IEEE TRANSACTIONS ON INDUSTRIAL INFORMATICS, VOL. 17, NO. 5, MAY 2021

Compensation for Power Loss by a Proof-of-Stake Consortium Blockchain Microgrid

Jiawei Yang, *Graduate Student Member, IEEE*, Amrit Paudel, *Graduate Student Member, IEEE*,
and Hoay Beng Gooi, *Life Senior Member, IEEE*

***Abstract*—Distributed generation in the microgrid becomes increasingly significant, as it eliminates the power losses from long-distance electricity transmission lines. Distributed energy resources owners who can both produce and consume energy are defined as prosumers. To encourage the peer-to-peer (P2P) energy trading between prosumers, blockchain as a thriving technology is utilized in the P2P network due to its transparency, security, and rapidity in executing transactions. Due to its decentralized quality, any intermediaries are eliminated so that transactions happen directly among traders. This article introduces a consortium blockchain trading model to support P2P energy trading, using a proof-of-stake protocol. The pre-selected miners are responsible for compensating the power losses in distribution lines by energy transactions. The specific process of the blockchain establishment, as well as the smart contract creation, are demonstrated. In addition, a type of crypto-currency named "elecoin" is created in the P2P market, which is published by the mining mechanism of the blockchain. Finally, a case study is introduced to realise the functions of the proposed blockchain model. Simulation results show the feasibility and effectiveness of the proposed approach.**

***Index Terms*—Consortium blockchain, peer-to-peer (P2P) energy trading, power loss, pricing scheme, proof-of-stake (PoS).**

I. INTRODUCTION

With the rapid development of photovoltaic (PV) power generation and the open of local electricity markets in many countries, peer-to-peer (P2P) energy trading [1] becomes increasingly popular as it reduces participants' cost as well as the power loss in the distribution system. To ensure the security level and transparency of P2P transactions, blockchain technology is widely applied in the microgrid to support P2P energy trading in the distribution system. Therefore, "transactive energy" [2] becomes a new topic flourishing in the energy trading field. Relevant cryptocurrency such as Bitcoin are invented as the payment method without the need of any third parties.

A. Related Work

The mechanism of Bitcoin working in a network is introduced in [3]. Trading by exchanging cryptocurrency from digital wallets saves time of money transfer [4]. Such cryptocurrency like Bitcoin is published mainly by mining. According to the proof-of-work protocol [5], miners who mine a block successfully could be rewarded with some Bitcoins. However, the main drawbacks of this protocol are that, the mining process is extremely energy-consuming. Large amount of mining consumption cost could depress the incentive to mine, when the value of crptocurrency cannot overwhelm the cost. In addition, once the most computation power of a miner exceeds 50% of the whole network, it can taker over the mining work as a monopoly role. This consequence could be easily achieved especially when the number of miners is limited. To solve this problem, another consensus protocol named proof-of-stake (PoS) is created [6]. The probability of winning a mining competition is determined by miners' respective stake. Nowadays, blockchain technology is divided into three types: first, private chain: the chain is ruled by a centralized entity; second, consortium chain: some preselected miners maintain the distributed ledger; and third, public chain: anyone in the world with different levels of computation power could engage in the mining pool and mine blocks. Compared with the other two blockchain techniques, consortium blockchain is preferred because of its modest cost, better scalability, and shorter delay [7].

Several works related to the consortium blockchain have been done. Kang *et al.* [8] propose a PoS based consortium blockchain concept and demonstrate a distributed system model to introduce the components of the blockchain: users, miners, and verifiers. Both miners and clients with mobile devices could be verifiers. The preselected miners could also be chosen from the users. In [9], the authors use consortium blockchain to enable localized P2P energy trading among plug-in hybrid electric vehicles. But load aggregators (LAGs) are defined as the only preselected miners, creating a nonflexible mining environment, as the identity of LAGs is constant and cannot be switched to another groups. In addition, the energy consumption of mining, which cannot be ignored is not described in this article. Li *et al.* [10] use the same blockchain structure to secure energy trading with the help of internet of things. They define a credit bank as a trusted

Manuscript received March 23, 2020; accepted June 30, 2020. Date of publication July 7, 2020; date of current version February 22, 2021. This work was supported by A*STAR under its 2nd Singapore-Germany Academic-Industry 2+2 Collaboration under Award A1990b0060. Paper no. TII-20-1517. *(Corresponding author: Jiawei Yang.)*

The authors are with the School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore 639798, Singapore (e-mail: jiawei003@e.ntu.edu.sg; amrit003@e.ntu.edu.sg; ehbgooi@ntu.edu.sg).

Color versions of one or more of the figures in this article are available online at https://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TII.2020.3007657

bank node with enough energy coins. This bank could provide energy coins loans for transaction participants according to their credit values, which offers a way to publish the cryptocurrency. However, this credit bank as a virtual third-party entity shows no advantage compared to the services provided by the practical bank. Customers could still use traditional online payment platform rather than paying by energy coins. It is significant to realize the benefit and potential of cryptocurrency trading.

In many microgrids studies, power loss is usually neglected because the energy is transmitted in the distribution system [11] without long-distance transmission. But without considering power losses, the power flows of P2P energy trading cannot match the physical situation. For the power losses allocation in the distribution system, Usman *et al.* [12] proposes a multiphase branch current decomposition method to fairly allocate the losses to the end-users. But a different method in [13] based on the injected active and reactive power expresses that, the losses should be allocated to the loads and generators depending on their loss contribution. In the P2P energy transaction market, the transparency of a loss allocation framework is required to guarantee economic fairness and efficiency. Nikolaidis *et al.* [14] harmonize the distribution networks with the P2P trades by proposing a graph-based loss allocation framework. Another study in [15] presents a different method, which allocates the grid cost in the P2P trading. The attribution of the power loss costs is related to the impact caused by the power flows of each transaction in this study. In conclusion, except for the amount of energy needed from buyers, some members of the microgrid have to send more energy to compensate for the power losses. So, to provide a feasible P2P energy trading model, it is necessary to take the power loss into consideration. A technical approach in [16] proposes a method to calculate the power loss and store this information in the blockchain. It proves that blockchain can be used for technical operations in microgrids, such as the issue of power losses tracking and attribution.

B. Motivation and Contribution

Unfortunately, most papers about energy trading do not demonstrate or focus on the process of blockchain implementation [10], [16]–[19]. These studies provide specific demonstration about their own ideas or proposed optimization methods, but with little introduction of blockchain technology. They assume that their ideas could be implemented in the blockchain framework successfully without experiments. Moreover, smart contracts cannot execute complicated computation, let alone those pricing scheme considering complex optimization and iteration algorithms [20]. These factors make their ideas unfeasible.

In this article, the establishment of blockchain and its process of implementation are demonstrated. The idea of this article focuses on motivating prosumers with extra energy to trade to meet consumers' load demand while contributing to the power losses during energy delivery. The contributor (prosumer) and its mining opportunity are both determined by the PoS protocol. The rewarded cryptocurrency is named "elecoin" in this article. The objective is to create a P2P energy trading model where elecoin becomes the only currency of energy trading and incentivizes prosumers to fulfill the power losses.

