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A Proof-of-Stake public blockchain based pricing scheme for peer-to-peer energy trading ☆

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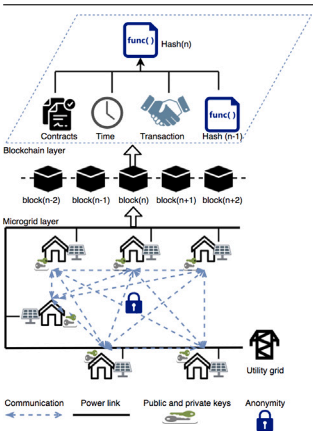
GRAPHICAL ABSTRACT



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ABSTRACT

Peer-to-peer (P2P) energy trading allows prosumers to trade energy directly without intermediaries. To provide a payment system and record transaction information, public blockchain is designed to match the decentralized feature of the P2P market. The incentive for nodes outside the microgrid is removed but it is maintained for the prosumers within the microgrid. Therefore the number of miner competitors is limited to decrease the mining difficulty and its power consumption. Proof-of-Stake (PoS) consensus protocol defines the function of blockchain with its mining mechanism. Miners sacrifice part of their stake to compensate for the power losses and reduce the price gap from the traditional prosumer-to-grid trading (Feed-in-tariff). Moreover, the proposed model also contributes to increase the social welfare by improving producers' income and consumers' cost-saving through the designed pricing scheme, which eliminates the price gap between buying and selling. Successful mining is encouraged by rewards accordingly. A case study is introduced where a microgrid model with 27 prosumers is tested with the PoS public blockchain-based pricing scheme. The process of model implementation and smart contract creation are specifically demonstrated. Numerical results prove the feasibility and effectiveness of the proposed method.

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1. Introduction

The increasing deployment of renewable energy generation in the existing power systems drives the energy market paradigm shift from a centralized structure to a decentralized one. Peer-to-peer (P2P) energy trading is one of the emerging architectures of the decentralized energy market in the distribution system and microgrids. P2P energy trading allows neighboring prosumers that are equipped with a certain capability of power generation to trade their energy with each other directly. The detailed background of the P2P energy system and conceptual understanding of different aspects of P2P energy trading are specifically introduced in [1,2]. Local energy consumption reduces service fees charged from intermediaries and provides a more economical trading environment [3–5]. To support the payment system and secure participants' private information related to energy transactions, a blockchain system becomes an ideal tool to be implemented in microgrids [6,7]. The idea of using blockchain technology with the P2P energy market has been progressed from theoretical assumption to simulation or even practical implementation, in which the design of the pricing scheme plays a crucial role in transaction execution.

An effective pricing scheme could help to reduce the costs of the participants and increase the welfare of the P2P market. Several approaches, such as game theory [5,8], price-based demand response [9–11], double auction mechanism [12,13], negotiation approach [14–16], distributed optimization approach [17] are available in the literature to design the pricing scheme in the energy trading. In classical transaction models, the behaviors of participants in energy trading are modeled using game theory. The model introduced in [5] proposed interactive demand-side management and the dynamic pricing scheme based on game theory. The dynamic price is calculated by using the Stackelberg game. In [8], the energy trading game models are realized with iterative algorithms to achieve Nash equilibrium (NE) where NE represents the amount of energy to be traded and the corresponding trading prices. The authors in [9] generalize a pricing mechanism for the energy sharing market in which prosumers' cost-saving and market welfare are enhanced. In [10,11], the real-time pricing mechanisms are designed to maximize the social welfare. The double auction approach applied in [12,13] facilitates the interaction among participants. Prosumers play the role of price makers to optimize the trading strategy and increase their profits. The authors in [13] propose the double auction method with the Ethereum blockchain network to design three uniform prices for the P2P energy market. Most of the aforementioned methods are iterative approaches and computationally intensive, but the blockchain system is not able to afford intense computation especially when smart contracts are utilized, which may cause large latency problems [18].

In the blockchain-based energy trading systems, Ethereum [19,20] and Hyperledger Fabric [21] are the two most popular and widely used platform for P2P transactions. In the Hyperledger-based blockchain system, the Byzantine Fault-Tolerant (BFT) protocol [22] including reputation-based BFT (RBFT) and practical BFT (PBFT) is the main standard for all participants to achieve their trading consensus. The authors in [23] design a Hyperledger based blockchain to support energy crowdsourcing with batteries and distributed generation facilities. A similar blockchain type is implemented in [24] with a game model to increase sellers' profits and reduce buyers' utility sacrifice. In general, Hyperledger Fabric is an effective blockchain system when the pricing scheme design requires enormous computation. It is because the series of BFT protocols mostly support the design of private or permissioned blockchain [21,25] in which the computation load is largely decreased as the P2P trading is supervised and supported by a centralized agent. However, this feature of Hyperledger-based blockchain violates the decentralized structure of the P2P market where the transaction needs to be executed without any central authorities. Besides, malicious nodes could dominate private and permissioned chains by controlling only limited nodes (central agents). Conversely, in the public chain scenario, they need to control at least 2/3 nodes. The same problem also occurs with the Proof-of-Authority (PoA) consensus protocol which is newly published by the Ethereum platform [26].

To fulfill the requirement of a decentralized trading structure and ensure the security level of energy trading, the public blockchain systems are more suitable for the P2P energy market. The Ethereum platform provides a great variety of consensus protocols for the public blockchain design. These consensus protocols define the way of adding new blocks into the blockchain. Proof of Work (PoW) has been proven a successful protocol in Bitcoin [27], and the right to mining new blocks depends merely on participants' computation power. The requirement for mining power of computation increases with the number of blocks and miners. It will cause high mining expenses with the large amount of energy consumption [7]. To solve this problem, Proof-of-Stake (PoS) [28,29] is invented and the chance of mining is changed to rely on participants' stake. Thus, the computation load is decreased and the decentralized trading structure is fulfilled. The authors in [30] demonstrated an Ethereum blockchain-based P2P energy trading framework and regional energy balance and carbon emission mitigation are achieved by its proposed pricing scheme. Charging and discharging scenarios of electric vehicles are taken into consideration with blockchain technology in [31–34]. In conclusion, the Ethereum blockchain is better than the Hyperledger Fabric in public blockchain implementation and crypto-currency initialization, which offers a faster payment platform for the P2P energy market.

Since the private or consortium blockchain type is commonly utilized by many researchers [23–25,35] in the P2P energy trading which is always applied with an authorized agent, this study proposed a fully public chain to match the decentralized structure of the P2P market. However, for those studies in public blockchain-based pricing schemes, the main problem is the implementation since the smart contracts are primarily created for simple calculation and cannot afford large iterative computation. Therefore, complex pricing methods like game theory [3,5,8,36] could not be realized by the public chain. The number of iterations required should be small to realize with the public chain and our proposed pricing scheme has that feature. More unacceptably, some use of the blockchain system is even based on the theoretical assumption in many research studies [13,30,32,37]. The process of implementation should be demonstrated to prove the feasibility of the proposed ideas.

