IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received September 6, 2020, accepted September 17, 2020, date of publication September 28, 2020, date of current version October 8, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.3027192

A Blockchain-Enabled Secure Power Trading Mechanism for Smart Grid Employing Wireless Networks

ZIMING LIU[1], (Student Member, IEEE), DAZHI WANG[1], JIAXING WANG[1], XINGHUA WANG[2], AND HAO LI[3]

[1]College of Information Science and Engineering, Northeastern University, Shenyang 110819, China
[2]School of Humanities and Law, Northeastern University, Shenyang 110819, China
[3]School of Mechanical Engineering, Hubei University of Automotive Technology, Shiyan 442002, China

Corresponding author: Dazhi Wang (neu_7426@163.com)

ABSTRACT The rapid growth of renewable energy has increased the requirements of the smart grid for communication and processing capabilities. As an effective solution to collect and manage information, the wireless network can improve the efficiency of renewable energy management. But due to the wireless data transmission risk and centralized power trading, the smart grid employing wireless networks cannot guarantee the security of the electricity market and the high consumption of renewable energy. Recently, as an emerging data-sharing technology, the blockchain has attracted widespread attention and is considered to have the potential to solve above problems. In this paper, we propose a blockchain-enabled secure power trading mechanism for the smart grid employing wireless networks. The blockchain is introduced to record power data collected by the wireless network, and the smart contract can make reasonable trading decisions based on this. The dual-chain structure composed of local energy trading blockchain and renewable energy trading blockchain improves the efficiency of power trading and renewable energy consumption. To strengthen the stability of renewable energy producers and expand their scale, we also design a blockchain-enabled renewable energy incentive mechanism. Finally, the modified Southern California Edison 56 bus test feeder model validated our mechanism.

INDEX TERMS Wireless network, blockchain, security, power trading mechanism, smart grid.

I. INTRODUCTION

The past years have witnessed the rapid development of the wireless network in various fields [1], [2]. Due to the efficient data collection and communication methods of wireless networks, there are many applications in smart grids, such as wireless automatic meter reading, real-time pricing, and remote meter reading, which provide new technical support for the expanding electricity market [3].

Meanwhile, the production of renewable energy is growing rapidly, according to the survey of the International Renewable Energy Agency Innovation and Technology Centre (IITC), renewable energy will account for 36% of the global grid in 2030 [4]. In this case, the wireless network can effectively monitor renewable energy generation and provide power trading information for users in the electricity market.

The associate editor coordinating the review of this manuscript and approving it for publication was Zhipeng Cai.

The security of wireless networks has become the key to ensuring the stable operation of the smart grid.

The application of wireless network communication provides a new approach for information collection and transmission in the electricity market. However, the smart grid employing wireless networks are facing some challenges while achieving efficient energy management. The traditional electricity market relies on centralized information processing methods to manage power trading data, and the concentrator node in wireless network can accept trading information sent by all user nodes to help the electricity market set the market-clearing price [5]–[7]. This centralized method may cause some security issues such as single-point of failure or performance bottlenecks [8]. Although some distributed approaches use sensor nodes to store and process data, thereby avoiding the security issue caused by the centralized organization [9]–[12], they are hard to deploy distributed power trading in practice due to the lack of trust between consumers and producers. Within this context, the electricity market dominated by renewable energy producers cannot be developed. More seriously, the combination of the smart grid and wireless network exacerbates the above problems during the power trading [13]. Therefore, the electricity market needs a mechanism to ensure the security of power trading and enhance the trust between consumers and producers while making renewable energy is efficiently consumed [14].

Recently, the rise of blockchain technology has promoted the development of research in various fields [15]–[17], and provides promising solutions to above problems [18], [19]. Blockchain is a distributed database technology with features such as decentralization, traceability, transparency, and non-tampering [20]–[22]. Because of its ability to significantly improve trading security, it also has been used to construct power trading mechanisms [23]–[25]. Pieroni *et al.* [26] proposed a blockchain-based P2P power trading mechanism that can bring more possibilities to the power flow. Mengelkamp *et al.* [27] used the blockchain as a trusted communication channel and used smart contracts to match supply and demand. Stadler *et al.* [28] thought that blockchain can be used to build a distributed power trading, and can achieve a balance between energy production and consumption in the local grid. However, these schemes have fail to reduce the barriers to entry in the traditional electricity market, and therefore cannot allow renewable energy retailers to enter. Moreover, they also lack a processing method for overall power trading.

Motivated by the above challenges, we propose a blockchain-enabled power trading mechanism for smart grid employing wireless network. The proposed mechanism is built in an active distribution network (ADN), which has a high penetration rate of renewable energy resources, and meets the optimal power flow (OPF) constraints. We introduce the local energy trading blockchain (LETB) to record and publish information on the local electricity market, and use the regional renewable energy trading blockchain (RETB) to record renewable energy producers information. The dual-chain structure composed of LETB and RETB can consume renewable energy in different regions in stages while ensuring trading security. Consumers will trigger smart contracts in LETB and RETB in turn to generate distribution plans based on their demand. Then the smart contract comprehensively considers attributes such as the reputation, capacity, and bidding price of the producers in the grid to match power trading and publish the distribution plan. After the power distribution is completed, consumers will give feedback to the blockchain based on the quality of the power distribution. The smart contract can be triggered to modify the reputation value of the producer and pay the reward based on the feedback result. Specifically, the main contributions are given as follows.

1) We propose a distributed power trading decision-making method in the smart grid. By introducing blockchain and smart contracts to transmit data and make-decision in the wireless network, the trust and security issues of centralized power trading are solved.
2) We design a distributed power trading mechanism to reduce consumers' electricity purchase costs and the grid burden. The proposed mechanism consists of smart contracts on the LETB and the RETB, which can reasonably consume local energy storage and regional renewable energy in stages.
3) We design a blockchain-enabled incentive mechanism for renewable energy power trading to encourage producers expanding the scale and improving the quality of power generation. The smart contract can automatically and fairly pay remuneration to renewable energy producers according to the incentive algorithm.
4) We use the Ethereum blockchain and Southern California Edison (SCE) 56-bus test feeder to demonstrate the specific implementation of the blockchain-enabled distributed power trading mechanism.

The progress of this article is as follows: In the next section, we introduce some related works. In Section III, we model the system and solve it under the constraints of OPF. Section IV describes the approach. Section V models of case studies and simulation results. Section VI summarizes this article and describes future work.

II. RELATED WORK

This section review some of the latest work on electricity markets, power trading mechanisms, and briefly introduces blockchain technology.

A. TRADITIONAL APPROACHES

In the initial stage of electricity market construction, various countries, such as the United States (PJM, New York) and Australia [6], adopted a centralized structure due to higher resource allocation efficiency. The centralized structure can obtain all the information of the participants, including the demand characteristics of all consumers, the supply characteristics of all producers, and the relevant internal and external constraints. Give this context, if regulators with sufficient calculation and analysis capabilities can make decisions to maximize social welfare, then the centralized power trading can achieve the result of maximizing social welfare. Oviedo *et al.* [7] proposed that the centralized structure has a lower deployment cost, but relatively distributed architecture requires higher information processing capabilities. With the advancement of wireless networks, wireless sensor networks have gradually become a key technology to collect and process power trading information. Kim and Jin [29] designed a branch-based wireless sensor network, which can efficiently collect the power consumption data of each user in a centralized power trading without conflicts due to the time synchronization of smart meters. The electricity market with centralized power trading is common, but the centralized structure will bring centralization issues, such as single points of failure. Worse still, considering the application of wireless networks, its data transmission risks may exacerbate the above security problems.

