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RESEARCH ARTICLE

A Blockchain Consensus Mechanism to Optimize Reputation-Based Distributed Energy Trading in Urban Energy System

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ABSTRACT In modern cities, consumers with distributed energy resources (DERs) can trade energy by managing their consumption and supply. Blockchain is considered to provide technical support for establishing a distributed energy market, while the current mainstream blockchain technology cannot meet the requirement of efficiency and scalability under such a transaction scenario. In addition, the potential defaults of market players also hinder market implementation. Therefore, a reputation-based distributed energy trading mechanism and the corresponding blockchain consensus method considering reputation management are proposed in this paper. Firstly, a distributed reputation management mechanism is designed to systematically evaluate the user's behavior in the market. Secondly, to address the limitations of traditional consensus methods in the distributed energy market distributed reputation control is introduced into the node model of blockchain, and a new energy blockchain consensus method named DPoR is proposed to solve the technical bottleneck under the distributed energy trading scenario. We also present a corresponding transaction mechanism to encourage market participants to maintain their reputations. Finally, the simulation results verify the effectiveness of the proposed transaction mechanism in this paper, and the presented blockchain consensus mechanism can meet the performance requirements under distributed energy trading scenarios in terms of high efficiency, low consumption, and openness.

INDEX TERMS Blockchain, distributed energy trading, reputation management, consensus mechanism.

I. INTRODUCTION

With the deployment of renewable energy generation devices, the electricity industry is undergoing significant changes [1]. In the new electric power system, distributed energy resources (DERs) are taking up an important proportion of customers with DERs can trade energy by managing their consumption and generation [2], which is organized by a centralized energy trading system in the traditional model. But the centralized trading model is limited by the central institution's own computing power and user privacy protection concerns, which cannot handle massive transactions, nor can it guarantee the openness and transparency of transactions. Moreover, the default problem in DER transactions is much more serious due to the uncertainty of DER outputs and owners' desire to pursue profits [3]. The default behaviors can lead to a lack of trust between users and hinder the implementation of the distributed energy trading market. Thus, it is crucial to assess users' reputation level depending on their trading behavior. Nevertheless, it is challenging for traditional centralized management schemes to design an appropriate trading mechanism considering the users' reputation level.

Distributed energy trading may be able to avoid the above concerns caused by conventional centralized structure. However, it brings additional problems, such as security

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and privacy issues, which are urgently needed for cutting-edge technologies [4], [5]. The centralized ledger databases, such as LedgerDB [6], provide strong external auditability and rapid verification features. Nevertheless, considering the decentralized characteristic of distributed energy trading, the decentralized ledger technology (DLT) would have the prominent compatible. The well-known DLT is VeDB [7], which provides great performance trusted features. However, these above techniques only emphasize the verifiability and performance characteristics without the reputation attribute, which is not suited for the reputation-based energy trading. Due to the cons of these ledger databases, we turn to discuss the blockchain technology. Since its decentralization, de-trusting characteristics, traceability, hard-to-tamper, and self-executing smart contracts [8], [9], blockchain involves the creation and maintenance of a series of irrevocable blocks without the supervisory of a central trusted authority [10]. Deploying blockchain technology into distributed energy trading is a promising solution to address the above problems [11], [12]. Instead of empowering a single authority to dominate the whole network, blockchain splits the authority power into all stakeholders, rendering the joint operation of the network in a democratic way [13]. Since its first introduction by Bitcoin in 2008 [14], blockchain has entered a significant period of rapid expansion with the continual development of digitization technology [15]. Although the initial origin of blockchain is digital currencies [16], [17], it can be broadly applied to other non-monetary area, such as smart home [18], smart transportation [19], [20], energy trading [21], and so on. Currently, some energy blockchain companies such as Conjure, MyBit, and SolarCoin have built end-to-end distributed PV trading platforms based on Ethereum [21], where consumers can purchase electricity directly from photovoltaic producers using blockchains. Consequently, the incorporation of distributed energy trading and blockchain can promote the power system development towards decentralization.

Distributed energy trading is characterized by a large number of participants, massive information volume, decentralized participant locations, and a low market entry threshold, which demands high efficiency and scalability of blockchain technology [22]. The design of the consensus mechanism has a strong impact on the security, scalability, reliability, and security of the blockchain systems [23]. The consensus mechanism, by which mutually distrustful nodes follow the same mechanism to achieve data consistency, is a subprotocol of the blockchain system [24]. It is the core component of blockchain which defines the validity of data and network fault-tolerant with the increasing number of nodes [25], [26]. Recently, researchers have attempted to promote the efficiency of blockchain networks by introducing novel consensus mechanisms, such as Proof-of-Work (PoW), Proof-of-Stake (PoS), Delegate-Proof-Of-Stake (DPoS), Practical Byzantine Fault Tolerance (PBFT) [27], and so on. On the other side, the users' reputation level should be quantified based on their energy trading behavior. Recent works have proved that reputation can help to improve the efficiency of blockchain and enhance the fairness of markets [28], though the reputation evaluation index for market players is too simple to reflect the impact of users' behavior.

