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Consortium Blockchain for Secure Energy Trading in Industrial Internet of Things

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***Abstract*—In Industrial Internet of Things (IIoT), Peer-to-Peer (P2P) energy trading ubiquitously takes place in various scenarios, e.g., microgrids, energy harvesting networks, and vehicle-to-grid networks. However, there are common security and privacy challenges caused by untrusted and nontransparent energy markets in these scenarios. To address the security challenges, we exploit the consortium blockchain technology to propose a secure energy trading system named energy blockchain. This energy blockchain can be widely used in general scenarios of P2P energy trading getting rid of a trusted intermediary. Besides, to reduce the transaction limitation resulted from transaction confirmation delays on the energy blockchain, we propose a credit-based payment scheme to support fast and frequent energy trading. An optimal pricing strategy using Stackelberg game for credit-based loans is also proposed. Security analysis and numerical results based on a real dataset illustrate that the proposed energy blockchain and credit-based payment scheme are secure and efficient in IIoT.**

***Index Terms*—Blockchain, industrial Internet of things, energy trading, security and privacy, Stackelberg game.**

I. Introduction

INDUSTRIAL Internet of Things (IIoT) has attracted enormous attention from academics and industries, which is a significant component of the future transformation of industrial systems [1], [2]. IIoT offers interconnection and intelligence to industrial systems through sensing devices and actuators with ubiquitous networking and computing abilities [3]. However, it is a great challenge for the industrial systems to satisfy the ever-increasing energy demands of IIoT applications, while IIoT nodes continue to grow in both numbers and performance requirements [4], [5]. To address this challenge, previous studies have presented Peer-to-Peer (P2P) energy trading among IIoT nodes, such as electric vehicles [6]. The IIoT nodes can trade their surplus energy with other nodes in a P2P manner to locally satisfy energy demands, improve energy efficiency, and decrease transfer losses for promoting green industrial systems.

Many emerging technologies have been introduced into green industrial systems, e.g., energy harvesting, wireless power transfer, and vehicle-to-grid [7]. Combined with these technologies, industrial systems develop various efficient and sustainable P2P energy trading scenarios [6]. There are three typical P2P energy trading scenarios for IIoT as following.

- *Microgrids*: Smart buildings with solar panels or wind generators can form microgrids, in which the buildings harvest ambient energy and trade energy with each other by a P2P manner among the microgrids.
- *Energy harvesting networks*: Industrial nodes with energy harvesting ability can obtain energy from renewable energy, also charge themselves through a mobile charger using wireless power transfer by P2P energy trading.
- *Vehicle-to-grid networks*: Electric vehicles acted as energy storage devices perform charging operations at load valley, and feed their energy back into the power grid to reduce load peaks. Vehicles can also sell their energy to neighboring charging vehicles in a P2P manner with the help of local aggregators [8], [9].

Although P2P energy trading plays a vital role in IIoT, there are common security and privacy challenges for general P2P energy trading scenarios. I) It is insecure for IIoT nodes to carry out large-scale decentralized energy trading in untrusted and nontransparent energy markets. II) IIoT nodes with surplus energy may be not willing to participate as energy suppliers due to their concerns about privacy [10]. In this case, energy supply and demand are unbalanced among IIoT nodes. III) In P2P energy trading, there is an intermediary to audit and verify transaction record among IIoT nodes. This intermediary suffers from problems such as single point of failure and privacy leakage [11]. Therefore, it is important to design a unified and secure energy trading system for various energy trading scenarios in IIoT [11]. In addition, it is necessary to encourage more IIoT nodes with surplus energy to act as energy sellers by designing proper incentives.

Recently, blockchain technology is studied in energy trading because of its advantages of decentralization, anonymity and trust. Blockchain is an open, distributed ledger that records transactions in a verifiable and permanent way, which is the underlying fabric for Bitcoin. A digital currency named

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"NRGcoin" based on Bitcoin protocols was presented for renewable energy trading in smart grids [12]. The authors in [11] utilized a blockchain with multi-signatures to solve transaction security problems in decentralized smart grids. However, due to high cost to establish a general blockchain in energy-limited IIoT nodes, the existing methods may not work well in P2P energy trading among IIoT nodes.

Our previous work [9] has indicated that consortium blockchain has high potential to establish decentralized electricity trading system with moderate cost. Consortium blockchain is a specific blockchain with authorized nodes to maintain distributed shared databases. Based on [9], this paper further exploits consortium blockchain technology to develop a unified and secure P2P energy trading system with consortium blockchain, named energy blockchain. The energy blockchain can be widely adopted in different scenarios of IIoT, including the vehicle-to-grid scenario in [9]. Unlike focusing on pricing of electricity trading in [9], we first observe typical P2P energy trading scenarios in IIoT. After that, we present a unified energy trading framework including energy buyers, sellers and aggregators. The energy blockchain is established on the pre-selected energy aggregators to publicly audit and share transaction records in general energy trading scenarios without the need of a trusted intermediary. Besides, similar to that in Bitcoin, transaction confirmation delays on the energy blockchain restrict fast transactions resulting in low efficiency [13]. To address this challenge, we design a credit-based payment scheme to support fast and frequent energy trading. IIoT nodes can finish fast payment through applying for loans according to their credit values from credit banks. An optimal loan pricing strategy for credit banks is proposed to maximize utility of the credit banks in IIoT.

The main contributions of this paper are three-fold:

- *Unified energy blockchain*: We observe typical energy trading scenarios in IIoT, and establish a unified energy blockchain with moderate cost for IIoT.
- *Credit-based payment*: To reduce the limitation of transaction confirmation delays, we design a credit-based payment scheme to support frequent energy trading enabling fast payment.
- *Optimal pricing strategy*: For the credit-based payment scheme, we propose an optimal pricing strategy using Stackelberg game for credit-based loans to maximize the utility of the credit bank. Numerical results show that our energy blockchain and the credit-based payment scheme are efficient and effective.