In this context, the main contribution of this article is threefold: first, a PoS based consortium blockchain: under the consortium condition, we propose a PoS blockchain not only to improve the security level of transactions and reduce the energy of mining, but also to publish elecoins to reward the prosumers who compensate the power losses. In this model, the energy of mining consumption is taken into consideration. Second, an elecoin-payment-based P2P energy trading model: we introduce a power distribution model to estimate the power losses and suggest an optimal solution to increase the incomes of miners. Third, a feasible implementation of blockchain technology: the process of setup and implementation of blockchain is specifically demonstrated. Therefore, implementing blockchain in the energy trading model becomes practical.

Numerical results show that our PoS consortium blockchain is an effective and efficient way to motivate prosumers to fill the power losses gap and maximize traders' income or cost savings.

II. PRICING SCHEME FOR P2P ENERGY TRADING

Before applying a consortium blockchain into a microgrid, the P2P energy trading market needs a pricing scheme to realize its superiority, i.e., that customers could trade their energy at a more acceptable price than trading with the utility grid. In this article, prosumers are assumed to be equipped with PV panels. Modern technologies are currently unable to support every prosumer with an energy storage system (ESS), due to the high cost of capital investment as well as the installation and maintenance of batteries. Therefore, not all the prosumers could be equipped with ESS. To simplify the trading model in this section, all the prosumers are assumed to be not equipped with ESS. Their generated energy should be consumed or traded at once.

The load demand and generated energy of prosumers in a microgrid during every time slot are defined as

$$L_i = [L_i^1, L_i^2, L_i^3, \ldots, L_i^T] \quad i \in [1, 2, 3, \ldots, n] \tag{1}$$

$$G_i = [G_i^1, G_i^2, G_i^3, \ldots, G_i^T] \quad i \in [1, 2, 3, \ldots, n] \tag{2}$$

where n is the total number of peers in each microgrid, and T is the number of time slots.

For prosumer i, the amount of excess energy it needs to export or that of unmet energy it should import can be calculated as

$$P_{im,i} = L_i - \min(L_i, G_i) \tag{3}$$

$$P_{ex,i} = G_i - \min(L_i, G_i). \tag{4}$$

The total energy sale (TES) and the total energy purchased (TEP) at time slot t are defined as

$$\text{TES}^t = \sum_{i=1}^{n} P_{ex,i}^t \tag{5}$$

$$\text{TEP}^t = \sum_{i=1}^{n} P_{im,i}^t. \tag{6}$$

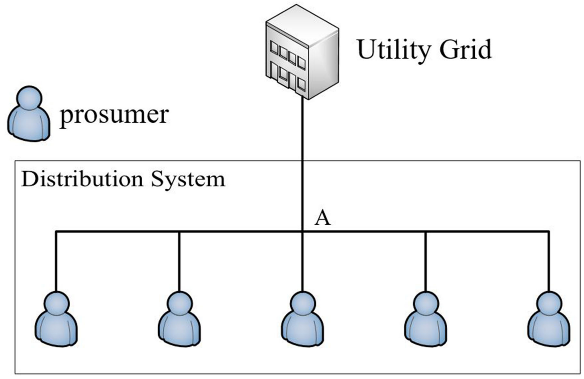


Fig. 1. Electrical wires of a microgrid.

The pricing scheme of this P2P model is established on the basis of cryptocurrency payment. The "elecoin" (ELC) is thereby utilized to measure the value of energy. According to the rationale explained in [20] and with constraints of the electricity price proposed by the utility grid, we simplified the method in [20] and the trading price in every transaction can be described as

$$\gamma^t = \frac{\text{TES}^t}{\text{TEP}^t} \tag{7}$$

$$\text{ELC}^t_{\text{sell}} = \begin{cases} \frac{\text{ELC}_{\text{usell}}.\text{ELC}_{\text{ubuy}}}{(\text{ELC}_{\text{ubuy}}-\text{ELC}_{\text{usell}}).\gamma^t+\text{ELC}_{\text{usell}}} & 0 \le \gamma^t \le 1 \\ \text{ELC}_{\text{usell}} & \gamma^t > 1 \end{cases} \tag{8}$$

$$\text{ELC}^t_{\text{buy}} = \begin{cases} \text{ELC}^t_{\text{sell}}.\gamma^t + \text{ELC}_{\text{ubuy}}.(1-\gamma^t) & 0 \le \gamma^t \le 1 \\ \text{ELC}_{\text{usell}} & \gamma^t > 1 \end{cases} \tag{9}$$

where γ are the ratio value of the TES and TEP, $\text{ELC}_{\text{usell}}$ and ELC_{ubuy} are selling and buying price for the transaction between the prosumer and the utility grid. The value of energy is transferred into "elecoin," so ELC is used to represent the price of energy.

From this proposed pricing scheme, it can be noted that although the amount of generated energy from PV panels is uncontrollable, the selling price of the prosumers is influenced by their controllable load demand. With the support from the smart contract of the consortium blockchain explained in Section IV, prosumers can trade their energy directly at the price of the proposed pricing scheme, without the help from any practical or virtual third-party entities (such as energy sharing provider). Although, smart contracts are not able to operate complicated calculations, the equations above are simple enough to be executed.

III. POWER LOSS ESTIMATION

In a feasible P2P energy trading strategy, the transactions should match the losses of the distribution system in addition to the transactive energy. To achieve this objective, power losses during energy delivery should be taken in to consideration. The calculation result for the value of power losses is stored in the blockchain. Fig. 1 illustrates the basic structure of a microgrid.

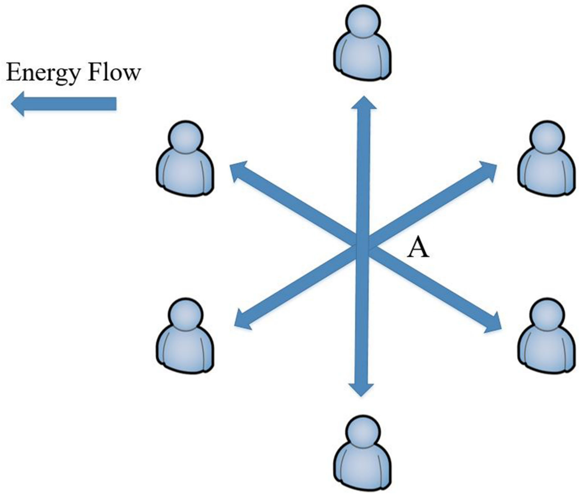


Fig. 2. Simple structure of the distribution system.

According to the structure of the energy delivery within a microgrid, different transactions in the same time slot may cause a superposition of the power flows between prosumers and consumers. Although, these transactions cause nonlinear coupling of power flows on the same branch from different prosumers, we can still estimate the power losses by the following calculation method. First, in this P2P energy trading network, the distribution system can be simplified to a simpler structure, which is shown in Fig. 2.