It is worth mentioning that current blockchain based energy trading projects still directly adopt the above traditional consensus mechanisms in blockchain networks. However, to the best knowledge of us, the consensus mechanism specifically designed for reputation based distributed energy trading is still rare. Furthermore, there are several challenges with existing consensus algorithms that hinder the secure and effective construction of a reputation based distributed energy trading system, which can be concluded in the following three aspects: 1) lack of a comprehensive reputation evaluation system to include the trading behavior of users, such as contract performance reputation, bill default reputation, and so on; 2) the distributed energy trading mechanism considering the users' reputation level to regulate their behavior is rarely investigated; 3) from the perspective of security, efficiency, and scalability, the current consensus mechanisms have the limitations, which inevitably restrain the performance of distributed energy trading.

To address the aforementioned problems, we are motivated to combine the energy trading process and consensus mechanism with reputation management to restrict users' transaction behaviors. The aim of this work is to design a lightweight consensus mechanism called delegated proof of reputation (DPoR), which includes a comprehensive user reputation evaluation system calculated by the analytic hierarchy process (AHP) method, to facilitate the implementation of distributed energy trading. In contrast with the existing literature, the prominent novelty and contribution of this paper are as follows:

1) We leverage the AHP approach to establish the comprehensive users' reputation metric evaluation system including contract performance reputation, bill default reputation, curve deviation reputation, and consensus node reputation. The behaviors of users during blockchain consensus and energy trading will be measured through their reputation scores.
2) To protect and motivate honest market participants, we present a reputation-based optimal distributed energy trading mechanism, prioritizing the users with high reputation value under the same bid and making the entity with higher reputation profit.
3) To facilitate the implementation of a distributed energy market, the consensus mechanism of DPoR is proposed to classify users based on the historical reputation level and two audit node selection schemes presented. The proposed DPoR can mitigate the computing power consumed on solving meaningless problems and maintain the prominent performance.

The rest of this article is structured as follows. The related works are demonstrated in Section II. Section III introduces the reputation management rules of market participants. Section IV describes the blockchain consensus method. Section V proposes an energy trading mechanism considering participants' reputations. Section VI provides a case study and discussions. Finally, Section VII presents the conclusion of this work.

II. RELATED WORKS

In this section, related works about blockchain based distributed energy systems and blockchain consensus mechanisms are elaborated.

A. BLOCKCHAIN ON THE DISTRIBUTED ENERGY SYSTEM

In academic research, blockchain is one of the most extensively studied information and communication technologies, which has been widely applied to distributed energy systems. For example, [29], our previous work proposes a generic framework for a blockchain platform that enables peer-to-peer (P2P) energy trading in the electricity retail market and also presents a P2P energy trading mechanism with the double-auction principle to facilitate direct energy trading among producers and consumers. Reference [30] designs a decentralized trading architecture and related electricity trading process based on the consortium blockchain to ensure the security and privacy of two-sided electricity trading between electric vehicles (EVs) and smart grids. Reference [31] presents energy cryptocurrency NRGcoin which provides a blockchain-based reward mechanism for both production and consumption of renewable energy. In [32], blockchain is introduced for green certificate trading to promote the voluntary adoption of distributed renewable energy. In [33], blockchain technologies are employed to guarantee the seamless and secure implementation of decentralized demand side management. Reference [34] proposed a two-stage EVs charging method enabled by blockchain. A blockchain-based trading algorithm is proposed to implement an autonomous and trustworthy joint energy-reserve prosumer-centric market in [35]. Reference [36] proposes a decentralized energy trading scheme in a blockchain environment that integrates privacy protection and efficiency. In [37], the authors developed a decentralized P2P energy trading platform, called DeTrade, which facilitates the decentralization, decarbonization, and digitalization of energy systems. Reference [38] provides a distributed energy management platform based on the confirmed blockchain for the trading management of renewable energy microgrids.

B. BLOCKCHAIN CONSENSUS MECHANISM

The most famous and mainstream consensus mechanism is perhaps Proof-of-Work (PoW) [14], which is widely used by Bitcoin and Ethereum. According to the statistics from [39], PoW accounts for 55% of the hundreds of energy blockchain projects, and PoW requires nodes to solve computationally expensive hash puzzles, the mining process, to compete for billing rights, which has disadvantages such as low efficiency and high resource consumption [40]. Consequently, due to the cons of PoW is wasting a massive time and sources on the intricate but useless mathematic puzzle [41], the criticism of PoW has created other consensus mechanisms, which involve Practical-Byzantine-Fault-Tolerance algorithms (PBFT) [42], Proof-of-Stake (PoS) [43] and Proof of Solution (PoSo) [44]. PBFT aims to achieve consensus via message exchange between nodes [42]. In such circumstances, it offers $(f-1)/3$ fault tolerance in the process of consensus to meet the requirement of high-frequency trading, where f denotes the amount of node. The PBFT, On the flip side, cannot meet the scalability requirements of the distributed energy trading market because its overly complex communication mechanism causes its performance to degrade rapidly as the number of nodes increases [45]. PoS introduces a monetary concept to reduce the time and energy wasted in the mining process but it also brings security risks and cryptocurrency is also not necessary in the energy trading process [43]. As an extension of PoS, DPoS further improves the efficiency of block creation by introducing a delegated mechanism [46]. Afterward, the authors in [47] propose Roll-DPoS, which is actually the randomized version of DPoS, to solve the unique challenges brought by the Internet of Things (IoT) based blockchain applications. Under such circumstances, the number of nodes for block generation and verification is largely reduced during the process of mining and is proportionate to the scale of the system [48]. Although the introduction of a delegated mechanism can address the scalability issues [49], DPoS has a significant drawback in that the strong nodes tend to acquire a stronger impact on whole networks and then bring the monopoly [50]. Then, [44] proposes a blockchain consensus mechanism called Proof of Solution (PoSo), which can seamlessly incorporate mathematical optimization and minimize the workload associated with searching and verifying the optimum.

