}, \forall w \in \Omega \tag{20}$$

$$C^{i,w}_{Tra}(\boldsymbol{x^{i,w}_{Tra}}) + Ce^{i,w}_{Pay} \leqslant C^{i,w}_{Non}(\boldsymbol{x^{i,w}_{Non}}), \forall\ i \in \mathcal{N}, \forall w \in \Omega \tag{21}$$

$$\sum_{i}Ce^{i,w}_{Pay} = 0, \forall i \in \mathcal{N}, \forall w \in \Omega \tag{22}$$

where positive parameter α^{w}_{i} reflects the bargaining power in the bargaining process. $\boldsymbol{x^{i,w}_{Non}}$ and $\boldsymbol{x^{i,w}_{Tra}}$ are the vectors of decision variables of prosumer i without/with ET, and

$$\boldsymbol{x^{i,w}_{Non}} = [P^{i,t,w}_{Pb}, P^{i,t,w}_{Ps}, P^{i,t,w}_{Ec}, P^{i,t,w}_{Ed}, SOC^{i,t,w}], \boldsymbol{x^{i,w}_{Tra}} = [P^{i,t,w}_{Pb}, P^{i,t,w}_{Ps}, P^{i,t,w}_{Ec}, P^{i,t,w}_{Ed}, SOC^{i,t,w}, P^{i,t,w}_{trading}].$$

Given the prices and multiple scenarios, the reaction of prosumers is modeled by the lower-level problems (7)–(22). The objective function (7) at lower-level includes two terms. The first term represents the internal cost function of prosumer i without ET ($C^{i,w}_{Non}$). The second term models the transaction cost, which equals to the summation of internal cost function ($C^{i,w}_{Tra}$) and payments for neighbors ($Ce^{i,w}_{Pay}$). The inner cost function without/with direct ET is expressed as (8) and (9), which comprises the energy transaction cost with retailer and the degeneration cost of battery. The different of two expressions is whether direct ET $P^{i,t,w}_{trading}$ is considered in constraint (10), which keeps the power balance of each prosumer at each time slot and each scenario. Constraint (11) ensures that the summation of exporting power for prosumers with surplus energy equals to the sum of importing power for remaining prosumers. The energy transaction between retailer and prosumers is bounded by constraints (12)–(13). Constraints (14)–(15) define the limitations of charging and discharging, while constraint (16) bounds the maximum and minimum state of a battery. The battery storage changes according to the energy balance constraint (17) at t = 1 and (18) at use equation. Expected state of charge (SOC) at $t = 24$ should satisfy the constraint (19). α^{w}_{i} in constraint (20) reflects the different bargaining power of prosumers in the bargaining process,

$$\alpha^{w}_{i} = \frac{\sum_{t}P^{i,t,w}_{trading}}{\sum_{i}\sum_{t}P^{i,t,w}_{trading}}, \forall\ i \in \mathcal{N}, \forall\ t \in \mathcal{T}, \tag{23}$$

where the summation of α^{w}_{i} equals 1. Constraint (21) ensures that the cooperative revenue is greater than individual operation, which engages prosumers in direct ET. Constraint (22) means the summation of all payments should be equal to the sum of all revenues.

4. Solution methodology

Generally, the bi-level problem can be transformed as a single level problem by leveraging KKT condition [35]. However, since the GNB based direct ET model at lower-level is a power function, we decompose and solve it in two separate steps instead of solving the problem directly. In this way, the bi-level problem can be converted into a single level problem and solved by the commercial software.

4.1. Decomposition of the GNB problem

The GNB problem, at lower-level, is decomposed into two subproblems: solving the operation cost minimization problem (P1) and then determining the bargaining problem (P2), which can be solved sequentially [26].

Firstly, prosumers cooperate with neighbors to share energy and minimize the total operation cost. Direct ET among prosumers contributes to the social cost reduction in lower level. At the same time, prosumers can receive payments from direct ET via the bargaining, which incentivizes them to participate in P2P ET. Thus, we firstly solve the problem P1 for yielding the optimal scheduling. And then, prosumers bargain with each other to determine the benefits allocation in problem P2. The lower-level problem is divided as follows:

P1: Operation cost minimization problem

$$\mathcal{TC}^{w}_{Operation} = \min\sum_{i}^{\mathcal{N}}C^{i,w}_{Tra}(\boldsymbol{x^{i,w}_{Tra}}), \tag{24}$$

subject to constraints (10)–(19).

P2: Bargaining problem

$$\mathcal{TC}^{w}_{Benefits} = \max\prod_{i}^{\mathcal{N}}\left(\eta^{i,w,*} - Ce^{i,w}_{Pay}\right)^{\alpha^{w}_{i}} \tag{25}$$

subject to constraints (20)–(22), where $\eta^{i,w,*} = C^{i,w}_{Non}(\boldsymbol{x^{i,w}_{Non}}) - C^{i,w}_{Tra}(\boldsymbol{x^{i,w}_{Tra}})$ is the operation cost saving of prosumer i through ET.

