

Enabling Energy Trading in Cooperative Microgrids: A Scalable Blockchain-based Approach with Redundant Data Exchange

Haojun Huang, Wang Miao, Zhaoxi Li, Jialin Tian, Chen Wang, and Geyong Min

Abstract—Blockchain has recently been regarded as an important enabler for building secure energy trading in microgrid systems due to its inherent features of distributively providing immutable data record, storage and sharing across networks in a Peer-to-Peer (P2P) manner. However, designing highly-efficient and scalable blockchain-enabled energy trading mechanisms is extremely challenging because of the unique features of microgrid systems, e.g., bandwidth constrained and high-latency communications and large-scale Renewable Energy Source (RES) integration. To address this challenge, we propose a novel scalable blockchain-based energy trading (SBET) framework for cooperative micro-grid systems, which includes four planes, i.e., data plane, consensus plane, smart plane, and application plane. Different from the existing solutions without consideration of network transmission, these four planes are designed with the capability of perceiving the status of block generation and transmission over interrupted P2P networks, and thus proactively improving the consensus process to guarantee the reliability of energy trading in cooperative microgrids. Meanwhile, built on this framework, a novel redundant data exchange strategy is proposed to improve the scalability of block creation with the presence of large-scale RES penetration and interrupted and dynamic communication links. Simulation results show that the proposed system framework outperforms the benchmark blockchain solutions. Furthermore, we investigate the potential applications of the proposed solutions in the practical microgrid systems to facilitate a clear understanding of the mechanisms of the proposed solutions.

Index Terms—Blockchain, Microgrid, Energy Trading, Redundant Data Exchange

I. INTRODUCTION

With the advent of diverse Renewable Energy Sources (RESs), e.g., solar power, wind power and tidal energy, the power infrastructure has evolved from the traditional centralised power grid into distributed and smart microgrid systems, where the energy is generated, traded and consumed locally. Compared with the traditional power grid infrastructure, the emerging microgrid systems bring the benefits of more efficient and clean energy generation, higher system resiliency against potential power outage, and lower cost for end users. According to the renewable energy report published by European Environment Agent [1], the share of RESs in the

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TABLE I: State-of-the-art of network design for TI services

Authors	Ref	Main Focus
E. Munsing et al.	[4]	Blockchain-based microgrid management
P. Danzi et al.	[5]	Blockchain-based proportional-fairness power management strategy
M. Silvestre et al.	[2]	Blockchain-based voltage management
W. Jian et al.	[6]	Auction and blockchain technologies driven energy transmission
Z. Li et al.	[3]	Blockchain-enabled distributed energy trading
N. Aitzhan et al.	[7]	Token-based distributed energy trading in microgrids
S. Wang SolarCoin	[8] [9]	Blockchain-driven energy trading and operation Reward-based solar energy trading in the global level
NRGCoin	[10]	Decentralised virtual currency for energy trading among prosumers
Electronic Energy Coin	[11]	Blockchain-based cryptocurrency for green energy trading
KWHCoin	[12]	Digital tokens based cryptocurrency renewable energy exchange
TerraGreen Coin	[13]	Blockchain based system management platform for biomass waste
Dajie Blockchain	[14]	Blockchain-based energy trading in microgrid systems

final power consumption in the EU has doubled since 2005, increasing from 8.7% to 18.88%, and will reach 32% by 2030. Along with the increase of the RES share, the emission of CO₂ has been reduced 20% by 2020 compared to that in 1990. It can be seen that the RES-based microgrid system plays a critical role in power grid systems toward more sustainable and environment-friendly. However, before reaping the merits of RES-based microgrid systems, one of the key challenges that should be carefully coped with is the security of microgrid system operation, e.g., power trading among geographically distributed microgrids and end users [2], [3]. For example, in cooperative microgrid systems, the power price is dynamically determined by diverse factors, e.g., the amount of the power generation, the cost of the energy storage, potential demands, and so on. In this regard, a malicious attacker can potentially benefit from modifying the energy data in the trading market. Therefore, how to secure the process of the energy trading becomes an urgent research issue in the design of reliable, secure and high-performance cooperative microgrid systems.

Owning to the inherent features of anonymity, traceability, decentralization, transparency, and auditability, blockchain created as the underlying technology of crypto-currency financial sectors [15] has been regarded as a promising solution to

secure energy trading in the cooperative microgrid. Specifically, blockchain exploits two key technologies, distributive data ledger across networks and smart contracts among nodes respectively, to enhance the security of microgrid system operation. In this regard, the power trading data is stored and shared in the form of sealed blocks chronologically linked into a chain in a distributive, immutable and Peer-to-Peer (P2P) manner. This brings the microgrid systems capable of providing credentials, storing learning logs and maintaining transparency and privacy of trading data. Meanwhile, smart contracts can provide minimum participation of human being and hence ensure the security of power tradings without a third party. Therefore, considerable research efforts [2]–[14] have been made in the area of blockchain-based microgrid system design, listed in Table I, from both academia and industry communities. For example, the authors in [4] designed a blockchain-based system framework with the aim of enabling the secure management and optimisation of microgrid systems with a high penetration of RESs. To improve voltage control in microgrid systems, a blockchain-based proportional-fairness management strategy was developed [5], where a cluster of distributed energy sources serve as the voltage managers and the exchange of credits is exploited to offer incentives fairly between voltage managers. To cope with the real-time power demand shortage, the authors in [8] developed an energy trading and operation platform based on blockchain technology with the goal of securely providing P2P energy exchange. Despite being such a promising technology, directly applying blockchain in microgrid systems is challenging because of the unique features of microgrid system operation. For example, different from the centralised power grid system, the renewable energy resources in microgrid systems, e.g., wind power and tidal power, are deployed at hard-to-reach areas, e.g., mountain, desert and ocean. The communications among different renewable resources are characterised by limited bandwidth, long delay and communication interruption. Therefore, exploiting the blockchain technology to revolutionise and secure the operation of microgrid systems should take these factors into consideration. Unfortunately, the existing studies failed to capture these features in these algorithm and system design, as communication issues, e.g., long delay, could lead to serious performance degradation of blockchain operation with respect to block generation and validation.