On the other hand, the power losses in the microgrid or electricity network while delivering energy from one node to another node increase the trading expense and cause the price gap between the buying price and selling price [9,38]. To solve this problem, this study designs a PoS consensus protocol with consideration of power loss compensation and it is able to cooperate with the pricing scheme to generate the optimal price for both sellers and buyers. The proposed blockchain method not only realizes its advantages on the transaction level but also helps in power losses analysis. Therefore, this study focuses on establishing a PoS based public chain with a relatively simple and feasible pricing scheme. The PoS consensus protocol with the pricing scheme is able to eliminate the pricing gap and increase social welfare. The contributions of this study are:

- A fully public blockchain to match the decentralized P2P energy trading market.
- A PoS consensus protocol application with a proper mining mechanism considering power losses to reduce the price gap.
- A simple and effective pricing scheme design with a small number of iterations which could be afforded by smart contracts.
- A clear demonstration of the implementation process and advantages of the proposed model over traditional prosumers to utility grid trading.

The remaining of this study is organized as follows: Section 2 shows the proposed pricing scheme design. Section 3 introduces the PoS based public blockchain considering power losses with smart contract creation and welfare analysis. The case study as well as the implementation process of the proposed method is shown in Section 4. Section 5 includes the conclusion of the study and its related future research direction.

2. Pricing scheme for P2P energy trading

The proposed pricing scheme aims to generate a more acceptable price for both buyers and sellers than trading with a utility grid. There should be no price gap between the buying price and selling price so that all traders could achieve their maximum benefits. The gap caused by power losses will be addressed in Section 3. In this study, prosumers of a microgrid are assumed to be equipped with PV panels and battery systems. After their power generation and stored energy run out, the demand of prosumers is firstly fulfilled by P2P energy trading with other prosumers. Their surplus power or unbalanced demand will be satisfied by trading with the utility grid as the last resort. Since the buying price and selling price for trading with the utility grid are constant values, the proposed pricing scheme only calculates the price for the transactions within the microgrid. The payment system in this study is supported by the blockchain system. To provide a fast trading platform, a proposed crypto-currency named *elecoin* is applied and thus the value of every product mentioned is measured by it.

In a microgrid with N prosumers, every trading could be set up as an element of a matrix P of order $n_c \times n_p$, where n_c and n_p denotes the number of consumers (buyers) and the number of producers (sellers) and are indexed by i and j respectively. It should be noted that n_c and n_p are not constant values in different time slots. It relies on prosumers' respective demand and generation to define the role of prosumers. Prosumers in the microgrid could assume different roles in different time slots based on their demand and generation. In each time slot t, the matrix P could be expressed as:

$$P = \begin{bmatrix} p_{11}^t & p_{12}^t & \cdots & p_{1n_p}^t \\ p_{21}^t & p_{22}^t & \cdots & p_{2n_p}^t \\ \vdots & \vdots & \ddots & \vdots \\ p_{n_c1}^t & p_{n_c2}^t & \cdots & p_{n_cn_p}^t \end{bmatrix} t \in [t_1, t_2, \dots, t_h] \tag{1}$$

where $n_c + n_p <= N$, and p_{ij} refers to the amount of power transferred between consumer i and producer j.

Accordingly, the power losses of every transaction can be represented as

$$P_L = \begin{bmatrix} p_{l_{11}}^t & p_{l_{12}}^t & \cdots & p_{l_{1n_p}}^t \\ p_{l_{21}}^t & p_{l_{22}}^t & \cdots & p_{l_{2n_p}}^t \\ \vdots & \vdots & \ddots & \vdots \\ p_{l_{n_c1}}^t & p_{l_{n_c2}}^t & \cdots & p_{l_{n_cn_p}}^t \end{bmatrix} \tag{2}$$

Therefore, the total amount of power exported by producers is

$$p_{ex}^t = \sum_{j=1}^{n_p} \sum_{i=1}^{n_c} p_{ij}^t \tag{3}$$

The amount of power purchased by consumer i within the microgrid is:

$$p_i^t = \sum_{j=1}^{n_p} p_{ij}^t \tag{4}$$

The total amount of power needed by all consumers is the sum of the energy imported from producers and the utility grid, which can be defined as

$$p_{im}^t = \sum_{i=1}^{n_c} (p_i^t + p_{u_i}^t) \tag{5}$$

where $p_{u_i}^t$ refers to the amount of power purchased from the utility grid by consumer i. It could be 0 if $p_{ex}^t - p_{im}^t >= \sum_{j=1}^{n_p} \sum_{i=1}^{n_c} p_{l_{ij}}^t$.

The supply–demand ratio ϵ^t for the microgrid in each time slot t is defined as

$$\epsilon^t = \frac{p_{ex}^t}{p_{im}^t} \tag{6}$$

According to [39], the correlation between the price of products and the supply–demand ratio is negative proportional. Therefore, the selling price S of power could be defined as

$$S^t = \frac{b}{\lambda \epsilon^{m,t} + 1} \tag{7}$$

where m is the exponential number of ϵ. The value of m depends on its specific application scenario, which will be defined in the case study section.

The selling price is set as $S(0)$ offered by FIT and the buying price is set as $B(0)$ offered by the utility grid. When $\epsilon^t = 0$, consumers could only purchase products from the utility grid, so that the new selling price $S(1)$ equal to $B(0)$. Conversely, if $\epsilon^t >= 1$, consumers' demand is fulfilled by producers' supply. The price $S(1)$ should be no more than the price offered by the utility grid $S(0)$ so that the power could be sold from producers. To calculate b and λ, substituting (0, $B(0)$) and (1, $S(0)$) into (10) and extending it to the iteration n, the price could be defined as

$$S^t(n+1) = \frac{B^t(n)}{\frac{B^t(n) - S^t(n)}{S^t(n)} \epsilon^{m,t} + 1} \tag{8}$$

where $0 < \epsilon < 1$.

According to the economic balance of a market, the buying price $B^t(n+1)$ could be deduced by

$$p_{im}^t\, B^t(n) = p_{ex}^t\, S^t(n+1) + (p_{im}^t - p_{ex}^t).B^t(n) \tag{9}$$

Thus, the buying price is

$$B^t(n+1) = S^t(n+1)\epsilon^t + B^t(n)(1 - \epsilon^t) \tag{10}$$

The iteration stops when $S^t(n) = B^t(n)$ (no price gap). The proof of the convergence criteria is shown in Appendix section.

As the selling price equals the buying price after iterations, the price of power is symbolized uniformly by S for the rest of the paper. The proposed pricing scheme generates the trading price without a price gap. Both buyers and sellers could trade at the price of the proposed scheme to increase their benefits by improving their income or their cost savings in comparison to trading with the utility grid. The contents of the pricing scheme are simple inverse-proportion equations that could be able to afford by the smart contracts. The iteration number of each equation will be clarified in the case study section to prove its feasibility in smart contract implementation.

