Energy Trading with Demand Response in a Community-based P2P Energy Market

Min Zhang, Frank Eliassen, Amir Taherkordi, Hans-Arno Jacobsen, Hwei-Ming Chung, and Yan Zhang
Dept. of Informatics, University of Oslo (UiO), N-0316 Oslo, Norway
Email: {minz; frank; amirhost; hansarnj; hweiminc}@ifi.uio.no; yanzhang@ieee.org

Abstract—Peer-to-peer (P2P) energy trading among neighbouring prosumers is considered as a promising trading method for the future smart grid. Demand response management becomes a critical challenge due to increased penetration of renewable energy. Earlier work mostly considers P2P trading models with only prosumers, while we believe there will still be a role to play for electricity suppliers in local energy markets in the foreseeable future. This paper therefore proposes a trading model in a community based P2P electric energy market that includes local energy suppliers and a community coordinator as market participants, in addition to pure energy consumers, and prosumers. We develop a demand response mechanism for the proposed trading model, in which dynamic pricing for suppliers is used. The community coordinator negotiates with suppliers on the external energy price and trades with them on behalf of the households within the P2P energy market. In our proposed trading model, the behaviour of the suppliers and the community households are modelled as two non-cooperative games. We propose a distributed algorithm to determine the equilibrium of the games. Simulation results show that our model has great effect on reducing the net peak load and increasing the market participants’ profit. Additionally, the proposed mechanism is shown to act as an efficient incentive for pure energy consumers to become prosumers.

Index Terms—Microgrid, P2P energy trading, demand response, renewable energy

I. INTRODUCTION

Promoted by the massive benefits of green energy and the rapid growth of smart grid technologies, there is a global trend towards promoting development and deployment of renewable energy technologies. More households are investing in PV panels to regulate their own power consumption or contribute to self-supply of electricity—a transformation from an energy consumer to a so-called prosumer. They can even make a profit by selling their excess solar electricity to their neighbours. Peer-to-peer (P2P) energy trading among prosumers has emerged as a next-generation energy management mechanism with the goal of improving the efficiency of integrating distributed renewable energy resources.

However, due to the characteristics of randomness, volatility, and intermittency in renewable energy generation, a growing amount of shared renewables increases the complexity of the electricity power system and the local energy balancing market. It is therefore important to develop new business models and the related mechanisms that enable efficient and maximum integration of renewables in local areas. The research on P2P energy trading is still at an early stage and there is no consensus on what type of market model and energy trading mechanism yields the best results [1]. The state-of-the-art P2P markets can be categorised into two groups: full P2P markets and community-based markets [2]. In full P2P markets, prosumers and consumers directly negotiate with each other to sell and buy electricity. For example, Sorin et al. [3] proposed a full P2P market for local producers and consumers, without going through a central entity, which relies on a multi-bilateral economic dispatch. However, full P2P markets suffer from the problems of scalability, concerning the negotiation process among peers, and the local energy balance controlled by grid operators.

Compared with the full P2P markets, community-based markets overcome the aforementioned challenges by employing a community coordinator who manages the P2P trading activities inside the community, as well as intermediating between the community and the wholesale energy markets. The community coordinator is required to negotiate among all the prosumers and either helps with matching each buyer with a proper seller [4] or sets up a market clearing price for all the participants [5]. With a market clearing price, it becomes possible to apply dynamic pricing based demand response mechanisms on the local P2P market. For example, in [6], a P2P energy sharing model for microgrid demand response is proposed using a dynamic internal pricing model, in which internal prices are used for P2P energy trading among local prosumers.

In terms of future market design, most state-of-the-art work aims to maximise the benefit of local prosumers. Existing solutions assume that the power generation from the prosumers is either enough for the whole community or supplied directly from the main grid [4] [7], without considering the households who are not willing to join the P2P market. Hence, local energy retailers or suppliers, and local pure energy producers are excluded from the local energy market. However, some of the above assumptions may not be realistic. For example, it may take a long time for all the communities to reach a full energy self-supply mode, and we need backup market solutions in case local energy production from prosumers fails for various reasons. Therefore, it is necessary to consider different scenarios for the future local energy market. As an alternative to the future market with only prosumers and consumers, we believe that there will still be a role to play for electricity suppliers in local energy markets in the foreseeable future.