Although the above researches only address the problem of consensus efficiency and scalability, the significance of consensus security is overlooked. In practice, blockchain based energy trading systems are vulnerable to malicious attacks during the consensus process, which has a significant on the performance of blockchain. Thus, recent studies have begun to introduce reputation (or credit) mechanisms into blockchain systems. Proof-of-reputation (PoR) is proposed in [51], which sets the node with the highest reputation value to become the block generator, and the top 20% of nodes become the verifiers of blocks. Reference [52] proposes Dynamic-reputation Practical Byzantine Fault Tolerance (DBFT), similarly in DBFT, the first 60% of nodes are allowed to participate in consensus according to the credit ranking. Both mentioned mechanisms use a delegated consensus approach to make the highest reputation nodes act as audit nodes, which improves system performance while maintaining security. Reference [53] propose a reputation scheme to encourage the nodes to participate in network collaboration in a good way. The authors claim that our reputation-based incentive module can be implemented on state-of-the-art PoX mechanisms, which is called PoRX and can make PoX mechanisms achieve better consensus states. In [54] and [55], the author selected a set of judge nodes. Only nodes with reputation values higher than the trust threshold can obtain the accounting right.

Therefore, in this paper, we propose a DPoR mechanism, which incorporates the delegated mechanism and PoR consensus, specialized for reputation based distributed energy trading based on their energy trading performance.

III. REPUTATION MANAGEMENT

Compared with general commodity trading, energy trading contracts are usually drawn before the actual execution of the transaction. Additionally, in a distributed energy market, users may default to pursue more benefits as the energy prices fluctuate. The uncertainty in renewable energy generation and energy demand can cause the actual and contracted trading amounts to differ, which may lead to user defaults. The default behavior may lead to a lack of trust in the distributed energy market, thus affecting the enthusiasm of both sides. Therefore, it is necessary to introduce a reputation management mechanism to define the rating of users' trustworthiness.

Blockchain technology has a natural compatibility with reputation management. The storage mechanism of blockchain can realize the distributed storage of each user's reputation and avoid tampering behavior. The consensus mechanism enables the update of each user's reputation to be recognized by the majority of users, which eliminates oligopoly. The smart contract-based reputation update avoids human errors and realizes the openness and transparency of update rules and processes. In such a context, users with high reputation scores can obtain the advantage position whether in consensus or distributed energy trading. A multi-metric AHP method for reputation calculation is proposed in this section.

For energy blockchain, each user is not only a participant in the distributed energy market but also a maintainer of the blockchain-based transaction system, so the reputation scores are stored as a 5-tuple: $< R, R_{cp}, R_{bd}, R_{cd}, R_{cn} >$.

Note that $R \in [0, 1]$ is called the comprehensive reputation score, and this reputation score is calculated based on the contract performance reputation score R_{cp}, the bill default reputation score R_{bd}, the curve deviation reputation score R_{cd}, and the consensus node reputation score R_{cn}.

Note that $R_{cn}, R_{cp}, R_{bd}, R_{cd}$ are also numbers from [0,1]. Specially, R_{cn} is only for consensus node (see Sections IV for more detail), and R_{cp}, R_{bd}, R_{cd} are calculated based on the rules as follow:

$$R_{cp} = \frac{\sum_{i=1}^{n} \min\left\{\frac{Q^i_{actual}}{Q^i_{contract}}, 1\right\}}{n} \tag{1}$$

$$R_{bd} = \frac{f_i}{F_i} \tag{2}$$

$$R_{cd} = \max\left\{1, \frac{P_i^{real} - P_i^{order}}{P_i^{order}}\right\} \tag{3}$$

where Q_i^{actual} is the actual energy consumption/generation at trading period i, $Q_i^{contract}$ is the energy consumption/ generation agreed in the contract at trading period i, f_i represents the number of your paid electricity bills, F_i represents the actual amount of bills to be paid, P_i^{real} denotes the actual power generation/consumption curve, and P_i^{order} denotes the power generation and consumption of the agreed curve.

Although several metrics are listed, the importance of each metric is different. Based on pairwise comparisons, the AHP method can obtain the priorities of multiple criteria. Thus, the AHP is one of the most popular multi-criteria decision-making methods for calculating the weights of multi-criteria problems, in which both qualitative and quantitative aspects are considered [44]. By comparing every two elements, AHP can stratify the specific problem and define the weights of each criterion. One of the kernel pros of AHP is that it can clarify the hierarchy of relative problems and decompose the perplexing original problems into easier sub-problems. From the perspective of vertical, the weight of every criterion can be gained by the judgment matrix during the process of the AHP method.