3. PoS based blockchain design for P2P energy market

The proposed blockchain is set up based on the Ethereum platform with PoS consensus protocol. The reason behind choosing the public blockchain is that as P2P energy trading provides a distributed structure for trading, the blockchain should also meet the fully decentralized requirement of the P2P energy market. This means that there is no central agent. The whole structure of the PoS blockchain-based P2P energy trading is illustrated in Fig. 1.

A public blockchain is an effective method to record transaction information and preserve the privacy of the participants. In a PoS based blockchain, traders propose their transaction application by broadcasting to the whole network (microgrid), and then, this proposal is verified by the other prosumers. After the approval of the verification, the transactions are executed by smart contracts automatically. For the extension of the blockchain, miners are randomly chosen from prosumers based on their proportional stake (crypto-currency) invested by themselves. In other words, a more personally invested stake leads to more chances to mine the new block for the network. The chosen

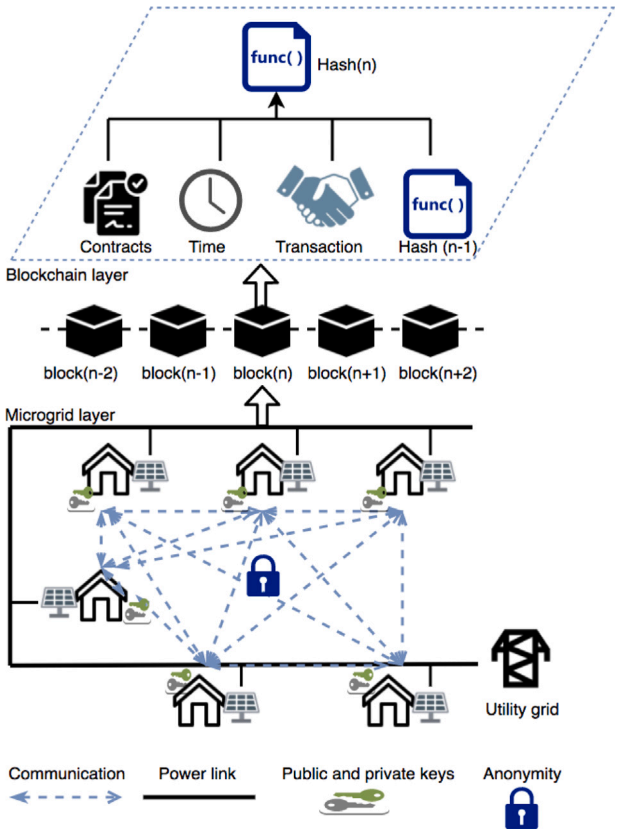

Fig. 1. The structure of the P2P energy trading supported by blockchain system.

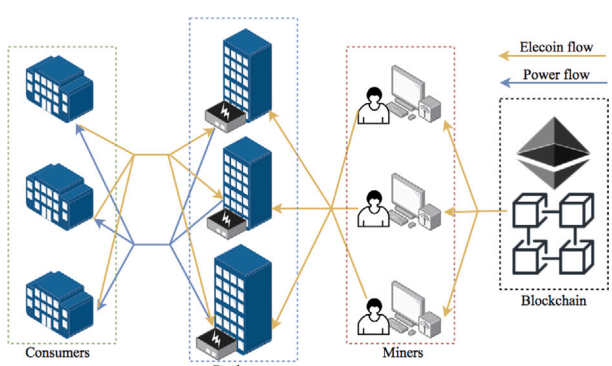

Fig. 2. The role of miners in P2P energy trading.

miners pack the transaction information using the hash function. The hash function is a cryptographic method to translate practical data into a set of code that is extremely difficult to trace back to its original data. The hash function in the public blockchain is defined as

$$Code(n) = H(Trans, Contrs, Time, Nonce, Code(n-1)) \tag{11}$$

where $Trans$ means the transaction information; $Contrs$ refers to the smart contracts; and $Nonce$ represents the block number.

From (11), the hash code of the nth block includes the hashing result of the code of $(n-1)^{th}$ block, which establishes the chain linking every block. After more than $(2/3)N$ prosumers verify the new block as valid, it is then added to the blockchain, and miners are rewarded with a certain number of *elecoin*. Otherwise, it is invalid, and the miners should be punished by losing their previously invested stake and new miners will be chosen.

For the security of the public Ethereum chain, a malicious node needs to own the control of more than $(2/3)N$ prosumers and overwrite all of the previous transaction contents as well as rehash them [40]. This type of attack requires enormous computation expense which could be considered as impossible. Besides, users' privacy is protected by the anonymity feature of the blockchain system and they could check the details of previous transactions by using their public key where transparency is also provided.

Another issue of a public blockchain is that large quantities of mining engagement or peer participation could enormously increase the mining expense which dilutes miners' incentives [41]. The conventional method to solve this issue is to increase the mining difficulty (Bitcoin). This solution is unacceptable as a high mining difficulty level still leads to huge power consumption. The proposed method is to provide the financial incentive for prosumers within the microgrid but not for the nodes outside the microgrid. In the proposed smart contract design, the elecoin cannot be exchanged for fiat currency. The elecoin is designed only for energy trading with no purpose of raising funds, therefore nodes outside the microgrid would not compete for being the miners as the elecoin has no investment potential. For the prosumers within the microgrid, the elecoin becomes valuable because it could be traded with energy to balance their load demand or surplus energy generation. Thus, only prosumers within the microgrid are motivated to engage in the mining process, which is shown in (12), so that the mining difficulty could be initialized in a low value to prevent large mining consumption.

$$(Miners_k, Consumer_i, Producer_j) \in N\,Prosumers \tag{12}$$

3.1. Mining analysis considering power losses

To eliminate the price gap caused by power loss from electricity delivery, the miners are responsible to sacrifice part of their rewards in the proposed blockchain model to compensate for the price gap, which is shown in Fig. 2. According to Fig. 2, the pricing scheme proposed in Section 2 could be realized in the P2P energy trading market because the price gap is filled as

$$S^t\left(P_{ex}^t + \sum_{j=1}^{n_p}\sum_{i=1}^{n_c} p_{l_{ij}}^t\right) = S^t * Min\left[P_{ex}^t, P_{im}^t\right] + M^t \tag{13}$$

$$M^t = \left(\sum_{j=1}^{n_p}\sum_{i=1}^{n_c} p_{l_{ij}}^t\right) \times S^t \tag{14}$$

where S^t refers to the trading price from the pricing scheme; M^t refers to miners' sacrifices in time slot t; $Min[P_{ex}^t, P_{im}^t]$ represents the total power of consumers purchased from producers. When prosumers purchase energy form the utility grid, $P_{im}^t >= P_{ex}^t$. If consumers do not purchase from the utility grid, the value of P_{im}^t equals P_{ex}^t.