A few works have been carried out that involve suppliers in
the local P2P market [8], [9]. These works allocate demand response mechanisms for the prosumers, with the assumption that the supplier just passively provide electricity at a pre-announced price, leaving the supplier out of the demand response model. However, it is known that the supplier usually plays an important role as a balance responsible party (BRP) who takes care of the local energy balance. Therefore it is essential to take active suppliers into account when developing demand response mechanisms for local P2P markets.

In this paper, considering P2P energy trading from the market point of view, we design a P2P energy market and develop a new demand response mechanism for local energy trading with active involvement of suppliers. The main contributions of this paper are as follows.

1. We design a community-based P2P market that is more realistic in the foreseeable future, consisting of heterogeneous market participants: pure consumers, prosumers equipped with solar generation, local suppliers equipped with their own energy generation (e.g., solar or wind park, and conventional power plant), and a community coordinator.

2. We apply a demand response mechanism using dynamic pricing with active involvement of suppliers. To the best of our knowledge, this is the first model that adopts dynamic pricing for suppliers in P2P energy trading.

3. We propose two non-cooperative games to model the behaviour of the involved market participants and to reach a global Nash equilibrium. Simulation results indicates that our model has great effect on reducing the net peak load and increasing the profit of the market participants.

II. SYSTEM MODEL

The designed market is shown in Fig. 1. It is assumed that there are $N$ prosumers (of which some are pure consumers), $M$ suppliers, and a community coordinator. The suppliers are assumed to be equipped with their own energy generation and they intend to sell the produced energy to the community households when the local solar generation from the prosumers cannot meet the demand. A day is divided into $T$ time slots. Let $T = \{1, ..., T\}$ denote the set of time slots. Prosumers (or pure consumers) decide on the amount of energy that they want to buy or sell for each time slot (e.g., each hour) based on their own solar power generation and load consumption. Then, they send the energy buying or selling requests to the coordinator. The coordinator calculates the internal pricing for selling and buying energy among prosumers based on the net load (total supply minus total demand). Suppliers also send their energy/price bids to the coordinator. The coordinator negotiates with suppliers on the external energy price and trades with them on behalf of all the prosumers and consumers.

From the market point of view, the community coordinator can be managed by a single utility (e.g., an aggregator) using a centralised infrastructure (e.g., cloud), or can be co-managed by a decentralised autonomous organisation (DAO) consisting of multiple stakeholders using blockchain technology [4]. The possible stakeholders that may be willing to join the network can be: 1) the local government that attempts to promote green energy among households; 2) the solar panel companies who aim to sell their solar products; 3) distribution system operators (DSO) and transmission system operators (TSO) who attempt to govern the energy balancing; 4) smart meter operators who own the energy consumption data of households.

III. PROBLEM FORMULATION

The proposed problem is modelled as a multi-agent system consisting of three types of agents: supplier agent, prosumer agent, and coordinator agent. Note that we categorise the pure consumers as a special case of prosumers with zero energy generation. The coordinator works on setting up the prices based on two pricing models: an external pricing model for importing energy from suppliers to the local community and an internal pricing model for the internal trading among local prosumers. Suppliers compete with each other aiming to maximise their own profits, and their behaviour is modelled as a non-cooperative game. The behaviour of prosumers is also modelled as a non-cooperative game, in which players decide on their load demand based on the internal energy prices in order to maximise their personal payoff.