In recent years, the distributed power trading has gradually become a hot research topic, which has been preliminarily explored by Piclo [30] and Sonnen community [31] in practice. The distributed market structure is more suitable for smart grids where renewable energy accounts for a relatively large proportion, and combined with the wireless network can better consume renewable energy. Shen *et al.* [32] given a multi-level model combined with energy storage systems. By combining distributed generations, energy storage systems, and the network, Yu *et al.* [33] provided a regional autonomous energy system and defined the power supply and energy storage capacity index in the system. Nick *et al.* [34] through the optimal allocation of the multi-objective optimization of the distributed energy storage system, so that the system can achieve a balance between economic goals and technical requirements. Although the proposed approaches alleviate the voltage deviation, eliminate line congestion and reduce the load and the operating cost, traditional optimized control cannot effectively absorb renewable energy locally, and centralized power trading management may also cause single-point failures and performance bottlenecks. Similarly, the power trading between consumers and producers has also been explored in [35] and [36]. Tushar *et al.* [37] used the mid-market price as the pricing mechanism of the proposed P2P trading and proposed the canonical coalition game framework, to ensure that honest producers can get steady profits. Particularly, these schemes do not consider how to overcome the price barriers imposed by the existing electricity market, and these distributed power trading mechanisms are difficult to deploy due to the mistrust between consumers and producers.

B. BLOCKCHAIN AND RELEVANT APPROACHES

1) BLOCKCHAIN AND SMART CONTRACT

Blockchain is originally the distributed database technology behind the Bitcoin project [38]. The data on the blockchain is stored in blocks. In a block, the part that stores data is called the block body, and the part that stores the hash of the previous block, the hash of the block body and the time stamp, etc. is called the block header. The data in the blockchain is stored by all nodes in the network, and these nodes are agreed on the blockchain through a consensus mechanism. The hash of the previous block can be regarded as a pointer. These pointers make all blocks form a chain from back to front. If the adversary wants to modify the data stored in a block, all blocks after this block need to be changed, which is difficult to achieve. In addition, according to this chain structure, any information also can be traced back by the nodes in the blockchain [39]. The blockchain can be divided into three categories based on different access mechanisms: public, consortium, and private blockchain. The public blockchain can be accessed by all nodes, is completely decentralized, and has high security. The consortium blockchain is maintained by some more influential authority nodes with higher blockchain transaction throughput. And the private blockchain is usually used to store data distributed among trusted nodes within the organization.

The emergence of smart contract technology has greatly expanded the functions of the blockchain [40]–[43]. A smart contract is a piece of program code running on the blockchain. In the Ethereum blockchain platform that first proposed the concept of smart contracts, every node needs to deploy an Ethereum virtual machine (EVM) [44]. When the smart contract is called by a blockchain node, all nodes run programs in their local EVM and use the consensus mechanism to produce a consistent result. Profited from Turing's complete smart contract language, smart contracts can implement more complex algorithm functions, and have broad application prospects in power trading scenarios.

2) BLOCKCHAIN-BASED APPROACHES

Recently, the emergence of blockchain technology has promoted the development of distributed power trading mechanisms and demand-side management, which has brought new ideas for electricity market managements [41]. Li *et al.* [45] used blockchain technology to record the information of consumers and producers in the real-time electricity market. According to the openness and transparency of the blockchain, the two sides can safely exchange their power information, thus improving the security of the power system without significantly affecting the operation cost. Park and Kim [46] used blockchain to validate the electricity market in the smart grid to supervise consumers and producers who are not fully trusted. Liu *et al.* [47] introduced a blockchain-based trading model into electric vehicle power trading, in which the proposed trading mechanism can improve the economics of both buyers and sellers of electric vehicles. Kang *et al.* [48] designed a blockchain-enabled trading model for electric vehicles in the smart grid. The incentive mechanism in the smart contract encourages electric vehicles to release energy to balance local power demand and achieve demand response. It can be seen that blockchain-based approaches provide a security guarantee for power trading and can also incentivize users. However, the above solutions are based on the existing centralized electricity market and cannot be adapted to the distributed environment. In addition, since the price model of OPF is not considered, it is difficult to accurately reflect the actual power demand. Therefore, the power trading mechanism based on the blockchain needs further research to make it reasonable.

III. PROBLEM FORMULATION

This section introduces the operation model in ADN, the system model of our blockchain-enabled distributed power trading mechanism and our design goals. Some of the necessary symbols are shown in **Table 1**.

A. OPERATION MODEL

The operation model of our mechanism includes following entities: regulated power plants, distributed renewable

TABLE 1. Symbols and definitions.

Symbol	Definition
$P_{G,i}$	Active power of generation node i
$Q_{G,i}$	Reactive power of generation node i
P_{DGi}	Active power generated by solar panel at the node i
P_{static}	Static mathematical model of uncontrollable loads' active power
Q_{static}	Static mathematical model of uncontrollable loads' reactive power
SoC	State-of charge of energy storage device
$P_{i,t}^{load}$	Injected power of the load at the node i
P^{loss}	Active power loss of the ditribution network
P_t^{cha}	Charging power of the ESS in the system at time t
P_t^{dis}	Discharge power of the ESS at time t
P_t^{sl}	Injected power of the slack bus in the grid at time t
S_i	Apparent power node i
C_{MCP}	Active power market clear price coefficients
P_{DG}	Power of renewable energy generation
C_{stor}	Price coefficients of local energy storage cost
P_{stor}	Power of local energy storage
m	Power demand of consumer
rt	Threshold reputation of consumer
p	Local producer
es_p	Energy storage of local producer
r_p	Reputation of local producer
t_d	Accumulated stable power generation time of renewable energy producer
T_D	Period of consumer's demand
T_d	Period of renewable energy producer stable generation
m_d	Capacity of renewable energy producer

energy generating units, controllable loads, uncontrollable loads and energy storage batteries. Their specific definitions are as follows, where i denotes the bus index of the distribution system, t denotes the time period, V_{imin} represents the lowest value of the node voltage that meets the power system standards, and V_{imax} represents the highest value of the node voltage that meets the power system standards.

1) REGULATED POWER PLANT

The regulated power plant is mainly controlled power generation node set G includes small thermal power units, gas turbines, and fuel cells. The constraint conditions for active power and reactive power must meet are:

$$P_{Gi,min} \le P_{Gi,t} \le P_{Gi,max} \tag{1}$$

$$Q_{Gi,min} \le Q_{Gi,t} \le Q_{Gi,max} \tag{2}$$

For $i \in G$ at t are considered to have quadratic cost functions as $C_{i,t}(P_{Gi,t}) = \alpha_{i,t}P_{Gi,t}^2 + \beta_{i,t}P_{Gi,t} + \gamma_{i,t}$. In the above model, $P_{Gi,t}$ is the active power of generation node i at time t. $Q_{Gi,t}$ is the reactive power of generation node i at time t. In order to ensure the power quality and power supply safety requirements, node i should meet the constraints (1) and (2).

2) DISTRIBUTED RENEWABLE ENERGY

Renewable energy generation is mainly photovoltaic (PV) generation in this paper.

$$P_{DGi,min} \le P_{DGi,t} \le P_{DGi,max} \tag{3}$$

The active power generated by the solar panel at the i node at time t satisfies the above constraints, where $P_{DGi,max}$ and $P_{DGi,min}$ are the upper and lower limits of photovoltaic power output, respectively.

3) CONTROLLABLE LOADS

Electric vehicles (EV) is the main controllable load in the power system. We define the controllable loads as $S_{i,t} = P_{i,t} + jQ_{i,t}$ for $i \in CL$ (controllable loads node set). For example, the electric vehicle from appliances with flexible power profile but fixed energy demand $E_{i,demand}$ in 24 h. The mathematical model of controllable load is as [49]:

$$E_{i,demand} = \sum_{t=1}^{T} S_{i,t}\Delta t \tag{4}$$

where, T is the length of the time-horzion and Δt is the time interval. $S_{i,t} = 0$, for $t = 1, \ldots, t_{i,start}, t_{i,end}, \ldots, T$.