II. Blockchain Enabled Energy Trading for IIoT

A. A Unified P2P Energy Trading Framework

In IIoT, P2P energy trading activities ubiquitously take place among IIoT nodes to balance energy supply and demand. Fig. 1 shows three typical P2P energy trading scenarios mentioned in Section I, i.e., microgrids, energy harvesting networks and vehicle-to-grid networks. It is essential for these typical energy trading scenarios to present a unified energy trading framework, and thus to establish an energy blockchain

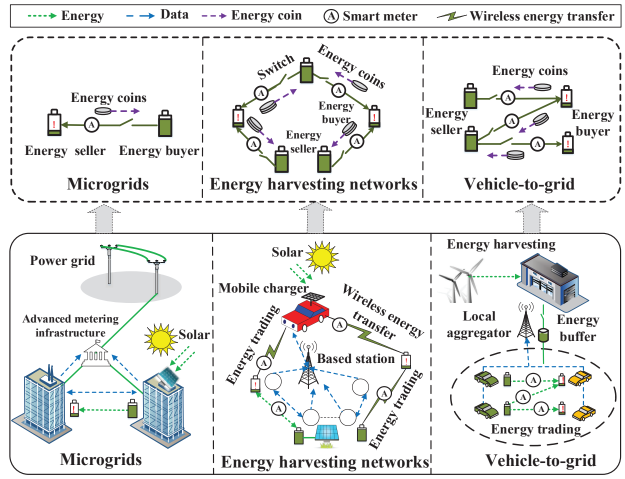

Fig. 1: Typical energy trading scenarios in IIoT.

for secure energy trading [14]. The unified energy trading framework consists of three common entities as follows.

- *Energy nodes*: IIoT nodes (e.g., smart buildings, industrial sensors, and electric vehicles) play different roles in P2P energy trading: energy buyers, sellers, and idle nodes that neither buy energy from other nodes nor sell energy to others. Each node chooses its own role according to energy state and future work plans.
- *Energy aggregators*: Energy aggregators (EAGs) work as energy brokers to manage trading-related events and provide wireless communication services for IIoT nodes. In different energy trading scenarios, EAGs correspond to different physical entities. E.g., advanced metering infrastructures in microgrids can be the EAGs. In energy harvesting networks, an enhanced based station with computing and storage abilities can be an EAG. In vehicle-to-grids, local aggregators can act as the EAGs.
  Fig. 2 shows four entities in an EAG: a transaction server, a credit bank, an account pool, and a memory pool. The transaction server collects energy requests from energy nodes, and matches energy trading pairs of these energy nodes. Here, a digital cryptocurrency named energy coin works as energy nodes' digital assets to trade energy in IIoT [9]. Each energy node has an energy coin account to store personal transaction records. There is a corresponding wallet to manage personal energy coins in this account. We use random pseudonyms as public keys of an energy node's wallet, named wallet addresses, to replace true address of the wallet for privacy protection. The mapping relationships between all the wallets and corresponding wallet addresses and energy coin accounts are stored in local account pools. The account pools in EAGs record and manage energy coins fund in personal wallet addresses of energy nodes. The memory pool stores all transaction records of local energy nodes.
- *Smart meters*: A built-in smart meter in each IIoT node calculates and records the amount of traded energy in real time. The energy buyers pay the energy sellers according to the records of smart meters.

TABLE I: MAIN TERMS IN ENERGY BLOCKCHAIN

Terms	Description
Energy nodes	The IIoT nodes in the energy blockchain.
Energy sellers	The energy nodes with surplus energy to sell.
Energy buyers	The energy nodes with energy demand.
Borrowers	Energy buyers that borrow energy coins from credit banks.
Credit banks	The entities that provide energy coins to borrowers based on their credit values.
Transaction servers	The entities that collect and count energy requests, and thus match transaction pairs of energy trading.
Account pools	The entities that record wallets, wallet addresses and energy-coin accounts in EAGs.
Memory pools	The entities that store all transaction records of local energy nodes.
Wallets	The entities that store energy coins.

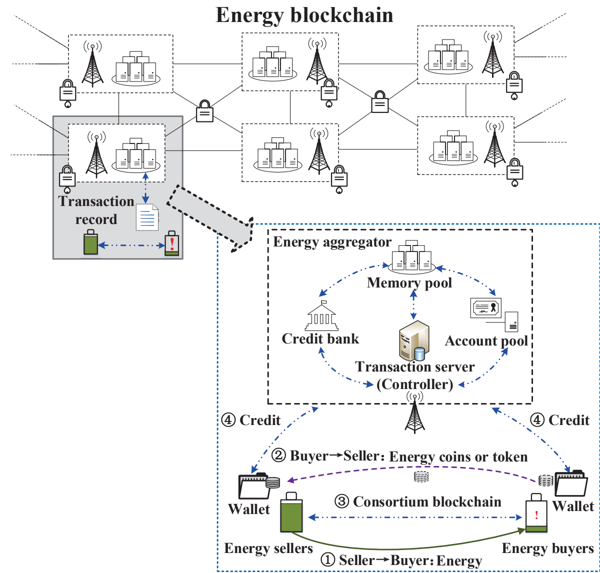

Fig. 2: Secure P2P energy trading with energy blockchain.

B. Unified Energy Blockchain for Secure P2P Energy Trading

In order to support secure P2P energy trading, we exploit consortium blockchain to establish an energy blockchain based on the unified P2P energy trading framework. For traditional blockchains, an important transaction audit stage, named consensus process, is executed before transaction records forming a blockchain. This stage is carried out by all nodes in traditional blockchains with high cost. Unlike that, the energy blockchain performs the consensus process on pre-selected EAGs with moderate cost. These EAGs collect and manage their local transaction records. The transaction records are structured into blocks after finishing the consensus process among the EAGs, and thus stored in the memory pool.

The following are more details about key operations of the energy blockchain with the help of EAGs. The main terms in the energy blockchain are listed in Table I.

1) System initialization: In energy blockchain, we utilize an efficient Boneh-Boyen short signature scheme for system initialization. After registration on a trusted authority, e.g., a government department, each energy node becomes a legitimate entity. An energy node i with true identity ID_i joins the system and gets its public&private keys (PK_i & SK_i) and certificate ($Cert_i$). The certificate $Cert_i$ can be used to uniquely identify the energy node through binding registration information of the energy node. Node i obtains a set of ω wallet addresses $\{WID_{i,k}\}_{k=1}^{\omega}$ from the authority. The authority generates a mapping list $\{ID_i, PK_i, SK_i, Cert_i, \{WID_{i,k}\}_{k=1}^{\omega}\}$, and stores the list in the account pools. When node i executes system initialization, node i uploads its wallet addresses being used to the account pool of its nearest EAG. Node i checks the integrity of its wallet, and downloads the latest data about its wallet from a memory pool and the credit bank in the EAG. The memory pool stores all transaction records in the energy blockchain, and the credit bank records credit-based payments.