4.2. Equivalent single-level mixed integer linear programming problem

Since the existence of the bilinear product in (1) and (6), the bi-level problem (1)–(6) and problem P1 (10)–(19), (24) is a nonlinear problem. To solve the problem by a commercial solver, it should be converted into an equivalent single-level mixed-integer linear programming (MILP) problem. The details of the conversion are as follows.

1) By leveraging KKT condition, the bi-level problem is equivalently reformulated as a nonlinear single-level problem by replacing the lower-level problem (10)–(19), (24). And the nonlinear terms comprise complementary slack conditions and bilinear products.
2) The complementary slack conditions introduced by the product of Lagrange multipliers and constraints are replaced by utilizing the big-M method [36].
3) Based on the strong duality theory, the bilinear products in (1) and (6) are rewritten as equivalent linear expressions [37].

The equivalent single-level MILP formulation is depicted as follows:

$$\max\sum_{w}^{\Omega}\sum_{t=1}^{\mathcal{T}}\sum_{i=1}^{\mathcal{N}}\pi^{i,w}\Big(\mu^{t}_{Ds}P^{i,t,w}_{Ps} - \mu^{t}_{Db}P^{i,t,w}_{Pb} - c^{i}_{E}(P^{i,t,w}_{Ec} + P^{i,t,w}_{Ed}) + \lambda^{i,t,w}_{pro}(P^{i,t}_{load} - P^{i,t,w}_{Gen}) + \lambda^{i,t,w}_{Pb}P^{\max}_{Pb} + \lambda^{i,t,w}_{Ps}P^{\max}_{Ps} + \lambda^{i,t,w}_{Ec}P^{max}_{Ec,i} + \lambda^{i,t,w}_{Ed}P^{max}_{Ed,i} + \lambda^{i,t,w}_{SOC_{max}}SOC^{max}_{i} + \lambda^{i,t,w}_{SOC_{min}}SOC^{min}_{i} + \lambda^{i,w}_{SOC2}SOC^{i}_{exp} + SOC^{i}_{ini}Cap^{i}\lambda^{i,1,w}_{SOC1}\Big) + \beta\sum_{i=1}^{\mathcal{N}}\left[\zeta^{i} - \frac{1}{1-\gamma}\sum_{w=1}^{\Omega}\pi^{i,w}\eta^{i,w}\right] \tag{26}$$

s.t. (2)–(6), (10)–(19),

$$\lambda^{i,t,w}_{pro} + \lambda^{i,t,w}_{Pb} \leqslant \mu^{i,t}_{Pb}, \forall i \in \mathcal{N}, \forall t \in \mathcal{T}, \forall w \in \Omega \tag{27}$$

$$-\lambda^{i,t,w}_{pro} + \lambda^{i,t,w}_{Ps} \leqslant -\mu^{i,t}_{Ps}, \forall i \in \mathcal{N}, \forall t \in \mathcal{T}, \forall w \in \Omega \tag{28}$$

$$\lambda^{i,t,w}_{pro} + \lambda^{t}_{trading} = 0, \forall i \in \mathcal{N}, \forall t \in \mathcal{T}, \forall w \in \Omega \tag{29}$$

Table 1
Parameters of prosumers

Capacity	$P_{Pb,i}^{\max}(MW)$	$P_{Ps,i}^{\max}(MW)$	$P_{Ec,i}^{\max}(MW)$	$P_{Ed,i}^{\max}(MW)$
	15	15	3.00	3.00
Battery	η_{Ec}^{i}	$1/\eta_{Ed}^{i}$	$Cap^{i}(MW)$	$c_E^{i}(CNY/MW)$
	0.95	1.05	10.00	80
SOC	$SOC_{\max}^{i}$	$SOC_{\min}^{i}$	SOC_{ini}^{i}	SOC_{exp}^{i}
	0.85	0.20	0.33	0.85

$$-\lambda_{pro}^{i,t,w}+\lambda_{Ec}^{i,t,w}-\eta_{Ec}^{i}\lambda_{SOC1}^{i,t,w}\leqslant c_E^{i},\forall i\in\mathcal{N},\forall t\in\mathcal{T},\forall w\in\Omega \tag{30}$$

$$\lambda_{pro}^{i,t,w}+\lambda_{Ed}^{i,t,w}+1\Big/\eta_{Ed}^{i}\lambda_{SOC1}^{i,t,w}\leqslant c_E^{i},\forall i\in\mathcal{N},\forall t\in\mathcal{T},\forall w\in\Omega \tag{31}$$

$$\lambda_{SOC_{max}}^{i,t,w}+\lambda_{SOC_{min}}^{i,t,w}+Cap^{i}\lambda_{SOC1}^{i,t,w}-Cap^{i}\lambda_{SOC1}^{i,t+1,w}=0,\forall i\in\mathcal{N},\forall t\in\mathcal{T},\forall w\in\Omega \tag{32}$$