In this paper, we leverage the AHP to get the weights of each factor and calculate the comprehensive reputation score R. The basic steps of the AHP are shown as follows:

1. Firstly, analyze the relationships between the elements.
2. Secondly, compare the importance of each element and obtain the judgment matrix A according to the criteria of the AHP evaluation which is shown in Appendix Table 7.

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & & & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix} \tag{4}$$

3. Then solving and consistency check of the judgment matrix.
4. Finally, check the consistency of the weights CR, the formula is shown in the Appendix. When CR<0.1, the consistency of the single-level ranking is satisfactory; when $CR \geq 0.1$, the value of the judgment matrix element needs to be adjusted.

According to the AHP method, the comprehensive reputation score R can be represented as:

$$R = \omega_1 R_{cp} + \omega_2 R_{bd} + \omega_3 R_{cd} + \omega_4 \chi_{cn} R_{cn} \tag{5}$$

$$\chi_{cn} = \begin{cases} 1 & participant\ is\ a\ consensus\ node \\ 0 & otherwise \end{cases} \tag{6}$$

where $\omega_1, \omega_2, \omega_3, \omega_4 \in [0, 1]$ represent the weights of each factor and satisfy $\omega_1 + \omega_2 + \omega_3 + \omega_4 = 1$. The rules of the reputation framework are implemented as the scripts in smart contracts supported by the blockchain system. Once the execution condition is satisfied, the scripts will automatically update the reputation scores stored in the database. Any creation, deletion, and modification of smart contracts will be broadcast to all participants.

IV. DESIGN OF BLOCKCHAIN SYSTEM BASED ON DELEGATE PROOF OF REPUTATION

The reputation metric is a quantitative assessment of the trustworthiness of the participants. We hold the viewpoint that nodes who behave honestly in the electrical energy market are more willing to maintain the stable and efficient operation of the entire energy blockchain system, thus this paper adopts the DPoS to improve the efficiency of the blockchain.

In DPoR, we have leveraged the AHP method to establish the reputation management scheme to quantify their market behavior. Thereafter, the verifiers are selected by their reputation performance instead of computing power, thereby significantly mitigating the consensus workload. Since there exist different reputation levels, the nodes with higher reputations will have the priority to participate in the verifier set. Then, the selected verifiers take the burden of verifying the current task by turns. Therefore, the security of the selection process is enhanced. The risk of conspiracy among nodes is alleviated. Meanwhile, the cost of implementation of blockchain is decreased due to the lightweight DPoR consensus mechanism.

In Section III, part 3.1 introduces the node structure, part 3.2 provides the node classification and the design of block structure, part 3.3 mainly describes the selection rules of audit nodes, part 3.4 gives the workflow of DPoR, and part 3.5 lists the penalty rules for malicious nodes and incentives for audit nodes.

A. NODE STRUCTURE

In our consensus mechanism, the reputation of each node is modeled and also requires to be recorded and agreed upon by all the other nodes. Logically, the proposed system may require another data chain to store the node's reputation. Therefore, we redesigned the node structure to affiliate the proposed design, which is presented as follows.

$$S = \langle A, B, R \rangle \tag{7}$$

where S represents the basic attributes of nodes in the energy blockchain, A represents the node's address, B represents the wallet balance, and R represents the comprehensive reputation score we proposed in Section II. When a new prosumer connects to the energy blockchain, the initial reputation value will be assigned by 1.

B. CLASSIFICATION OF BLOCKCHAIN NODES BASED ON REPUTATION AND THE BLOCK STRUCTURE

In the energy blockchain system designed in this paper, all nodes can be divided into the following three categories according to the roles they play.

Participant node (PN): There is no need for the PN to save all the transaction information, it only saves the transaction information related to themselves instead. PN can participate in the energy trading market via the system platform, but it is not qualified to audit and update transaction information.

Candidate node (CN): Once a PN participates in multiple rounds of electric energy transactions (such as completing more than 1000 orders) and triggers the reputation threshold set by the system, it will choose whether to become a CN and join the candidate pool. The CN will have the opportunity to become the audit node, audit the transaction information, update the ledger, and get the block reward. When a PN is satisfied and willing to become a candidate node, it must update the complete blockchain information in its own local system.

Audit node (AN): The ANs will be elected from the candidate pool. Only a limited number of ANs will be set to participate in transaction audits and record updating.

In a traditional blockchain system, each node needs to calculate the meaningless nonce, and the first node with the correct answer will get the record updated and rewarded which is inefficient and energy-wasting. In the consensus mechanism designed in this paper, the elected ANs produce blocks in order and they have to submit their own node address A after auditing the transaction.

Algorithm 1 Random-based ANs selection scheme

Input: C_i, R_{set}, N
Output: V_i
1: set reputation threshold $R_s = R_{set}$
2: set the total number of AN*s* N
// **Preparation phase:**
// Check whether the CN*s* in the candidate pool satisfy the reputation threshold
3: **for** ($s = 1; s \leq size(C_i); s++$) **do**
4: get the reputation of CN*s* C_i^R
5: **if** ($C_i^R < R_s$) **then**
6: Remove nodes that do not meet the reputation from the candidate pool
7: **end if**
8: **end for**
// **Selection phase:**
9: $V_i = random(C_i, N)$

C. SELECTION RULES OF ANS BASED ON DPOR

DPoR contains double layers of consensus, firstly, the consensus on the selection of ANs, then is the consensus on data. In this paper, we consider the actual electricity market construction process and design two different AN selection schemes that adapt to the maturity of the market.