To fill this gap, a novel Scalable Blockchain-enabled Energy Trading (SBET) framework is proposed in this paper in the scenario of cooperative microgrid systems. The proposed framework consists of four complementary planes, including data plane, consensus plane, smart plane, and application planes. Distinguished from the traditional blockchain architecture, the aim of our framework is to enable the operation of blockchain-based power trading capable of perceiving the transmission performance of the underlying infrastructure and analysing the effect of network transmission on the block processing, e.g., block creation, transmission and validation. To improve the reliability and scalability of the proposed system framework, a new redundant data exchange mechanism is presented to guarantee that the blocks are received and validated by the majority of the network nodes with unstable,

dynamic and interrupted network transmissions. Simulation results demonstrate the performance improvement of the proposed SBET compared with the traditional blockchain-based power trading solutions. In addition, we point out the potential applications of our solution to highlight its usage in the practical micrigrig systems.

The remainder of this paper is organized as follows. First, we present the system model and problem formulation in Section II. Then, we present the proposed framework of SBET and its components in details in Section III, followed by a performance evaluation via simulation experiments and investigation of potential applications in Section IV. Finally, we conclude the paper in Section V.

II. SYSTEM MODEL AND PROBLEM FORMULATION

A. System Model

It is considered that the cooperative smart microgrid (MG) system shown in Fig. 1 consists of the utility grid and several MGs, denoted as $\mathcal{E} = \{e_1, e_2, \dots, e_n\}$, which takes advantage of RESs to generate, consume and trade electric power. Each MG $e_i \in \mathcal{E}$ can be simplified as a collection of power sources, energy storage system, transaction ledger and wallet [3]. The power source, e.g., solar panels, wind or tidal generators, is responsible for the production and supply of electric power which is further stored in the energy storage system as available remaining energy, $Q_i(t)$. Considering that the regional MG not only provides power to local users, but also sells excess energy to consumers of nearby MGs in a P2P manner, the ledger and wallet are in charge of keeping track of energy transactions, \mathcal{T}_j , and the rest of own coins, $C_i(t)$, respectively.

During energy trading, there are two types of MGs involved in as power supplier, e_j^{sell} , and power consumer, e_j^{buy} , where e_j^{sell} transmits electric power Q_j to e_j^{buy} through the power grid, followed by the payment of p_j coins to e_j^{sell} in return [6]. In addition, each regional MG communicates with others and transmits transaction data, which mainly records the information of electricity buying and selling among different MGs. Such information mainly includes the serial number, timestamp of transaction, quantity of electricity traded, the total price, as well as the information of suppliers and consumers. Thus, \mathcal{T}_j can be given by

$$\mathcal{T}_j = \{n_j, t_j, Q_j, p_j, e_j^{sell}, e_j^{cons}\}, \quad (1)$$

where n_j , referring to timestamp, suppliers and consumers as $t_j - e_j^{sell} - e_j^{cons}$, is a unique serial number for \mathcal{T}_j .

Suppose that some regional MGs may be inaccessible to each other occasionally due to communication issues such as long delay, caused by their location at abundant-in-energy but hard-to-reach areas, e.g., mountain, desert and ocean. The online state of each regional MG, $S_{e_i}(t)$, is set as a binary-state variable to check whether e_i is reachable at time slot t as

$$S_{e_i}(t) = \begin{cases} 1, & e_i \text{ is accessible,} \\ 0, & \text{otherwise,} \end{cases} \quad (2)$$

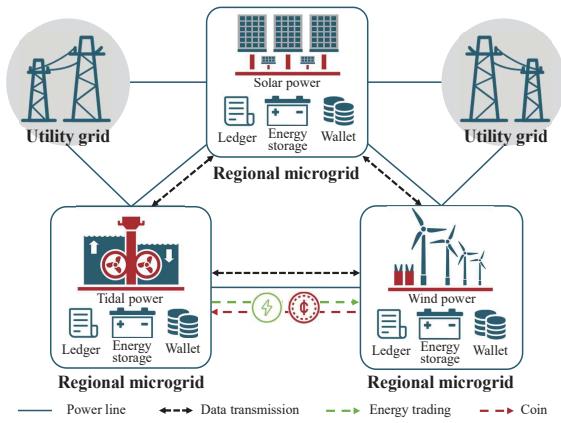


Fig. 1: Energy trading in cooperative microgrids.

which affects the synchronization between e_i and other MGs on energy trading. This will lead to partial data stored in each MG during energy trading, requisiting that redundant data exchange should be executed to enable efficient energy trading among all MGs.