$$\lambda_{SOC_{max}}^{i,24,w}+\lambda_{SOC_{min}}^{i,24,w}+Cap^{i}\lambda_{SOC1}^{i,24,w}+\lambda_{SOC2}^{i,w}=0,\forall i\in\mathcal{N},\forall w\in\Omega \tag{33}$$

$$0\geqslant\lambda_{Pb}^{i,t,w}\perp P_{Pb}^{i,t,w}-P_{Pb}^{\max}\leqslant 0,\forall i\in\mathcal{N},\forall t\in\mathcal{T},\forall w\in\Omega \tag{34}$$

$$0\geqslant\lambda_{Ps}^{i,t,w}\perp P_{Ps}^{i,t,w}-P_{Ps}^{\max}\leqslant 0,\forall i\in\mathcal{N},\forall t\in\mathcal{T},\forall w\in\Omega \tag{35}$$

$$0\geqslant\lambda_{Ec}^{i,t,w}\perp P_{Ec}^{i,t,w}-P_{Ec}^{\max}\leqslant 0,\forall i\in\mathcal{N},\forall t\in\mathcal{T},\forall w\in\Omega \tag{36}$$

$$0\geqslant\lambda_{Ed}^{i,t,w}\perp P_{Ed}^{i,t,w}-P_{Ed}^{\max}\leqslant 0,\forall i\in\mathcal{N},\forall t\in\mathcal{T},\forall w\in\Omega \tag{37}$$

$$0\geqslant\lambda_{SOC_{max}}^{i,t,w}\perp SOC^{i,t,w}-SOC_{i}^{max}\leqslant 0,\forall i\in\mathcal{N},\forall t\in\mathcal{T},\forall w\in\Omega \tag{38}$$

$$0\leqslant\lambda_{SOC_{min}}^{i,t,w}\perp SOC^{i,t,w}-SOC_{i}^{min}\geqslant 0,\forall i\in\mathcal{N},\forall t\in\mathcal{T},\forall w\in\Omega \tag{39}$$

$$0\leqslant P_{Pb}^{i,t,w}\perp\mu_{Pb}^{i,t,w}-\lambda_{pro}^{i,t,w}-\lambda_{Pb}^{i,t,w}\geqslant 0,\forall i\in\mathcal{N},\forall t\in\mathcal{T},\forall w\in\Omega \tag{40}$$

$$0\leqslant P_{Ps}^{i,t,w}\perp-\mu_{Ps}^{i,t,w}+\lambda_{pro}^{i,t,w}-\lambda_{Ps}^{i,t,w}\geqslant 0,\forall i\in\mathcal{N},\forall t\in\mathcal{T},\forall w\in\Omega \tag{41}$$

$$0\leqslant P_{Ec}^{i,t,w}\perp c_E^{i}+\lambda_{pro}^{i,t,w}-\lambda_{Ec}^{i,t,w}+\eta_{Ec}^{i}\lambda_{SOC1}^{i,t,w}\geqslant 0,\forall i\in\mathcal{N},\forall t\in\mathcal{T},\forall w\in\Omega \tag{42}$$

$$0\leqslant P_{Ed}^{i,t,w}\perp c_E^{i}-\lambda_{pro}^{i,t,w}-\lambda_{Ed}^{i,t,w}-1\Big/\eta_{Ed}^{i}\lambda_{SOC1}^{i,t,w}\geqslant 0,\forall i\in\mathcal{N},\forall t\in\mathcal{T},\forall w\in\Omega \tag{43}$$

Constraints (27)–(33) are the dual constraints for the constraints (10)–(19). The complementary slackness conditions are shown in constraints (34)–(43).

4.3. Bargaining problem

For the bargaining problem, the GNB theoretic model defines the rule of the benefits allocation. We can achieve the cooperative revenue $\eta^{i,w,*}$ and calculate the bargaining power α_i^{w} after solving the problem P1. Then, the benefits of prosumers are obtained by the payment function (25).

By taking the log transformation of (25), the bargaining problem P2 is rewritten as:

$$\begin{aligned}&\mathcal{TC}_{Benefits}^{w}=\min\sum_{i}^{\mathcal{N}}-\alpha_i^{w}log\left(\eta^{i,w,*}-Ce_{Pay}^{i,w}\right),\forall w\in\Omega\\ s.t.\quad&(20)-(22)\\&\eta^{i,w,*}=C_{Non}^{i,w}\left(\boldsymbol{x}_{Non}^{i,w}\right)-C_{Tra}^{i,w}\left(\boldsymbol{x}_{Tra}^{i,w}\right),\forall i\in\mathcal{N},\forall w\in\Omega\end{aligned} \tag{44}$$

As the problem is a convex optimization problem, we can solve it by the commercial solver and obtain the market clearing.