1) RANDOM-BASED AN SELECTION SCHEME

In the early market, most nodes in the system do not satisfy the requirements to become CNs. To guarantee the successful operation and prevent the nodes from conspiring, the selection of ANs can be given to a trusted third-party institution (e.g., electric power utility) so that the blockchain system can operate under the supervision of a trusted third-party institution. The third-party institution will select N nodes randomly from the candidate pool as ANs where all the nodes in the candidate pool have the same probability and broadcast the auditing order so that the ANs will block in the specified order. The algorithm is shown as follows.

Note that R_{set} can only be set once and is used to pre-screen all PNs. Market entities with high reputations may become ANs due to their historical market performance. C_i represents the nodes in the candidate pool. V_i represents a list of ANs.

2) VOTING-BASED AN SELECTION SCHEME

As the market is open for some time and there are enough candidate nodes in the system, a Voting-based AN selection scheme can be used to achieve further decentralization of the market. In this paper, by designing a smart contract with a voting mechanism, all the nodes in the candidate node pool are mobilized to vote, and after the voting, the votes of all the nodes are ranked from high to low, and the top N amount of CNs with the highest votes are appointed as ANs, the nodes are ranked according to their reputation when they get the same votes. The voting results will be recorded on the blockchain and cannot be tampered with, which ensures the openness and transparency of the voting results. The algorithm is shown as follows.

Algorithm 2 Voting-based AN selection scheme

Input: C_i, R_{set}, N
Output: V_i
set reputation threshold: $R_s = R_{set}$
set the total number of ANs: N
// **Preparation phase:**
// Same as shown in Algorithm 1
// **Voting phase**
$andidate\_List = C_i[address]$
display the address of all CNs
if ($C_i^R > R_{set}$) **then**
  voting between CNs
  $Candidate\_List_{votes} + +$
end if
// **Sorting phase**
sort $Candidate\_List_{votes}$
$V_i = (Candidate\_List_{votes}, N)$

D. WORKFLOW OF DPOR

Since N amounts of ANs are selected and the audit order is announced, these nodes will act as ANs during a certain period T (e.g., one week or one month), and each AN has the same audit time t.

The workflow of DPoR is given in Figure1 as follows:

1) Audit order definition: ANs definite the audit order and select leader by order.

2) Block header generation: When AN i audits the transaction, it packs the transaction data and calculates the root hash $Root_i$ by using the hash function.

$$M_i = \langle Root_i, A_i, P\_hash \rangle \tag{8}$$

where M_i represents the block header hash calculated by AN i, A_i represents its own node address, and P_hash means the previous hash of the previous block.

3) Broadcast: When the block header's calculation is finished, AN i will broadcast the block header to the remaining ANs in the format of $< Root_i, A_i, P\_hash >$.

4) Data verification: When the remaining ANs receive the block header, they will verify the transaction data and the node's address to check whether it comes in order.

5) Data consensus: When more than 2/3N-1 ANs pass the verification, this block will be added to the blockchain and broadcasted to all nodes in the network; Otherwise, this block will be abolished and the transactions will be re-audited by the next AN.

AN needs to continuously audit the transaction to calculate the root hash and then combine the previous block hash and its own address to generate the block header during its audit time t.

E. REPUTATION UPDATE RULES AND INCENTIVES FOR ANS

1) MALICIOUS BEHAVIOR

Although the blockchain system selects trading subjects that perform honestly in the energy trading market as ANs, it does not exclude that the ANs will make malicious behaviors that endanger the stable operation of the trading system and the malicious behaviors in the system are analyzed as follows:

a) Malicious non-auditing behavior: The AN may maliciously not audit the transaction during its specified auditing time t.
b) Malicious voting behavior: A malicious node may maliciously submit an opposing vote to prevent the block from passing when auditing the block header.
c) Malicious tampering behavior: A malicious node may manipulate the content of the reviewed transactions during its own auditing period T.

2) PENALTY MECHANISM FOR MALICIOUS NODES

If the AN has malicious non-audit behavior in its own audit period T, to maintain the stable operation of the system from stagnation, the node will be automatically skipped as its audit time t has expired, and the node will be removed from the AN list and deprived of the re-entry qualification of the node.