A. Supplier-side Game

We consider multiple suppliers in a local energy market who compete with one another based on supply function equilibrium [10]. Let $M = \{1, ..., M\}$ denote the set of suppliers. Let $\beta_{j,t}$ denote the bid of supplier $j \in M$ at time slot $t$. Let $s_{j,t} = \beta_{j,t} \cdot p_{\text{ex}}^{s_j}$ denote the affine supply function, where $s_{j,t}$ is the total amount of energy supply by supplier $j$ at time slot $t$. Here we refer to $p_{\text{ex}}^{s_j}$, the price calculated by the coordinator as external price, and it is used for trading with suppliers. Let $D_t$ denote the aggregated net load of all the prosumers. Since suppliers provide the corresponding energy to meet the energy shortage of the prosumers, the total energy provided by suppliers equals to the aggregated net load of the prosumers. Therefore,

$$D_t = \sum_{r \in M} s_{r,t}. \tag{1}$$
Since the suppliers are assumed only to sell energy to the prosumers, rather than purchasing energy from the prosumers, we have $D_i = 0$. Hence, the external price can be expressed as a function of the bids submitted by all of the suppliers, and the aggregated net load from the prosumers.

$$p_{i,t}^{ex} = \sum_{q \in M} s_{q,t} D_q = \sum_{q \in M} \frac{D_i}{\beta_{i,t}}.$$  \hspace{1cm} (2)

The supply function of supplier $j$ can be described by the the bids from all suppliers and the aggregated net load.

$$s_{j,t} = \beta_{j,t} \cdot p_{i,t}^{ex} = \frac{\beta_{j,t} D_i}{\sum_{q \in M} \beta_{q,t}}.$$  \hspace{1cm} (3)

The profit function of the electricity supplier $j$ can be determined as the benefit from selling the electricity minus the cost of producing it.

$$\pi_{j,t}(\beta_{j,t}, \beta_{-j,t}) = s_{j,t}(\beta_{j,t}, D_i)p_{i,t}^{ex}(\beta_{j,t}, D_i) - C_{j,t}(s_{j,t})$$  \hspace{1cm} (4)

where $C_{j,t}(\cdot)$ is the generation cost function of supplier $j$ at time slot $t$. $\beta_{-j,t}$ represents the set of bids from all other suppliers but supplier $j$. Note that the cost function varies with the energy source. Here we use a general quadratic function to model the cost of energy generation from mixed energy source:

$$c(s_{j,t}) = a_2 s_{j,t}^2 + a_1 s_{j,t} + a_0,$$  \hspace{1cm} (5)

where $a_2, a_1$ and $a_0$ are positive coefficients [11].

We substitute (2) and (3) into (4) and define the payoff function for supplier $j$ when other suppliers’ bids are fixed:

$$\pi_{j,t}(\beta_{j,t}, \beta_{-j,t}) = \frac{\beta_{j,t} D_i}{(\sum_{q \in M} \beta_{q,t})^2} - c_{j,t}\left(\frac{\beta_{j,t} D_i}{\sum_{q \in M} \beta_{q,t}}\right).$$  \hspace{1cm} (6)

The supplier-side non-cooperative game is defined as follows.

- **Players:** The set of suppliers $M$.
- **Strategies:** Each supplier $j$ selects a bid $\beta_{j,t}$ to maximise its payoff.
- **Payoffs:** For an action $\beta_{j,t}$, supplier $j$ receives a payoff defined in (6). The payoff function for supplier $j$ depends on the strategies of all the other players as well as its own strategy.

Let $\beta^*_j$ denote the Nash equilibrium strategy of suppliers at time slot $t$, and

$$\pi_{j,t}(\beta^*_j) \geq \pi_{j,t}(\beta_{j,t}, \beta^*_a) \quad \forall j \in M,$$  \hspace{1cm} (7)

where $\beta^*_a = \{\beta^*_j\}$.

**Theorem 1:** The supplier-side game is an n-person game, and has an unique pure strategy Nash equilibrium.

**Proof:** There exists a unique strategy Nash equilibrium for this game if the following optimization problem is strictly concave and has a unique solution [11].

$$\begin{align*}
\text{maximize} & \quad \pi_{j,t}(\beta_{j,t}, \beta_{-j,t}) \\
\text{subject to} & \quad \beta_{j,t} \geq 0
\end{align*}$$  \hspace{1cm} (8)

It is easy to see that the payoff function is strictly concave as its second order derivative is always negative. In this case, there exists a unique solution for equation (8) and the existence of the Nash equilibrium of this game is proven.