5. Case study

In this section, numerical simulations are presented to evaluate the performance of the proposed energy management model. The model is solved by using the Gurobi solver [38] in the Python environment on a computer with an Intel Core i7 of 3.4 GHz and 8 GB memory.

Table 2
TOU prices between retailer and DN (Unit: CNY/MW).

Time	Purchase	Sell
[1, 7), [23, 24]	400	350
[7, 10), [15, 18), [21, 23)	790	680
[10, 15)[18, 21)	1200	1120

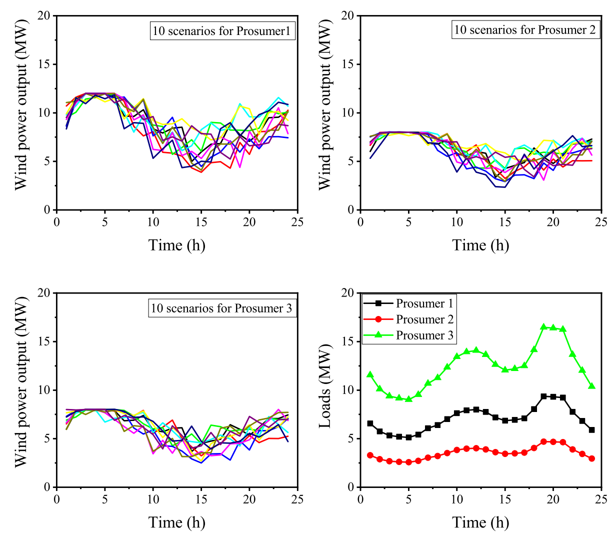


Fig. 3. Stochastic scenarios and loads for Prosumers.

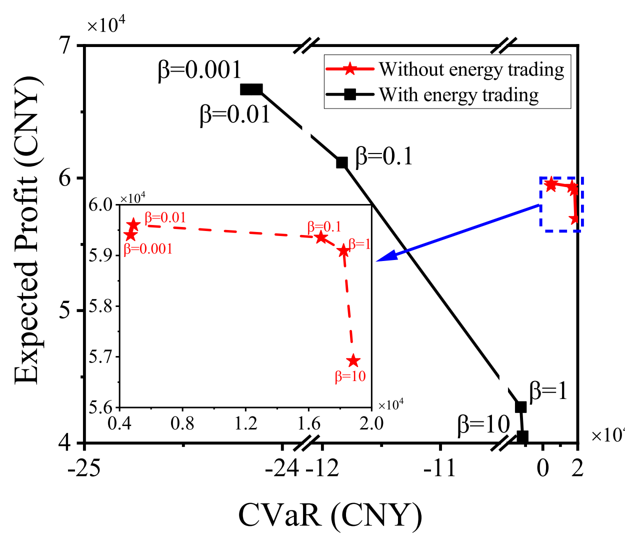


Fig. 4. Expected profit and CVaR of the retailer for different value of β.

5.1. Operational condition

A cooperative Stackelberg game based bi-level model is tested with a retailer and three prosumers. The retailer, as an agency, integrates energy transaction between the DN and prosumers. Coordinated by the retailer, all prosumers participate in direct ET with neighbors. The parameters in simulations are summarized in Table 1. Time of use (TOU) price serves as a trading price between the retailer and DN, which is shown in Table 2.

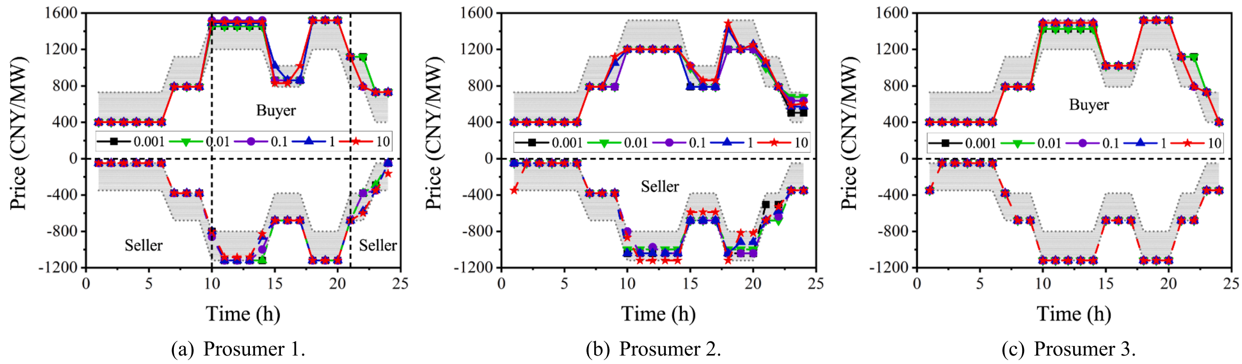


Fig. 5. Price without ET (Negative value means selling prices).