Then, it has been proved that, the value of power losses can be expressed as the function of the active and reactive power of the node A as well as its sending bus voltage V_A

$$P_{\text{loss}} = \frac{R_A}{V_A^2}(P_A^2 + Q_A^2). \tag{10}$$

The coefficients β_{Pi} is introduced for the attribution of the power losses from Prousmer i (Pi) on node A. If there are n prosumers connect to the branch A, the power loss attribution equations can be defined as

$$P_A = \beta_{P1}.P_A + \beta_{P2}.P_A + \cdots + \beta_{Pn}.P_A \tag{11}$$

where $1 = \beta_{P1} + \beta_{P2} + \cdots + \beta_{Pn}$.

The ratio of P_A to Q_A is defined as K

$$\frac{P_A}{Q_A} = K. \tag{12}$$

Using (12), (11) can be written as

$$K.Q_A = K.\beta_{P1}.Q_A + K.\beta_{P2}.Q_A + \cdots + K.\beta_{Pn}.Q_A. \tag{13}$$

Therefore, the attribution of the power losses for the reactive power can be defined as

$$Q_A = \beta_{P1}.Q_A + \beta_{P2}.Q_A + \cdots + \beta_{Pn}.Q_A. \tag{14}$$

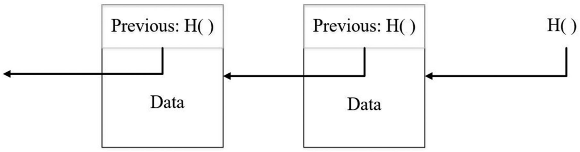


Fig. 3. Structure of a blockchain.

Using (11) and (14), (10) can be redefined as

$$P_{\text{loss}} = \frac{R_A}{v_A^2}\left[(P_A^2 + Q_A^2)\sum_{i=1}^{n}\beta_{Pi}^2 + 2(P_A^2 + Q_A^2)\sum_{i,j=1}^{n}\beta_{Pi}\beta_{Pj}\right] \tag{15}$$

$$P_{\text{loss}} = P_{\text{loss}}\sum_{i=1}^{n}\beta_{Pi}^2 + 2P_{\text{loss}}\sum_{i,j=1}^{n}\beta_{Pi}\beta_{Pj}. \tag{16}$$

From the abovementioned equations, it can be concluded that the total power losses in a time slot can be calculated as the sum of every power loss caused by respective transactions. In this section, these equations outline the method to estimate the value of power losses of a microgrid, before implementing the whole blockchain model.

IV. BLOCKCHAIN FOR P2P TRANSACTIONS

The blockchain framework is an effective method to defend the security of transactions. Nodes in the P2P network validate the proposal of transactions sent by the traders. A smart contract executes the transaction automatically once all the trading conditions are fulfilled. Miners mine a block to store the information by encrypting the transactions to a set of hash code and add this block to the blockchain. A hash code of a block is made from hashing both the content of the block itself and the hash code of its previous block. Therefore, the connection between blocks are set up to form a blockchain. Every block's hash code is connected to each other, so that a slight change in anyone of it will cause a Domino effect that all the hash codes will reflect to this change and become invalid [21]. Fig. 3 shows the structure of a blockchain made by the hash function.

To overwrite a blockchain, a malicious node needs to control most of the nodes in the network and overwrite all the content of the previous block, whereas surpass the mining speed of all the honest nodes. Longer the chain is, more difficult to overwrite. This is one of the advantages behind the blockchain technology.

In the blockchain technology, all the transactions are stored in the block and secured by encryption. Hash function $[H(x)]$ is utilized to secure the information of transactions. These types of information are translated into a set of hash code which is extremely difficult to trace back to the previous information $[H(x)$ is a one-way function], including the information of users, transactions, time, smart contracts, and the hash code of the last block.

$$\text{Hash code} = H(t, \text{user}, \text{trans}, \text{contract}, H(t-1)). \tag{17}$$

A. Consortium Blockchain for the Power Loss Compensation

In this consortium blockchain, only some of the nodes are selected to be the miners. To motivate energy sellers to send more energy to make up for the power losses, they are qualified to serve as miners so that they could be rewarded. This means that in every time slot, the miners are chosen from the sellers. According to the PoS protocol, miners are obliged to deposit their stake to compete for the right to mine. The stake is the elecoins whose value equals to prosumers' excess energy in their respective digital wallet, which is calculated by (4). The one who owns most cryptocurrency has the biggest chance to mine. If the miners' generation surplus is insufficient for the loss compensation, the prosumers with the second largest stake should then be selected. They are added to the mining pool until the total generation surplus is enough to compensate the power losses. The rewards will be proportional to their respective contribution. When the total amount of the generation surplus from the microgrid is still not enough, utility grid will take the place of miners. The one who owns most cryptocurrency has the biggest chance to mine. The trading price of electricity in this article is assumed to be $\text{ELC}_{\text{sell}}^t$ and $\text{ELC}_{\text{buy}}^t$ per kilowatt which is described in the pricing scheme (Section II).

When a prosumer wins the opportunity to mine a block, part of its stake will be paid to compensate for the total power losses in the microgrid in the time slot. Considering the energy consumption of mining in each time slot (P_{mine}^t), the value of the energy a miner consumes should be less than the value of the rewarded y ELCs

$$\sum_{i=1}^{n} P_{\text{loss}}^t + P_{\text{mine}}^t < \frac{y^t}{\text{ELC}_{\text{buy}}^t}. \tag{18}$$

This equation informs that the value of the rewarded ELCs could purchase more energy from the utility grid than it sacrifices for the compensation.

However, in a PoS blockchain, if the miner behaves maliciously during the mining period, the block will not be validated and he will also be punished by losing all of its stake. To prevent miners from such illegal behaviours, all nodes in the network ensure that the value of rewarded coins is less than the miner's stake. Therefore, malicious operations could cost more than they earned from the rewards. With the abovementioned constraints, the value of the rewarded elecoins should be limited as follows:

$$\sum_{i=1}^{n} P_{\text{loss}}^t + P_{\text{mine}}^t < \frac{y^t}{\text{ELC}_{\text{buy}}^t} < G_i^t - L_i^t. \tag{19}$$

Another advantage of these constraints is about the financial balance of the market. If the value of the rewarded elecoins is too high, the market could not provide enough products (i.e., electrical energy) to support the value of the cryptocurrency. Finally, the elecoins become valueless.

Miners could also engage in trading its energy if there is surplus energy after mining. So the income of energy trading in a time slot can be calculated as

$$\text{income} = \text{ELC}^t_{\text{sell}} \cdot \left(G_i^t - L_i^t - \sum_{i=1}^{n} P^t_{\text{loss}} - P^t_{\text{mine}} \right). \tag{20}$$

At last, for the seller who mines block, the profit of it in the time slot is calculated as

$$\text{profit} = y^t - \text{ELC}^t_{\text{buy}} \cdot \left(\sum_{i=1}^{n} P^t_{\text{loss}} + P^t_{\text{mine}} \right) + \text{income}. \tag{21}$$

For those who do not win the right of mining, their profit value is same as their incomes.

$$\text{profit} = \text{income} = \text{ELC}^t_{\text{sell}} \cdot (G_i^t - L_i^t). \tag{22}$$

From these algorithms and constraints, the seller who wins to mine could earn more than other sellers. This financial incentive strives sellers to compete for the mining right and the opportunity to compensate for the power losses in the proposed consortium blockchain. This model connects mining mechanism with power loss compensation, which provides a better match between transactions and power flows.