B. Problem Formulation

Blockchain, featured as decentralization, traceability and auditability, is used to provide reliable data sharing and storage for energy trading in the cooperative MG systems. All MGs will connect to each other through IoT, 4G/5G, WiFi, Ad Hoc networks, and the Internet. Each MG e_i is in charge of data block storage, data confirmation and block creation. In addition, e_i will record its own energy trading data, broadcast them to other MGs, i.e., $e_1, \dots, e_{i-1}, e_{i+1}, \dots, e_n$, and also receive other transactions in the cooperative MG systems. The data confirmation will be conducted after a settled waiting time t_{max} . MG e_i , who receives the confirmation message of \mathcal{T}_j , will respond a reply with “Yes” if the received \mathcal{T}_j is consistent with its own retained locally.

Assuming that the timing for data confirmation is t_c , the ratio of MGs who have verified each transaction \mathcal{T}_j can be denoted as

$$r(\mathcal{T}_j) = \frac{\sum_{e_i} S_{e_i}(t_c) \Upsilon_{\mathcal{T}_j}^{e_i}}{\|e_i\|}, \quad (3)$$

where $\Upsilon_{\mathcal{T}_j}^{e_i}$ is a binary-state variable that will be 1 if the reply of e_i for \mathcal{T}_j is “Yes” and $\|e_i\|$ is the total number of MGs. Once the ratio $r(\mathcal{T}_j)$ is more than γ , \mathcal{T}_j will be successfully verified, which also can be defined by a binary-state variable as

$$\Upsilon_{\mathcal{T}_j} = \begin{cases} 1, & r(\mathcal{T}_j) \geq \gamma, \\ 0, & r(\mathcal{T}_j) < \gamma, \end{cases} \quad (4)$$

where γ is a constant in the transaction validation of blockchain. The data block b_k will be created with several verified energy transactions, $\mathcal{T}_1, \mathcal{T}_2, \dots$, through the data confirmation after t_{max} and finally added into energy trading blockchain $l(b_1, b_2, \dots)$.

Notice that a number of MGs may not be on-line during the whole transaction verification because of the communications among them characterised by limited bandwidth, long delay and communication interruption, thus some trading data cannot

be verified through one-time data transaction. Therefore, this study aims to maximize the number of verified transactions through redundant data exchange in the presence of serious communication delay or link blockage, which can be expressed as

$$\max \quad \frac{\sum_{\mathcal{T}_j} \Upsilon_{\mathcal{T}_j}}{\|\mathcal{T}_j\|}, \quad (5)$$

where $\sum_{\mathcal{T}_j} \Upsilon_{\mathcal{T}_j}$ and $\|\mathcal{T}_j\|$ are the number of verified and total energy transactions, respectively.

III. SBET: FRAMEWORK AND COMPONENTS

This section mainly elaborates the proposed framework of SBET for scalable energy trading over networks by introducing blockchain. We firstly present its framework with the details of each plane, and then emphasize the key technical components and its working principle to create energy trading blockchain among cooperative microgrids.

A. Blockchain-based Framework

The proposed framework of SBET is illustrated in Fig. 2, which consists of four planes, i.e., data plane, consensus plane, smart plane, and application plane, and works as follows. Initially, each energy trading request will access the application plane to activate its desired functionalities and services. Then, a variety of energy trading data stemmed from energy providers and consumers will be collected and re-collected through redundant data exchange if some transactions have not been received by most MGs in the data plane. After that, such data will be broadcasted to consensus plane for its validation through a set of participants with the popular consensuses like Power of Work (PoW), Delegated Proof of Stake (DPoS), and Practical Byzantine Fault Tolerance (PBFT) [15], [16], [17]. Meanwhile, it will automatically perform flexible programs ordered by application plane in the smart plane for scalable energy trading data management under certain conditions. Finally, the valid energy trading data will be distributively stored and preserved by a set of participants, all running the same blockchain software, in the data plane in the form of blocks.

Data plane is the layer designed for distributively storing energy trading data in the form of blockchain. It allows a set of MGs in this plane to broadcast their trading data, and further re-broadcast the missing transactions caused by communication interruption or delay during the process of reaching consensus, as shown in Lines 1-2 and 19 of Algorithm 1, respectively. Furthermore, each MG independently packs received transaction data with a hash algorithm into a block as Line 29 and then links this block into the chain as Line 34 in Algorithm 1. Such abundant data in the chain would require the data plane to run on the general-purpose infrastructure with Network Function Virtualization (NFV) [18], which decouples software from hardware and runs network function in software, for its efficient storage. Based on these, the data plane integrates some efficient Software-Defined Networking (SDN) based controllers installed typical protocols like OpenFlow and Restful at the edge of networks for better transmission performance among block creators and verifiers, including the