When the AN maliciously submits an opposing vote or maliciously manipulates the audit content, it will be punished by the deduction of reputation value, and its reputation value will be updated according to formula (9).

$$R_{cn}{}^{*} = R_{cn} - \frac{1}{1 + e^{-((\lambda \sum_{k=0}^{T} a_k - \sum_{k=0}^{T} v_k))}} \tag{9}$$

where λ is the penalty factor, which is set to 3 in this paper, a_k represents the malicious behavior of node i in the kth audit time t, respectively, v_k represents the normal behavior of node i, the node will be deducted the corresponding reputation for its malicious behavior, and when its reputation

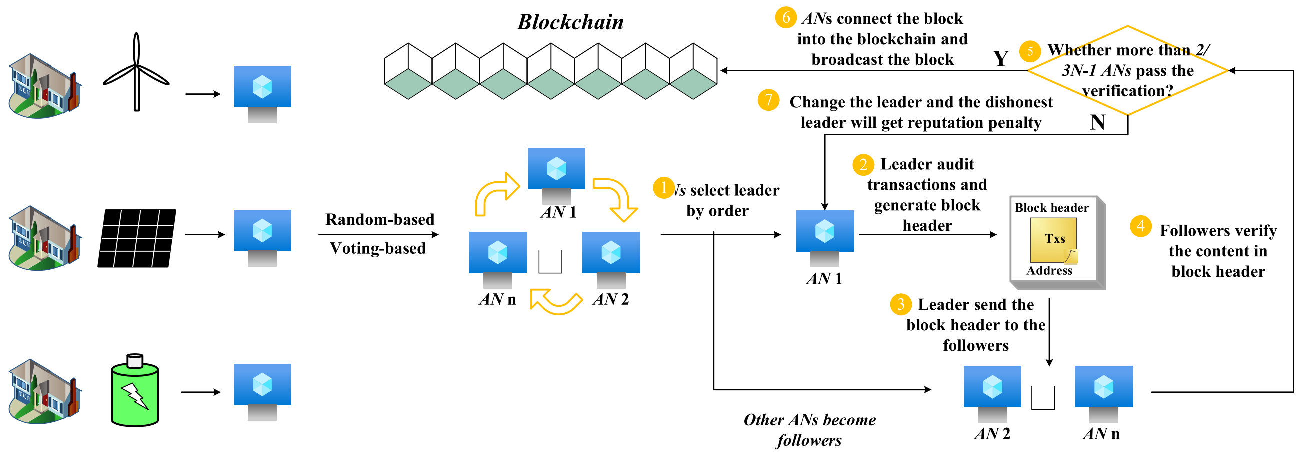

FIGURE 1. Flow chart of DPoR.

is lower than the set reputation threshold, the system will automatically eliminate it from the list of audited nodes and the candidate node pool.

3) INCENTIVES FOR ANS

The performance of DPoR is positively related to the performance of the ANs, the stronger the computing power of the AN, the faster the transaction audit process and the faster the records are uploaded to the blockchain. When the blocks generated by the AN pass the verification and are successfully connected to the blockchain, the node will be rewarded.

In this paper, two audit node selection schemes are proposed, therefore two reward schemes are set up correspondingly.

a: REWARDS FOR RANDOM-BASED SELECTED ANS

In this case, each AN is randomly selected by a trusted third-party institution from the candidate pool. The AN will get all transaction fees from the blocks it billed. Since each AN has the same auditing time t, the more transactions it audits, the more profit it earns. To increase their profit, ANs will spontaneously improve their performance and the whole blockchain system will also be improved simultaneously.

b: REWARDS FOR VOTING-BASED SELECTED ANS

In this case, all ANs are selected by a voting process between CNs. If the CNs do not vote actively, it will lead to a centralized system, so the rewards are set separately for the nodes that audit and the nodes that vote, and the rewards are set as shown in equations (10) and (11).

$$In_i^V = \gamma \sum_{k=0}^{T} \sum_{l=0}^{t} r \times m \tag{10}$$

$$In_i^{vote} = (1-\gamma) \frac{\sum_{k=0}^{T} \sum_{l=0}^{t} r \times m}{\sum vote} \tag{11}$$

where In_i^V is the profit received by node i which is voted as AN, k represents the kth auditing time for AN i, r represents transaction fee, and m is the number of transactions reviewed by the node. γ is the reward factor, which is set to 0.8 in this paper. R_i^{vote} represents the voting incentive received by the CN that voted for node i in the voting phase.

V. BLOCKCHAIN-BASED ENERGY TRADING MECHANISM CONSIDERING REPUTATION

A. DESIGN OF DISTRIBUTED ENERGY TRADING MECHANISM CONSIDERING THE REPUTATION OF TRADING AGENTS

In a distributed energy trading system, blockchain can be integrated to remove centralized transaction intermediaries and store transaction records in a transparent and immutable way. Double auctions can match multiple buyers and sellers at the same time and are widely used in various aspects of economic markets, such as stock, bond, and energy trading. In this paper, we propose a distributed energy trading mechanism considering the reputation of the trading parties based on the traditional double auctions. Firstly, reputation is included in the competitive ranking process, which means under the same conditions, the user with a high reputation will be matched with priority. After the user submits an offer, the system will calculate the ranking price of each user considering the user's reputation.

For the buyer, the ranking price is calculated as follows:

$$Rank_{buyer} = D_b \cdot R_b \tag{12}$$

where D_b is the demand price submitted by the buyer and R_b is the buyer's reputation scores.

For the seller, the ranking price is calculated as follows:

$$Rank_{seller} = O_s \cdot (1 - R_s) \tag{13}$$

where O_s is the selling price submitted by the seller and R_s is the seller's reputation score.