Another advantage of this proposed consortium blockchain is the flexibility of the role of miners. In different time slots, the amount of prosumers' respective energy generation and load could also be different. Some prosumers might become consumers if their generated energy cannot meet the load, and thus, they lose the chance to compete for the miners. Conversely, consumers can also become prosumers (miners) if they have extra energy in a different time slot. In summary, every prosumer in the microgrid have the chance to be the miner. The group of miners is not constant.

To achieve the financial balance of the P2P energy trading market, the quantity of the elecoins should be limited. The value of total elecoins rolling in the market should not exceed the elecoin value of the total generated energy, which can be expressed as

$$\text{ELC}_{\text{total}} < \sum_{t=o}^{24} \left(\text{ELC}^t_{\text{buy}} \cdot \sum_{i=1}^{n} G_i^t \right) \tag{23}$$

It should be noted that, the elecoin value at the right side of this constraint is not a constant value. It has a positive proportional relation with the number of prosumers in the network. This feature encourages more prosumers to participate in the P2P energy trading market, so that more elecoins could be published by mining. As long as there are electrical wires to connect them and ensure the energy delivery, even prosumers from different microgrids can also join this consortium blockchain model. The trading model of transactions between different microgrids are described in [22]. At last, all the abovementioned information will be stored and secured by the blockchain. The value of elecoins mined out by each miner is determined by the average value of its maximum and minimum. Because enormous published elecoins will decrease its own value in the market, whereas a little rewarded elecoins value will depress miners' motivation of mining

$$y^t = \frac{(y^t_{\max} + y^t_{\min})}{2}. \tag{24}$$

Finally, the whole working process of the consortium blockchain is

Algorithm 1: The Procedures of a Working Blockchain.

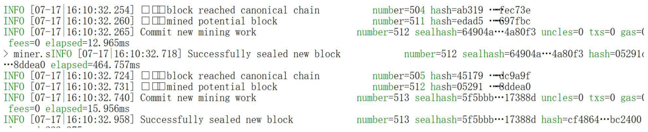
```
for: each $trader_i \in [microgrid]$ do
initialize a broadcast of new transactions to the microgrid;
other users in the microgrid collect and verify the new block for the new transactions;
end for
if: all transactions are valid and not already executed then
users express their acceptance of the block;
else
    transactions are not allowed;
end if;
for $miner_i \in [prosumers]$ do
  deposit its stake;
  mine the accepted block:
  $Hashcode_i = H(block, Hashcode_{i-1})$;
  receive rewarded coins
end for
if block is mined legally then
  receive the deposit back;
else
    lose its deposit;
end if
```

In this algorithm, every participant (user) in the blockchain network owns a private key and a public key. Traders use their private key to decrypt their proposed transaction and broadcast it to the network. Then, the other users from this network will check this proposed transaction and verify it by using their public key, which cannot change the content of the transaction. If the transaction is legal or it is approved by the other users, a new block will be encrypted and added to the blockchain.

There is also a demand response factor behind this model. As the number and the stake of competitors for mining is enormous in peak generation periods but few in the off-peak, it motivates prosumers to increase energy consumption in the peak generation periods, and reduce their load demand during the off-peak period to preserve their PV generation. This benefit could alleviate the damage of the "duck curve" caused by PV generation.

Although, the transparency of transactions is open to users, traders' personal information such as their real names is inaccessible. Because their privacy is highly defended by anonymity, which is another advantage of blockchain technology. Miners also have no access during mining [17]. Fig. 4 illustrates the interface of mining, where no private content is shown. In this figure, two blocks were successfully mined.

To sum up, the functions of the proposed consortium blockchain realized in this article are: tamper-proof to cyberattack; issuance of cryptocurrency; compensation for the power loss; and security for privacy.



```
INFO [07-17|16:10:32.254] □◫block reached canonical chain          number=504 hash=ab319 …fec73e
INFO [07-17|16:10:32.260] □◫mined potential block                  number=511 hash=edad5 …697fbc
INFO [07-17|16:10:32.265] Commit new mining work                 number=512 sealhash=64904a…4a80f3 uncles=0 txs=0 gas=(
 fees=0 elapsed=12.965ms
> miner.sINFO [07-17|16:10:32.718] Successfully sealed new block         number=512 sealhash=64904a…4a80f3 hash=05291(
…8ddea0 elapsed=464.757ms
INFO [07-17|16:10:32.724] □◫block reached canonical chain          number=505 hash=45179 …dc9a9f
INFO [07-17|16:10:32.731] □◫mined potential block                  number=512 hash=05291 …8ddea0
INFO [07-17|16:10:32.740] Commit new mining work                 number=513 sealhash=5f5bbb…17388d uncles=0 txs=0 gas=(
 fees=0 elapsed=15.956ms
INFO [07-17|16:10:32.958] Successfully sealed new block          number=513 sealhash=5f5bbb…17388d hash=cf4864…bc2400
```

Fig. 4. Mining interface of the blockchain.

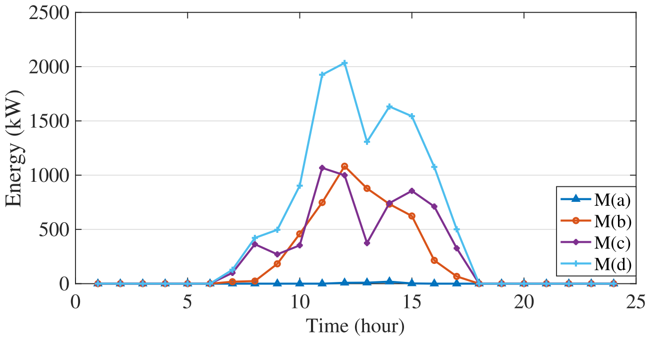


Fig. 5. Total amount of TES^t of four microgrids.

B. Smart Contract Creation

In the consortium blockchain, smart contract is responsible for the execution of trading [23]. Once the “pay and take” condition is fulfilled, transactions will be executed by smart contracts automatically

Algorithm 2: Transaction Execution of Smart Contract.

```
for each $smartcontract_i \in [block_i]$ do
    receive money from the seller;
    receive electricity from the buyer;
end for
if the value of money and electricity is fair then
    execute this transaction;
else
    return money and electricity to the traders
end if;
```

Once the content of the smart contract is implemented, it is immutable.