### B. Prosumer-side Game

Let $N = \{1, \ldots, N\}$ denote the set of prosumers. It is assumed that prosumer $i \in N$ is able to generate $E_{i,t}^g$ amount of energy at time slot $t \in T$. Note that a pure consumer who is not equipped with solar generation is treated as a special case of prosumer with $E_{i,t}^g = 0$. Let $x_{i,t}$ denote the amount of energy that prosumer $i$ consumes at time slot $t$. Therefore, the buying/selling request of prosumer $i$ is $E_{i,t}^q - x_{i,t}$. When $E_{i,t}^q - x_{i,t} > 0$, prosumer $i$ acts as a seller. Otherwise, the prosumer acts as a buyer. Prosumers adjust their energy consumption $x_{i,t}$ according to the buying price $p_1^q$ and selling price $p_1^s$ that are used for trading with other prosumers. Here, we call $p_1^q$ and $p_1^s$ the *internal prices*. In our proposed model, the payoff of prosumer $i$ is described using a piecewise function as proposed in [14].

$$U_{i,t}(x_{i,t}) = \begin{cases} 
\alpha_i \ln(1 + x_{i,t}) + p_1^q(E_{i,t}^q - x_{i,t}), & E_{i,t}^q - x_{i,t} > 0 \\
\alpha_i \ln(1 + x_{i,t}) + p_1^s(E_{i,t}^q - x_{i,t}), & E_{i,t}^q - x_{i,t} \leq 0
\end{cases}.$$  \hspace{1cm} (9)

where $\alpha_i \ln(1 + x_{i,t})$ is the utility that the prosumer $i$ achieves from consuming $x_{i,t}$ amount of energy at time slot $t$. $\alpha_i$ is the reference parameter of prosumer $i$. Note that a prosumer with higher $\alpha_i$ will be more interested in consuming more energy to achieve its maximum utility. $p_1^q(E_{i,t}^q - x_{i,t})$ is the revenue that prosumer $i$ receives by selling the excess energy and $p_1^s(E_{i,t}^q - x_{i,t})$ is the cost of the prosumer $i$ from buying energy at time slot $t$. The energy consumption $x_{i,t}$ is bounded by its base load that should always be supplied, denoted as $x_{i,t}^{min}$, and an up-bounded maximum load consumption $x_{i,t}^{max}$ and $x_{i,t}^{min} \leq x_{i,t} \leq x_{i,t}^{max}$.

Similar to the supplier-side problem, the prosumer-side problem can also be described as a non-cooperative game as follows.

- **Players:** The set of prosumers $N$.
- **Strategies:** Each prosumer $i$ decides on the amount of energy $x_{i,t}$ that it attempts to consume to maximize its payoff.
- **Payoffs:** For an action $x_{i,t}$, prosumer $i$ needs to either buy or sell $|E_{i,t}^q - x_{i,t}|$ amount of energy and receives a payoff as described in equation (9). The payoff function for prosumer $i$ depends on the strategies of all the other players as well as its own strategy.

Similar to the supplier-side game, the existence and uniqueness of the prosumer-side game can be proven accordingly. In the Nash equilibrium, for given internal prices from the coordinator, none of the prosumers has an incentive to deviate from its optimal energy usage as long as the other prosumers’ strategy stays unchanged.

### C. Pricing Models of the Coordinator Agent

The coordinator collects all the bids sent from suppliers, as well as all the energy buying and selling requests from prosumers. It also sets up external and internal prices based on an external pricing model and an internal pricing model, respectively.
1) External Pricing Model: Every time when the coordinator collects all the energy buying and selling requests from prosumers, it calculates the total energy supply $E^a_t$ and demand $E^d_t$ by

$$
E^a_t = \sum_{i \in N} \max\{E^g_{i,t} - x_{i,t}, 0\},
$$

$$
E^d_t = \sum_{i \in N} \max\{x_{i,t} - E^g_{i,t}, 0\},
$$

and calculates the net load, $D_t$, of all the prosumers:

$$
D_t = E^d_t - E^a_t. 
$$

Since the suppliers are assumed only to sell energy to the prosumers, rather than purchasing energy from the prosumers, we only consider the situation that $E^a_t \leq E^d_t$. The external price for buying energy from suppliers is then calculated using equation (2).