Once the ranking orders are calculated, the selling orders will be sorted in an ascending order of Rank_{seller}, and

$$Rank_{seller} = O_s \cdot (1 - R_s) \tag{13}$$

where O_s is the selling price submitted by the seller and R_s is the seller's reputation score.

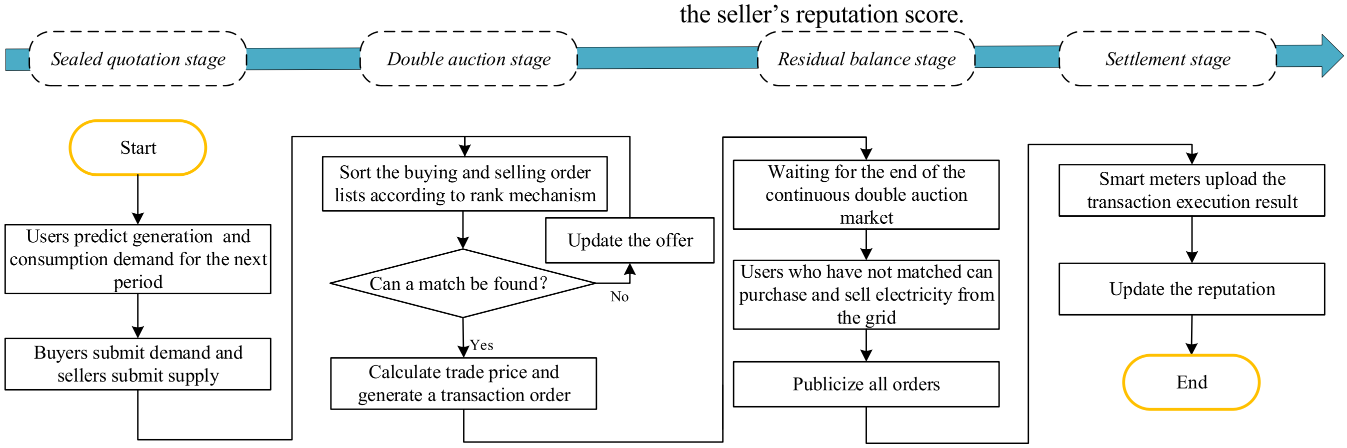

FIGURE 2. **Distributed energy trading process in a certain period.**

the buying orders will be sorted in a descending order of Rank_{buyer}. The match making between sellers and buyers will start from the top of the selling and buying order lists. A matching is found when it comes across a bidding order from buyer b and an offering order from seller s with $D_b > O_s$. To make the auction scheme beneficial to the trading party with a higher reputation, the clearing price is calculated by:

$$P = O_s + \frac{\chi_b \max(R_b, R_s) + \chi_s \min(R_b, R_s)}{R_b + R_s} \cdot (D_b - D_s) \tag{14}$$

$$\chi_b + \chi_s = 1 \tag{15}$$

$$\begin{cases} \chi_b = 1 & R_b > R_s \\ \chi_s = 1 & R_b < R_s \end{cases} \tag{16}$$

Finally, a transaction order will be formed, which specifies the buyer's address, the seller's address, the execution time, the amount of energy delivery, and the clearing price. Note that some orders may not be able to find a match after a credit-based double auction. To keep a balance between supply and demand, the electric power utility acts as the seller or buyer of the transaction. The trade price will be the unified purchase or sale price.

This paper divides a day into 24 time periods, each period carries out energy trading in the next period, and the trading process of each period is mainly divided into the following 4 stages, the trading process is shown in Figure 2.

1) Closed bidding stage: Both sides of the power purchase and sale submit quotations based on their own needs and distributed energy output forecasts.

2) Double auction stage: The system follows the sorting and aggregation rules of the above-mentioned trading mechanism to sort and aggregate buyers and sellers, and calculate the clearing price, and generate trading orders. For users who fail to match successfully at the beginning of the transaction, they can modify their own declaration information within that time and repeat the matching and aggregation operation.

3) Residual balance stage: After the end of the continuous double auction session, users who have not completed matching can purchase and sell electricity from the electric power utility, and then the system will publicize all trading orders, and both sides of the transaction need to prepare for the next stage of energy delivery by the order results.

4) Settlement stage: The system will settle the energy delivery of the previous period, and the smart meter will automatically read the actual electricity generated and consumed by both sides of the transaction and settle the amount according to the order clearing price.

B. SMART CONTRACT-BASED REPUTATION UPDATE METHOD AND ENERGY TRADING STRATEGY

The smart contract is a computer program deployed on the blockchain that can be executed automatically. All nodes in the blockchain network will copy and execute the smart contract, and when the preset conditions are satisfied, the smart contract will be executed automatically to achieve automatic settlement without a third-party intermediary.

This paper accomplishes the above-mentioned node reputation management and energy trading through smart contracts. The smart contract mainly contains a user registration function, quotation function, sorting and matching function, and transaction settlement function.

1) User registration function: Users call this function on the blockchain platform to upload their own information for registration, and the blockchain platform will assign IDs as their identity in accordance with the registration. After registration, the initial reputation of the user will be given by 1.

2) Quotation function: Users can call the quotation function to upload their own quotations in the corresponding

TABLE 1. Basic settings and simulation environment.