Table 3
Role of prosumers.

Buyers	Sellers
Prosumer1(11:00–21:00) prosumer3(1:00–24:00)	Prosumer1(1:00–10:00, 22:00–24:00) prosumer2(1:00–24:00)

Wind power has great intermittent and uncertainty, which brings challenges to energy management. To simulate real conditions of wind generation, 10000 scenarios are randomly generated by the Monte Carlo simulation method. Considering a compromise between computational efficiency and accuracy, the ARMA model and fast forward algorithm based scenario-reduction technique are utilized to obtain representative scenarios [39]. Following [39], 10 representative scenarios are considered to demonstrate the merits of the proposed method. The loads and stochastic scenarios for prosumers of wind generations are depicted in Fig. 3.

5.2. Impact of risk aversion on the retailer's decision

The CVaR, expected profit and the retail prices which related to the value β are analyzed to depict retailer's attitude towards risk and the impact of β on retailer's decision. We set the confidence level $\alpha = 0.95$, and β varies from 0.001 to 10.

5.2.1. Expected profit VS CVaR

To analyze the impact of the risk aversion on retailer's profit, the efficient frontier of the profit versus the CVaR for different parameters of β is depicted in Fig. 4. As can be seen, high profit of a retailer comes from higher risk. Retailer prefers risk-seeking at $\beta = 0.001$ without considering risk, which results in maximum benefits. On the contrary, conservative retailer expects a lower profit with $\beta = 10$. The negative value of CVaR in some scenarios indicates the losses caused by the risk. Therefore, as a decision maker, the retailer should carefully make a tradeoff between the expected profit and CVaR.

The behaviors of prosumers without/with ET also affect profits of the retailer, and then affect its decision. Without ET, as represented by a red dotted line in Fig. 4, the expected profit of retailer varies from 59405.58 CNY ($\beta = 0.001$) to 56918.72 CNY ($\beta = 10$) with the increase of β while the CVaR ranges between 4701.38 CNY and 18841.34 CNY. In contrast, the range of expected profit and CVaR is much larger for the prosumers with ET. The reason is that compared to operation independently, the range of total energy delivery between the retailer and prosumers increases with the cooperation among followers. In other words, the tolerable risk range becomes larger after the cooperation. This result also confirms the conclusion that profit is proportional to risk.

5.2.2. Impact of the variation of β on retail prices

The transaction prices between a retailer and prosumers depend on retailer's attitude towards risk, which is caused by the uncertainty of DER. By setting minimum and maximum value, the retailer maximizes social welfare through determining reasonable prices within the price range. Thus, a risk-seeking retailer may offer competitive prices to engage prosumers in energy sharing while taking on relatively high risk. In contrast, the risk-averse retailer may provide higher prices with the rise in parameter β to suppress the energy transaction.

In the context of prosumers without ET, as shown in Fig. 5, the impact of β on the optimal pricing strategy is investigated to clearly illustrate the attitude of retailer toward risk. The purchasing price is defined as the price that prosumers purchase energy from a retailer, and selling price means the price that prosumers sell energy to a retailer. For self-interest, the retailer tends to provide higher purchasing prices and lower selling prices for prosumers. Based on the forecast data in Fig. 3, we roughly divide prosumers as buyers or sellers according to the net demand (load minus the expectations of generation). And the role of prosumers at a specific time is shown in Table 3.

At these time periods, the purchasing prices increase while

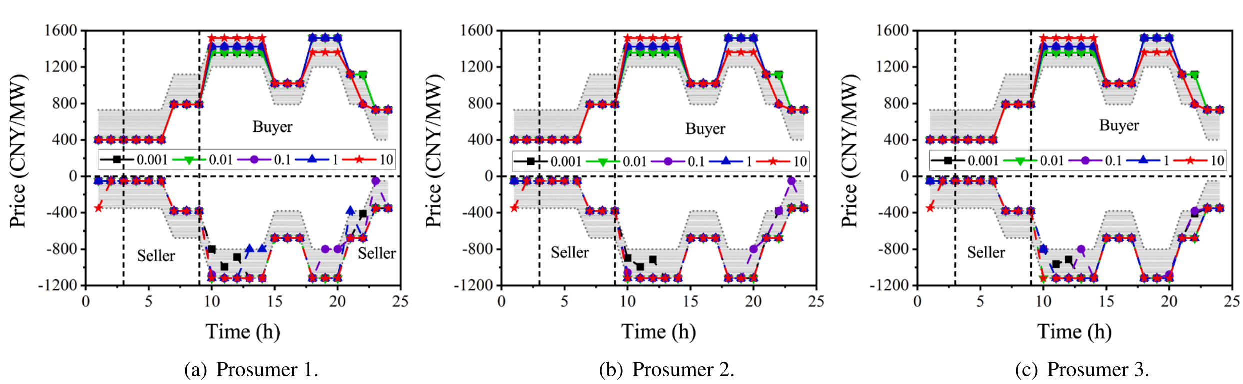
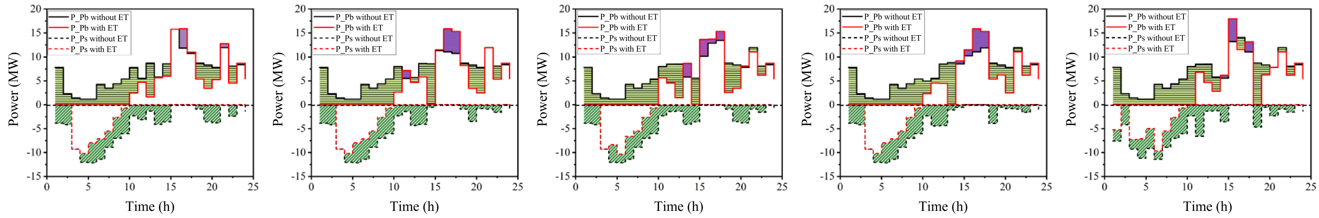