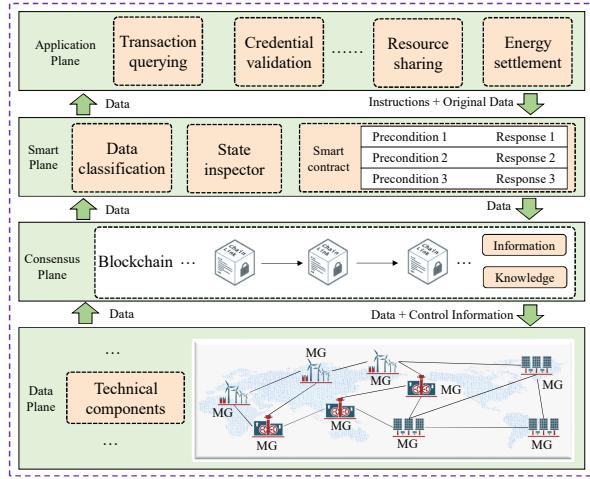


Fig. 2: The framework and components of SBET.

inspection of synchronization, planning for storage allocation, quick query of specific data, etc. To execute those instructions with high-speed, the data plane includes the WEBee [19] in the physical-level data communication among heterogeneous devices across the network and a distributed Deep Reinforcement Learning (DRL) based approach [20] to ensure the security for data collection and data sharing. With the support systems, the data plane is enabled of the extensible property revealing the potential for large-scale energy trading data.

Consensus plane is the plane responsible for reaching consensus on block creation in a distributive manner. Its main technical details are shown in Lines 10-34 of Algorithm 1 and further introduced in Section IV-B. A set of MGs in this plane can interact with each other across the network to reach an agreement on the validation of consistent, immutable blocks, with the aim of maximizing the number of verified transactions as shown in Eq. (5) without any centralized intermediaries. It adopts popular consensuses, such as PoW, DPoS, and PBFT, to accomplish the consensus process among all participating MGs, with the knowledge and information extracted from the data in the upper planes with Deep Learning (DL), DRL, Federated Learning (FL) based solutions to promise reliable communication resource scheduling between MGs [15]. In this manner, the mutual acknowledged data is stored immutably in the block to prevent any further falsification. In fact, the consensus plane additionally facilitates data extraction from the data plane to upper planes and promotes the interconnections between planes in SBET.

Smart plane is the intermediate plane that automatically performs the instructions from application plane. It is responsible for the operations of energy trading data originated from the interactions of MGs, e.g., data querying, settlement and analysis, and offers smart contracts for MGs to execute flexible programs for data management, triggered by certain conditions. For instance, the record of an energy transaction among energy providers and consumers to be queried is instantly sent to the consensus plane by smart contracts. Such data is traceable and irreversible. To ensure authentication and neutrality, the smart plane will follow the principle of BDLP [21], which introduces multiple types of transactions into block

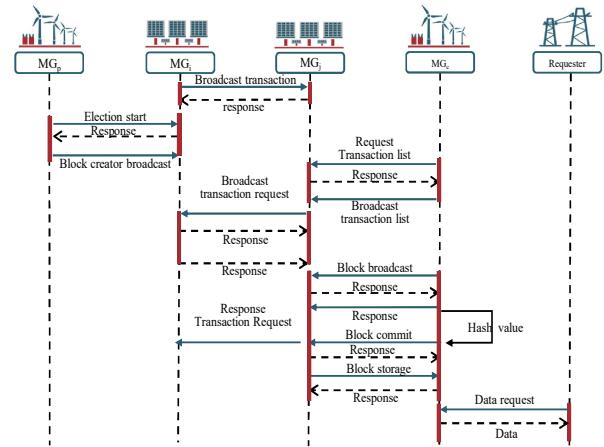


Fig. 3: The consensus process for block creation among all MGs.

creation, to provide a secure environment for the execution of smart contracts. In addition, DL/DRL/FL-based solutions and tools like data classification, optical character reader and decision tree [22], will be adopted in this plane to optimize the ways of storing enormous trading data, promoting efficient utilization of data validation and establishing an advanced microgrid ecosystem. All of these can help to analyze the submitted data to inspect the current energy trading of a user and provide more intelligent, flexible and complex smart contracts for various scenarios. With these properties, the smart plane is able to guarantee better security and automation and reduce related transaction costs associated with contracts across the blockchain networks.

Application plane is the interactive plane that works as the interface for MGs to provide multiple functionalities with completely decentralized services for energy trading with the double-auction-based allocation mechanisms and adaptive aggressiveness technique [6]. This plane integrates existing technologies, such as the fair nonrepudiation service provisioning scheme [23], to develop various APIs and Apps. Typical applications include transaction querying and energy settlement, etc, built on hash values of all transactions and traded energy recorded in blocks. In addition, many other applications will be executed on the combination of application plane and its lower planes. This is a usual case when performing functions like network monitoring, security checking, and access control.

B. Working Principle to Create Energy Trading Blockchain

Technically, the working principle for the creation of scalable energy trading blockchain, as illustrated in Fig. 3, works as follows:

Each e_i broadcasts its trading data, defined in Eq. (1), to other e_u after a waiting time $\zeta_{e_i \rightarrow e_u}$, given by

$$\zeta_{e_i \rightarrow e_u} = [1 - \frac{d(e_u, e_i)}{d_{max}}] \times t_{max}, \quad (6)$$

where t_{max} is the maximum waiting timer of node e_u to guarantee that it can receive the feedback from e_w , $d(e_u, e_i)$ denotes the distance between nodes e_u and e_i , and d_{max} is its maximum transmission range.

