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Peer-to-Peer Energy Trading for Residential Prosumers with Battery Storage Systems

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ABSTRACT

This paper proposes a residential peer-to-peer (P2P) energy trading market for prosumers with battery storage systems. To this end, a P2P energy trading mechanism, including the rules for buying and selling energy, is presented. In addition, the supply function bidding method is adopted to match the power supply imbalance and calculate the market-clearing price. Based on the proposed model, a single-objective optimization problem is designed to minimize the total energy cost of all prosumers. To avoid the unfair benefit distribution for market participants, we further put forward a multi-objective optimization problem to solve the issue and reduce the total energy cost as much as possible. The simulation results validate and compare the performance on cost reduction of the proposed two optimization problems.

Keywords: Peer-to-peer energy trading, battery energy storage system, supply function bidding

1. INTRODUCTION

With the rapid development of telecommunication and computer science, tremendous revolutions are taking place in the current energy trading platform. As a hot research topic, the application of the peer-to-peer (P2P) energy trading market has been demonstrated a remarkable way to achieve cost reduction for market participants [1]. Due to the affordable investment and high renewable energy penetration, the P2P energy trading platform is welcomed by many prosumers who not only pursue reducing electricity cost but also want to play a part in environmental protection [2]. However, under a highly competitive P2P energy trading market, market participants can only rely on their perceptions to trade energy with others, which is prone to significant losses by irrational behaviors [3].

This paper aims to study how residential prosumers should buy and sell electricity to maximize their profit under such a P2P energy trading platform. To secure the fairness of the energy trading, we propose a supply function mechanism to clear the market. Unlike the scenario in [4], [5] and [6], where the supply function mechanism is applied to the energy trading market that a participant has the fixed role to play (buyer or seller), the prosumers in our work are designed to be either energy buyer or seller depending on their hourly energy generation and consumption. In addition, many existing papers (such as [7] and [8]) have proposed demand-side management (DSM) to further cut down the energy cost. In our work, the DSM is achieved using battery energy storage system (BESS) charging/discharging to indirectly control the energy demand. Moreover, two optimization problems are introduced for the system operator to help prosumers determine the optimal trading strategies: a single-objective optimization problem is designed to optimize social welfare; a multi-objective optimization problem is designed to help the system operator fairly distribute the benefits to market participants. Finally, a comparison between the proposed two problems is discussed in the case study.

2. MODELLING OF THE P2P TRADING SYSTEM

In our work, the operation time for the P2P trading market is set from 7:00 to 18:00, where the sampling time interval is set as 1 hour. Therefore, there are 10 time intervals a day for P2P energy trading. Forward sampling is taken here in this paper, e.g., the first time

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period within the 24-hour is from 7:00 am to 8:00, the second time period is from 8:00 to 9:00, etc. Notation $t\ (t = 1,2,3 \dots,10)$ is used to represent these time periods.

2.1 System description

We consider a residential P2P trading system consisting of a traditional utility company and N residential prosumers. The utility company supplies the electricity to the community at the retail price. For each prosumer, a rooftop PV system with BESS is distributed to every residential home, where a smart meter is installed to record energy generation and consumption. The work for the system operator is to calculate the market clearing price (MCP) according to prosumers' bids/offers, announce the winners, and proceed with transactions. During the transaction, the system operator acts as an information exchanger and does not intervene in the transactions within the market. In the proposed model, prosumers can play two different roles. Prosumer buyers whose PV generation is lower than demand should consider purchasing electricity from either the P2P market or utility companies. On the other hand, prosumers also can discharge BESS to fully or partially feed the energy demand. Due to the economic issue, we assume that prosumer buyers are not allowed to sell any energy to the P2P market and the grid. Prosumer sellers whose PV generation is higher than the demand could plan to sell the available electricity to the P2P market or to the grid to make a profit. In our model, it is not necessary for prosumer sellers to sell all extra energy to the P2P market and the grid as they can choose to store them in their private BESS. To keep the market electricity price stable, prosumer sellers are forbidden to buy electricity from the P2P market and the grid.