Fig. 6. Price with ET among prosumers (Negative value means selling prices).



(a) $\beta = 0.001$. (b) $\beta = 0.01$. (c) $\beta = 0.1$. (d) $\beta = 1$. (e) $\beta = 10$.

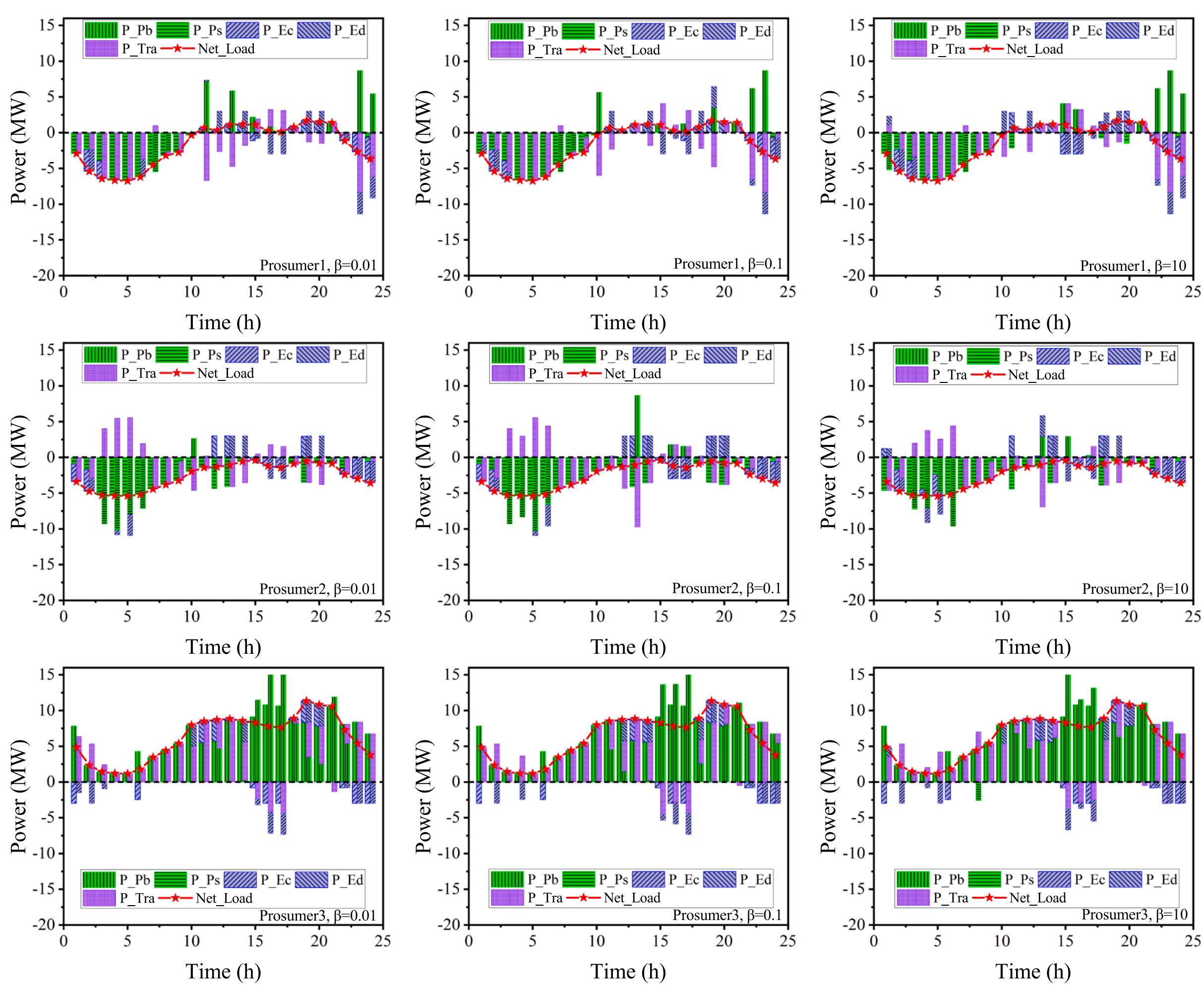
Fig. 7. Prosumers trade energy with the retailer (Negative sign means selling).