V. CASE STUDY

In this section, we establish the proposed consortium blockchain by using the Geth (a software used to link to the Ethereum platform). Golang and MATLAB are used to program the role of prosumers and their respective energy generation and load demand. The content of smart contract is written in Solidity language on the Remix, which is anintegrated development environment provided by Ethereum. Other software packages such as Truffle and Web3 are also required. We also introduce four microgrids [M(a) to M(d)] with different number of users (prosumers) respectively. Each prosumer is equipped with PV panels to generate energy. Their total amount of TES^t and that of TEP^t profile are shown in Figs. 5 and 6, respectively.

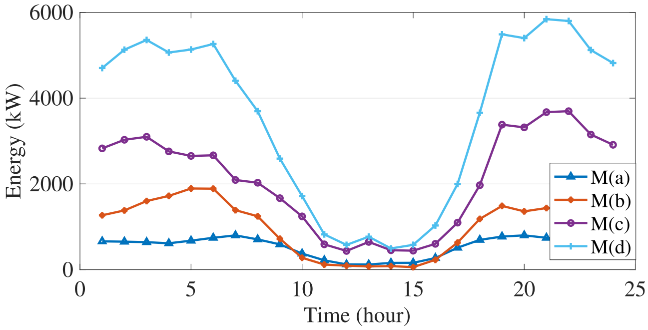


Fig. 6. Total amount of TEP^t of four microgrids.

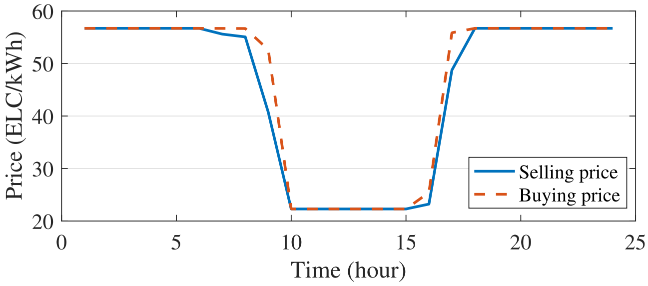


Fig. 7. Internal trading price of M(a).

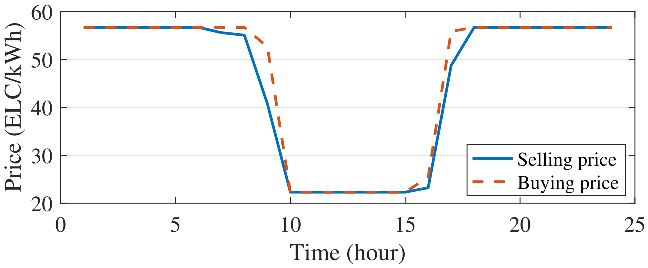


Fig. 8. Internal trading price of M(b).

A. Pricing Scheme Implementation

These four microgrids (a, b, c, d) include 3, 9, 21, and 33 prosumers, respectively. Because of the dependence on the Ethereum platform, the value of one unit of elecoin in this article is defined as

$$1\text{ELC} = 1 \times 10^{-5}\text{Ether}. \tag{25}$$

According to the load demand and energy generation of these prosumers and the pricing scheme introduced in Section II, the trading price within each microgrid can be calculated and shown in Figs. 7, 8, 9, and 10, respectively.

During the peak generation time, the price of each microgrid is different, because the amounts of each prosumers’ load demand and energy generation are different from those of others.

B. Consortium Blockchain Implementation

To implement the proposed consortium blockchain, the genesis block (the first block of a blockchain) is created to set up the difficulty level of mining and store the PoS protocol. Then,

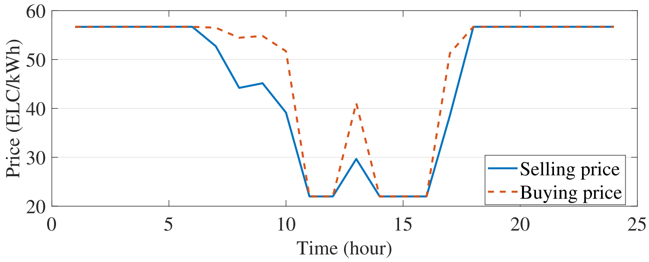


Fig. 9. Internal trading price of M(c).

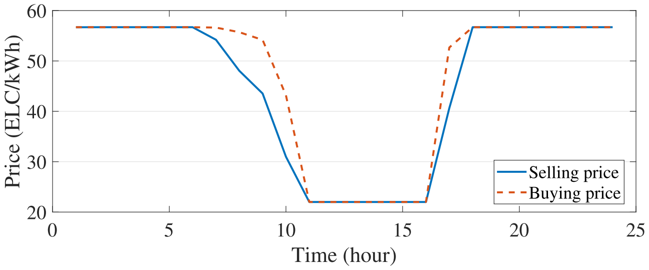
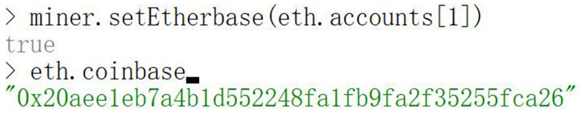


Fig. 10. Internal trading price of M(d).



```
> miner.setEtherbase(eth.accounts[1])
true
> eth.coinbase
"0x20aee1eb7a4b1d552248fa1fb9fa2f35255fca26"
```

Fig. 11. Interface of miner selection.

depending on the amounts of load demand and energy generation of each prosumer, the PoS protocol preselects the miner based on their extra energy (stake) deposited in the smart contract. The interface of miner selection is shown in Fig. 11. The first line of the code is the command of preselection and the address code in green colour is the account of the preselected miner.

And then, prosumers as nodes in the blockchain network are connected. A smart contract is written to execute transactions, which have been verified by all of the prosumers. Taking 12:00 pm in Fig. 6 for example, in the microgrid(b), one of the prosumers owns most extra energy (about 170 kW) at that time slot, thereby becoming the miner. Meanwhile, another prosumer needs 20 kW energy to fulfill its load demand. Therefore, the transaction happens between these two prosumers. This transaction is then executed by the smart contract automatically once it receives the achieved conditions of energy and money. Fig. 12 demonstrates the interface of transaction execution by the smart contract. post_*cons* and post_*prod* refer to the prosumers who need to purchase energy and sell energy, respectively. In this time slot, only one transaction is announced in the microgrid, so the value of the portion is 1 (100 percent). The amount of the traded energy proposed by the buyer is less than that of the seller, because this seller is also a miner, so it needs to sacrifice more energy to compensate for the power loss aforementioned.

The content at the right side of Fig. 12 is the structure of the transaction's block introduced in Section IV. The value of the power loss (kW) is calculated by the estimation algorithms from the Section III, which is shown in Table I. The number of miners is shown at the right side of the power loss value if the number is not single.