All e_1, e_2, \dots, e_n perform consensus to select a node from themselves to create a candidate block, as illustrated in Fig 3, with the received data. First, a pre-specified e_p will broadcast the election message to e_1, e_2, \dots, e_n . Each node e_i , who receives this message, will respond a reply with “Yes” if it is unoccupied, otherwise “No”. Finally, the block creator e_c will be selected in the possibility of p_i from κ MGs $e_1, e_2, \dots, e_\kappa$ who respond with the message “Yes”. Here, p_i is dependent on response time t_i and storage space s_i , and can be given by

$$p_i = \frac{t_i \times s_i}{\sum_{k=0}^{\kappa} t_k \times s_k}. \quad (7)$$

Then, the selected block creator e_c will be broadcasted to all nodes.

The selected block creator e_c will then inform all MGs that a new block is going to be created. All other MGs e_1, e_2, \dots, e_n will respond e_c with the unique serial number list of local transactions which may be partially missing and different with each other. Therefore, e_c will hold a complete list of transactions to be verified which will further be broadcasted to other MGs. The MGs receiving the complete will reply e_c with their response messages.

Once receiving the complete list, each ordinary MG e_i will compare it with its own database with a binary-state variable $D_i(\mathcal{T}_j)$, which is defined as

$$D_i(\mathcal{T}_j) = \begin{cases} 1, & \mathcal{T}_j \text{ is stored in database of } e_i, \\ 0, & \text{otherwise.} \end{cases} \quad (8)$$

If $D_i(\mathcal{T}_j) = 0$, i.e., \mathcal{T}_j does not exist in its database, e_i will broadcast the request to all other MGs to maximize the number of transactions that can be verified, as defined by Eq. (5). Given a node e_j , that holds the deficient data, will reply the request with transaction data and $\text{Hash}(\mathcal{T}_k)$. If the ratio $r(\mathcal{T}_k)$, denoted as $S_{\mathcal{T}_k}/\|\mathcal{T}_k\|$, is larger than γ , e_i will add this transaction to its database, where \mathcal{T}_k is the missing data that e_i requested and $S_{\mathcal{T}_k}$ represents the amount of conforming transaction data of \mathcal{T}_k . Then, e_i will send a response message to block creator e_c to inform its data integrity.

After receiving the response, e_c starts to create a new energy block with complete data and broadcast the candidate block b_k to other MGs. Once receiving it, e_i will check the Hash Value of transactions in their databases through $\text{Hash}(\mathcal{T}_k)$ which can verify the data consistency without data breach. If the data keeps consistent, e_i will broadcast its hash value to all other MGs. Once receiving more than γ same hash values, e_i will send a commit message to e_c . After receiving more than γ commit message, which means that a new block b_k has been created, e_c will inform $e_1, \dots, e_{c-1}, e_{c+1}, \dots$ to add such a block to the ever-increasing blockchain $l(b_1, b_2, b_3, \dots, b_k, \dots)$.

The pseudocode of the proposed SBET to create energy trading blockchain is illustrated in Algorithm 1. It is initialized with the received transaction data of each MG. Then, it sends the receiving data to all MGs and selects a block creator shown in Lines 1-3 and Lines 4-13, respectively. After that, the selected block creator broadcasts a list of transactions to be verified to each MG who then asks the assistance of other MGs to transmit missing data to it, in the form of consensus, as

Algorithm 1: Technical working principle of SBET

Input: Data τ_i and γ

Output: $l(b_1, b_2, \dots, b_k, \dots)$

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1 foreach  $e_i \in \mathcal{E}$  do
2    $e_i \rightarrow \mathcal{E}$  with  $\tau_i$ 
3  $e_p \rightarrow \mathcal{E}$  with election message
4 foreach  $e_i \in \mathcal{E}$  do
5   if  $e_i$  is unoccupied then
6      $e_i \rightarrow e_p$  with “Yes” at  $\xi_{e_i \rightarrow e_u}$ 
7      $e_i \rightarrow \mathcal{E}_{yes}$ 
8   else
9      $e_i \rightarrow e_p$  with “No” at  $\xi_{e_i \rightarrow e_u}$ 
10 foreach  $e_i \in \mathcal{E}_{yes}$  do
11    $p_i = \frac{t_i \times s_i}{\sum_{k=0}^n t_k \times s_k}$ 
12    $c = \arg \max_{i=0}^{i=\|\mathcal{E}_{yes}\|} p_i$ 
13    $e_p \rightarrow \mathcal{E}$  with elected  $e_c$  for block creator
14 foreach  $e_i \in \mathcal{E}$  do
15    $e_c \rightarrow e_i$  with block start message
16    $e_i \leftarrow e_c$  with transaction number list
17 foreach  $e_i \in \mathcal{E}$  do
18    $e_c \rightarrow e_i$  with complete transaction number list  $\mathcal{T}$ 
19    $e_i \rightarrow \mathcal{E}$  with number list of deficient transactions
20 foreach  $e_j \in \mathcal{E}$  do
21   if  $e_j$  receives request for transaction  $\mathcal{T}_k$  from  $e_i$  and  $D_j(\mathcal{T}_k) = 1$  then
22      $e_j \rightarrow e_i$  with  $\mathcal{T}_{kj}$  and  $\text{Hash}(\mathcal{T}_{kj})$ 
23      $\text{Map}(\mathcal{T}_{kj}) += 1$ 
24     if  $\text{Map}(\mathcal{T}_{kj}) \geq \gamma$  then
25       store  $\mathcal{T}_{kj}$  in  $e_i$ 
26    $e_i \rightarrow e_c$  with a commit message
27 foreach  $e_i \in \mathcal{E}$  do
28    $e_c \rightarrow e_i$  with created block  $b_k$ 
29   if  $\text{Hash}(\tau_i) = \text{Hash}(b_k)$  then
30      $e_i \rightarrow \mathcal{E}$  with  $\text{Hash}(\tau_i)$ 
31     if  $\text{Num}(\text{consist Hash}) > \gamma$  then
32        $e_i \rightarrow e_c$  with commit message
33 if  $e_c \text{ Num(commit message)} > \gamma$  then
34    $b_k \rightarrow l(b_1, b_2, \dots, b_k, \dots)$ 