2) Internal Pricing Model: The profit of the coordinator is calculated as the difference of internal and external prices minus the operational cost.

$$
R(p^a_t, p^b_t) = p^a_t E^d_t - p^a_t E^a_t - p^b_t D_t - (\eta p^x_t + b),
$$

where $(\eta p^x_t + b)$ is the cost used for running the coordinator at time slot $t$ and $b$ is a constant value that represents the equipment depreciation cost. $\eta$ and $b$ are positive coefficients. The internal prices are bounded by $\lambda^s \leq p^s_t \leq p^b_t \leq \lambda^x_t$, where $\lambda^s$ represents the fixed price of selling energy back to the main grid. This price limitation guarantees that the prosumers always prefer trading their energy with other neighbouring prosumers rather than dealing with the suppliers or the main grid.

It is important to define the profit of the coordinator since profit keeps a market running. Nian et al. [6] proposes a pricing model by maximising the coordinator’s benefit, while some other models such as Nian et al. [5] presents an extra benefit model for the coordinator to charge a so-called service fee. The coordinator’s profit in our model can be defined as follows:

- The maximum profit of the coordinator can be obtained when $p^s_t = p^b_t = \lambda^x$. In this way, it makes no difference for the prosumers to directly trade with the suppliers and the main grid. However, this may increase the customer churn (i.e., fewer users will choose to join the P2P market) and reduce incentives for consumers to invest in renewable energy generation.

- The minimum profit can be obtained when $p^s_t = p^b_t = \lambda^s$. However, since $\lambda^s \leq p^s_t \leq p^b_t \leq \lambda^x$, the coordinator will have a negative profit margin. This will lead to less motivation for the stakeholders to establish such a P2P energy trading marketplace.

According to the utility function in equation (12), the profit of the coordinator is highly related to the local solar energy generation and load consumption. For example, when $E^a_t \ll E^d_t$, such as on a cloudy day or in the evening, in order to guarantee $\lambda^s \leq p^s_t \leq p^b_t \leq \lambda^x$, there is almost no profit for the coordinator. Therefore, we categorise two types of solar environments according to the profit that the coordinator can obtain.

**Period 1: Solar sufficient time when $R(p^a_t, p^b_t) > 0$.** When there is sufficient solar energy generation, the internal prices are defined to guarantee the profit of the coordinator, such that

$$
R(p^a_t, p^b_t) = \Theta_t, 
$$

where, $\Theta_t$ is a constant value that represents the profit that the coordinator can obtain at time slot $t$. To guarantee the final convergence of the model, internal prices are set to be a linear function of the net load and the aggregated suppliers’ bids. Thus,

$$
p^a_t = \lambda_t \frac{D_t}{\sum_{r \in M} p^b_{r,t}} t \in T, 
$$

$$
p^b_t = \mu_t \frac{D_t}{\sum_{r \in M} p^b_{r,t}} t \in T. 
$$

In this way, given $D_t$, and one of the pre-defined coefficients $\lambda_t$ or $\mu_t$, we can find a unique internal prices pair $[p^a_t, p^b_t]$.

**Period 2: Solar insufficient time when $R(p^a_t, p^b_t) \leq 0$.**

When $E^a_t \ll E^d_t$, the internal price will be set to $p^a_t = p^b_t = p^x_t$, which maximises the profit of both the coordinator and the prosumers who act as sellers; at the same time, the internal buying price is not higher than the external price.