decreasing the selling price when the β grows. The retailer provides higher prices for prosumer 1 and 3 to reduce the demand at peak time (10:00–14:00, 18:00–20:00). With the value of β increasing from 0.001 to 10, the purchasing prices increase from 1455.43 CNY/MW to 1520 CNY/MW and 1426 CNY/MW to 1492CNY/MW, respectively. Correspondingly, to promote energy consumption in prosumers, selling prices are lower for prosumer 1 and prosumer 2 at 1:00–10:00. Although the retailer may try to maximize their profit, pricing constraints (4) and (5) drive the price in a reasonable range. To satisfy these constraints, retailer provides the favorable prices for prosumers when the energy delivery is small, e.g. for buyers at 1:00–9:00 and for sellers at 11:00–18:00.

Since prosumers with ET may negotiate with each other to react to the prices, a retailer will consider the overall demand to determine the prices. Compared with prosumers without ET, the different prices for prosumers with ET is not obvious, as shown in Fig. 6. The retailer provides high sale price at 10:00–24:00 and low repurchase price at 1:00–9:00 for prosumers to improve its revenue. In this way, the prices incentivize P2P ET and encourage renewable energy consumption among prosumers for peak shaving and valley filling. As soon as β becomes larger, the retailer changes its retail prices for prosumers to a higher value during 10:00–14:00.

5.2.3. Price discrimination

The retailer, as a leader, may determine different prices for prosumers to maximize the social welfare. Several factors are required to analyze the price discrimination, such as the role of prosumers (buyer or seller), prosumers without/with ET, energy delivery between retailer



(a) $\beta = 0.01$ (b) $\beta = 0.1$ (c) $\beta = 10$

Fig. 8. Power profiles of prosumers under different β (Negative sign means selling).

Table 4
Costs for prosumers without/with ET (Negative sign means benefits).

β	Metric (CNY)	Prosumer			Total costs
		1	2	3	
0.01	Cost without ET	−343.76	−23047.57	170842.30	147450.97
	Opeartion cost	28665.59	4150.82	92311.14	125127.55
	GNB Payment	−36942.75	−30443.87	67386.63	\
	Cost with ET	−8277.16	−26293.05	159697.76	125127.55
	Benefit	7933.40	3245.48	11144.54	22323.42
	Quantity (MWh)	−56.20	−23.11	79.31	\
0.1	Cost without ET	−365.17	−23189.48	170578.28	147023.63
	Opeartion cost	24079.87	13155.50	87196.80	124432.17
	GNB Payment	−31656.92	−40515.71	72172.64	\
	Cost with ET	−7577.06	−27360.21	159369.44	124432.17
	Benefit	7211.89	4170.73	11208.84	22591.46
	Quantity (MWh)	−51.54	−29.78	81.31	\
1	Cost without ET	−176.75	−23493.78	170578.28	146907.75
	Opeartion cost	43625.82	3855.95	76950.41	124432.17
	GNB Payment	−52153.11	−30167.82	82320.93	\
	Cost with ET	−8527.29	−26311.87	159271.33	124432.17
	Benefit	8350.54	2818.09	11306.95	22475.58
	Quantity (MWh)	−68.50	−22.78	91.28	\
10	Cost without ET	−565.64	−25250.96	170578.28	144761.68
	Opeartion cost	14058.43	8394.05	100769.47	123221.95
	GNB Payment	−20936.86	−38068.94	59005.80	\
	Cost with ET	−6878.43	−29674.89	159775.28	123221.95
	Benefit	6312.80	4423.93	10803.00	21539.73
	Quantity (MWh)	−45.49	−31.76	77.25	\

and prosumers, and so on. As for prosumers without ET, there are several different prices for buyers and sellers in Fig. 5. For buyers, the prices for prosumer 1 are lower than prosumer 3 at 15:00–17:00 because of the lower net demand. Nevertheless, the selling prices are disordered for sellers at 22:00–24:00 since the net demand is almost the same for prosumer 1 and 2 at 22:00–24:00.

The prices are generally consistent for cooperative prosumers. The reason is that compared to only schedule inner energy, prosumers meet the balance of supply and demand through active P2P ET and reduces the dependence on the retailer if price discrimination exists. In other words, the cooperation allows prosumer to seek energy from neighbors rather than solely depending on the retailer. Thus, compared with the price discrimination offered to prosumers without ET, the retailer may provide price discrimination at fewer time slots.