As successful mining could be rewarded, the value of rewards should be limited on a reasonable scale. Unsuccessful mining leads to punishment of stake loss, and thus, the value of rewards x should be less than miners' invested stake. Meanwhile, the power loss compensation is afforded by them. The value of rewards should be larger than miners' sacrifices and mining expenses so that miners are motivated to maintain the extension of the blockchain system. Assume that the value of the invested stake is y, the constraint could be expressed as

$$\left(p_{l_{ij}}^t + p_{com_{ij}}^t\right) \times S^t < x_k < y_k \tag{15}$$

where $p_{com_{ij}}^t$ refers to the mining consumption of the transactions happened between consumer i and producer j for miner k at time slot

t. For each time slot t, if the total cost for miners during each time slot is C^t_{epn}, the value of it is calculated as

$$C^t_{epn} = \sum_{j=1}^{n_p} \sum_{i=1}^{n_c} \left(p^t_{l_{ij}} + p^t_{com^t_{ij}} \right) \times S^t \tag{16}$$

The total amount of rewards for miners is restrained as

$$C^t_{epn} < \sum_{k=1}^{n_m} x^t_k < \sum_{k=1}^{n_m} y^t_k \tag{17}$$

Since rewarding the miners is the main way to publish the elecoin and to ensure its value, the total number of mined *elecoin* should also be regulated by the market balance rule according to the support of the total amount of power production (unrestricted number of elecoin published will decrease its value as the amount of product is limited). Therefore, the inequality for a day is defined as

$$\sum_{t=t_1}^{t_n} C^t_{epn} < \sum_{t=t_1}^{t_n} \sum_{k=1}^{n_m} x^t_k < \sum_{t=t_1}^{t_n} min[\sum_{k=1}^{n_m} y^t_k, \sum_{j=1}^{n_p} G^t_j] \tag{18}$$

where G^t_j is the power generation value of producer j.

From inequality (18), the amount of elecoin published in the microgrid should meet the balance with the total energy generated, which is expressed by $\sum_{j=1}^{n_p} G^t_j$. Then, considering (17), the value of total published elecoin should be less than the minimum value of miners' total invested stake and the total energy generated. In other words, more generation capability allows more crypto-currency publication which reflects the potential of expansion for the proposed model.

The value of mining expense is expressed in (16), in which the power loss value is related to the distance and the amount of electricity delivered. The power loss is estimated as a nonlinear function of p_{ij} with the linear relationship with distance d_{ij} as follows

$$\sum_{j=1}^{n_p} \sum_{i=1}^{n_c} p_{l_{ij}} = \sum_{j=1}^{n_p} \sum_{i=1}^{n_c} \sigma_{ij} * d_{ij} * p^2_{ij} \tag{19}$$

where the value of power loss coefficient σ relies on the configuration and application scenarios of the microgrid [42].

The mining consumption value is correlated to the performance of miners' computational facilities and mining difficulty initialized for the blockchain. It is calculated as

$$\sum_{j=1}^{n_p} \sum_{i=1}^{n_c} P_{com^t_{ij}} = D \sum_{k=1}^{n_m} g_k \gamma^t_k A_k ; \gamma^t = \begin{cases} 1 & x_k > 0 \\ 0 & x_k = 0 \end{cases} \tag{20}$$

where g_k is the power consumption ratio of miner k's chips (kW/T) and A_k is its computation capability (T). The mining difficulty is given by D and n_m is the total number of selected miners at time slot t. γ refers to the mining engagement of prosumer k.

The approximate values of the mining expenses are given by Eqs. (16) and (19). It should be noted that, n_c, n_p and n_m are not fixed values for different time slots. The roles (consumer, producer, or miner) of prosumers are determined by their generation and demand profile as well as their mining engagement. Prosumers could transfer their roles in P2P energy trading by rearranging their amount of energy consumption, generation, and invested stakes.

3.2. Smart contract creation

The proposed smart contracts in this study are categorized into two types. The first type is for transaction execution and the second type is to implement the proposed PoS consensus protocol. The respective procedures of automatic transaction execution and PoS implementation for both types of smart contracts are presented in Algorithm 1 and Algorithm 2, respectively. These smart contracts are written in codes and their execution supports a fully decentralized trading market without intermediaries.

Algorithm 1 Transaction execution of smart contract

0: **for** each $smartcontractI_i \in [block_i]$ **do**
0: price calculation
1: **if** transactions are verified as valid **then**
1: receive elecoin from consumer i;
1: receive the message of power delivery from producer j;
2: **else**
Fail the transaction
3: **end if**
3: **end for**
4: **if** the value of elecoin and that of power are matched **then**
4: execute this transaction;
5: **else**
5: return money and give command to stop power delivery;
5: transaction fails;
6: **end if**;

Algorithm 2 PoS implementation of smart contract

0: **for** each $smartcontractII_i \in [block_i]$ **do**
0: receive miners' invested stakes
1: **if** Transactions are failed after mining **then**
1: miners lose stakes;
2: **else**
miners get rewards
3: **end if**
3: **end for**=0

3.3. Utility and welfare analysis

In this study, the participants of P2P transactions include consumers, producers and miners. The cost of energy trading by prosumers' battery systems is considered. $ES^{t_n}_n$ is set as the amount of energy in prosumer n's battery at the end of time slot t_n; ρ_1 and ρ_2 are the charging and discharging efficiencies of the battery. The self-discharging rate is denoted as ρ_3. The dynamic of the battery energy level is modeled as follows

$$ES^{t_n}_n = ES^{t_{n-1}}_n * (1 - \rho_3) + \left[T_c * ES_c * \rho_1 - \frac{T_d * ES_d}{\rho_2} \right] \tag{21}$$

where ES_c and ES_d are charging and discharging power with their respective operation time T_c and T_d during every time slot.

If the annual cost of prosumer n's battery system is C_{bn}, then the daily equivalent cost $C_{dn_{pr}}$ of the battery system is calculated as $\frac{C_{bn_{pr}}}{365}$. Another cost of energy trading is the generation cost which is symbolized as C_g. In general, the cost function of prosumer n can be defined as a quadratic convex form of its power generation G_n [43]

$$C_{gn} = a_n G^2_n + b_n G_n + c_n \tag{22}$$

where a_n, b_n and c_n are the cost function parameters of prosumer n and these parameters depend on the type of generation source. Since we consider PV generation, the cost function parameter a is zero and the parameters b and c can be calculated as follows [44]

$$b = \frac{C_{inv}}{G_{pv,rated}} \times \frac{ds(1+ds)^L}{(1+ds)^L - 1} \times \frac{1}{8760} \tag{23}$$

$$c = \frac{C_{o\&m}}{8760} \tag{24}$$

where C_{inv} is the cost of the PV system; $G_{pv,rated}$ is the installed capacity of the PV system; ds is the discount rate; L is the investment lifetime; and $C_{o\&m}$ is the annual operation and maintenance cost of the PV system. The daily cost of producer j is $\sum_{t=t_1}^{t=t_h} C^t_{gj} + C_{dj}$. With cost function (22), the proposed blockchain framework is also applicable for prosumers with thermal generators.