2.2 Energy Cost and Profit

The energy flows of a prosumer can be represented in Fig. 1. In this figure, $x_n^{B-L}(t)$ is the energy supplied by the BESS to load. $x_n^{PV-B}(t)$ is the energy from PV system to BESS. $x_n^{B-P2P}(t)$ and $x_n^{B-G}(t)$ are the energy sold by from BESS to the P2P market and grid, respectively; $x_n^{P2P-L}(t)$ and $x_n^{G-L}(t)$ are the energy supplied to the load from the P2P market and the utility company, respectively; $x_n^{PV-G}(t)$ and $x_n^{PV-P2P}(t)$ are the energy sold from PV generation to the P2P market and grid, respectively; $x_n^{PV-L}(t)$ is the energy supplied to the load from the PV system; $x_n^{G-B}(t)$ and $x_n^{P2P-B}(t)$ are the energy from the grid and the P2P market to BESS, respectively. It is noted that the parameters above are all non-negative. The energy purchasing cost $C_n(t)$ for a

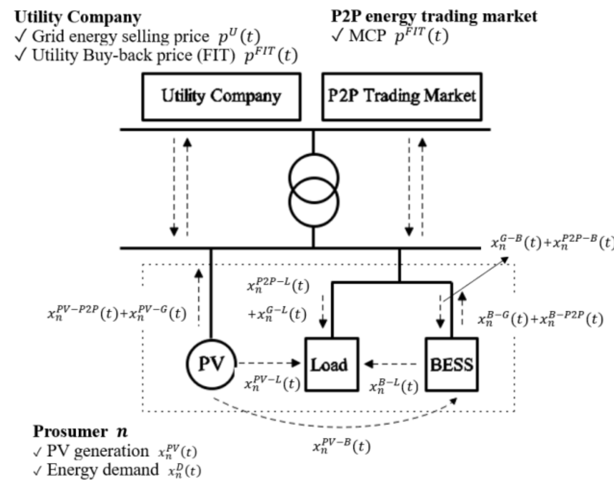

Fig. 1. Prosumer with energy trading conditions

prosumer buyer and the energy selling benefit $P_n(t)$ for a prosumer seller are expressed in (1) and (2), respectively.

$$C_n(t) = p^{MCP}(t)\left(x_n^{P2P-L}(t) + x_n^{P2P-B}(t)\right) + p^U(t)\left(x_n^{G-L}(t) + x_n^{G-B}(t)\right) \tag{1}$$

$$P_n(t) = p^{MCP}\left(x_n^{PV-P2P}(t) + x_n^{B-P2P}(t)\right) + p^{FIT}(t)\left(x_n^{PV-G}(t) + x_n^{B-G}(t)\right) \tag{2}$$

where $p^U(t)$ is the grid electricity price, $p^{FIT}(t)$ is the grid feed-in-tariff (FIT) purchasing price, and $p^{MCP}(t)$ represents the P2P market clearing price which will be calculated at a later stage.

In Eq. (1), the first term represents the purchasing cost from the P2P market, the second term represents the purchasing cost from the grid; in Eq. (2), the first term represents the energy selling benefit to the P2P market, the second term is the electricity selling benefit to the grid. To attract customer participation, a constraint in (3) is enforced to ensure that the final value of MCP must be between the FIT price and grid price.

$$p^{FIT}(t) < p^{MCP}(t) < p^U(t) \tag{3}$$

Denote by $\hat{C}_n$ the daily cost for prosumer n and $\hat{P}_n$ the daily benefit for this prosumer. Notations $\hat{C}_{total}$ and $\hat{P}_{total}$ represent the gross daily cost and profit of all prosumers, respectively. These costs and profits satisfy the following relations.

$$\hat{C}_n - \hat{P}_n = \sum_{t=1}^{T} C_n(t) - \sum_{t=1}^{T} P_n(t) \tag{4}$$

$$\hat{C}_{total} - \hat{P}_{total} = \sum_{n=1}^{N}\sum_{t=1}^{T} C_n(t) - \sum_{n=1}^{N}\sum_{t=1}^{T} P_n(t) \tag{5}$$