4) UNCONTROLLABLE LOADS

Uncontrollable loads mainly include street lights, medical institutions and other non-power-off or power-limiting loads in general. The static mathematical model is given as:

$$P_{static} = P_N[a_p(v/v_n)^2 + b_p(v/v_n) + c_p)] \tag{5}$$

$$Q_{static} = Q_N[a_q(v/v_n)^2 + b_q(v/v_n) + c_q)] \tag{6}$$

where V_N is the rated voltage, P_N and Q_N are the active and reactive power at the rated voltage, respectively. Each coefficient can be obtained by the least square method fitting according to the actual voltage static characteristics.

$$a_p + b_p + c_p = 1 \tag{7}$$

$$a_p + b_p + c_p = 1 \tag{8}$$

Equations (5) and (6) show that the active power and reactive power of the uncontrollable loads are composed of three parts, the first part is proportional to the square of the voltage and represents the power consumed by the constant impedance, the second part is proportional to the voltage and represents the power corresponding to the constant current load, the third part is the constant power component.

5) ENERGY STORAGE SYSTEM

Energy storage systems (ESS) are devices that can store and release energy. They play a vital role in the reliability and power quality of power systems [50].

$$E_{i,t} = E_{i,t-1} + \Delta T(P_{i,t}^{cha}\eta_{cha} - P_{i,t}^{dis}\eta_{dis}) \tag{9}$$

$$P_{i,t} = P_{i,t}^{dis} - P_{i,t}^{cha} \tag{10}$$

$$E_{i,c}SoC_{min} \le E_{i,t} \le E_{i,c}SoC_{max} \tag{11}$$

$$0 \le P_{i,t}^{cha} \le P_{i,max}^{cha} \tag{12}$$

where $E_{i,t}$ represents the energy storage of the energy storage element located at node i at time t. Its upper and lower limits are determined by $E_{i,c}SoC_{max}$ and $E_{i,c}SoC_{min}$ as the charging efficiency and discharge efficiency, $E_{i,c}$ is the rated capacity, SoC_{min} and SoC_{max} $\in(0,1]$ are the minimum and maximum state of charge, which prevent the battery from overcharging and overdischarging. $P^{cha}_{i,max}$ and $P^{dis}_{i,max}$ are the maximum charge and discharge powers, respectively.

6) NETWORK LOSS OF DISTRIBUTION NETWORK

The active power of the branch i, j can be expressed as:

$$P_{ij,t} = U^2_{i,t}G_{ij} - U_{i,t}U_{j,t}(G_{ij}\cos\delta_{ij} + B_{ij}\sin\delta_{ij}) \quad \forall t \in T, \forall(i,j) \in J \tag{13}$$

where, $G_{ij} + jB_{ij}$ is the admittance of the branch. Therefore, the active power loss of the branch can be expressed as:

$$\begin{aligned} P^{loss}_{ij,t} &= P_{ij,t} + P_{ij,t} \\ &= (U^2_{i,t} + U^2_{j,t})G_{ij} - 2U_{i,t}U_{j,t}G_{ij}\cos\delta_{ij} \end{aligned} \tag{14}$$

Since δ is usually very small, $\cos\delta_{ij} = -\delta^2_{ij}/2$. Substituting this into Equation (14) can be obtained:

$$P^{loss}_{ij,t} = (U_{i,t} - U_{j,t})^2G_{ij} + (\delta_i - \delta_j)^2U_{i,t}U_{j,t}G_{ij} \tag{15}$$

The voltage amplitude is not sensitive to changes in the active power injection, so it can be regarded as a constant value. Therefore, the change part of the system network loss is only related to the node active power injection, which can be expressed as:

$$P^{loss}_t = \sum_{ij}(\delta_i - \delta_j)^2U_{i,t}U_{j,t}G_{ij} \tag{16}$$

B. SYSTEM MODEL

We propose a blockchain-enabled distributed power trading mechanism in the distributed electricity market. There are four kinds of participants in our scheme: the consumer, the local producer, the renewable energy producer and the grid. The details of them are described as follows.

- **Consumer,** who is the party with power demand in the electricity market, and will purchase power from local producers, renewable energy producers and grid, including the uncontrollable loads, controllable loads and ESS proposed in the system model.
- **Local producer,** who is an entity that is geographically similar to the consumer, can generate power through rooftop photovoltaics and sell the electrical energy stored in ESS.
- **Renewable energy producer,** who is mainly the distributed photovoltaic power plant, and provides energy for the electricity market.
- **Grid,** who is consists of other large power plants and regulated power plants, which can supply power to consumers when other producers cannot meet their demand.

In our scheme, each participant is connected to a blockchain network and is able to use the blockchain function. We assume that every participant is rational and will not act against their interests, that is, consumers will pursue the lowest electricity purchase cost and better power quality. In addition, local producers and renewable energy producers will also not set unreasonable electricity prices.

C. DESIGN GOALS

In this paper, we aim to meet the OPF designing a system that can combine the advantages of blockchain and distributed power trading. We propose the energy balance formula in the system, and transformed the operation model proposed in subsection A into a second-order cone programming (SOCP).

For each bus i, Let $S_i = P_i + jQ_i$ be node i's net complex power injection. The ADN we build meets the following power balance.

$$\sum_{i=1}^{n-1} P^{load}_{i,t} + P^{loss}_t + P^{cha}_t = P^{dis}_t + \sum_{i=1}^{n-1} P^{DG}_{i,t} + P^{Sl}_t \tag{17}$$

where $P^{load}_{i,t}$ represents the injected power of the load, P^{loss}_t represents the active power loss of the grid, P^{cha}_t represents the charging power of the ESS in the system at time t, P^{dis}_t is the discharge power of the ESS at time t, $P^{DG}_{i,t}$ represents the photovoltaic generation in the system at time t, P^{Sl}_t represents the injected active power of the slack bus in the grid at time t.

Equations (1)-(17) constitute a non-linear programming (NLP) problem. At the same time, because of the non-convexity of the power flow equation, it is difficult to obtain the global optimal solution. The second-order relaxation can transform the original problem into a convex optimization.

$$\begin{cases} U_{j,t} = u^2_{j,t} & \forall t \in T, \forall j \in J \\ I_{ij,t} = I^2_{ij,t} & \forall t \in T, \forall(i,j) \in J \end{cases} \tag{18}$$

$$\begin{aligned} &P_{ij,t} - r_{ij}I_{ij,t} \\ &\quad = \sum_{k\in v_j} P_{kj,t} + P^{load}_{j,t} + P^{cha}_{j,t} \quad \forall t \in T, \quad \forall(i,j) \in J \end{aligned} \tag{19}$$

$$\begin{aligned} &Q_{ij,t} - x_{ij}I_{ij,t} \\ &\quad = \sum_{k\in v_j} Q_{kj,t} + Q^{load}_{j,t} \quad \forall t \in T, \quad \forall(i,j) \in J \end{aligned} \tag{20}$$

$$\begin{aligned} &U_{j,t} \\ &\quad = U_{i,t} - 2(r_{ij}P_{ij} + x_{ij}Q_{ij,t}) + (r^2_{ij} + x^2_{ij})I_{ij,t} \\ &\qquad \forall t \in T, \quad \forall(i,j) \in J \end{aligned} \tag{21}$$

where $U_{j,t}$ is the voltage of node j at time t, P_{ij} is the active power transmitted by line (i, j) at time t, r_{ij} and x_{ij} are the resistance and reactance of line (i, j), $P^{load}_{j,t}$ and $Q^{load}_{j,t}$ are the active and reactive power transmitted by line (i, j) at time t, respectively. v_j is a subset of node set J. The original problem is further transformed into second-order cone programming as follows. Using commonly used commercial solvers such as CPLEX, MOSEK, etc. can quickly find the global optimal solution.

$$\left\| \begin{matrix} 2P_{ij,t} \\ 2Q_{ij,t} \\ I_{ij,t} - U_{j,t} \end{matrix} \right\|_2 \le I_{ij,t} + U_{j,t} \quad \forall t \in T, \quad \forall(i,j) \in J \tag{22}$$