TABLE I
VALUE OF POWER LOSS (KW) IN EACH TIME SLOTS

Time	M(a)	M(b)	M(c)	M(d)
6	0	0	0	0
7	0	1.0679	5.9787	7.6938
8	0	1.4342	21.8027	25.3044 (2)
9	0	10.977	16.2275	29.7935 (2)
10	0	16.683	21.2026	54.1850 (4)
11	0	7.1826	35.4688 (2)	49.3806 (3)
12	0.4824	19.3136	26.2496	34.6933
13	0.5523	4.5809	22.4478	46.1694 (2)
14	1.1146	4.9941	27.1912	29.7194
15	0.1309	3.5652	26.6059 (2)	34.7434 (2)
16	0	12.874	36.1708 (3)	61.8341 (5)
17	0	4.0097	19.5728	30.0559(3)
18	0	0	0	0

In some time slots, there is no transaction proposed by prosumers, thereby no power loss.

According to the rationale of cryptocurrency mining [24], [25], the value of P^t_{mine} is in proportion to the difficulty level of mining set in the genesis block as well as the amount of mined cryptocurrency. In the Bitcoin mining pool, every bitcoin requires 968 kW energy to mine. Thus, in this model, the value of P^t_{mine} can be calculated as

$$P^t_{\text{mine}} = \frac{968.y^t.D}{BD} \tag{26}$$

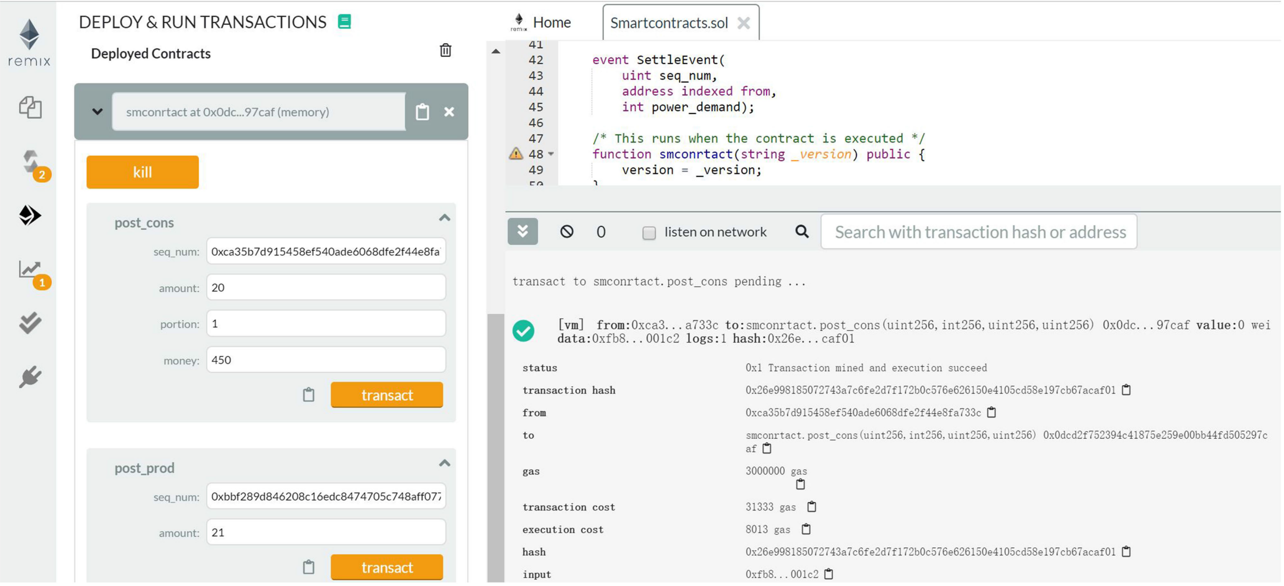
where D and BD refer to the difficulty level of mining elecoin and bitcoin, respectively.

The incentives for the miners such that the value of rewarded elecoins are more than the value of power losses and mining energy. The profit earned by a miner in a certain time slot is

$$\text{profit}_{\text{mine}} = y^t - \text{ELC}^t_{\text{buy}} \cdot \left(\sum_{i=1}^{n} P^t_{\text{loss}} + P^t_{\text{mine}} \right) \tag{27}$$

The difficulty level of mining is set between 130 000 and 200 000 in this model. So according to the data for the energy generation and load demand of prosumers, in different time slots, the profit (ELCs) miners can receive after mining blocks is shown in Table II.

In the second row of the table, due to less prosumers in the microgrid(a), when their self-generation energy has already fulfilled their demand, there would be no trading between prosumers, thereby no profit made by miners in many time slots. Another feature should be noted that the preselected miners can be different prosumers in different time slots. This proposed model relies on the consensus algorithm of PoS to select the miners. The one that owns the most amount of excess energy is most likely to become a miner. The number of blocks of these four respective microgrids is also related to the number of transactions, which is illustrated in Fig. 13. The blockchain consists of more blocks that could provide a more tamper-proof environment to secure transactions. In a microgrid, the total number of elecoins mined out during one day is correlated to



post_cons

seq_num: 0xca35b7d915458ef540ade6068dfe2f44e8fa

amount: 20

portion: 1

money: 450

post_prod

seq_num: 0xbbf289d846208c16edc8474705c748aff077

amount: 21

```
    event SettleEvent(
        uint seq_num,
        address indexed from,
        int power_demand);

    /* This runs when the contract is executed */
    function smconrtact(string _version) public {
        version = _version;
```

```
transact to smconrtact.post_cons pending ...

[vm]  from:0xca3...a733c to:smconrtact.post_cons(uint256,int256,uint256,uint256) 0x0dc...97caf value:0 wei
data:0xfb8...001c2 logs:1 hash:0x26e...caf01
status                 0x1 Transaction mined and execution succeed
transaction hash       0x26e998185072743a7c6fe2d7f172b0c576e626150e4105cd58e197cb67acaf01
from                   0xca35b7d915458ef540ade6068dfe2f44e8fa733c
to                     smconrtact.post_cons(uint256,int256,uint256,uint256) 0x0dcd2f752394c41875e259e00bb44fd505297c
                       af
gas                    3000000 gas
transaction cost       31333 gas
execution cost         8013 gas
hash                   0x26e998185072743a7c6fe2d7f172b0c576e626150e4105cd58e197cb67acaf01
input                  0xfb8...001c2
```

Fig. 12. Transaction execution interface of the smart contract.

TABLE II
PROFIT (ELCs) OF MINERS IN EACH TIME SLOT

Time	M(a)	M(b)	M(c)	M(d)
6	0	0	0	0
7	0	474.2076	2815.5613	3630.6821
8	0	636.6539	9894.8549	11748.2606
9	0	4527.8525	7414.2005	13450.8574
10	0	2914.4002	9136.3812	19495.1836
11	0	800.2239	6502.6203	9053.1018
12	240.1728	1254.6894	4812.4276	6360.4283
13	274.4017	973.4606	7685.9453	8464.3686
14	548.1407	872.3897	4985.0493	5448.5434
15	65.5593	622.7957	4877.7376	6369.6165
16	0	2565.1595	6631.2935	11336.2376
17	0	1754.4747	8370.2685	13192.2023
18	0	0	0	0

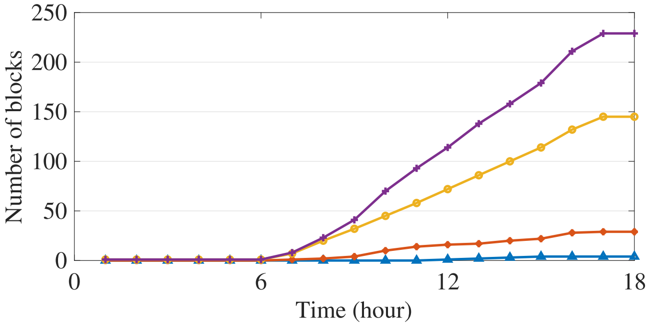


Fig. 13. Increasing number of blocks of the four microgrids.

the number of prosumers as well as their energy generation and load demand. Fig. 14 illustrates this correlation between these factors.