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shown in Lines 14-26. After receiving the commit message, the selected block creator starts to identify the legality and coherence among all MGs, as illustrated in Lines 27-33. Finally, a series of blocks have been created and added into the blockchain illustrated in Line 34.

IV. PERFORMANCE EVALUATION AND POTENTIAL APPLICATIONS

In this section, we evaluate the performance of our proposed framework with blockchain-based experiment platform for energy trading, and investigate its potential applications.

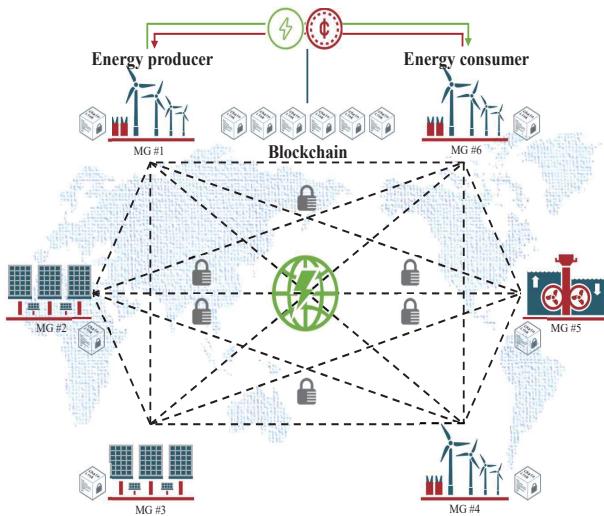


Fig. 4: The blockchain-based experiment platform for energy trading among cooperative microgrids over networks.

A. Performance Evaluation

To evaluate the superiority of SBET, we conduct extensive simulation experiments in the Java environment and compare it with the blockchain-based distributed solutions [6], [7] with popular consensuses PoS and PBFT [15]. For the sake of convenience, the solutions built on PoS and PBFT in [6], [7], respectively, are abbreviated to ETPS and SPFT. All simulations are executed on a universal server, equipped with an Intel(R) Core(TM) i5-9400 CPU@2.90GHz processor and a 16GB main memory. The blockchain-based platform illustrated in Fig. 4 for energy trading data includes 5 MGs (e.g. providers and consumers) serving as block validators and creators with the virtual memory of 28.8MB. There is 278.125KB energy trading stored in 5 MGs in the form of blocks. Each block includes 10 ~ 25 data arrays. The size of block is set to be 19.398KB. The interval period to set up a novel block is 0.5 seconds. Similar to [7], the threshold γ of $S_{T_k}/\|e_i\|$ is set to 2/3. The maximum waiting time t_{max} changes in the range of [0.5, 2.0]s. The popular Distributed Denial-of-Service (DDoS) attack will be launched to some critical MGs in the simulation experiments. Built on these settings, three metrics, referring to block creation time, query latency and query accuracy, have been taken into consideration in our simulation experiments.

1) *Average time of block creation:* Figs. 5 and 6 illustrate the average time of block creation as the time intervals change from 0.5s to 2.0s and block size, i.e., the number of transactions contained in a block, ranges from 10B to 25B, respectively. The data volume added into blockchain is set to be 100 and 200. In detail, the average time of block creation refers to the time taken from the election of the block creator to the generation of a block and adding it to the blockchain, which is counted by simulation programs as the corresponding program running time at each MG.

As shown in Figs. 5 and 6, the average time of block creation gradually increases along with the time interval for all three methods, but behaves as an N-shaped curve when the block size increases especially for ETPS. This means that

block creation time for power trading data is dependent on not only the ever-increasing data and storage resources, but also the block size and time intervals. For each given time interval and given block size, the average time for SBET to create a block is twice as that of SPFT on account of one more round of data exchange of SBET, while that of ETPS is nearly a hundred times than the other two methods due to its complex verification and block generation processes. This indicates that different consensuses, for example, PoS and PBFT, have significant impacts on the block creation. Furthermore, the average time taken by all three methods with data column set as 100 is greater than that with data column set as 200 because the loss of data caused by communication interruption has a greater impact on the average time spent on transaction verification when the total transaction data volume is smaller. In addition, it can be seen from Figs. 5 and 6 that the average time of block creation is basically at the millisecond level, which greatly verifies the feasibility of SBET as a real-time energy transaction verification system in the cooperative microgrids.