### IV. Algorithm Design

In our proposed model, prosumers and suppliers need to make decisions based on other players’ strategies. We design a distributed algorithm such that the prosumers and the suppliers do not need to communicate with other players to know their strategy. Instead, they calculate the needed values based on the energy trading prices sent by the coordinator. The algorithm is based on the projected gradient method [12]. Let $k$ denote the iteration number. Let $x^k_{i,t}$ denote the load of prosumer $i \in N$ in the $k^{th}$ iteration at time slot $t$. Then, the energy buying/selling request sent from prosumer $i$ is $E^g_{i,t} - x^k_{i,t}$. Let $\beta_{j,t}$ denote the bid from supplier $j \in M$ in the $k^{th}$ iteration at time slot $t$. Let $\beta^k_{j,t}$ denote the internal buying and selling price in iteration $k$. Let $\beta^b_{i,t}$ and $\beta^p_{i,t}$ denote the internal buying and selling price in iteration $k$, respectively. For each time slot $t$, each agent updates its decision based on the other related agents’ decisions iteratively until no agent attempts to change its decision. Therefore, the results will eventually converge to a single point for every agent. At the $k^{th}$ iteration, since the solar generation is unchanged during the iteration, prosumers update their energy buying/selling request $E^g_{j,t} - x^k_{i,t}$ only by updating $x^k_{i,t}$, according to the following iterative equation.

$$
x^k_{i,t} = \left[x_{i,t}^{k-1} + \theta_{i,t} \frac{\partial U_{i,t}(x_{i,t}^{k-1})}{\partial x_{i,t}^{k-1}} \right]^+, 
$$
where $\theta_{i,t}$ is the step length of the prosumer agent $i$. $[\cdot]^+$ represents the projection onto the feasible set, which guarantees the load of prosumer $i$ is bounded by $x_{i,t}^{\min} \leq x_{i,t} \leq x_{i,t}^{\max}$. When receiving all energy buying/selling requests from the prosumers, the coordinator will calculate the net load $D_{i,t}$, and send it to suppliers. Then, suppliers update their bids $\beta_j^k$ based on the external price $p_{i,t}^{ex,k-1}$ from the last iteration according to the following iterative equation,

$$
\beta_{j,t}^k = \beta_{j,t}^{k-1} + \gamma_{j,t} \frac{\partial p_{j,t}(\beta_{j,t}^{k-1})}{\partial \beta_{j,t}^{k-1}},
$$

(17)

where $\gamma_{j,t}$ denotes the step length of supplier $j$. Note that, suppliers do not need to know the other suppliers’ bids. They calculate the sum of bids submitted from the received external price according to (2). After receiving the updated bids from all suppliers, the coordinator will update the external price $p_{i,t}^{ex,k}$ and the internal price pair $[p_{i,t}^{b,k} \quad p_{i,t}^{s,k}]$ according to the pricing model and broadcast the prices to suppliers and prosumers. This iterative process will keep repeating until the results from all agents converge. The distributed algorithm is illustrated in Figure. 2 and Algorithm 1.

**Algorithm 1 Trading negotiation.**

1: Initialization: $k=0$

2: repeat

3: For each $i$ in prosumer agents: calculate $x_{i,t}^k$ according to (16), then send $E_{i,t}^k - x_{i,t}^k$ to coordinator agent.

4: Coordinator agent: calculate $D_{i,t}^k$, then send it to supplier agents.

5: For each $j$ in supplier agents: calculate $\beta_{j,t}^k$ according to (17), then send it to coordinator agent.

6: Coordinator agent: calculate $p_{i,t}^{ex,k}$, $p_{i,t}^{b,k}$, $p_{i,t}^{s,k}$, and broadcast them.

7: until $|p_{i,t}^{ex,k} - p_{i,t}^{ex,k-1}| < \epsilon$.