2) Choosing roles in energy trading: For P2P energy trading, energy nodes choose their roles (i.e., energy buyers and sellers) according to their current energy status and energy demands for future work plans. Energy nodes with surplus energy may become energy sellers to meet local energy demands from energy buyers.

3) Trading energy between buyers and sellers: Energy requests including the amount of energy from energy buyers are sent to the transaction server of a nearby EAG. The transaction server in the EAG works as a controller to count the total energy demands and to broadcast these demands for local energy sellers. The EAG works as an energy broker for energy nodes to set traded prices according to current energy market, and motivates local energy sellers for participation. The energy sellers determine their selling energy and give responses back to the controller. The controller matches the energy supply and demand among energy nodes. Then the energy is transmitted from the energy sellers to corresponding buyers by power lines or wireless power transfer.

4) Payments using energy coins: As shown in Fig. 2, an energy buyer transfers energy coins from its wallet to a wallet address given by the energy seller. The energy buyers without enough energy coins can apply a token from credit banks based on credit grades to finish payments. More details are given in Section III. The energy seller obtains the latest blockchain data from the memory pool of EAGs to verify this payment activity. The energy buyers generate new transaction records. These transaction records are verified and digitally signed by energy sellers, and thus the records are uploaded to EAGs for audit. After that, the credit values of both the energy seller and buyer are respectively increased.

To balance energy demand and supply in our energy blockchain, we provide incentives to encourage energy nodes to meet local energy demands out of self-interest. During a certain period, the energy seller with the most contribution to energy supply in an EAG is rewarded by energy coins according to contribution metering of energy flows between energy sellers and buyers. This is a specific proof-of-work for energy nodes of energy contributions, which is named as proof-of-flow (i.e., the total amount of traded energy).

5) Building blocks in energy blockchain: EAGs collect all local transaction records during a certain period, and then encrypt and digitally sign these records to guarantee authenticity and accuracy. Fig. 2 shows that the transaction records are

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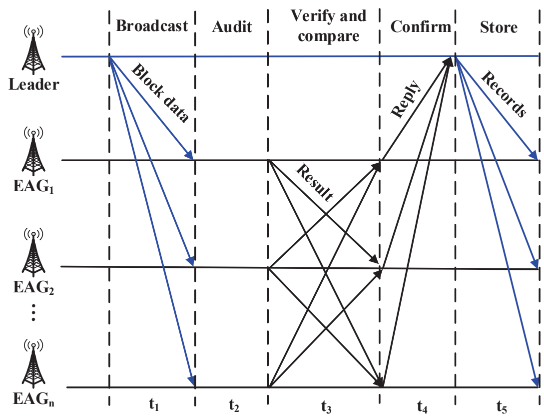

Fig. 3: The consensus process for energy blockchain.

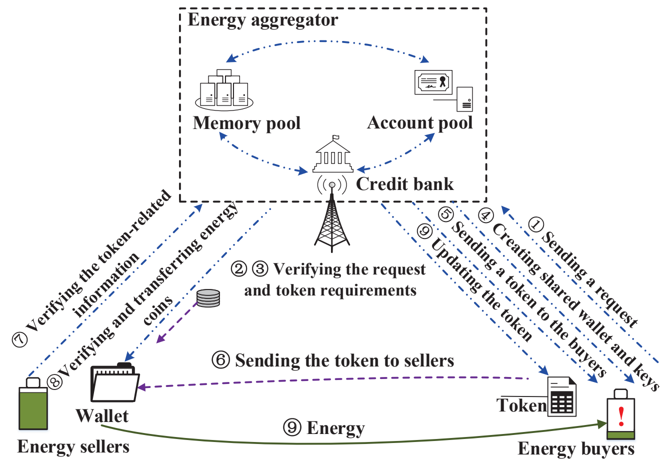

Fig. 4: Credit-based payment scheme for P2P energy trading.

structured into blocks. For traceability and verification, each block contains a cryptographic hash to the prior blocks in the energy blockchain. Similar to that in Bitcoin, the EAGs try to find their own valid proof-of-work about data audit (i.e., a hash value meeting a certain difficulty). An EAG calculates the hash value of its block based on a random nonce value φ, the previous block hash value, timestamp, and transactions' merkel root and so on (denoted as $history_{data}$) [15]. Namely, $Hash(\varphi + history_{data}) < Difficulty$. Here, $Difficulty$ can be adjusted by the system to control the speed of finding out the specific φ. After finding a valid proof-of-work (i.e., φ), the faster miner (EAG) broadcasts the block and the specific φ to other EAGs. Other EAGs audit and verify the transaction records in the block and φ. If other EAGs agree on the block, data in this block will be added in a linear, chronological order in the energy blockchain, and the fastest miner is awarded by energy coins.

6) Carrying out consensus process: The consensus process is carried out by authorized EAGs and a leader who is the fastest EAG with a valid proof-of-work. Fig. 3 shows that the leader broadcasts block data, timestamp and its proof-of-work to other authorized EAGs for verification and audit. For mutual supervision and verification, these EAGs audit the block data and broadcast their audit results with their signatures to each other. After receiving the audit results, each EAG compares its result with others and sends a reply back to the leader. This reply consists of the EAG's audit result, comparison result, signatures, and records of received audit results. The leader analyzes the received replies from EAGs. If all the EAGs agree on the block data, the leader will send records including current audited block data and a corresponding signature to all authorized EAGs for storage. After that, this block is stored in the consortium blockchain, and the leader is awarded by energy coins. If some EAGs don't agree on the block data, the leader will analyze the audit results, and send the block data to these EAGs once again for audit if necessary.

The energy blockchain has good scalability that can keep up with the network scale with a large number of IIoT nodes. Unlike public blockchains, the consensus process of the energy blockchain is carried out on a small number of authorized EAGs [16]. As the network grows, the pre-defined nodes are also able to scale their computing power and storage resource in line with the increase in number of transactions [17]. The total time needed for reaching consensus of a new block is stable regardless of the network size, when the authorized EAGs formation is complete and remains as a constant [18].