From this figure, the number of mined elecoins roughly presents a positive relation with the number of prosumers in one microgrid. The difference exists in only few of them, due to the higher amount of energy transaction demand of these "special microgrids," thereby increasing the number of transactions leading to a huge number of mined cryptocurrency.

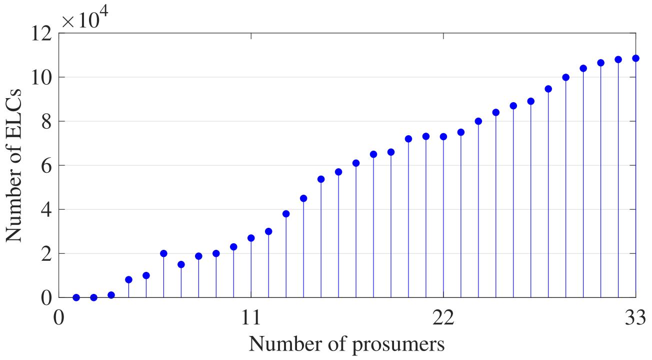


Fig. 14. Correlation between the number of mined elecoins and that of prosumers.

VI. DISCUSSION

In the proposed consortium blockchain, elecoins published by mining are utilized to reward miners, motivating them to make compensation for the power losses. The amount of elecoins a miner can mine out depends on the difficulty of mining. The value of difficulty is set from 130 000 to 200 000, which is much less than that of bitcoin mining (about $7 * 10^{12}$). In a full public chain like the Bitcoin, blockchain designers should improve the mining difficulty to an extremely high level to depress the mining speed. Because the amount of cryptocurrency is limited but the number of miners is uncontrollable. Therefore, it requires a certain time period to create a block. But in this consortium blockchain, only preselected miners have the right to mine and they are also users within a microgrid, and thus, the difficulty can set at a proper value so that the time duration for mining a block can be completed in seconds. In other words, transactions can be terminated almost immediately. It is possible that a miner could mine its own transactions, but the content of Fig. 4 proves that miners cannot recognize their own transactions and any malicious operations will be punished by confiscating their deposited stake.

Before all the ELCs have been mined out, the number of rewarded (published) ELCs is related to its amount of extra energy ($y_{\max}$) in the corresponding time slot in (22), which is a method to maintain the value of this cryptocurrency. As the mining difficulty of this proposed consortium blockchain is much lower than the public chain such as Bitcoin, the cryptocurrency will be mined out sooner to ensure a constant number of ELCs reusing in the market. Once all the ELCs are mined out, miners can still be rewarded with elecoins from the gas-price and gas-limit mechanism like ether [26], which are paid by traders or nodes of the network, as this blockchain model is set up based on the Ethereum platform. This means that the rewarded ELCs can be then calculated as:

$$y^t = \text{gas}_{\text{limit}} \cdot \text{gas}_{\text{price}} \tag{28}$$

In another word, the proposed model ensures a relatively consistent and stable monetary system.

Moreover, because of the lower mining difficulty, the cost of electricity consumed in mining is also reduced. One mined elecoin requires only $1.8 * 10^{-5}$ kW compared to 968 kW for a mined bitcoin. Although, the value of an elecoin equals to $1 * 10^{-5}$ ether currently, its value relies directly on the electricity. This means that its value is more stable than the other types of cryptocurrency published by public chains.

When this proposed blockchain is compared to the private chain, it is more flexible in miner selection. Miner's role can be replaced in different time slots. More importantly, a private chain requires a central agent to implement it. But in the consortium blockchain, the advantage of decentralization is still kept. Transactions are verified by all nodes in the microgrid and the PoS consensus algorithm facilitates the P2P trading mode in the electricity market. With the support of blockchain technology, any third entities such as banks or energy providers [20] could be eliminated.

From the simulation results in the case study, it has been proved that this blockchain model are able to support the microgrid with more number of prosumers. When more prosumers participate in the P2P trading model, more elecoins can be mined out and traded within the microgrid. This feature shows the ability of expansion of the proposed consortium blockchain model.

VII. CONCLUSION

This article proposed a consortium blockchain model to secure the P2P energy trading. It was restricted by the PoS consensus algorithm. The natural advantages of the blockchain technology such as security of users' privacy, transaction transparency, and shorter delay were fully realized. The case study proved that the proposed blockchain model could help not only in saving users' trading cost, but also can execute the technical operation of the microgrid, such as compensation for the power losses in the electrical cables.

Furthermore, the specific procedures of establishing a blockchain and its smart contract were demonstrated in this article. The restriction on the cryptocurrency publication was also provided. The proposed blockchain model provided a more flexible trading and mining environment for participants as miners can be switched in various time slots. The simulation results show the proposed consortium blockchain an efficient and effective way in implementing the pricing scheme and ensuring miners' profit after compensating for the power loss.

In the proposed pricing scheme, the trading price of energy is influenced by the controllable load demand which affects the value of γ^t. Future work will focus on how prosumers could change the trading price by making changes to their energy consumption.

ACKNOWLEDGMENT

Any opinions, findings and conclusions or recommendations expressed in this material are those of the author(s) and do not reflect the views of the A*STAR.

REFERENCES

[1] M. Khorasany, Y. Mishra, and G. Ledwich, "Peer-to-peer market clearing framework for ders using knapsack approximation algorithm," in *Proc. IEEE PES Innovative Smart Grid Technol. Conf. Europe*, Sep. 2017, pp. 1–6.

[2] J. Li, C. Zhang, Z. Xu, J. Wang, J. Zhao, and Y. A. Zhang, "Distributed transactive energy trading framework in distribution networks," *IEEE Trans. Power Syst.*, vol. 33, no. 6, pp. 7215–7227, Nov. 2018.

[3] S. Nakamoto *et al.*, "Bitcoin: A peer-to-peer electronic cash system," 2008. [Online]. Available: https://bitcoin.org/bitcoin. Accessed on: Jul. 17, 2019.

[4] P. Chen, B. Jiang, and C. Wang, "Blockchain-based payment collection supervision system using pervasive bitcoin digital wallet," in *Proc. IEEE 13th Int. Conf. Wireless Mobile Comput., Netw. Commun.*, Oct. 2017, pp. 139–146.

[5] H. Cho, "ASIC-resistance of multi-hash proof-of-work mechanisms for blockchain consensus protocols," *IEEE Access*, vol. 6, pp. 66 210–66 222, 2018.