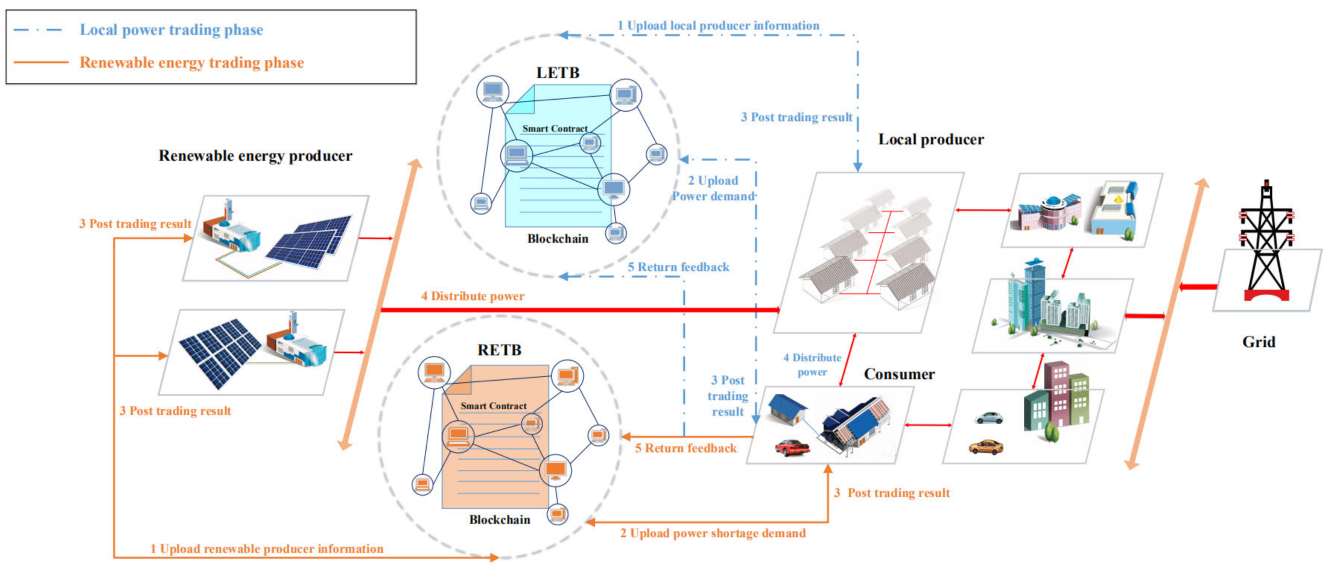


FIGURE 1. The framework of the blockchain-enabled distributed power trading mechanism.

The objective function is the OPF model of the open electricity market with the smallest active power purchase cost settled at the marker clear price:

$$minF = P_{loss}+C_{MCP} \cdot \sum_{i=1}^{n} P_{DG,i}+C_{stor} \cdot \sum_{i=1}^{n} P_{stor,i} \tag{23}$$

While satisfying OPF constraints, we established the objective function of the system. The cost of active power purchase according to the market clearing price is defined by $C_{MCP} \cdot \sum_{i=1}^{n} P_{DG,i}$ (C_{MCP} are the active power market clear price), in addition to the thermal losses that are characterized by P_{loss}. The cost of local energy storage is expressed by $C_{stor} \cdot \sum_{i=1}^{n} P_{stor,i}$. Therefore, in our trading mechanism, the electricity price for consumers should meet the constraint of equation (24).

In addition, our trading mechanism should also meet the goal of effectively conducting distributed power trading in the distributed electricity market, and incentivizing renewable energy producers to provide stable power and expand their power generation scale.

IV. APPROACH

In this section, we introduce the power trading mechanism of the blockchain-enabled distributed electricity market. Main operations of the system are illustrated in Fig.1.

A. OVERVIEW

Our approach is divided into three phases: initialization phase, local power trading phase and renewable energy trading phase. In the initialization phase, the LETB and RETB blockchain networks will be established in various regions, and each entity in the electricity market will join the corresponding blockchain. Subsequently, in the local power trading phase, consumers and producers public their demand and capacity in the LETB, so that the smart contract can arrange power distribution plans reasonably. After the local power distribution is completed, the smart contract will modify the reputation value of each producer based on consumers' feedback and give them incentives. Furthermore, the approach enters the renewable energy trading phase when local power distribution fails to meet consumers' demand. The remaining power is completed by the renewable energy producers through smart contract matching to complete the power distribution plan. If the above operation fails to meet the load power plan, the local grid will supply the remaining power as a backup.

B. INITIALIZATION PHASE

In this phase, consumers and producers belong to similar geographical locations establish the LETB network based on the consortium blockchain, and select some entities with a high reputation as the authorized nodes to maintain the LETB. Meanwhile, renewable energy producers and consumers set up RETB networks. Then, consumers join nearby LETB and RETB, local producers join nearby LETB, and renewable energy producers join nearby RETB. They publish some identity information in these blockchains for registration. The smart contract assigns each registered entity an initial reputation value r_p, which can change as the trading progresses. By doing so, the reputation value as a basic affects the trading order of producers in power trading, which further affects the economic benefits of them. More specifically, producers can increase their reputation value through successful trading and enhance their competitiveness. In contrast, the poor power generation effect will also reduce their reputation.

Then, the nodes in the blockchain will set the locational marginal price (LMP). LMP is a pricing constrain, if the producer's bidding price is higher than LMP, the power trading will not proceed. Based on the theoretical basis of real-time electricity price, the Lagrangian function formed by the goals and constraints, where the Lagrangian constraint factor for node injection power balance is the corresponding marginal cost of the node injection power. Therefore, the blockchain nodes call the smart contract to calculate LMP according to the following equation.

$$\rho_{pi} = \lambda_{pi} = \frac{\partial C_{pi}(P_{Gi})}{\partial P_{Gi}} - \eta_{min} + \eta_{max}$$
$$\rho_{qi} = \lambda_{qi} = \frac{\partial C_{qi}(Q_{Gi})}{\partial Q_{Gi}} - \xi_{min} + \xi_{max} \tag{24}$$

where pi and qi are the node injected power, λ_{pi} is the node injected power-constrained Lagrange multiplier, η is the generator set active power-constrained Lagrange and ξ is the Lagrange multiplier of the generator reactive power constraint. Finally, LMP will serve as the basis for retail investors to determine the price of renewable energy in our distributed power trading. And to make the economic effect obvious, the price should be higher than the feed-in tariff (the pricing mechanism is not within our scope) [51].

C. LOCAL POWER TRADING PHASE

In the local power trading phase, local producers provide power to consumers under the guidance of LETB's smart contracts. We use p to denote the local producer, the special details are shown as follows.

- **Step 1**: [Upload local producer information].

The local producer p triggers the smart contract to upload his information (es_p, v_p) to LETB, where es represents the salable local storage, v represents the local energy storage bidding price. Whenever a producer uploads information, the smart contract will execute a sorting algorithm to sort all producers according to their bidding price.

- **Step 2**: [Upload power demand].

The consumers' power demand will trigger the smart contract in LETB to upload consumer information for local trading. Specifically, the consumer uploads (m, rt) to LETB, in which m is the consumer's power demand and rt is the reputation threshold value of local producers. Then, the smart contract generates the results of this trading according to the consumer's power demand. The smart contract will select some local producers that satisfy $r_p \geq rt$ according to the order of bidding price from low to high, until the sum of es_p of all the selected producers can meet the consumer's demand, or all producers have been selected (as shown in **Algorithm** 1). Finally, the power trading results will be published on the blockchain.

- **Step 3**: [Distribute power].

According to the running results of the smart contract in the previous step, blockchain will convey the information to the transmission and distribution system operator (TSO) completes the distribution plan. In this step, we assume that producers will not cancel the trading, and the power trading information is accurately provided by the smart meter. At the same time, TSO and the power trading blockchain network will continue to check and confirm the information to ensure that each power trading can be completed correctly.

Algorithm 1 Local Energy Trading

Input: m, rt, $(es_{p1}, \ldots, es_{pn})$, $(r_{p1}, \ldots, r_{pn})$;
Output: Local power trading results;

for all $k = 0$; $k < n$ and $m > 0$; $k{+}{+}$ **do**
  if $es_{pk} \neq 0$ and $r_{pk} > rt$ **then**
    if $m >= es_{pk}$ **then**
      $m \leftarrow m - es_{pk}$;
    else
      $m \leftarrow 0$;
    end if
    $es_{pk} = 0$;
  end if
end for
return Local producer sort $p_1, \ldots, p_k$

- **Step 4**: [Return trading feedback].