III. Credit-based Payment for Fast P2P Energy Trading

In energy blockchain, all authorized EAGs need to audit and verify transaction records in new blocks (i.e., the consensus process). It takes a certain time, named transaction confirmation time, to finish the consensus process. And thus energy coins for transaction payments are finally arrived at corresponding wallet address. Although transaction confirmation time in our energy blockchain is shorter than that of Bitcoin (about 60 minutes) [19], [20], it is still not convenient and practical for IIoT nodes to frequently trade energy. Some energy buyers may have no energy coins to trade energy frequently. To address this problem, we design a credit-based payment scheme to support fast trading, therefore enabling frequent P2P energy trading through energy-coin loans.

In Fig. 4, a credit bank in each authorized EAG works as a trusted bank node with enough energy coins. The credit banks provide energy coin loans for energy nodes according to their credit values, then the energy coins will be transferred from the credit banks' accounts to the wallet addresses shared between the credit banks and borrowers. More details about operation steps of the credit-based payment scheme are given as follows.

1) Token requesting: A borrower B_i (i.e., energy buyer i without enough energy coins) can apply a token based on its credit value from a local credit bank to finish payments.

- Step 1: B_i sends a request including the true identity ID_i, certificate $Cert_i$, all used wallet addresses $\{WID_{i,k}\}_{k=1}^{K}$, loan amount $amount_i$, and current credit value $credit_i$ to an EAG m, namely,
$$B_i \to EAG_m : request_i = \{ID_i || \{WID_{i,k}\}_{k=1}^{K} || Cert_i || credit_i || amount_i\}.$$
- Step 2: After receiving $request_i$, the credit bank verifies the identity of B_i and checks fund-flows of the given

$\{WID_{i,k}\}_{k=1}^{K}$ according to the records in account pools and credit banks. Thus the credit bank calculates current wealth of B_i.

- Step 3: B_i is allowed to obtain a token when the following requirements hold: i) there is some wealth in B_i's energy-coin account; ii) the account has a regular income (e.g., selling its energy for earning energy coins); and iii) the credit value of B_i is not negative. The credit bank calculates an optimal loan amount of B_i and the corresponding interest rate and penalty rate, i.e., loan prices. More details about loan pricing are given in Section IV.
- Step 4: The credit bank creates a shared wallet ($wallet^i_{cb}$) and sends public&private keys of this wallet (i.e., PK^i_{cb}, and SK^i_{cb}) to B_i. The PK^i_{cb} is the shared wallet address for B_i and the credit bank. Both B_i and the credit bank are allowed to use the energy coins in $wallet^i_{cb}$, and top up this wallet if necessary.
- Step 5: B_i receives a response including a token ($Token_i$) and a signature of this token $Sign_{SK_{cb}}(Token_i)$ as follows.
  $$EAG_m \to B_i : response = \{(PK^i_{cb}, SK^i_{cb})||Token_i|| Sign_{SK_{cb}}(Token_i)||Timestamp\},$$
  where $Token_i = \{balance_i||t||Cert^i_{cb}||amount_i||Cert_{cb}|| buffer||pre\_record_i||Timestamp\}$,
  and $pre\_record_i = \{RP_i(s,f)||Hash(TX_i)_{i=1,2,..,h}\}$.
  Here, $Token_i$ includes current balance $balance_i$, loan amount $amount_i$, an authorization certificate $Cert^i_{cb}$, validity duration t of $wallet^i_{cb}$, repayment buffer of the loan $buffer$, and previous loan records pre_record_i. B_i should repay energy-coin loan during $buffer$, otherwise, B_i will suffer with a late fee (i.e., penalty). pre_record_i consists of a loan repayment record $RP_i(s,f)$ and a hash value of previous credit-based payment records $Hash(TX_i)$. In $RP_i(s,f)$, s is the number of repaying loan within $buffer$ in previous loan records, while f is the number of failing to repay loan in time.

2) Energy coin payment: During energy trading, B_i uses energy coins in $wallet^i_{cb}$ to finish payment. Each payment based on the $wallet^i_{cb}$ is verified and recorded by the local credit bank. The credit bank puts the hash value of payment-related data into pre_record_i for checking out wealth of B_i when necessary. More details about payment operations are given as follows.

- Step 1: The borrower B_i sends the following $Payment$ including the token ($Token_i$), the token signature, and the authorization certificate ($Cert^i_{cb}$) to an energy seller S_j. S_j verifies $Cert^i_{cb}$ and the validity duration of $wallet^i_{cb}$ (i.e., t) in $Token_i$, and checks all previous credit-based payment records in the energy blockchain to confirm current balance in $wallet^i_{cb}$.
  $$B_i \to S_j : Payment = \{Token_i||Cert_i||Cert^i_{cb} Sign_{SK_i}(Token_i)||Timestamp\}.$$
- Step 2: S_j sends the $Token_i$, an energy bill, and a wallet address for receiving energy coins (WID_{S_j}), a digital signature of the above information to the credit bank.
  $$S_j \to EAG_m : Energy\_bill = \{Cert_j||Bill||WID_{S_j} ||Payment||Sign_{SK_j}(Payment)||Timestamp\}.$$
- Step 3: The credit bank verifies the receiving $Token_i$ by comparing to the original $Token_i$ recorded in the credit bank. The credit bank checks that whether the balance in $Token_i$ is enough to pay for the $Bill$. If yes, the credit bank transfers energy coins in $wallet^i_{cb}$ to WID_{S_j} for finishing payment. If not, the credit bank sends a notice of insufficient balance to B_i.
- Step 4: After that, the credit bank updates balance information of $wallet^i_{cb}$ and $Token_i$, and adds its digital signature into the new token $Token^{new}_i$. The above credit-based payment record is audited and recorded in the energy blockchain, at the same time, the new token is sent to the buyer for updating.

3) Repay energy-coin loan: After validity duration of $token_i$, B_i will receive the newest token $token^{newest}_i$ including all hash values of the credit-based payment records using $token_i$.