The satisfaction level of consumers related to the quantities of products purchased under various scenarios is modeled by the utility function [45]. A proper utility function which could be used in energy trading should satisfy the following conditions.

- The value of satisfaction level should be 0 with no energy trading happens.
- The maximum value could be obtained within the scale of the function.

To achieve the above requirements and for the purpose of clear illustration, a widely adopted utility function U_{p_i} in energy field is used for consumer i within the microgrid which is a piece-wise quadratic function.

$$U^t(p_i^t) = \begin{cases} 2r_i^t p_i^t - \omega_i (p_i^t)^2 & p_i^t < \frac{r_i^t}{\omega_i} \\ \frac{(r_i^t)^2}{\omega_i} & p_i^t >= \frac{r_i^t}{\omega_i} \end{cases} \tag{25}$$

where r_i^t and ω_i are the private parameters of consumer i and they distinguish the consumer from the others. The value of r_i^t may vary along with the time or behavior of consumers, and ω_i is a constant value that relies on specific energy trading scenarios.

As the pricing scheme is already proposed and demand response management is not in the scope of this study, the amount of energy demands proposed in each time slot t is assumed inflexible and necessary for consumer i. So it is the minimum value to achieve the maximum value of the utility function and can be defined as

$$p_i^t = min[\arg\max_{p_i^t = p_i^t + p_{ui}^t} \quad \|U^t(p_i^t)\|] \tag{26}$$

where $p_i^t + p_{ui}^t$ is the demands of consumer i consisting of the power purchased from producers and the utility grid.

If there is no trading between the utility grid and consumer i, the value of p_{ui}^t is 0. According to (25), the value of $p_i^t + p_{ui}^t$ is $\frac{r_i^t}{\omega_i}$. Therefore,

$$r_i^t = \omega_i \times (p_i^t + p_{ui}^t) \tag{27}$$

Substituting the result from (26) into (25), the utility function can be rewritten as

$$U(p_i^t)^t = \begin{cases} \frac{(r_i^t)^2}{\omega_i} & p_{ui}^t = 0 \\ \frac{(r_i^t)^2}{\omega_i} - \omega_i (p_{ui}^t)^2 & p_{ui}^t > 0 \end{cases} \tag{28}$$

With the consideration of power purchased, the welfare function of consumer i is defined as follows

$$W_i^t = U^t(p_i^t) - S^t p_i^t \tag{29}$$

The welfare function for all consumers within the microgrid for one day is

$$W_c = \sum_{t=t_1}^{t_h} \sum_{i=1}^{n_c} \left(U^t(p_i^t) - S^t p_i^t - C_{gi}^t \right) - \sum_{i=1}^{n_c} C_{dj} \tag{30}$$

For producers, the welfare function is calculated as their incomes minus the cost of battery systems and PV generation

$$W_p = \sum_{t=t_1}^{t_h} \left[S^t \, (p_{ex}^t + \sum_{j=1}^{n_p} \sum_{i=1}^{n_c} p_{l_{ij}}^t) - \sum_{j=1}^{n_p} C_{gj}^t \right] - \sum_{j=1}^{n_p} C_{dj} \tag{31}$$

The welfare function for miners within the microgrid is the differentials between their rewards and power loss compensation with mining consumption:

$$W_m = \sum_{t=t_1}^{t_h} \left(\sum_{k=1}^{n_m} x_k^t - S^t \sum_{j=1}^{n_p} \sum_{i=1}^{n_c} \sigma_{ij} d_{ij} p_{ij}^2 - D \sum_{k=1}^{n_m} g_k \gamma_k^t A_k \right) \tag{32}$$

Finally, the optimization problem is to obtain the value of the exponential number m in (8). The optimal value of m should achieve the maximum of the welfare functions of consumers, producers and miners (social welfare) for one day. Mathematically,

$$m = \arg\max_m \quad \|(W_c + W_p + W_m)\| \tag{33}$$

4. Case study

In this section, the proposed PoS based public blockchain is applied to a microgrid model with 27 prosumers. The blockchain system is established on the Ethereum platform where *GethClient* is installed to initialize the genesis block and mining mechanism. The content of smart contracts is written in *Solidity* programming language. WEB3.js and the *Truffle* software package are installed to call the smart contracts. The mining difficulty is initialized from 130,000 to 300,000 and the computation capability of each miner is modeled by a common AMD Radeon 7650 A DDR3 MXM over $1.8 * 10^{-5}$ TH/s. The value of crypto-currency depends on the market and it is realized by Initial Coin Offering (ICO) which is beyond our research scope. In this study, the *elecoin* is set up relying on the ERC-777 Token standard and its value is based on *Ether* whose value is stabler than the other published crypto-currency. In this study, the value of *elecoin* is defined by the power generation capability of the microgrid with the total number of elecoin initialized for the blockchain system. As the elecoin has no investment potential, it can be seen as a product (money equivalence) to be traded with energy. To better quantify the value of the elecoin, it is set as a constant value as an example for the case study.

$$1 \ elecoin = 0.42 \ cents \tag{34}$$

As the buying price is 22.93 cents/kWh (Singapore dollars) and the selling price is 9.3 cents/kWh offered by the utility grid and FIT respectively, based on (34), the buying price and selling price are defined as 56.7 *elecoin* and 22 *elecoin* respectively. The value of rewards x_k^t is selected randomly within the constraint, inequality (18).

An OPAL-RT real time digital platform with MATLAB software is used to set up the proposed microgrid model. Lithium-ion batteries are considered and its charging/discharging efficiency is taken as 90% and the annual cost of maintenance is considered $3.7 * 10^4$ *elecoin*. Since PV panels are considered as the local power generation source, it is assumed that the active period of the P2P market is from 7:00 to 18:00. The parameter ω_i of utility function is taken as 0.25 so that the value of r_i^t could be calculated based on the amount of power purchased and (27). The other parameters of PV systems and power loss are listed in Table 2, Appendix A.2. Since our main objective is to develop blockchain system for energy trading, the values of the parameters shown in Appendix A.2 are assigned for the simulation purpose only and the detail calculation of those parameters is beyond the scope of this paper.

After the above initialization, the proposed blockchain system is started by *Geth* which is shown in Fig. 3. Then, in Fig. 4, according to the demands of consumers and extra generated power of producers, the trading prices of different time slots are calculated by smart contracts based on the proposed pricing scheme (PS).