2) *Query latency and accuracy:* Figs. 7 and 8 elaborate the query latency and accuracy of the blockchain-based cooperative microgrids. Fig. 7 presents their query delay as the number of block creators changes from 3 to 12, while Fig. 8 shows the query accuracy of SBET, SPFT and ETPS with 10%-40% malicious nodes or missing transactions caused by communication interruption.

In Fig. 7, the query delays of all three blockchain-based methods are around 25ms, which are negligible and verifies the feasibility of SBET in terms of transaction querying in the blockchain-based cooperative microgrids. In contrast, the query delay of the centralized solutions is about 50ms, but has not been illustrated in Fig. 7 since only one node, rather than two or more ones, acts as the server. In Fig. 8, the query accuracy of SBET performs well when the ratio of malicious nodes is not bigger than 33.33%, which follows the working principle of the current blockchain. However, the cost of a single attacker to make more than one-third of nodes malicious in P2P networks far exceeds the profit he/she can get by modifying the transaction. Therefore, the condition that the ratio of malicious nodes is greater than 33.33% rarely happens. Owing to redundant data exchange, the query accuracy of SBET can be guaranteed even if there are less than one-third of transactions missing, caused by communication interruption, while the missing data in the other two methods cannot be stored in blockchain and be queried. These results greatly reflect the advantage of SBET in terms of security and effectiveness at little query latency cost, especially when there are limited bandwidth, long delays, and communication interruption in the cooperative microgrids.

B. Potential Applications

The proposed scalable blockchain-based with redundant data exchange has set up a referential prototype for energy trading data storage over cooperative microgrid networks, due to its inherent merits, namely, the reduced chance of error, detections of hidden frauds and the minimized cost of record

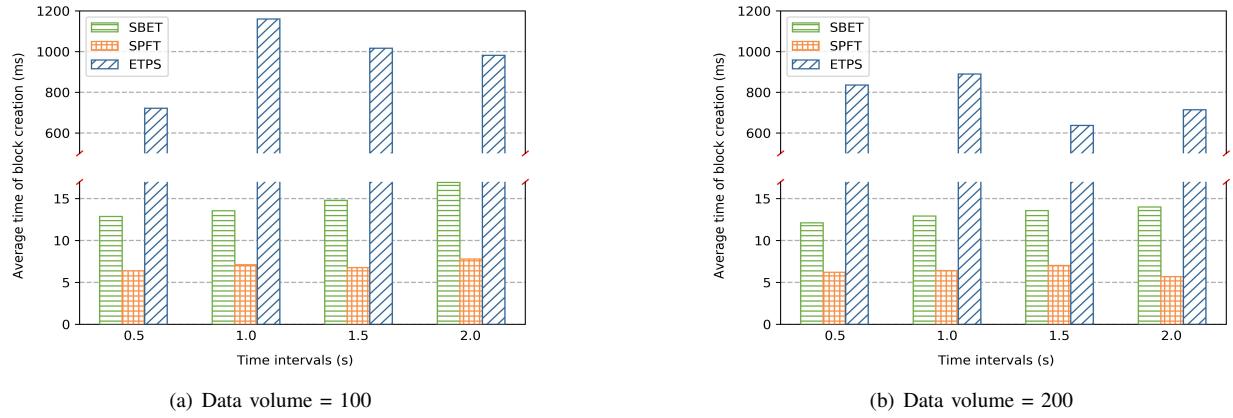


Fig. 5: The average time of block creation as time intervals change from 0.5s to 2s with different data volume.

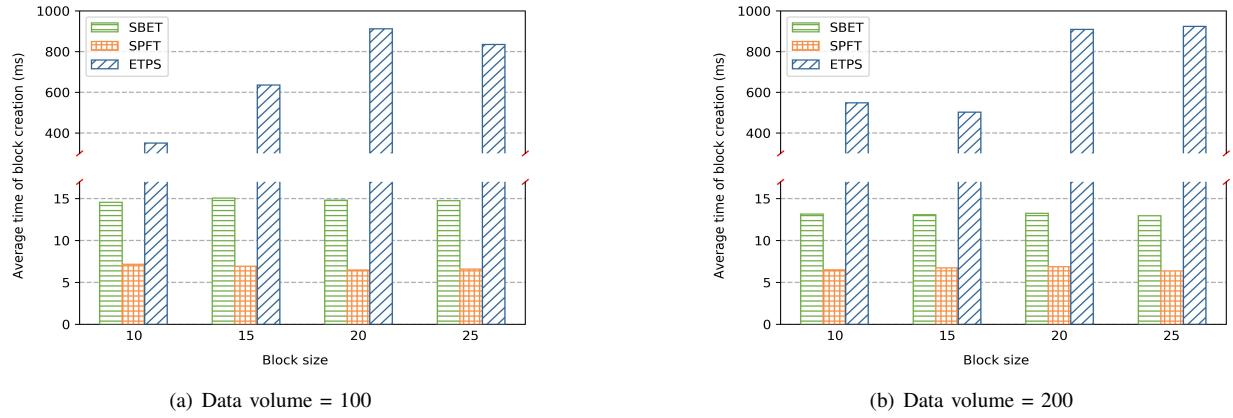


Fig. 6: The average time of block creation as the block size changes from 10 to 25 with different data volume.