The following are three cases about the loan repayment:

- *Case one:* If B_i repays the energy-coin loan within its repayment buffer, B_i repays the loan with an interest as a transaction fee to the credit bank. The interest rate is calculated in Section IV.
- *Case two:* If B_i cannot repay the loan in time, f in $RP_i(s,f)$ will be added one, and the credit value of the buyer will be decreased. The new credit value of the buyer is denoted as, $Credit^i_{n+1} = Credit^i_n - d \bullet amount_i$, where $Credit^i_n$ is the credit value of n^{th} energy transaction. d is a constant and $d > 0$. The credit bank generates a record about this event, and thus stores the record in the memory pool and uploads it to the energy blockchain. When the buyer finally finishing the energy-coin loan payment, B_i still suffers from a penalty with respect to the loan amount.
- *Case three:* If B_i rejects to repay or cannot repay the loan in a long time, such as one year, the credit bank will put the borrower into a blacklist and broadcast this information to all nodes in the energy blockchain. Then all the IIoT nodes and credit banks will reject to cooperate with this borrower.

IV. Optimal Loan Pricing in Credit-based Payment

In this section, we present the problem definition about the amount of energy-coin loan and loan pricing (i.e., interest rate and penalty rate) for borrowers to maximize economic benefits of credit banks. Energy buyers without enough energy coins act as borrowers to apply for loans from the credit bank in a local EAG. After that, the borrowers worked as energy buyers can buy energy from energy sellers.

A. Problem Formulation

In a local EAG m, for a borrower B_i, the amount of loan provided by a credit bank m (i.e., CB_m) is denoted as R_i. Here $i \in \mathbb{I}$ and $B_i \in \mathbb{B}$. The minimum energy resource demand for B_i is denoted as Q^{min}_i, and p_i is a given price of the energy resource before loan requests. The credit bank must provide $\frac{R_i}{p_i}$ loan to B_i for finishing energy payment. We consider that the local credit bank has enough energy coins to support

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loan requests from borrowers. If a local credit bank does not have enough energy coins for borrowers, the nearby credit banks can cooperate to support loan requests in the energy blockchain. The satisfaction function of B_i is denoted as

$$u_{sat} = d_i ln(\frac{R_i}{p_i} - Q_i^{min} + \theta_i), \tag{1}$$

where $d_i > 0$ and $\theta_i > 0$ are predefined factors for B_i.

The utility of B_i is expressed as,

$$u_i = \lambda_i[u_{sat} - \beta_i R_i t_i] - (1 - \lambda_i)\alpha_i R_i. \tag{2}$$

Where λ_i is repayment ability of a loan, namely, it is the probability that B_i can repay the loan within its repayment buffer. λ_i can be calculated by the loan repayment record $RP_i(s, f)$ of B_i (mentioned in Section III). Here, $0 < \lambda_i = \frac{s}{s+f} \leq 1$. β_i is interest rate of the loan depended by the credit bank. α_i is penalty rate of the repayment delay. We consider that the relationship between the interest rate and the penalty rate is $\alpha_i = \eta_i t_i \beta_i$ [21]. Here $\eta_i > 1$ is a predefined factor, e.g., 3.5, and $t_i > 0$ is the time when the loan began.

The reward of the credit bank consists of the loan interest from B_i, and the late fee (i.e., penalty) if B_i cannot repay the loan in time [21]. The overhead of the credit bank is $R_i t_i c_i$. Here c_i is unit cost of B_i's loan for the credit bank. Thus, the economic benefits of the credit bank are defined as follows.

$$u_{bc}^i = \gamma_i(\beta_i R_i t_i - R_i t_i c_i) + (1 - \gamma_i)\alpha_i R_i, \tag{3}$$

where γ_i is predefined credit grade factor depended on B_i's credit grade given by the credit bank (here, $0 < \gamma_i \leq 1$). γ_i is calculated from loan histories of borrowers. The credit grades of energy buyers are classified into different levels according to credit values of energy buyers. Higher credit grade brings higher γ_i. More details about the value of γ_i are given in Section V-III.

A noncooperative Stackelberg game usually studies the multilevel decision making processes of a number of independent decision makers in response to the decision taken by the leading player of the game [22]. In this paper, we formulate a noncooperative Stackelberg game, where a credit bank is the leader and the borrowers are followers. The credit bank finally determines the penalty rate (i.e., α_i) for each borrower, respectively. Every borrower will respond with the best amount of loan (i.e., R_i) according to its penalty rate given by the credit bank. The game $\mathbb{G}$ is formally defined by its strategic form as

$$\mathbb{G} = \{(\mathbb{B} \cup \{CB_m\}), \{u_i\}_{i \in \mathbb{I}}, \{u_{bc}^i\}_{i \in \mathbb{I}}, R_i, \alpha_i\}. \tag{4}$$

The objective functions for the leader (i.e., the credit bank) and a follower (i.e., borrower i) in a local EAG are respectively denoted as follows.

$$\begin{aligned} &Leader : \max_{\alpha_i} \sum_{i=1}^{\mathbb{I}} u_{bc}^i(\alpha_i), \\ &\qquad\qquad s.t., \alpha_i \geq 0. \\ &Follower : \max_{R_i} u_i(R_i), \\ &\qquad s.t., R_i > Q_i^{\min} p_i - \theta_i p_i. \end{aligned} \tag{5}$$

B. Solution

We use the backward induction method to solve the Stackelberg equilibrium for the above formulated game [23]. We first solve B_i's optimal amount of loan (i.e., R_i^*), then the optimal interest rate and penalty rate are determined by the credit bank.

By differentiating u_i defined in Eqn. (2) with respect to R_i, we have

$$\frac{\partial u_i}{\partial R_i} = \frac{\lambda_i d_i}{R_i - Q_i^{min} p_i + \theta_i p_i} - \lambda_i \beta_i t_i - (1 - \lambda_i)\alpha_i, \tag{6}$$

$$\frac{\partial^2 u_i}{\partial R_i^2} = -\frac{\lambda_i d_i}{(R_i - Q_i^{min} p_i + \theta_i p_i)^2} < 0. \tag{7}$$

This means that u_i is a strictly concave function. We obtain the optimal strategy by solving $\frac{\partial u_i}{\partial R_i} = 0$ as follows,

$$R_i^* = \frac{\lambda_i d_i}{\lambda_i \beta_i t_i + (1 - \lambda_i)\alpha_i} + k_i, \tag{8}$$

where $k_i = Q_i^{min} p_i - \theta_i p_i$.