Taking time slot 10, for example, and with different values of the exponential number m, the proposed price without gap in time slot 10 is shown in Fig. 5. It could be observed that the trading price could be confirmed when the iteration number of calculations is over 5, which is completely affordable for smart contracts. Fig. 6 demonstrates the proposed trading prices of the whole active hours compared with the prices offered by the utility grid (UG) and FIT.

To find the optimal value of integer m, the welfare values $(W_c^t + W_p^t + W_m^t)$ for different m are calculated depending on the method offered in

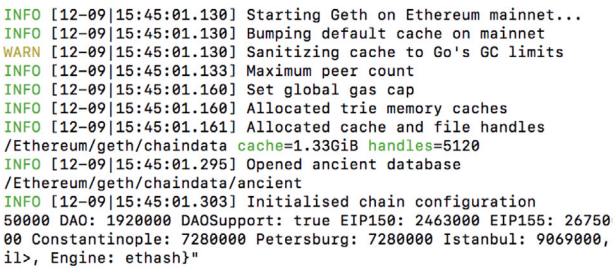

Fig. 3. The activation of PoS based blockchain system.

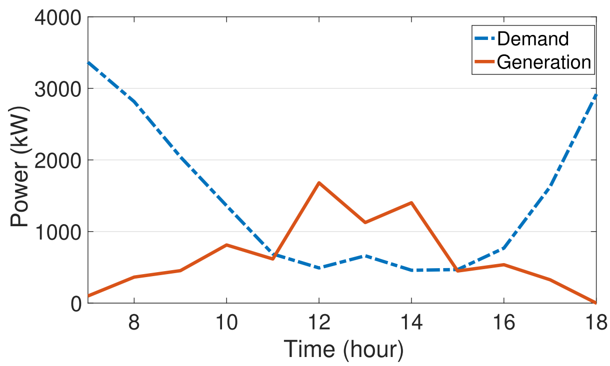

Fig. 4. The power demands and generation of prosumers.

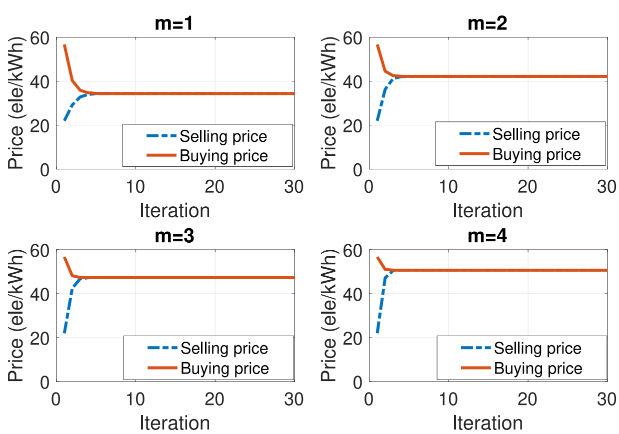

Fig. 5. The price calculation of time slot 10 with different m.

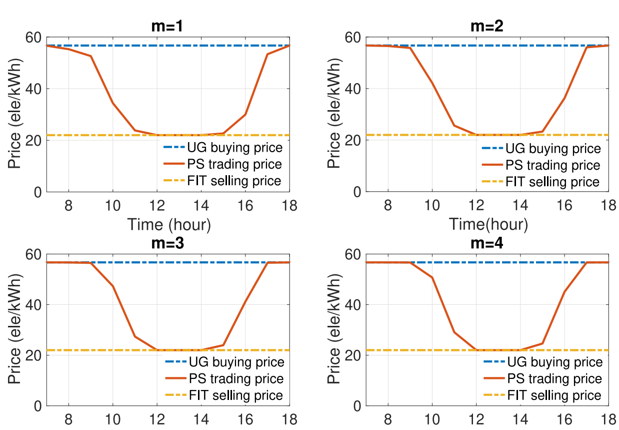

Fig. 6. Comparison of the proposed trading price with FIT price during a day.

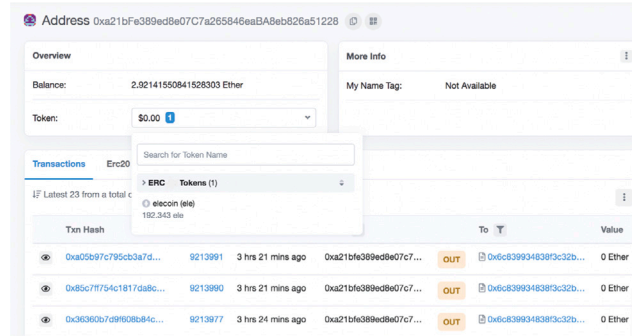

Fig. 7. The publication of elecoin for the blockchain system.

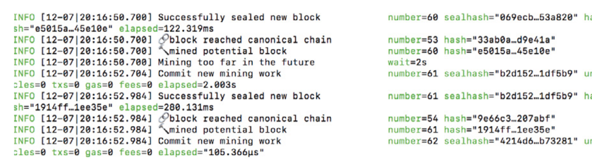

Fig. 8. The mining process of the PoS based blockchain.

Table 1
The value of welfare for different m ($ele * 10^3$).

Time	W(PAG)	W(m = 1)	W(m = 2)	...	W(m = ∞)
7	−184.99	−18.98	−19.22	...	−19.23
8	−139.85	351.75	348.73	...	348.27
9	−92.46	338.85	333.86	...	332.35
10	−39.76	385.33	381.05	...	373.1
11	−16.32	121.14	121.02	...	118.84
12	15.47	63.85	63.85	...	63.85
13	−4.27	114.96	114.96	...	114.96
14	10.26	55.26	55.26	...	55.26
15	−10.33	57.89	57.87	...	57.21
16	−20.41	135.58	134.13	...	129.4
17	−71.8	179.54	176.09	...	175.17
18	−165.43	−168.32	−168.32	...	−168.32
Sum	−719.9	1616.9	1599.3	...	1580.9

Section 3. The results compared with conventional prosumer-and-grid (PAG) trading are shown in Table 1.

From Table 1, it could be found that the optimal value of m that maximizes the total welfare is observed at $m = 1$. In addition, the proposed method increases the welfare of prosumers when it is compared with the PAG trading strategy. The welfare value remains unchanged in time slots 12, 13 and 14. Because in these time slots, the power generation of solar panels reaches its peak and the amount of power to be sold in the market exceeds that of demands, so the price remains unchanged at the least value of 22 ele/kWh regardless of the variation of m.

Taking $m = 1$ for the blockchain implementation, the ERC-777 crypto-currency *elecoin* (ele) is created and initialized in the smart contracts and published to the blockchain. It is shown in Fig. 7.

Once the transaction application is proposed within the microgrid, the mentioned verification and validation process begins under the condition of PoS consensus protocols. Depending on the quantities of mining competitors' invested stake, the miners for the corresponding time slots are selected and start mining the trading transactions. Fig. 8 illustrates the mining process and Fig. 9 shows the content of a mined transaction in a block.