2.3 State-of-charge Constraints

In the proposed model, it is assumed that every prosumer owns an individual BESS, and thus there will be the relevant constraints for BESS under charging and discharging status. Let $x_n^{BC}(t)$ and $x_n^{BD}(t)$ be the amounts of charged and discharged energy of the n–th prosumer's BESS at time slot t, respectively. Let $\eta_n^{BC}(t)$ and $\eta_n^{BD}(t)$ be the corresponding charging and discharging efficiencies, respectively. According to Fig. 2, $x_n^{BC}(t)$and $x_n^{BD}(t)$satisfy the following relations:

$$x_n^{BC}(t) = x_n^{PV-B}(t) + x_n^{G-B}(t) + x_n^{P2P-B}(t) \quad (6)$$

$$x_n^{BD}(t) = x_n^{B-P2P}(t) + x_n^{B-L} + x_n^{B-G}(t) \quad (7)$$

The state-of-charge (SoC) $SOC_n(t)$ is defined as [9]:

$$SOC_n(t) = \frac{E_n^{BESS}(t-1) + x_n^{BC}(t)\eta_n^{BC}(t) - \frac{x_n^{BD}(t)}{\eta_n^{BD}(t)}}{E_n^C} \quad (8)$$

which is further constrained by

$$SOC_n^{min} \le SOC_n(t) \le SOC_n^{max} \quad (9)$$

$$0 \le x_n^{BC}(t) \le x_{n,max}^{BC}, 0 \le x_n^{BD}(t) \le x_{n,max}^{BD}, \quad (10)$$

where E_n^C is the BESS capacity for prosumer n. SOC_n^{min} and SOC_n^{max} are the minimal and maximal values of allowable SoC, respectively; $x_{n,max}^{BC}$ and $x_{n,max}^{BD}$ are the maximum charging and discharging energy during a unit time. Since charging/discharging at the same time would cause unnecessary energy loss, it is assumed that charging and discharging should not happen at the same time, that is,

$$x_n^{BC}(t) \times x_n^{BD}(t) = 0. \quad (11)$$

2.4 Energy Balance Constraints

Constraints (12) and (13) ensure the energy balance of consumption and generation for all prosumers.

$$x_n^D(t) = x_n^{PV-L}(t) + x_n^{B-L}(t) + x_n^{G-L}(t) + x_n^{P2P-L}(t) \quad (12)$$

$$x_n^{PV}(t) = x_n^{PV-L}(t) + x_n^{PV-B}(t) + x_n^{PV-G}(t) + x_n^{PV-P2P}(t) \quad (13)$$

where $x_n^{PV}(t)$ is the energy generated by PV panels and $x_n^D(t)$ represents energy demand. Since buyers do not sell electricity and sellers do not buy electricity, the following relations hold:

$$\begin{cases} if\ x_n^{PV}(t) < x_n^D(t): \\ x_n^{B-G}(t) = x_n^{B-P2P}(t) = x_n^{PV-G}(t) = x_n^{PV-P2P}(t) = 0 \\ if\ x_n^{PV}(t) \ge x_n^D(t): \\ x_n^{P2P-L}(t) = x_n^{G-L}(t) = x_n^{G-B}(t) = x_n^{P2P-B}(t) = 0 \end{cases} \quad (14)$$

Based on (14), (12) and (13) can be re-written as:

$$\begin{cases} if\ x_n^{PV}(t) < x_n^D(t): \\ x_n^D(t) = x_n^{PV-L}(t) + x_n^{B-L}(t) + x_n^{G-L}(t) + x_n^{P2P-L}(t) \\ if\ x_n^{PV}(t) \ge x_n^D(t): \\ x_n^D(t) = x_n^{PV-L}(t) + x_n^{B-L}(t) \end{cases} \quad (15)$$

$$\begin{cases} if\ x_n^{PV}(t) \ge x_n^D(t): \\ x_n^{PV}(t) = x_n^{PV-L}(t) + x_n^{PV-B}(t) + x_n^{PV-G}(t) + x_n^{PV-P2P}(t) \\ if\ x_n^{PV}(t) < x_n^D(t): \\ x_n^{PV}(t) = x_n^{PV-L}(t) + x_n^{PV-B}(t) + x_n^{PV-G}(t) + x_n^{PV-P2P}(t) \end{cases} \quad (16)$$