We substitute Eqn. (8) into Eqn. (3), then

$$\begin{aligned} u_{bc}^i = &\tfrac{\lambda_i d_i[\gamma_i \beta_i t_i - \gamma_i t_i c_i + (1-\gamma_i)\alpha_i]}{\lambda_i \beta_i t_i + (1-\lambda_i)\alpha_i} + k_i[\gamma_i \beta_i t_i - \\ &\gamma_i t_i c_i + (1 - \gamma_i)\alpha_i]. \end{aligned} \tag{9}$$

For presentation, we simply the above equation as follows.

$$u_{bc}^i = \frac{h_1^b \beta_i - h_2^b + h_3^b \alpha_i}{\lambda_i \beta_i t_i + (1 - \lambda_i)\alpha_i} + h_4^b \beta_i - h_5^b + h_6^b \alpha_i, \tag{10}$$

where $h_1^b = \lambda_i d_i \gamma_i t_i$, $h_2^b = \lambda_i d_i \gamma_i t_i c_i$, $h_3^b = \lambda_i d_i (1 - \gamma_i)$, $h_4^b = k_i \gamma_i t_i$, $h_5^b = k_i \gamma_i t_i c_i$, $h_6^b = k_i(1 - \gamma_i)$.

By differentiating u_{bc}^i with respect to α_i, we have

$$\frac{\partial^2 u_{bc}^i}{\partial \alpha_i^2} = -\frac{2h_2^b \eta_i}{(\lambda_i + \eta_i - \lambda_i \eta_i)\alpha_i^3} < 0. \tag{11}$$

When $k_i < 0$, we have $\lim_{\alpha_i \to 0} u_{bc}^i = -\infty$ and $\lim_{\alpha_i \to +\infty} u_{bc}^i = -\infty$. When $k_i < 0$, for $0 < \alpha_i < \sqrt{-\frac{h_2^b \eta_i^2 t_i}{(h_4^b + h_6^b \eta_i t_i)(\lambda_i + \eta_i - \lambda_i \eta_i)}}$ and $\alpha_i > \sqrt{-\frac{h_2^b \eta_i^2 t_i}{(h_4^b + h_6^b \eta_i t_i)(\lambda_i + \eta_i - \lambda_i \eta_i)}}$, we have $\frac{\partial u_{bc}^i}{\partial \alpha_i} > 0$ and $\frac{\partial u_{bc}^i}{\partial \alpha_i} < 0$, respectively. The utility function u_{bc}^i first increases, and then decreasing with increasing α_i. The function is a strictly concave function [24]. The maximum value exists. So we get the optimal strategy by $\frac{\partial u_{bc}^i}{\partial \alpha_i} = 0$,

$$\alpha_i^* = \sqrt{-\frac{h_2^b \eta_i^2 t_i}{(h_4^b + h_6^b \eta_i t_i)(\lambda_i + \eta_i - \lambda_i \eta_i)}}. \tag{12}$$

When $k_i > 0$, $\alpha_i < 0$. Therefore, we have $\alpha_i^* = 0$. For simplicity, we can rewrite the optimal strategy of the bank by

$$\alpha_i^* = \begin{cases} 0, k_i > 0, \\ \min(\sqrt{-\frac{h_2^b \eta_i^2 t_i}{(h_4^b + h_6^b \eta_i t_i)(\lambda_i + \eta_i - \lambda_i \eta_i)}}, \alpha_i^{max}), k_i \leq 0, \end{cases} \tag{13}$$

and $\beta_i^* = \frac{\alpha_i^*}{\eta_i t_i}$.

In order to achieve Stackelberg equilibrium (SE), the credit bank needs to communicate with each borrower. *Algorithm 1*

Algorithm 1 Optimal Loan Pricing Algorithm

Initialize ${u_{bc}^{i}}^{*} = 0, u_i^* = 0, R_i^* = 0, \alpha_i^* = 0$
for The interest rate α_i from 0 to α_i^{max} **do**
  for Each borrower $i \in \mathbb{I}$ **do**
    if $k_i > 0$ **then**
      ${R_i}^* = 0, {\alpha_i}^* = 0$
      break
    end if
    Borrower i adjusts its loan amount R_i according to $R_i^* = \frac{\lambda_i d_i}{\lambda_i \beta_i t_i + (1-\lambda_i)\alpha_i} + k_i$.
  end for
  The bank adjusts its utility according to ${u_{bc}^{i}}^{*} = \gamma_i(\beta_i R_i t_i - R_i t_i c_i) + (1-\gamma_i)\alpha_i R_i$.
  if $u_{bc}^{i} \leq {u_{bc}^{i}}^{*}$ **then**
    The bank records the optimal interest rate and maximum utility $R_i^* = R_i, u_i^* = u_i, {u_{bc}^{i}}^{*} = u_{bc}^{i}, \alpha_i^* = \alpha_i$.
  end if
  if $u_{bc}^{i} \leqslant {u_{bc}^{i}}^{*}$ **then**
    break
  end if
end for
The SE$({R_i}^*, {\alpha_i}^*)$ is achieved.

is presented to provide a distributed way for all borrowers and the credit bank in order to iteratively reach the unique SE of the proposed game.

Theorem 1: A unique SE can always be achieved in the proposed Stackelberg game $\mathbb{G}$ between the credit bank and borrowers in the set $\mathbb{B}$ [22].

Proof: The utility function u_i in Eqn. (2) is strictly concave with respect to R_i, $\forall i \in \mathbb{I}$, i.e., $\frac{\partial^2 u_i}{\partial R_i^2} < 0$. Hence, for any penalty rate $\alpha_i > 0$, each borrower has a unique R_i to maximize u_i. Clearly, the game $\mathbb{G}$ reaches the SE when all the borrowers and the credit bank (i.e., players) achieve their optimized utilities, respectively, considering the strategy chosen by all players in the game. Therefore, it is obvious that the proposed game $\mathbb{G}$ reaches an SE as soon as the credit bank finds an optimized price α_i^*, while the borrowers choose their unique loan amounts. From Eqn. (11), we note that u_{bc}^{i} is strictly convex with respect to α_i. Hence, the credit bank is able to find a unique optimal price α_i^* based on borrowers' strategies. Therefore, there exists a unique SE. ■

V. Security Analysis and Numerical Results

In this section, we first provide security analysis about our energy blockchain. After that, we evaluate performance about the energy blockchain, and use a real dataset to analyze the performance of the credit-based payment scheme.