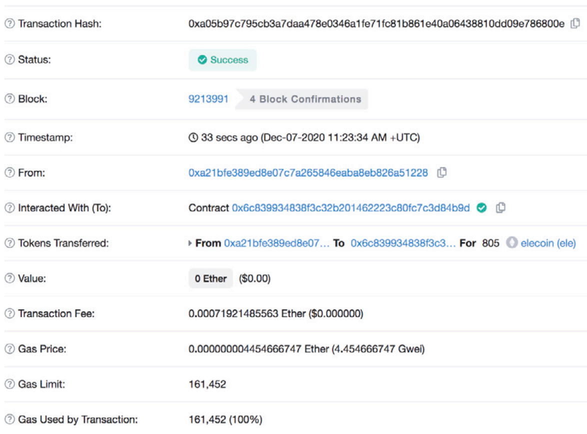

Fig. 9. The hashed transaction in a block.

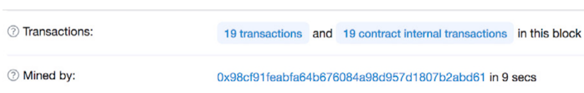

Fig. 10. The hash transaction in a block.

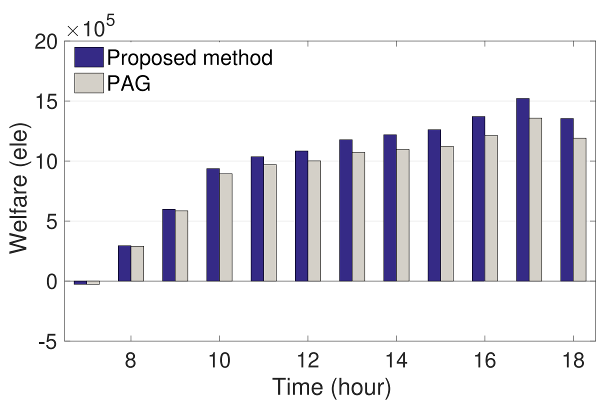

Fig. 11. The respective welfare of consumers in proposed method and PAG scenarios.

Since the miner selection is restrained within the microgrid, the mining speed observed in Fig. 8 is extremely fast as the mining difficulty could be set at a low level. Fig. 9 demonstrates a mined transaction where its hash code and the addresses of transaction traders (consumers and producers) and its smart contract are all presented. The consumer referred in this figure spent 805 *ele* for energy purchasing which realizes the transparency feature of the blockchain system. Furthermore, traders' privacy is protected as the specific identity behind the address is unknown. The information of a block with its transactions is shown in Fig. 10 where the block shown contains 19 transactions with their respective smart contract creation (known as contract internal transactions in Fig. 10).

The respective welfare of producers and consumers by using the proposed method compared with traditional PAG trading is shown in Figs. 11 and 12. Finally, the welfare of all prosumer types by using the proposed PoS blockchain-based pricing scheme is shown in Fig. 13.

Both producers and consumers improve their welfare from the proposed method according to Figs. 11 and 12. During the early hours (7 am to 9 am), the welfare of consumers is equivalent to or even

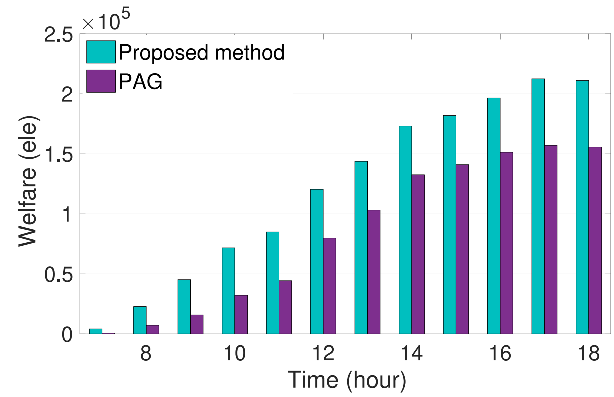

Fig. 12. The respective welfare of producers in proposed method and PAG scenarios.

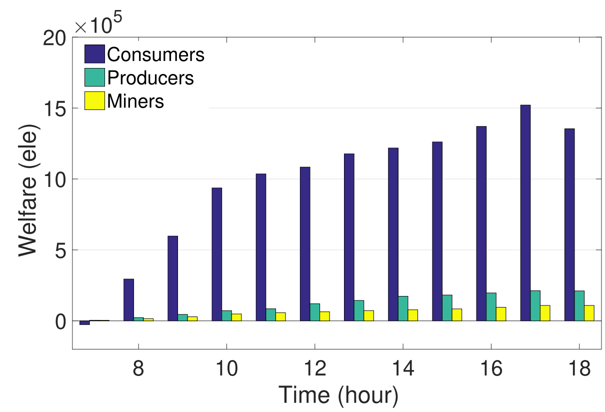

Fig. 13. The welfare of consumers, producers and miners.

slightly lower than the welfare they obtain from the PAG trading. It is because consumers' load demand is satisfied mostly by PAG trading as prosumers' generation capability is relatively lower during those time slots. This From Fig. 13, compared with another two types of participants, the consumers are more sensitive to the proposed method as their welfare value fluctuates most in different time slots and they also benefit most from the pricing scheme. The welfare value of miners is always positive, thereby being a strong incentive for them to keep extending the PoS based blockchain system.

4.1. Discussion

In the proposed PoS public blockchain-based pricing scheme method, the crypto-currency is published by the mining system used in energy transactions. The incentive for prosumers to becoming miners is ensured by the elecoin. To maintain the value of *elecoin*, the number of *elecoin* is ensured to meet the balance of energy generation. Although this requirement reveals the expansion potential of the blockchain system, the public blockchain still needs to increase its mining difficulty once the number of miners is over-congested and uncontrollable like Bitcoin. This is because the total number of crypto-currency is finite and the mining speed should be controllable. Thus, the number of prosumers within the proposed model is supposed to achieve its maximum based on different scenarios of microgrids.

The proposed *elecoin* is created based on the ERC-777 standard. The reason for not adopting the conventional ERC-20 standard is that consumers' payment cannot be returned if the transaction fails under the condition of ERC-20 [46]. This is obviously unacceptable for consumers. When all of the *elecoins* are mined out, miners could be rewarded for their successful mining by the $gas-limit$ and $gas-price$ mechanism [40] as the proposed method is established based on the Ethereum platform. According to this mechanism, miners are paid by the transaction applicants (consumers or producers) with transaction fees, whose value is calculated by multiplying the values of gas_{limit} and gas_{price}. In summary, the crypto-currency-based monetary system is still alive even if there is no more production of *elecoin*.

From the results of the case study, the social welfare of the microgrid is improved enormously compared with that of the traditional prosumer-to-grid trading. All transaction participants benefit from the proposed pricing scheme as their respective welfare is increased.