2.5 Market Clearing Price Computation

In our study, we use supply function method to derive the MCP: for a prosumer seller n at time t, denote by $x_n^{sell}(t)$ and $x_n^{buy}(t)$ the amount of electricity that prosumer n is going to sell and buy via P2P market, respectively. The expression of $x_n^{sell}(t)$ and $x_n^{buy}(t)$ can be described as:

$$x_n^{sell}(t) = x_n^{PV-P2P}(t) + x_n^{B-P2P}(t) \quad (16)$$

$$x_n^{buy}(t) = x_n^{P2P-L}(t) + x_n^{P2P-B}(t) \quad (17)$$

Assume that each prosumer seller defines the selling strategy by the supply function $x_n^{sell}(t)$. Without considering the maintenance cost and operation cost of PV systems, $x_n^{sell}(t)$ cab be decided using the electricity price $p(t)$ and a variable parameter $b_n(t)$ [10]:

$$x_n^{sell}(t) = b_n(t)p(t) \quad (18)$$

where for prosumer buyers, $b_n(t)$ will equal zero when prosumer n is buying electricity during time t. For prosumer sellers, they submit their supply functions as a bid to the system operator. In the proposed P2P market, MCP is determined when the supply equals the demand, that is $\sum_{n=1}^N x_n^{sell}(t) = \sum_{n=1}^N x_n^{buy}(t)$. Hence, $p^{MCP}(t)$ and $x_n^{sell}(t)$ can be determined using (20) and (21), respectively.

$$p^{MCP}(t) = \frac{\sum_{n=1}^N x_n^{buy}(t)}{\sum_{n=1}^N b_n(t)} \quad (19)$$

$$x_n^{sell}(t) = \frac{b_n(t)\sum_{i=1}^N x_i^{buy}(t)}{\sum_{i=1}^N b_i(t)} \quad (20)$$

2.6 Problem Formulation

In the proposed model, prosumers can either make benefit by selling electricity or spend money to buy electricity. When considering the fair benefit distribution to prosumers, the following optimization problem is to be solved:

$$\min\ (\hat{C}_1 - \hat{P}_1, \hat{C}_2 - \hat{P}_2, \dots, \hat{C}_n - \hat{P}_n) \quad (21)$$

s.t. (3), (9), (10) and (11).

For the system operator, the goal is to minimize the total energy cost for all prosumers. To optimize the social welfare, the proposed multi-objective optimization problem (22) needs to be transformed into a single-objective problem. For the social welfare optimization problem, $\hat{C}_{total} - \hat{P}_{total}$ is chosen as the sole objective function and the remaining individual objective functions

$\hat{C}_n - \hat{P}_n$ are considered as inequality constraints to ensure prosumers can get benefits by joining the proposed P2P market. Denote by $\hat{C}_n^{ori}(t)$ and $\hat{P}_n^{ori}(t)$ the daily cost and payoff of prosumer n, respectively, when this specific prosumer does not join the proposed P2P market. The constraint (23) is to ensure that all prosumers can get benefits from the proposed P2P market.

$$\hat{C}_n - \hat{P}_n \le \hat{C}_n^{ori} - \hat{P}_n^{ori}, (n = 1,2, \dots, N). \quad (22)$$

where

$$\begin{cases} if\ x_n^L(t) \ge x_n^PV(t): \\ \hat{C}_n^{ori}(t) = \left(x_n^L(t) - x_n^PV(t)\right) \times GP(t) \\ if\ x_n^L(t) < x_n^PV(t): \\ \hat{C}_n^{ori}(t) = 0 \end{cases} \quad (23)$$

$$\begin{cases} if\ x_n^L(t) < x_n^{PV}(t): \\ \hat{P}_n^{ori}(t) = \left(x_n^{PV}(t) - x_n^L(t)\right) \times FIT(t) \\ if\ x_n^L(t) \ge x_n^PV(t): \\ \hat{P}_n^{ori}(t) = 0 \end{cases} \quad (24)$$

Overall, the multi-objective problem can be written as:

$$\min\ (\hat{C}_{total} - \hat{P}_{total}) \quad (25)$$

s.t. (3), (9), (10), (11) and (23).