After power distribution is completed, the consumer will return feedback to LETB and pay the cost of electricity. We assume that this process is automatically completed by the consumer's smart meter device, which is impossible to cheat. Then, receiving this feedback, the smart contract on LETB adjusts the reputation value of the relevant producers. The reputation value of the producers who successfully complete the power distribution plan will be increased, and they will have a greater advantage in the next power distribution plan. While the reputation of producers with poor power quality will be reduced. Finally, the electricity price will be paid to the corresponding producers.

D. RENEWABLE ENERGY TRADING PHASE

If the consumer's power demand has not yet been met after the local power trading is completed, the approach enters the renewable energy trading phase. Renewable energy producers can trading with consumers through smart contracts in the blockchain to meet the demand. Specific steps are illustrated as follows.

- **Step 1**: [Upload renewable energy producer information].

Similar to the step 1 in the above phase, renewable energy producers in the electricity market should upload their information $d(\Delta T_d, m_d, C_d, t_d)$ to the blockchain network, where ΔT_d is the expected stable generation period of renewable energy, m_d indicates the available power supply capacity, C_d is the new energy producer's expectations electricity price, t_d is the cumulative supply time of new energy generation. To improve the accuracy of the power distribution plan, it is necessary to continuously enrich the information contained in each consumer in the distribution system (weather conditions, the nature of the power unit, market fluctuations, etc.).

- **Step 2**: [Trade renewable energy on RETB].

Local energy storage often fails to meet the power demand of consumers, so there may be a power supply shortage

Δm after local energy storage and residual power trading phase. The power shortage is provided by the distributed generation of renewable energy in priority. When there is a power shortage, the consumer will upload the power shortage to the RETB, Δm will trigger the smart contract of the RETB. According to the information in RETB, the renewable energy power generation node d will be found under the OPF condition. When the consumer's demand period T_D is within the stable generation period T_d of renewable energy producer and the power demand shortage of the consumer Δm is less than the generation capacity m_d of renewable energy producer, the system matches the consumer with the appropriate generation node through the RETB network (as shown in **Algorithm** 2).

Algorithm 2 Regional Renewable Energy Trading

Input: $\Delta m, T_D$;
Output: The renewable energy producer, d;

1: **for all** d such that $d \in D$ **do**
2: Upload node $d(\Delta T_d, m_d, C_{REG}, t_d)$;
3: **end for**
4: **while** $T_D \subset \Delta T_d[T_{start}, T_{end}]$ **and** $\Delta m < m_d$ **do**
5: Selecting node d from D;
6: renewable energy generation matching;
7: $t_d = t_d + T_D$;
8: **end while**
9: **return** $d(\Delta T_d, m_d, C_{REG}, t_d)$

• **Step 3**: [Distribute power].

Similar to the previous phase of the distribution power process, TSO completes the distribution plan between renewable energy producers and consumers according to the result of the smart contract.

• **Step 4**: [Return feedback and implement incentive].

After each renewable energy producer completes its distribution plan, the consumer returns the feedback of the completion of this distribution plan through the blockchain. According to this feedback, the smart contract on the RETB gives an incentive to renewable energy producer node d that completes the distribution plan, and the expected electricity price of node d is as follows:

$$C_d = C_{REG} \cdot [1 + \log_k(x + 1)] \tag{25}$$

where C_d is the electricity price after the incentive, C_{REG} is the current basic electricity price of renewable energy, k is the difficulty adjustment coefficient, x is the comprehensive parameter equation of the power supply unit, which is defined as $x = P \cdot t_d + s$. In this formula, P represents the scale of power generation, s represents the node's power generation stability during the ΔT period, $t_d \geq 0$ is the accumulated stable generation time of renewable energy producer. Renewable energy producers incentive function aims to encourage power producers to increase the construction and investment of renewable energy producers. Meanwhile, stable power generation performance and long cumulative

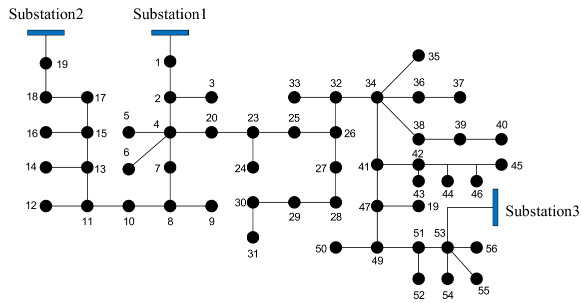


FIGURE 2. The SCE 56 bus feeder node figure.

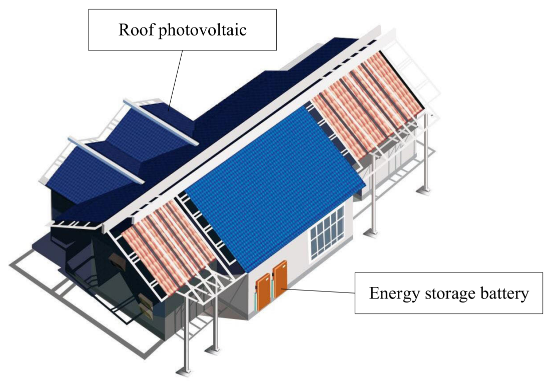


FIGURE 3. The household energy storage and rooftop photovoltaic.

power generation time can bring better economic benefits to power producers. Incentives $I = C_d - C_{REG}$ are tokens given to producers, and the incentives are economically realized by government agencies or grid operators.

Finally, if the power supply is still insufficient, the ADN will obtain power from the regional grid nearby, and finally complete the distribution plan.

V. EVALUATION

This section analyzes the on-chain part performance and the off-chain part performance separately to illustrate the feasibility of our approach.

A. EXPERIMENT ENVIRONMENT

The electrical data of our approach are simulated in Windows with an Intel Core CPU I7-9750H @ 2.60Ghz. We chose the SCE 56 bus test [52] as the platform to build the distribution network. It is a lightly loaded rural distribution feeder. In this distribution network, we integrate a 1 MW and a 0.8 MW photovoltaic power station. California Independent System Operator (CAISO) [53] generates a reasonable load distribution for 24 hours. Fig. 2 shows our modifications to the SCE 56-bus test feeder.

Rooftop photovoltaic and energy storage batteries are installed on home users on the SCE 56-bus test feeder as shown in Fig. 3. The 1 MW and 0.8 MW photovoltaic power stations are integrated on nodes 53 and 19 respectively.

We set that the energy storage battery of each consumer is charged via rooftop photovoltaic devices during the day

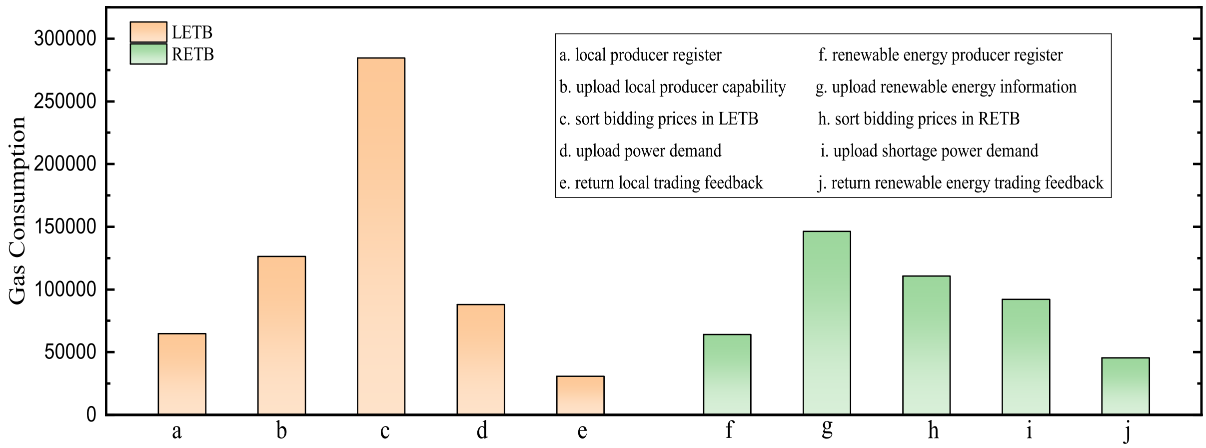


FIGURE 4. The average gas consumption.

and the consumer's power demand is less than the battery energy storage. In addition, we use Ethereum Geth client to build a consortium blockchain and a private blockchain to simulate LTEB and RETB respectively, and test the overhead of performing operations.