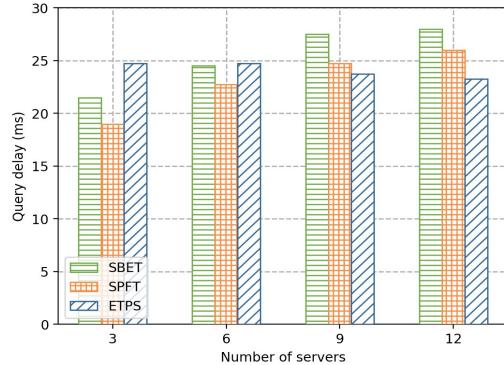


Fig. 7: The query delay as the number of block creators changes from 3 to 12.

storage. With these advantages, it can benefit power consumers by providing efficient and secure data exchange while maintaining transparency and correctness. Potential applications are included, but not limited to, as follows.

Blockchain-based eco-microgrid for industrial parks. An industrial park is considered as a collection of several factories which cooperate and share resources, e.g., energy, materials and natural resources, with each other and own large and varied electricity consumption. The blockchain-based eco-microgrid powered by renewable energy, e.g., solar and wind

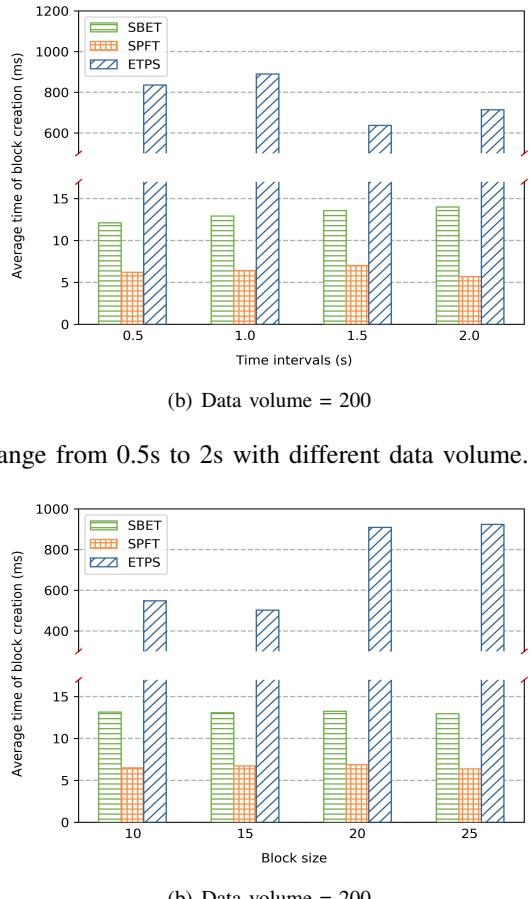


Fig. 8: The query accuracy as the ratio of malicious nodes and missing transactions change from 10%-40%.

sources, greatly reduces environmental pollution and provides stable power supply for enterprise production and work at a lower cost, especially when the utility power grid fails. In addition, Blockchain technology can greatly improve the scalability and reliability of the microgrid transactions in the face of frequent communication and link blockage between equipment and factories.

Blockchain-based smart microgrid for independent islands. Independent islands, far from the mainland, are faced with serious pollution and noise produced by the local thermal

power plant and the high cost of electricity caused by under-sea cables from the mainland. Blockchain-based cooperative microgrid provides the possibility of building an environment-friendly, low-cost, reliable and scalable electric power system for residents and factories of the islands. With this system, abundant renewable resources such as solar, wind and tidal energy can be converted into electricity, which could be further produced and sold locally for residents' production and living use. Meanwhile, blockchain technology guarantees the reliability of energy trading between different microgrids, e.g., photovoltaic microgrids and wind microgrids.

Blockchain-based cost-effective microgrid for remote villages. Currently, some villages have become weak areas in terms of power system due to their remote distance from cities, complex terrain, imperfect infrastructure and sparse population, where the power supply load is small, and power outages caused by faults occur frequently. Blockchain-based microgrid will greatly benefit power distribution system construction in a cost-effective, reliable and scalable manner, with full use of the abundant light and wind resources. In addition, the blockchain-based redundant data exchange proposed in this paper can well combat the frequent interruption of communication in remote villages, so as to ensure the reliability of the transaction and data exchange.

The innovative applications supported by SBET, indicate an important step into the future digital certification ecosystem with openness and security. Those changes in energy exchange are inevitable and more efforts will be made to find insights from the use of credentials and other academic activities while protecting all energy stakeholder' privacy. With these extracted insights, it allows the possibility of making better energy exploitation for students and minimizing potential frauds in the energy field.

V. CONCLUSION

Blockchain, characterized by decentralization, immutability and auditability, has become a promising technology to overcome issues associated with a centralized system in energy trading, and offer grand opportunities to refresh the functionality of energy trading among cooperative microgrids. Based on these observations, in this paper, we have proposed a blockchain-based energy trading framework for cooperative microgrids, which provides a more credible decentralized data warehouse and obtains better service performance compared to previous implementations in microgrids. Moreover, we have outlined potential applications for energy trading among cooperative microgrids. Simulation results with a set of energy trading data illustrate that SBET is superior to related approaches in terms of query delay and accuracy at the acceptable cost of block creation.

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