3. CASE STUDY

In this section, a community microgrid with 50 prosumers is investigated as a case study, where each prosumer owns PV panels and a BESS. The data of energy consumption and PV generation are obtained in [11]. In the case study, the capacity of BESS is set to 4.8 kWh, and the battery SoC is restricted to lie in between 20% and 80%. The charging/discharging efficiency are considered to be 90%. The maximum charging/discharging rate of the battery is 1 kW. The prosumer-based microgrid is connected to the main power grid, which can buy electricity at a FIT price. In the case study, FIT price is set as a flat number which is 8.4 cents/kWh (Since the data is based on the Australian community, Australian currency is the unit price in this case study). We have fetched the real grid price from an Australian electricity retailer, Red Energy, see Table 1. Since we only consider a one-day scenario, the battery degradation cost is reasonably ignored in this case study. The optimization results obtained by solving function (22) and (26) will be presented as follows. For simplicity, we abbreviate these two optimizations as Individual Energy Cost (IEC) optimization and Total Energy Cost (TEC) optimization, respectively.

Table 1. Energy unit Price by hours [12]

	(cents/kWh)
0:00-7:00	14.3
7:00-14:00	24.2
14:00-20:00	52.25
20:00-22:00	24.2
22:00-24:00	14.3

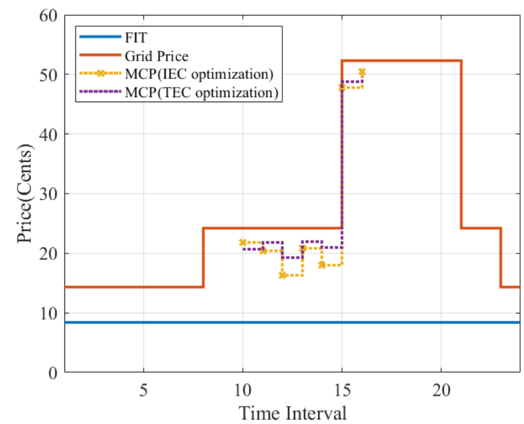

Fig. 4. Comparison of FIT, grid price and MCP

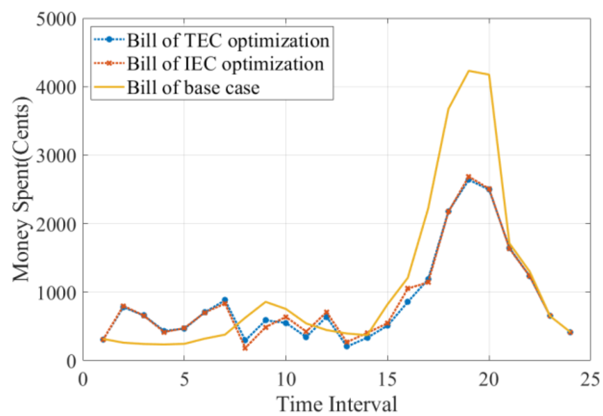

Fig. 5. Hourly energy cost by different methods

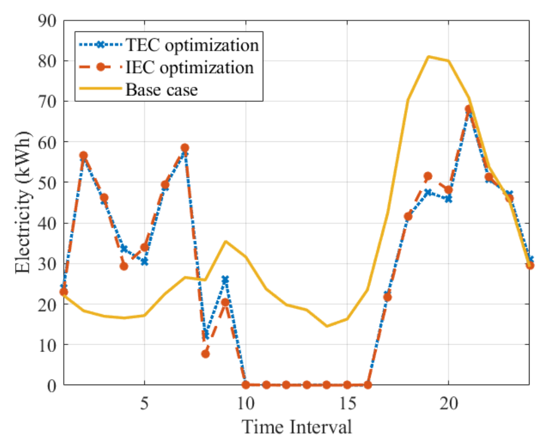

Fig. 6. Variations of the electricity traded from the grid

Firstly, we investigate the result of hourly MCPs. Fig. 4 shows the clearing prices among 50 prosumers in the system. As shown in this figure, the P2P market is mainly