B. RESULTS AND DISCUSSIONS

In the experiment, we test the gas consumption, electricity cost and grid load under the experimental environment to show the advantages of the operating effect of our system and the effectiveness of our algorithm.

1) GAS CONSUMPTION

In the smart contract of Ethereum, each operation requires a certain amount of gas, so the gas consumption can reflect the overhead of performing operations on the blockchain.

Fig. 4 shows the gas consumption of the main operations that need to be executed on the blockchain in our scheme. Among them, operations a, b, c in LETB and f, g, h in RETB are respectively performed by local producers and renewable energy producers, and the rest of the operations are performed by the consumer. We can see that sorting the producer's bidding price consumes the main number of gas. In addition, due to the large number of producers in LETB, the operation c consumes about 280,000 units of gas. By contrast, the number of renewable energy producers in RETB is smaller than the number of local producers in LETB, consuming about 110,000 units of gas. The rest of the operations are mainly to store data on the blockchain, and their gas consumption does not exceed 150,000, which is acceptable to all nodes in the system.

2) LOAD ANALYSIS

In this experiment, we test the grid loads in different scenarios to show the effectiveness of our approach. We compare the power changes of the SCE 56-bus feeder before and after blockchain-enabled power trading according to the energy trading situation.

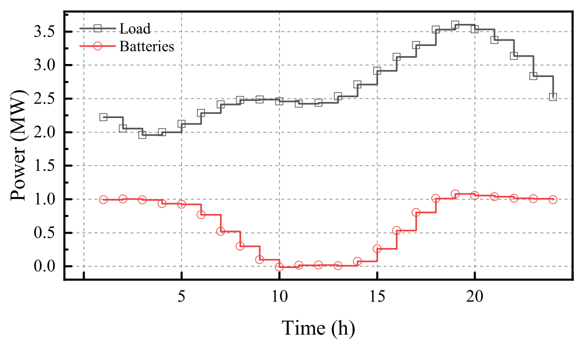


FIGURE 5. The power curve of load demand and battery powered.

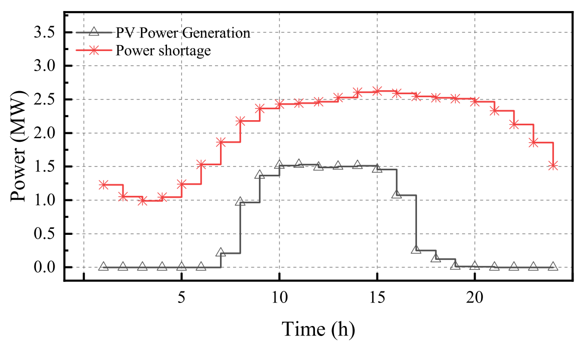


FIGURE 6. The power curve of power shortage and PV power generation.

Fig. 5 describes the change in load and local energy storage within 24 hours. The two peaks of power consumption of the load appear at 8 A.M. and 8 P.M. respectively. Local energy storage provides more power from 8 P.M. to 5 A.M. the next day. It can be seen from Fig. 5 that after 5 A.M. the next day, the local producer's batteries provide power for consumers distributed electricity market. However, due to the limitations of the current storage battery hardware facilities, the total power provided by local energy storage is still insufficient for the system.

Fig. 6 shows the changes in the consumer's power shortage and renewable energy producer 's PV power generation in

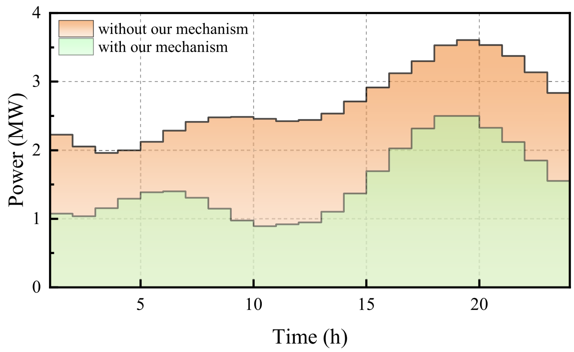


FIGURE 7. The total power demand of a day.

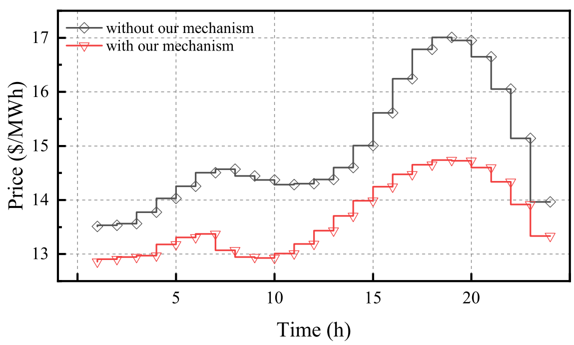


FIGURE 8. The price comparison of a day.

different time periods after the end of local power trading. We can see that the generation of renewable energy gradually increases after 8 A.M. and reaches its peak from 10 A.M. until 4 P.M.. During this period, renewable energy producers can provide large amounts of electricity. Therefore, when PV generation works normally, our mechanism can effectively alleviate the power shortage from 10 A.M. to 4 P.M..

Finally, Fig. 7 depicts the difference in the total load before and after implementing our blockchain-enabled power trading mechanism. The area under the line in the figure represents all the power demand by the consumer to the grid. Obviously, after using our mechanism, the power demand of the consumer on the grid must be less than without our mechanism in any time period. The orange part in the figure is the reduced power demand to the grid.

3) ELECTRICITY COST

In order to show the impact of our mechanism on the electricity cost purchased by consumers, we test and compare the changes in prices over time before and after the deployment of our mechanism.

As shown in Fig. 8, after using our power trading mechanism, the electricity price that consumers need to pay at any time is less than the original electricity price. In particular, the effect of our mechanism is more obvious during the peak time of electricity price at 8 P.M.. The consumer's electricity cost is reduced because he can purchase electricity from local producers and regional renewable energy producers at a bidding price lower than the average price of the grid, which can effectively reduce consumers' electricity cost.

Therefore, the experiment result shows that the proposed mechanism can effectively reduce consumers' power purchase prices and smoothen the power curve to reduce the load on the grid. By introducing blockchain technology, we have achieved effective distributed power trading without trusted third party, and the overhead of using blockchain is limited for consumers and producers.

VI. CONCLUSION

In this paper, we propose a security blockchain-enabled power trading mechanism for smart grid employing wireless network. By introducing blockchain technology, the problem such as data transmission and single-point of failure in the electricity market is solved, thereby improving the security of wireless networks. The proposed mechanism can realize trusted distributed trading between consumers and producers without trusted centralized party. The dual-chain structure consisting of the LETB and RETB makes full use of the local energy storage and the renewable energy in distributed power trading and meets consumer's demand under OPF constraints, thereby reducing its electricity costs and reducing grid burden. The incentive mechanism based on smart contracts can effectively encourage producers to improve power quality and expand production capacity. Finally, simulation experiments based on real cases prove the effectiveness of our mechanism.

In the future, we plan to expand the proposed research by adding some EVs to the electricity market model. Integrate EV energy trading and local power trading into the blockchain to build a decentralized energy trading system. In addition, we want to integrate more different types of renewable energy into the blockchain-enabled energy sharing market in follow-up research.