A. Security Analysis on Energy Blockchain

Unlike traditional communication security and privacy protection, our energy blockchain uses a consortium blockchain to ensure energy trading security and privacy protection. The blockchain-related security performances are listed as follows [25].

- Get rid of a trusted intermediary: In our energy blockchain, IIoT nodes trade energy in a P2P manner, which is unlike traditional centralized trading relying on a globally trusted intermediary. All the IIoT nodes have the equal right to trade energy with the help of authorized EAGs. The energy blockchain is robust and scalable without involvement of a globally trusted intermediary.
- Wallet security: Without corresponding keys and certificates, no adversary can open an IIoT node's wallet and steal energy coins from the wallet. As each IIoT node has a unique wallet corresponding to its energy coin account, we use multiple wallet addresses as pseudonyms of this wallet for privacy protection.
- Transaction authentication: All transaction data are publicly audited and authenticated by other entities including IIoT nodes and trusted EAGs. It is impossible to compromise all entities in the energy blockchain due to overwhelming cost. Even an EAG is compromised, the transaction data with something wrong will still be found out and corrected before structuring into a block.
- Data unforgeability: The decentralized nature of the consortium blockchain combined with digitally-signed transactions ensures that no adversary can pose as IIoT nodes to corrupt the network. It is because that the adversary cannot forge a digital signature of any node, or gain control over the majority of the network's resources [25]. An adversary controlling one or more EAGs in the energy blockchain cannot learn anything about the raw data, as it is encrypted with keys of IIoT nodes. The adversary cannot forge the audited and stored data in the energy blockchain [19].
- No double-spending: Energy coin relies on digital signatures to prove ownership and a public history of transactions to prevent double-spending. The history of transactions is shared using a P2P network and is agreed upon using a proof-of-work manner.

B. Performance Analysis on Energy Blockchain

We compare the transaction confirmation time under different frequencies of energy trading in different blockchains, and evaluate the performance of the average transaction speed of our proposed credit-based payment scheme. Here, the transaction speed refers to the number of finished energy trading in one hour. The total transaction confirmation time on the average means the average time of finishing the consensus process of an energy trading for an energy node. For the purpose of illustration, we simulate the performance among 50 pairs of IIoT nodes for 240 minutes. Similar to that in Bitcoin, the transaction confirmation time of traditional blockchains is 60 minutes, while that of our energy blockchain is set to be 10 minutes as an example [20]. The total number of pre-selected EAGs is 51 in our energy blockchain. The frequency of energy trading in one hour takes values from the set {1, 2, 3, 4, 5} with equal probability for IIoT nodes. Each IIoT node has twenty energy coins in the wallet for P2P energy trading.

Fig. 5(a) shows that, for a traditional blockchain (e.g., Bitcoin), the total transaction confirmation time on the average

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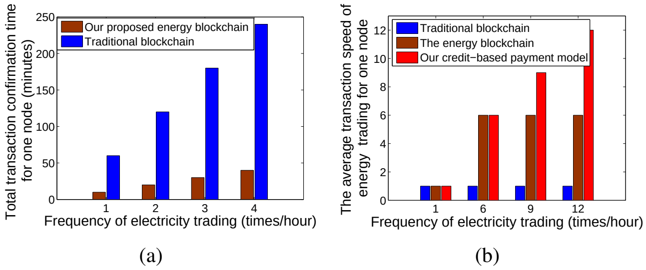

Fig. 5: Performance comparison about (a) transaction confirmation time and (b) transaction speed.

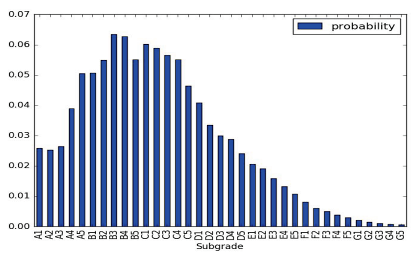

Fig. 6: Probability distribution histogram of credit grades in the real dataset.

for an energy node is much longer than that of our energy blockchain when the frequency of energy trading increases. This is due to the fact that our energy blockchain only carries out the consensus process on the pre-selected EAGs instead of all connected nodes in the traditional blockchain. Fig. 5(b) shows the average transaction speed of energy trading in different schemes. During energy trading, IIoT nodes without enough energy coins cannot perform next energy trading until the last trading finishing the consensus process. So as shown in Fig. 5(b), the traditional blockchain and our energy blockchain have an upper limit of the average transaction speed in one hour. While our credit-based payment scheme has a higher transaction speed on average because of the help of credit banks in EAGs. These credit banks provide enough energy coins to IIoT nodes to continuously perform energy trading on energy blockchain without the limitation of transaction confirmation delays. The results indicate that our proposed scheme supports fast P2P energy trading, therefore enabling frequent energy trading among IIoT nodes.

C. Performance Analysis on Credit-based Payment

We study the performances of proposed credit-based payment scheme based on a real dataset from a lending club's issued loans in [26]. This dataset includes current loan status (e.g., fully paid), latest payment information, credit values, and addresses, etc. According to the lending club loan data, there are 890 thousand observations with 35 gradually increasing credit grades ("A1", "A2",..., "B1", "B2",..., "G4", "G5") in Fig. 6. We consider 100 borrowers with different credit grades ranged from A1 to G5 in IIoT. The n_{th} credit grade has a corresponding credit grade factor $r_n = 1 - \frac{n-1}{N}$, here $N = 35$. The probability that a borrower belongs to a

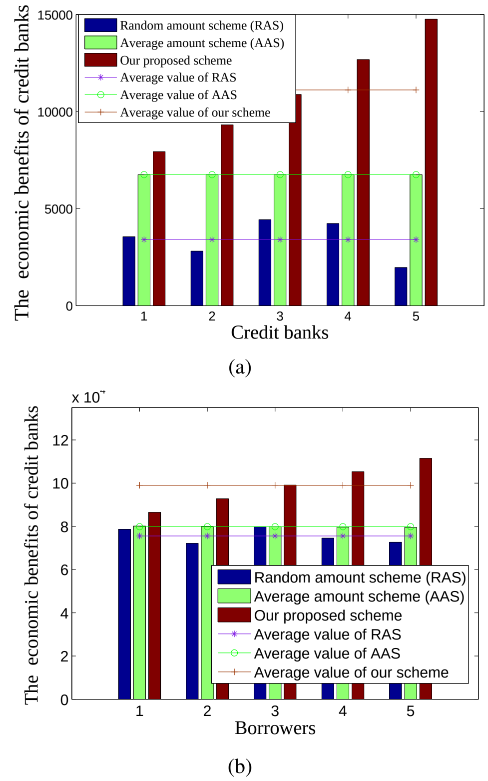

Fig. 7: Performance comparison about economic benefits of (a) credit banks and (b) borrowers.