[6] W. Y. Maung Maung Thin, N. Dong, G. Bai, and J. S. Dong, "Formal analysis of a proof-of-stake blockchain," in *Proc. 23rd Int. Conf. Eng. Complex Comput. Syst.*, Dec. 2018, pp. 197–200.

[7] H. Watanabe, S. Ohashi, S. Fujimura, A. Nakadaira, K. Hidaka, and J. Kishigami, "Niji: Autonomous payment bridge between bitcoin and consortium blockchain," in *Proc. IEEE Int. Conf. Internet Things IEEE Green Comput. Commun. IEEE Cyber, Phys. Soc. Comput., IEEE Smart Data*, Jul. 2018, pp. 1448–1455.

[8] J. Kang, Z. Xiong, D. Niyato, P. Wang, D. Ye, and D. I. Kim, "Incentivizing consensus propagation in proof-of-stake based consortium blockchain networks," *IEEE Wireless Commun. Lett.*, vol. 8, no. 1, pp. 157–160, Feb. 2019.

[9] J. Kang, R. Yu, X. Huang, S. Maharjan, Y. Zhang, and E. Hossain, "Enabling localized peer-to-peer electricity trading among plug-in hybrid electric vehicles using consortium blockchains," *IEEE Trans. Ind. Informat.*, vol. 13, no. 6, pp. 3154–3164, Dec. 2017.

[10] Z. Li, J. Kang, R. Yu, D. Ye, Q. Deng, and Y. Zhang, "Consortium blockchain for secure energy trading in industrial internet of things," *IEEE Trans. Ind. Informat.*, vol. 14, no. 8, pp. 3690–3700, Aug. 2018.

[11] B. Zeng, J. Zhang, X. Yang, J. Wang, J. Dong, and Y. Zhang, "Integrated planning for transition to low-carbon distribution system with renewable energy generation and demand response," *IEEE Trans. Power Syst.*, vol. 29, no. 3, pp. 1153–1165, May 2014.

[12] M. Usman, M. Coppo, F. Bignucolo, R. Turri, and A. Cerretti, "Multiphase losses allocation method for active distribution networks based on branch current decomposition," *IEEE Trans. Power Syst.*, vol. 34, no. 5, pp. 3605–3615, Sep. 2019.

[13] M. Khosravi, H. Monsef, and M. H. Aliabadi, “Approach for allocation of transmission loss based on contribution of generators and loads in injected complex power into network lines,” *IET Gener., Transmiss. Distrib.*, vol. 12, no. 3, pp. 713–725, 2018.

[14] A. I. Nikolaidis, C. A. Charalambous, and P. Mancarella, “A graph-based loss allocation framework for transactive energy markets in unbalanced radial distribution networks,” *IEEE Trans. Power Syst.*, vol. 34, no. 5, pp. 4109–4118, Sep. 2019.

[15] J. Guerrero, A. C. Chapman, and G. Verbic, “Trading arrangements and cost allocation in P2P energy markets on low-voltage networks,” in *Proc. IEEE Power Energy Soc. Gen. Meeting*, Aug. 2019, pp. 1–5.

[16] M. L. Di Silvestre, P. Gallo, M. G. Ippolito, E. R. Sanseverino, and G. Zizzo, “A technical approach to the energy blockchain in microgrids,” *IEEE Trans. Ind. Informat.*, vol. 14, no. 11, pp. 4792–4803, Nov. 2018.

[17] K. Gai, Y. Wu, L. Zhu, M. Qiu, and M. Shen, “Privacy-preserving energy trading using consortium blockchain in smart grid,” *IEEE Trans. Ind. Informat.*, vol. 15, no. 6, pp. 3548–3558, Jun. 2019.

[18] Q. He, Y. Xu, Y. Yan, J. Wang, Q. Han, and L. Li, “A consensus and incentive program for charging piles based on consortium blockchain,” *CSEE J. Power Energy Syst.*, vol. 4, no. 4, pp. 452–458, Dec. 2018.

[19] W. Hou, L. Guo, and Z. Ning, “Local electricity storage for blockchain-based energy trading in industrial internet of things,” *IEEE Trans. Ind. Informat.*, vol. 15, no. 6, pp. 3610–3619, Jun. 2019.

[20] N. Liu, X. Yu, C. Wang, C. Li, L. Ma, and J. Lei, “Energy-sharing model with price-based demand response for microgrids of peer-to-peer prosumers,” *IEEE Trans. Power Syst.*, vol. 32, no. 5, pp. 3569–3583, Sep. 2017.

[21] T. Tsurumaru and M. Hayashi, “Dual universality of hash functions and its applications to quantum cryptography,” *IEEE Trans. Inf. Theory*, vol. 59, no. 7, pp. 4700–4717, Jul. 2013.

[22] J. Yang, H. B. Gooi, and P. Amrit, “Blockchain framework for peer-to-peer energy trading with credit rating,” in *Proc. IEEE Power Energy Soc. Gen. Meeting*, Aug. 2019, pp. 1–5.

[23] J. Liu and Z. Liu, “A survey on security verification of blockchain smart contracts,” *IEEE Access*, vol. 7, pp. 77 894–77 904, 2019.

[24] K. J. O’Dwyer and D. Malone, “Bitcoin mining and its energy footprint,” in *Proc. 25th IET Irish Signals Syst. Conf., China-Ireland Int. Conf. Inf. Commun. Technol. (ISSC/CIICT)*, 2014, pp. 280–285.

[25] M. Rosenfeld, “Analysis of bitcoin pooled mining reward systems,” 2011, arXiv:1112.4980.

[26] V. Buterin *et al.*, “Ethereum white paper,” *GitHub Repository*, 2013.

Jiawei Yang (Graduate Student Member, IEEE) received the B.E. degree in electrical engineering and automation from Wuhan University, Wuhan, China, in 2018, and the M.E. degree in electrical and electronic engineering, in 2020 from Nanyang Technological University, Singapore, where he is currently working toward the Ph.D. degree in electrical engineering.

His current research interest includes P2P energy trading and blockchain application for energy trading.

Amrit Paudel (Graduate Student Member, IEEE) received the B.E. degree in electrical and electronic engineering from Pokhara University, Pokhara, Nepal, in 2012, the M.E. degree in energy engineering from the Asian Institute of Technology, Bangkok, Thailand, in 2016, and the Ph.D. degree in electrical and electronic engineering from Nanyang Technological University, Singapore, in 2020.

His current research interest includes microgrid energy management systems, P2P energy trading, blockchain technology, and distribution level electricity market.

Hoay Beng Gooi (Life Senior Member, IEEE) received the B.S. degree from National Taiwan University, Taipei, Taiwan, in 1978, the M.S. degree from the University of New Brunswick, Fredericton, NB, Canada, in 1980, and the Ph.D. degree from The Ohio State University, Columbus, OH, USA, in 1983, all in electrical engineering.

He is an Associate Professor with the School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore. His current research interests include microgrid energy management systems dealing with storage, electricity market, and spinning reserve.