REFERENCES

[1] C. Liang and F. R. Yu, "Wireless network virtualization: A survey, some research issues and challenges," *IEEE Commun. Surveys Tuts.*, vol. 17, no. 1, pp. 358–380, 1st Quart., 2015.

[2] Y. Xu, G. Wang, J. Yang, J. Ren, Y. Zhang, and C. Zhang, "Towards secure network computing services for lightweight clients using blockchain," *Wireless Commun. Mobile Comput.*, vol. 2018, pp. 1–12, Nov. 2018, doi: 10.1155/2018/2051693.

[3] S. Verma and P. Rana, "Wireless communication application in smart grid: An overview," in *Proc. Innov. Appl. Comput. Intell. Power, Energy Controls Impact Humanity (CIPECH)*, Ghaziabad, India, Nov. 2014, pp. 310–314.

[4] D. Saygin, R. Kempener, N. Wagner, M. Ayuso, and D. Gielen, "The implications for renewable energy innovation of doubling the share of renewables in the global energy mix between 2010 and 2030," *Energies*, vol. 8, no. 6, pp. 5828–5865, Jun. 2015.

[5] G. Liang, S. R. Weller, F. Luo, J. Zhao, and Z. Y. Dong, "Generalized FDIA-based cyber topology attack with application to the Australian electricity market trading mechanism," *IEEE Trans. Smart Grid*, vol. 9, no. 4, pp. 3820–3829, Jul. 2018.

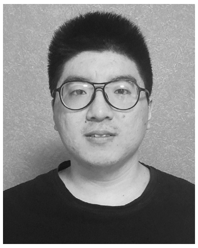
[6] A. L. Ott, "Experience with PJM market operation, system design, and implementation," *IEEE Trans. Power Syst.*, vol. 18, no. 2, pp. 528–534, May 2003.

[7] R. M. Oviedo, F. Ramos, S. Gormus, P. Kulkarni, and M. Sooriyabandara, "A comparison of centralized and distributed monitoring architectures in the smart grid," *IEEE Syst. J.*, vol. 7, no. 4, pp. 832–844, Dec. 2013.

[8] H.-C. Hsieh, J.-S. Leu, and W.-K. Shih, ''A fault-tolerant scheme for an autonomous local wireless sensor network,'' *Comput. Standards Interfaces*, vol. 32, no. 4, pp. 215–221, Jun. 2010.
[9] Z. Zhang, R. Li, and F. Li, ''A novel peer-to-peer local electricity market for joint trading of energy and uncertainty,'' *IEEE Trans. Smart Grid*, vol. 11, no. 2, pp. 1205–1215, Mar. 2020.
[10] K. Anoh, S. Maharjan, A. Ikpehai, Y. Zhang, and B. Adebisi, ''Energy peer-to-peer trading in virtual microgrids in smart grids: A game-theoretic approach,'' *IEEE Trans. Smart Grid*, vol. 11, no. 2, pp. 1264–1275, Mar. 2020.
[11] W. Tushar, T. K. Saha, C. Yuen, T. Morstyn, H. V. Poor, and R. Bean, ''Grid influenced peer-to-peer energy trading,'' *IEEE Trans. Smart Grid*, vol. 11, no. 2, pp. 1407–1418, Mar. 2020.
[12] A. Paudel, K. Chaudhari, C. Long, and H. B. Gooi, ''Peer-to-peer energy trading in a prosumer-based community microgrid: A game-theoretic model,'' *IEEE Trans. Ind. Electron.*, vol. 66, no. 8, pp. 6087–6097, Aug. 2019.
[13] C. Gentile, D. Griffith, and M. Souryal, ''Wireless network deployment in the smart grid: Design and evaluation issues,'' *IEEE Netw.*, vol. 26, no. 6, pp. 48–53, Nov. 2012.
[14] W. Cole, H. Lewis, B. Sigrin, and R. Margolis, ''Interactions of rooftop PV deployment with the capacity expansion of the bulk power system,'' *Appl. Energy*, vol. 168, pp. 473–481, Apr. 2016.
[15] X. Zhou, W. Liang, K. I.-K. Wang, H. Wang, L. T. Yang, and Q. Jin, ''Deep-learning-enhanced human activity recognition for Internet of healthcare things,'' *IEEE Internet Things J.*, vol. 7, no. 7, pp. 6429–6438, Jul. 2020.
[16] Y. Xu, J. Ren, Y. Zhang, C. Zhang, B. Shen, and Y. Zhang, ''Blockchain empowered arbitrable data auditing scheme for network storage as a service,'' *IEEE Trans. Services Comput.*, vol. 13, no. 2, pp. 289–300, Apr. 2020.
[17] X. Zhou, W. Liang, K. I. Wang, R. Huang, and Q. Jin, ''Academic influence aware and multidimensional network analysis for research collaboration navigation based on scholarly big data,'' *IEEE Trans. Emerg. Topics Comput.*, early access, Jul. 26, 2018, doi: 10.1109/TETC.2018.2860051.
[18] M. Andoni, V. Robu, D. Flynn, S. Abram, D. Geach, D. Jenkins, P. McCallum, and A. Peacock, ''Blockchain technology in the energy sector: A systematic review of challenges and opportunities,'' *Renew. Sustain. Energy Rev.*, vol. 100, pp. 143–174, Feb. 2019.
[19] L. Tian, J. Li, W. Li, B. Ramesh, and Z. Cai, ''Optimal contract-based mechanisms for online data trading markets,'' *IEEE Internet Things J.*, vol. 6, no. 5, pp. 7800–7810, Oct. 2019.
[20] Y. Xu, J. Ren, G. Wang, C. Zhang, J. Yang, and Y. Zhang, ''A blockchain-based nonrepudiation network computing service scheme for industrial IoT,'' *IEEE Trans. Ind. Informat.*, vol. 15, no. 6, pp. 3632–3641, Jun. 2019.
[21] S. Zhu, W. Li, H. Li, L. Tian, G. Luo, and Z. Cai, ''Coin hopping attack in blockchain-based IoT,'' *IEEE Internet Things J.*, vol. 6, no. 3, pp. 4614–4626, Jun. 2019.
[22] Z. Cai and Z. He, ''Trading private range counting over big IoT data,'' in *Proc. IEEE 39th Int. Conf. Distrib. Comput. Syst. (ICDCS)*, Dallas, TX, USA, Jul. 2019, pp. 144–153.
[23] Y. Xu, C. Zhang, Q. Zeng, G. Wang, J. Ren, and Y. Zhang, ''Blockchain-enabled accountability mechanism against information leakage in vertical industry services,'' *IEEE Trans. Netw. Sci. Eng.*, early access, Feb. 27, 2020, doi: 10.1109/TNSE.2020.2976697.
[24] X. Zhou, W. Liang, K. I.-K. Wang, and L. T. Yang, ''Deep correlation mining based on hierarchical hybrid networks for heterogeneous big data recommendations,'' *IEEE Trans. Comput. Social Syst.*, early access, May 8, 2020, doi: 10.1109/TCSS.2020.2987846.
[25] X. Zheng and Z. Cai, ''Privacy-preserved data sharing towards multiple parties in industrial IoTs,'' *IEEE J. Sel. Areas Commun.*, vol. 38, no. 5, pp. 968–979, May 2020.
[26] A. Pieroni, N. Scarpato, L. Di Nunzio, and F. Fallucchi, ''Smarter city: Smart energy grid based on blockchain technology,'' *Int. J. Adv. Sci. Eng. Inf. Technol.*, vol. 8, no. 1, pp. 298–306, 2018.
[27] E. Mengelkamp, B. Notheisen, C. Beer, D. Dauer, and C. Weinhardt, ''A blockchain-based smart grid: Towards sustainable local energy markets,'' *Comput. Sci. Res. Develop.*, vol. 33, nos. 1–2, pp. 207–214, Feb. 2018.
[28] M. Stadler, G. Cardoso, S. Mashayekh, T. Forget, N. DeForest, A. Agarwal, and A. Schönbein, ''Value streams in microgrids: A literature review,'' *Appl. Energy*, vol. 162, pp. 980–989, Jan. 2016.
[29] K. Kim and S.-I. Jin, ''Branch-based centralized data collection for smart grids using wireless sensor networks,'' *Sensors*, vol. 15, no. 5, pp. 11854–11872, May 2015.
[30] *Shaping Future Energy With Piclo Trial*. Accessed: Mar. 2015. [Online]. Available: http://www.goodenergy.co.uk/blog/articles/2015/03/10/shaping-the-future-of-energy-with-the-piclo-trial/
[31] *Sonnen Community Connects Households Makes Conventional Electricity Suppliers Obsolete Through Self-Generated Power*. Accessed: Jun. 2015. [Online]. Available: https://microsite.sonnenbatterie.de/en/sonnenCommunity
[32] X. Shen, M. Shahidehpour, Y. Han, S. Zhu, and J. Zheng, ''Expansion planning of active distribution networks with centralized and distributed energy storage systems,'' in *Proc. IEEE Power Energy Soc. Gen. Meeting (PESGM)*, Portland, OR, USA, Aug. 2018, pp. 126–134, doi: 10.1109/PESGM.2018.8585964.
[33] W. Yu, D. Liu, and Y. Huang, ''Operation optimization based on the power supply and storage capacity of an active distribution network,'' *Energies*, vol. 6, no. 12, pp. 6423–6438, Dec. 2013.
[34] M. Nick, R. Cherkaoui, and M. Paolone, ''Optimal allocation of dispersed energy storage systems in active distribution networks for energy balance and grid support,'' *IEEE Trans. Power Syst.*, vol. 29, no. 5, pp. 2300–2310, Sep. 2014.
[35] A. L. Dimeas and N. D. Hatziargyriou, ''Operation of a multiagent system for microgrid control,'' *IEEE Trans. Power Syst.*, vol. 20, no. 3, pp. 1447–1455, Aug. 2005.
[36] H. F. Wedde, S. Lehnhoff, E. Handschin, and O. Krause, ''Real-time multi-agent support for decentralized management of electric power,'' in *Proc. 18th Euromicro Conf. Real-Time Syst. (ECRTS)*, Dresden, Germany, 2006, pp. 9–25.
[37] W. Tushar, T. K. Saha, C. Yuen, P. Liddell, R. Bean, and H. V. Poor, ''Peer-to-Peer energy trading with sustainable user participation: A game theoretic approach,'' *IEEE Access*, vol. 6, pp. 62932–62943, 2018.
[38] C. S. Wright, ''Bitcoin: A Peer-to-Peer electronic cash system,'' *SSRN Electron. J.*, pp. 1–9, 2008.
[39] C. D'Adamo, S. Jupe, and C. Abbey, ''Global survey on planning and operation of active distribution networks–update of CIGRE C6.11 working group activities,'' in *Proc. IET Conf. Publications*, Prague, Czech Republic, 2009, pp. 0555–0559.
[40] X. Zhou, Y. Li, and W. Liang, ''CNN-RNN based intelligent recommendation for online medical pre-diagnosis support,'' *IEEE/ACM Trans. Comput. Biol. Bioinf.*, early access, May 14, 2020, doi: 10.1109/TCBB.2020.2994780.
[41] S. Zhu, Z. Cai, H. Hu, Y. Li, and W. Li, ''ZkCrowd: A hybrid blockchain-based crowdsourcing platform,'' *IEEE Trans. Ind. Informat.*, vol. 16, no. 6, pp. 4196–4205, Jun. 2020.
[42] X. Zhou, W. Liang, S. Huang, and M. Fu, ''Social recommendation with large-scale group decision-making for cyber-enabled online service,'' *IEEE Trans. Comput. Social Syst.*, vol. 6, no. 5, pp. 1073–1082, Oct. 2019.
[43] Y. Xu, C. Zhang, G. Wang, Z. Qin, and Q. Zeng, ''A blockchain-enabled deduplicatable data auditing mechanism for network storage services,'' *IEEE Trans. Emerg. Topics Comput.*, early access, Jun. 29, 2020, doi: 10.1109/TETC.2020.3005610.
[44] (2018). *Ethereum*. [Online]. Available: https://www.ethereum.org/
[45] Y. Li, W. Yang, P. He, C. Chen, and X. Wang, ''Design and management of a distributed hybrid energy system through smart contract and blockchain,'' *Appl. Energy*, vol. 248, pp. 390–405, Aug. 2019.
[46] S. Park and H. Kim, ''DAG-based distributed ledger for low-latency smart grid network,'' *Energies*, vol. 12, no. 18, p. 3570, Sep. 2019.
[47] H. Liu, Y. Zhang, S. Zheng, and Y. Li, ''Electric vehicle power trading mechanism based on blockchain and smart contract in V2G network,'' *IEEE Access*, vol. 7, pp. 160546–160558, 2019.
[48] 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.
[49] E. Munsing, J. Mather, and S. Moura, ''Blockchains for decentralized optimization of energy resources in microgrid networks,'' in *Proc. IEEE Conf. Control Technol. Appl. (CCTA)*, Mauna Lani Resort, HI, USA, Aug. 2017, pp. 2164–2171.
[50] M. I. Daoud, A. S. Abdel-Khalik, A. Massoud, S. Ahmed, and N. H. Abbasy, ''On the development of flywheel storage systems for power system applications: A survey,'' in *Proc. 20th Int. Conf. Electr. Mach.*, Sydney, NSW, Australia, Sep. 2012, pp. 2119–2125.
[51] J. Nyangon, J. Byrne, and J. Taminiau, ''An assessment of price convergence between natural gas and solar photovoltaic in the U.S. electricity market,'' *Wiley Interdiscipl. Rev., Energy Environ.*, vol. 6, no. 3, p. e238, May 2017.