TABLE II: Parameter Setting in the Simulation

Parameter	Setting
Predefined factor d_i	[20000, 20400]
Predefined factor θ_i	[2000, 2500]
Predefined factor t_i	(0, 10] month
Unit penalty η_i	3.5
Repayment ability λ_i	(0, 1]
Credit grade factor of γ_i	[0, 1]
Unit cost of loan c_i	[0.1, 0.2]

specified credit grade is distributed according to probability distribution histogram in Fig. 6. These borrowers are divided into 5 groups to apply for energy-coin loans from 5 credit banks, respectively. Each credit bank with limited energy coins only provides loans to 20 borrowers. We carry out two heuristic energy coin distribution schemes to compare performance with our proposed scheme. One heuristic scheme is that the borrowers are allowed to apply for a random amount of energy coins from five credit banks (denoted as Random Amount Scheme, RAS). Another one is that the borrowers can apply for average amount energy coins (denoted as Average Amount Scheme, AAS). Our scheme makes optimal pricing decisions for borrowers according to their information (e.g., income, loan records, credit value). More parameters about our proposed scheme are listed in Table II.

Fig. 7(a) shows the performance comparison of energy coin distribution schemes. For example, we set the interest rate of the loan is 0.1 in Random Amount Scheme (RAS) and Average Amount Scheme (AAS). We note that the credit banks can

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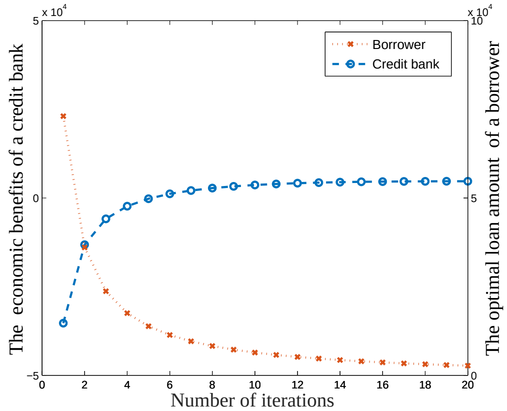
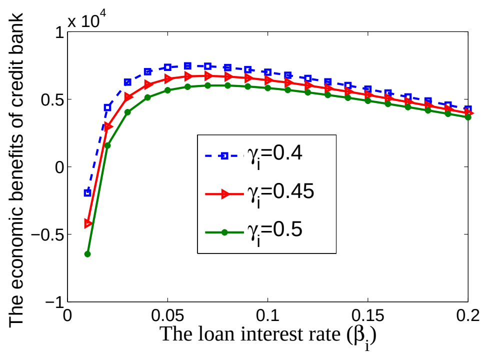
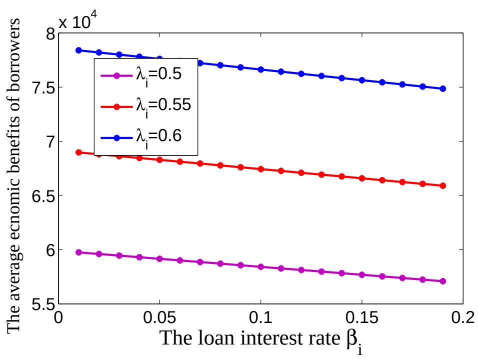


Fig. 8: Convergence evolution of economic benefits and optimal loan amount.



(a)



(b)

Fig. 9: Parameter impacts of parameter setting.

obtain optimal economic benefit in our proposed scheme. The average economic benefit for five credit banks in our proposed scheme is 64.8% higher than that of AAS, and 226.9% higher than that of RAS. Similar results can be found in Fig. 7(b). The average economic benefit for five borrowers randomly chosen in our proposed scheme is 24.1% higher than that of AAS, and 5.7% higher than that of RAS.

Fig. 8 shows the convergence evolution of economic benefits of a randomly chosen credit bank and optimal loan amount of a randomly chosen borrower, respectively. Note that both the economic benefits and optimal loan amount rapidly converges close to their optimal values after 19 iterations, respectively.

Fig. 9 shows performance impacts of credit grade factor γ_i on credit bank, and impacts of λ_i on borrowers. Fig. 9(a) shows that the economic benefits of credit bank decrease as γ_i increases. This is because that borrowers with higher credit grade are more likely to repay the loan in time leading to less penalty for the credit bank. While the repayment ability of borrowers λ_i has a positive impact on the average economic benefit of borrowers as shown in Fig. 9(b). In summary, according to Fig. 5 to Fig. 9, our proposed energy blockchain and the credit-based payment scheme are effective and efficient for energy trading in IIoT.

VI. Conclusions

In this paper, we have presented a unified energy blockchain based on consortium blockchain for secure energy trading in various typical scenarios of IIoT, such as micrograds, energy harvesting networks, and vehicle-to-grids. We also designed a credit-based payment scheme to overcome the transaction limitation caused by transaction confirmation delays, which supports fast and frequent energy trading by credit-based payment among energy nodes. We propose an optimal pricing strategy using Stackelberg game for energy-coin loans to maximize economic benefits of credit banks. We perform security and performance analysis to evaluate the energy blockchain and the credit-based payment scheme, respectively. Security analysis shows that our energy blockchain achieves secure energy trading, and numerical results illustrate that the energy blockchain and the credit-based payment scheme are effective and efficient for energy trading. There are several interesting problems that can be further studied, such as optimal energy aggregator selection, specific schemes designed for extreme scenarios including IIoT nodes with excellent or poor credit values.

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