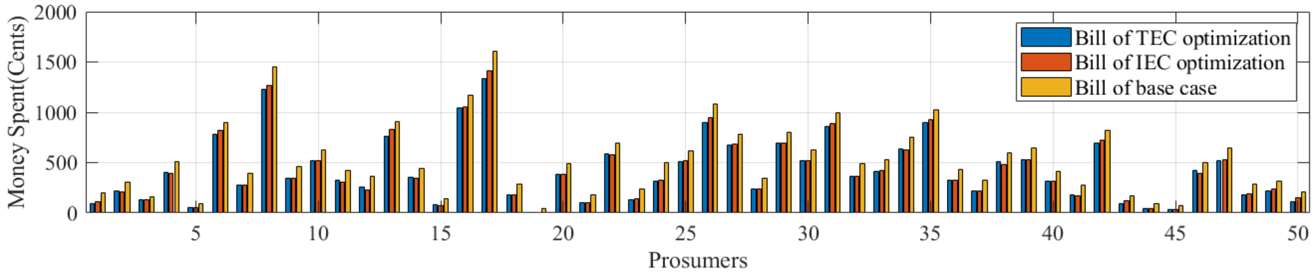

Fig. 7. The summary of the individual electricity bills

working during the afternoon at the most efficient working time of PV system. The biggest factor that affects the MCP is the grid price. When the grid price goes higher, the MCP will increase and vice versa. However, compared to the case of buying electricity from retailers, the electricity trading in P2P market is still a good way to secure the benefits for prosumers. On the other hand, both solutions obtain no MCPs from $t = 1$ to 9 and $\mathrm{t} = 17$ to 24. This is because that during these time periods, all prosumers are electricity buyers according to (15) and (16). Comparing the MCP between IEC solution and TEC solution from $t = 10$ to $\mathrm{t} = 14$, the MCP with TEC solution is more stable, which provides more flexibility to prosumers in the electricity trading.

Next, we investigate the overall electricity trading performance. Fig. 5 shows the total traded electricity purchased from the grid. Since PV generation is sufficient to activate the P2P trading market between $t = 10$ to $t = 16$, all participants who have electricity deficit tend to buy electricity from other prosumers with P2P clearing prices due to the price advantage. Fig.6 indicates the total electricity bills of all prosumers. Here the base case is under the condition when the proposed P2P market does not exist. Compared to the base case, the suggested TEC optimization and IEC optimization results encourage prosumers to charge BESS in the morning, where the stored energy is discharged in the evening to support peak demand. This strategy can significantly drop the electricity cost as the grid energy prices in the evening are almost tripled compared to the morning grid energy prices. According to Fig.4, 5 and 6, although the TEC optimization and the IEC optimization present the similar result, by calculation, the TEC optimization proposes more energy trading over the P2P market, where the total traded energy by TEC optimization is 124.8kWh, and this figure by IEC optimization is 117.7kWh. Moreover, regarding the total energy bill, it sharply declines by executing both optimization strategies, where the total electricity bill for all prosumers in the base case is 26427.4 cents while the total bill reduces by 20.4% to 21027.3 cents by executing TEC optimization and by 19.1% to 21378.50 cents by executing IEC optimization.

Finally, the daily electricity bills for each prosumer is discussed in Fig.7 based on three different strategies. Compared to the base case, both the TEC optimization and IEC optimization show a significant decline in the daily energy cost, especially for the prosumers who have high energy consumption. For the prosumers who have low daily energy demand, the proposed two optimizations can easily help them achieve almost zero energy cost through P2P energy trading (i.e., prosumers 5, 19, 44 and 45). Comparing the optimization results based on different objectives, a slight variation can be observed. By taking TEC optimization, there are 32 prosumers who receive a lower daily electricity bill than taking the IEC optimization. For the TEC optimization, the lowest total energy cost is achieved by sacrificing the other 18 prosumers' profits. In contrast, although the IEC optimization results show a slightly higher total energy cost, it can guarantee the fairness of benefit distribution that no prosumers will be worse off to reduce the cost of others.

4. CONCLUSION

In this paper, a prosumer-based P2P energy trading system is proposed considering P2P energy trading and BESS charging/discharging. The market clearing prices are co-determined using the supply function mechanism, which ensures equal rights for every market participant. Based on the proposed model, this paper gives two optimal energy trading strategies for different purposes. Simulation results show that the proposed trading mechanism can efficiently reduce the electricity bills for prosumers and increase the overall social welfare.

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