[52] M. Farivar, R. Neal, C. Clarke, and S. Low, "Optimal inverter VAR control in distribution systems with high PV penetration," in *Proc. IEEE Power Energy Soc. Gen. Meeting*, San Diego, CA, USA, Jul. 2012, pp. 1–7.

[53] *Real Time Demand Curves*. Accessed: Feb. 2020. [Online]. Available: http://www.caiso.com/outlook/SystemStatus.html

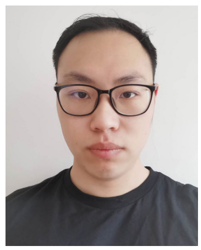


ZIMING LIU (Student Member, IEEE) received the B.S. degree in electrical engineering and automation from the Shenyang Institute of Engineering, Shenyang, China, in 2017. He is currently pursuing the M.S. degree in electrical engineering with Northeastern University, Shenyang. His research interests include wireless network communication, electricity market, power trading mechanism, and blockchain.

DAZHI WANG received the B.S. degree in automation from Southeastern University, Nanjing, China, in 1985, the M.S. degree in automation from the Shenyang Ligong University of China, Shenyang, China, in 1992, and the Ph.D. degree in control theory and control engineering from Northeastern University, Shenyang, in 2003. He is currently a Full Professor and the Head of the School of Information Science and Engineering, Institute of Power System and Drives, Northeastern University. His current research interests include renewable energy generation systems, power electronics, power quality control, and motor drives.

JIAXING WANG was born in Hebei, China, in 1995. He received the B.S. degree in automation from the Shenyang University of Technology, Shenyang, China, in 2018. He is currently pursuing the M.S. degree in control theory and control engineering with Northeastern University, Shenyang. His research interests include deep learning, and intelligent algorithms and its applications in intelligent fault diagnosis.

XINGHUA WANG received the B.S. degree in social sport from Beijing Sport University, Beijing, China, in 2014, and the M.S. degree in leisure and sport management from Hong Kong Baptist University, Hong Kong, in 2015. She is currently pursuing the Ph.D. degree in education economy and management with Northeastern University, Shenyang, China. She is currently a Lecturer with the P.E. Department, Northeastern University. Her research interests include sport management, sport marketing, and blockchain-based sports service.



HAO LI received the B.S. degree in mechanical engineering from the Hubei University of Automotive Technology, Shiyan, China. His research interests include blockchain and network security.