5. Conclusion

This study presents a PoS public blockchain-based pricing scheme for the P2P energy trading market, where miners are rewarded with successful mining or punished by losing their stake adversely. The payment system is supported by the proposed blockchain system with the utilization of a crypto-currency type named *elecoin*. Transactions are verified by all prosumers with the microgrid. Miners are selected based on their invested stake. part of their invested stake is sacrificed for power loss compensation. The price gap from the traditional trading between prosumers and the utility grid is reduced by the mining system with consideration of power losses. The calculation method for welfare functions is specifically presented.

In the case study section, the proposed method is tested by using a microgrid with 27 prosumers. The process of blockchain implementation and smart contract creation is demonstrated. The transparency of transactions and the security of customers' privacy are ensured by the blockchain system. The role of prosumers in different time slots is flexible according to their power generation and demand profiles. The results show that the proposed PoS public blockchain-based pricing scheme is an effective and feasible way in matching the decentralization structure of P2P energy trading and increasing the social welfare of microgrids.

Although nowadays various types of blockchain have been simulated or implemented for P2P energy trading, the general bottleneck is that the blockchain application used in the power system is still staying at the transaction level. Therefore, the future research direction is to explore the application of blockchain technology into the technical operations of power systems. A transaction could be treated as a simple control system where money and products are taken as the input and feedback respectively. This idea inspires us to focus our future work on implementing blockchain technology in the distributed control of power systems to expand its application scenarios.

CRediT authorship contribution statement

Jiawei Yang: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Writing - original draft, Visualization, Writing - review & editing. **Amrit Paudel:** Methodology, Validation, Data curation, Writing - review & editing. **Hoay Beng Gooi:** Validation, Writing - review & editing, Supervision. **Hung Dinh Nguyen:** Writing - review & editing, Supervision.

Appendix

Nomenclature

ϵ	Supply–demand ratio
γ	Mining engagement parameter of miner k
λ, b	Pricing parameters
ρ_1, ρ_2, ρ_3	Charging/discharging/self-discharging rate
σ	Power loss coefficient
a_j, b_j, c_j	Cost function parameters of producer j
A_k	Computation capability of miner k
B	Busing price of energy
C_g	Generation cost
C_b	Annual cost of a battery system
C_d	Daily cost of a battery system
C_{inv}	Cost of PV system
$C_{o\&m}$	Annual operation and maintenance cost of the PV system
D	Mining difficulty
d_{ij}	Power delivery distance between producer j and consumer i
ds	Discount rate
ele	Unit of crypto-currency *elecoin*
ES	Energy level of battery
FIT	Feed-in-tariff
G_j	Power generation of producer j
g_k	Power consumption ratio of miner k's chip
$G_{pv,rated}$	Installed capacity of the PV system
H	Hash function
h	Number of time slots
ICO	Initial Coin Offering
L	Investment lifetime
M	Power loss compensation
m	Exponential parameter for pricing scheme
N	Number of prosumers within a microgrid
n	Number of iterations
n_c	Number of consumers
n_m	Number of miners
n_p	Number of consumers
P	Power trading matrix
$P2P$	Peer to peer
p_{ex}	Total power exported by producers
p_{ij}^t	Power trading from producer i to consumer j at time slot t
p_{im}	Total power imported by consumers
p_{l-ij}^t	Power loss caused by power trading from producer i to consumer j at time slot t
P_L	Power loss matrix
p_{ui}	Power purchased from utility grid by consumer i
PAG	Prosumers and Grid
PoS	Proof-of-Stake
PS	Pricing Scheme
r_i, w_i	Utility function parameters of consumer i
S	Selling price of energy
T	Operation time
t	Time slot, goes from t_1
$U(p_i)$	Utility function of consumer i
UG	Utility Grid
W_c, W_p, W_m	Welfare functions for consumers/producers/miners
x_k^t	Rewards of miner k at time slot t
y_k	Invested stake of Miner k at time slot t

A.1. Convergence proof

$B(0)$ and $S(0)$ are set as the initial trading price for the pricing scheme where $B(0) > A(0)$.

Table 2
Parameters of generators and power loss.

Prosumer	b (ele/kWh)	c (ele/h)	$\sigma * d$ (ele)
1	10.55	43	0.00008
2	4.33	51	0.00054
3	9.88	28	0.00061
4	3.28	32	0.00043
5	10.13	19	0.00068
6	2.31	54	0.00069
7	7.84	49	0.0005
8	5.14	31	0.00016
9	9.49	11	0.00022
10	5.15	16	0.00019
11	8.49	35	0.00009
12	7.12	14	0.00014
13	5.19	51	0.00049
14	8.58	30	0.00071
15	4.74	70	0.00031
16	9.22	61	0.00035
17	3.78	47	0.00074
18	9.01	14	0.00072
19	11.23	39	0.00053
20	5.31	21	0.00075
21	9.91	47	0.00059
22	7.67	19	0.0003
23	13.36	30	0.00052
24	8.92	7	0.00023
25	10.69	54	0.00027
26	8.89	14	0.00053
27	10.81	28	0.00043

From (8),

$$S^t(n+1) = \frac{B^t(n)}{\frac{B^t(n)-S^t(n)}{S^t(n)}\epsilon^{m,t} + 1} \tag{35}$$

Then it could be calculated as

$$S^t(n+1) - S^t(n) = \frac{B^t(n)}{\frac{B^t(n)-S^t(n)}{S^t(n)}\epsilon^{m,t} + 1} - S^t_{(n)} \tag{36}$$

$$S^t(n+1) - S^t(n) = \frac{(B^t(n) - S^t(n)) * (1 - \epsilon^{m,t})}{\frac{B^t(n)-S^t(n)}{S^t(n)}\epsilon^{m,t} + 1} \tag{37}$$

Because before the convergence stops, $B^t(n) >= S^t(n)$ and $1 > \epsilon^{m,t}$, therefore $S^t(n+1) - S^t(n) > 0$. So it is guaranteed that the value of selling price is increasing. Obviously, with the increase of n, the value of $S^t(n)$ will remain as a constant value when $S^t(n+1) = S^t(n)$.

From (11),

$$B^t(n+1) = S^t(n+1)\epsilon^t + B^t(n)(1-\epsilon^t) \tag{38}$$

The value of the subtraction could be calculated as

$$B^t(n+1) - B^t(n) = S^t(n+1)\epsilon^t + B^t(n)(1-\epsilon^t) - B^t(n) \tag{39}$$

$$B^t(n+1) - B^t(n) = \epsilon^t * (S^t(n+1) - B^t(n)) \tag{40}$$

Since $S^t(n+1) - B^t(n) < 0$, it is guaranteed that the value of buying price is decreasing until its value equals to the selling price which is $S^t(n+1) = B^t(n)$. Finally, the buying price and selling price will achieve an equal constant value, which is proven by Fig. 5.

A.2. Parameters of generation unit and power loss

See Table 2.

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