Since the Nash equilibrium of supplier-side and prosumer-side games are unique, the iterative processes (14) and (15) will converge to the Nash equilibrium of the games after sufficiently small step sizes $\theta_{i,t}$ and $\gamma_{j,t}$ [12]. In fact, given the parameters in the pricing model at the coordinator, the algorithm converges to a point in which suppliers are playing their equilibrium strategy based on the prosumer’s energy buying/selling request data, and the prosumers also select their equilibrium strategy based on bids submitted by suppliers. In the equilibrium, none of the agents gains a benefit by deviating from their chosen strategy. The iteration complexity of the gradient descent that is used by suppliers is known as $O(1/\epsilon)$, where $\epsilon$ is the given relative accuracy and $\epsilon > 0$. Since computing the projection does not increase the complexity, the projected gradient method used by prosumers is also $O(1/\epsilon)$. Therefore, the overall complexity of this algorithm is $O(1/\epsilon)$. This low iteration complexity guarantees the algorithm converges sufficiently fast. Since prosumer and supplier agents run their own distributed algorithms and only send the updated parameters to the coordinator, the proposed model is able to achieve high scalability.

**V. NUMERICAL RESULTS**

To evaluate the proposed trading model, we have developed a Matlab program that implements the iterative algorithm. Actual data of the city of Austin, Texas is used for the case study [13]. The case study focuses on the sunny day of 1st, August 2018, with generally efficient solar generation. We use the grid acquisition price of $0.089 as the baseline for our proposed model [14]. This price is used by the Austin energy grid for rewarding prosumers for their solar generation. In the studied community, there are $N = 50$ households, in which 20 of them are equipped with rooftop PV panels. The other 30 households are pure electricity consumers with $E_t^g = 0$. There are $M = 3$ supplier companies that participate in the P2P market. The length of a time slot equals to one hour, i.e., $t = 1h$. The values of the parameter $a_{i,t}$ in equation (9) are randomly generated from a normal distribution with mean 0.7 and 0.8, for the prosumers with solar generation and the pure consumers, respectively. The loads of air conditioners, dish washers and washing machines, are categorised as shiftable loads. Since there is no solar generation during the evening, only the performance of the model from 7 to 19 o’clock is evaluated.

Fig. 3 illustrates the initial total energy consumption, the aggregated net load by all households with and without applying the proposed mechanism, respectively, and the total
solar generation. As shown in the figure, the initial total energy consumption keeps increasing from the morning until the evening, causing a peak load at around 17 o’clock.

The red curve illustrates the net load without applying the proposed P2P trading mechanism. Since a portion of the load demand is provided by the local solar generation (presented as green curve in the figure), the net load is much less than the total load demand. However, due to the limited solar generation in the early morning and in the late afternoon, the effect on the peak load hours is limited. Additionally, since the net load at the middle of the day is highly reduced because of the sufficient solar generation, it shows two peak loads and a higher peak-to-average ratio in the net load curve. After applying the proposed P2P trading mechanism, as shown in the blue curve, the net load during the peak hours is partially shifted to the off-peak hours, and a lower peak-to-average ratio is achieved.

Fig. 4: External and internal prices at different time slots

Fig. 4 presents the external and internal prices at different time slots. Due to insufficient local solar generation before 9 and after 17 o’clock, the internal prices are equal to the external price, according to the proposed internal pricing model. As shown in Fig. 4, compared with selling solar energy to the main grid at a fixed price of 0.089, the prosumers acting as sellers gain more benefit when trading the energy via the P2P community at a higher internal price. At the same time, prosumers acting as buyers can also obtain a benefit from buying energy from the P2P community at a lower internal price than directly buying from suppliers or the main grid.

Fig. 5 shows the average profit of prosumers with solar generation and pure consumers. It indicates that prosumers with solar generation get much more profit than pure consumers. This result proves that our proposed P2P trading mechanism works as an incentive that motivates consumers to invest in PV panels and become prosumers.

VI. CONCLUSIONS

We proposed a community-based P2P energy market consisting of heterogeneous market participants and developed a P2P energy trading model that performs demand response. The P2P trading problem was studied using two non-cooperative games. A distributed algorithm was developed to determine the equilibrium and to evaluate the system behaviour. The reported results indicate that our proposed P2P trading mechanism has efficient effect on reducing the net peak load and increasing profit of the market participants. Additionally, the proposed mechanism is shown to act as an efficient incentive for pure energy consumers to become prosumers.

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