5.3. Prosumers' response

The GNB based cooperative game allows prosumers to respond to the retail prices in cooperative manner. According to Section 4.1, the GNB problem is decomposed as a cost minimization problem (P1) and a bargaining problem (P2). To minimize the total operation cost through ET (P1), they negotiate with each other to respond to the retail prices. Then, the bi-level transaction problem is regarded as a game problem between a retailer and a group of prosumers.

5.3.1. Quantity of energy transaction between the retailer and a group of prosumers

The power profiles for energy delivery without/with ET are shown in Fig. 7. The shaded area in Fig. 7 indicates that local energy consumption with ET reduces transactions with the retailer. In other words, the quantity of energy demand without ET is larger than that with ET, which prosumers with ET turn to purchase energy from neighbors. ET among prosumers is more attractive comparing to retailer-oriented energy transaction, especially at peak hours (10:00–14:00, 18:00–20:00). Compared to purchasing electricity at peak hours, e.g. 11:00 ($\beta = 0.01$) and 13:00 ($\beta = 0.1$), prosumers guided by the risk-averse retailer reduce the peak demand by seeking energy from the battery when $\beta = 10$ while increasing the demand at flat period (15:00–17:00). Namely, prosumers try to minimize the overall cost by trading energy with each other.

5.3.2. Comparison of power profiles and benefit for prosumers without/with ET

To further study the relationship between risk level and ET among prosumers, power profiles for prosumers under different risk value β ($\beta = 0.01, \beta = 0.1, \beta = 10$) are shown in Fig. 8. The expected values of wind generation output and load in Fig. 3 are adopted to illustrate the scheduling results without/with ET. The results are located on the left/right side in histogram, respectively. As shown in Fig. 8(a), it is necessary to purchase energy from the retailer to meet the supply-demand balance for prosumer 3 without ET at 8:00–14:00. The energy gaps can be filled by ET among prosumers and battery discharging. It is verified that the collaboration among prosumers maintains the balance instead of seeking energy from the retailer. Table 4 shows the comparison of the operation costs that prosumers with ET ($\beta = 0.01$) reduce the cost from 147450.97 CNY to 125127.55 CNY, and achieve 15.14% cost saving. With the increase of β from 0.01 to 10, prosumers in Fig. 8 respond to the higher retail prices provided by the risk-aversion retailer. They schedule charging/discharging of battery and negotiate with neighbors to maintain the balance instead of interacting with the retailer. The total costs without/with ET simultaneously reduce from 144761.68 CNY (without ET) to 123221.95 CNY (with ET) when $\beta = 10$. In addition, by comparing the cost saving, we conclude that prosumers with ET increase the ability to withstand risks, e.g. with the value of β increasing from 0.01 to 10, the cost saving is 2689.29 CNY (without ET) and 1905.60 CNY (with ET), respectively.

For the bargaining problem (P2), the operating costs and their payments of prosumers without/with ET are presented in Table 4. We observe that direct ET reduces the operating costs of prosumer 3. The operating cost of prosumer 1 and 2, however, increase. The reason is that prosumers, especially prosumer 2, sell more wind power to neighbors instead of selling it back to the retailer. Thus, the energy utilization efficiency is improved because of the local DER consumption. Meanwhile, prosumer 3 pays money back to prosumer 1 and 2, while they export power to prosumer 3 through ET. As shown in Table 4, the payment is proportional to the quantity of energy transaction. By leveraging the bargaining power α_i calculated by (23), prosumers are awarded various benefits for participating in ET which simultaneously guarantees the fairness of the benefits allocation. Therefore, it is economically feasible for prosumers to actively participate in ET.

6. Conclusion

In this paper, we provide an analytical framework of a bi-level energy interaction scheme that can help the retail market to coordinate peer-to-peer (P2P) energy trading among prosumers. Therein, we propose a cooperative Stackelberg game-theoretic model by assuming the retailer as the leader and cooperative prosumers as followers. The retailer makes a trade-off between revenue and risk to determine the price discrimination, whereas Conditional Value at Risk is incorporated into the model to depict the retailer's attitudes for the risk. Meanwhile, the properties of P2P energy trading are studied, in which prosumers' cooperation improves the reaction ability to the retail price and weakens the retailer's market power. Further, the cooperation and benefits allocation among prosumers are captured by leveraging the general Nash bargaining (GNB) game, which incentivizes energy trading and ensures the fairness of the benefits allocation. The GNB problem with power function is solved sequentially by decomposing the problem into two traceable phases. Finally, simulation results show that the proposed model enhances the ability of energy management system to cope with risks while improving the expected revenue under different risk-aversion levels. Simulation results also show that the model is beneficial for P2P energy trading whereas prosumers effectively respond to the prices in a cooperative manner and fairly allocate the benefits.

A potential extension of the proposed work is the investigation of decision making process in multi-leader-follower games. Further, improving the solution efficiency through distributed solution method is another direction for further investigation.

Declaration of Competing Interest

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

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