Settings and simulation environment	
CPU	*Intel Core i5 CPU @ 1.4 GHz*
Simulation environment	*macOS*
Programming Languages	*Python*
Hash function	*SHA-256 function*
R_{set}	*0.9*
N	*6*
t	*1s*

TABLE 2. Judgment matrix for PN/CN.

PN/CN	R_{cp}	R_{bd}	R_{cd}
R_{cp}	1	5	3
R_{bd}	0.2	1	0.5
R_{cd}	0.33333	2	1

TABLE 3. Judgment matrix for AN.

AN	R_{cp}	R_{bd}	R_{cd}	R_{cn}
R_{cp}	1	5	3	0.1428
R_{bd}	0.2	1	0.5	0.1111
R_{cd}	0.333	2	1	0.1111
R_{cn}	7	9	9	1

TABLE 4. Weight of factors.

PN/CN		*AN*	
R_{cp}	0.65	R_{cp}	0.18
R_{bd}	0.12	R_{bd}	0.05
R_{cd}	0.23	R_{cd}	0.08
		R_{cn}	0.7

trading hours according to their own electricity generation/demand, and the user's identity information will be replaced by the registration ID to protect their privacy. The quotation will be like $\langle R; amount; price; buyer/seller \rangle$, where R represents the user's own reputation, amount and price means the user's energy demand and price, Buyer/Seller means the user's market role in this transaction cycle.

3) Sorting and matching function: The smart contract will sort the buyer and seller quotes according to the formulas (12)-(13) and place them in the candidate queue. Following this queuing process, the smart contract calculates the clearing price according to the formula (14) and confirms the amount of energy exchanged between each producer and consumer.

4) Balance function: For the user who fails to find a match in the specified period, they can purchase or sell electricity to the grid. The trade price will be the unified purchase or sale price.

5) Transaction settlement function: After the matching process of this trading period, the system will settle the transactions of the previous period, and the smart meter of the customer will read the actual electricity generated/used by the customer of the previous period, and then the reputation of each trading entity will be updated according to equation (2).

The order results generated by the smart contract will be written into the blockchain by the auditing node. For users who are successfully cleared through the blockchain platform, the platform will charge a certain fee as a handling fee for the subsequent auditing reward to the auditing node.

VI. CASE STUDY

In this section, we first conduct a case study regarding the reputation mechanism by the AHP method. Besides, the performance of the DPoR consensus mechanism and reputation based distributed energy trading is elaborated

For the distributed energy trading part, the Solidity coding program is leveraged to build the smart contract of the mechanism we proposed and deploy it onto the private chain which is configured by the Geth v1.9.23 client. For the consensus mechanism part, the Python program is used to show the proposed DPoR consensus technology for distributed energy trading. All computations are conducted on macOS, with the processor of Intel Core i5 CPU @ 1.4 GHz, and an 8G memory. The detailed information can be drawn in Table 1.

A. CASE STUDY FOR COMPREHENSIVE REPUTATION SCORE R

The Comprehensive reputation score R is calculated based on $< R_{cp}, R_{bd}, R_{cd}, R_{cn} >$. For the nodes that are not participating in the audit, R_{cp} is highly correlated with the user's income and also affects the market implementation. But the Judgment matrix for the ANs, R_{cn} is definitely the most important part, so the judgment matrix is set as follows.

In Table 2, $\lambda_{max1} = 3.003, CI = 0.001$ and $CR = 0.003 < 0.1$.

In Table 3, $\lambda_{max2} = 4.201, CI = 0.067$ and $CR = 0.074 < 0.1$. The consistency of two scenarios is satisfied. Thus, the weight of factors is shown in Table 4 as follows.

Then the comprehensive reputation score R can be represented as:

$$R = \begin{cases} 0.65R_{cp} + 0.12R_{bd} + 0.23R_{cd}, PN/CN \\ 0.18R_{cp} + 0.05R_{bd} + 0.08R_{cd} + 0.7R_{cn}, AN \end{cases}$$

B. SIMULATIONS OF CREDIT-BASED DISTRIBUTED ENERGY TRADING MECHANISM

In this part, we are dedicated to demonstrating the performance of credit-based distributed energy trading mechanisms. Two scenarios are considered with the same offering price, where the buyers' reputation is higher in scenario 1 and the sellers' reputation is higher in scenario 2. Besides, we have chosen the trading mechanism proposed in Refs. [28] RBT (Reputation-based trading) and traditional double auction mechanism for comparison in each scenario.

The number of participators is set as 12, where users A, B, C, D, E, and F indicate buyers and a, b, c, d, e, and f represent sellers. The scenario setting and users' reputation scores are calculated in Tables 9 and 10, and the declaration information is shown in Tables 5 and 6.

TABLE 5. **Judgment matrix for AN. User sealing quotation (Scenario 1: Buyer's reputation is better than seller's).**

Buyer	Offering price (CNY/(kW·h))	Amount (kW·h)	R	$Rank_{buyer}$
A	0.63	100	0.9	0.567
B	0.68	80	0.87	0.5916
C	0.62	120	0.95	0.589
D	0.7	50	0.8	0.56
E	0.66	90	0.89	0.5874
F	0.65	110	0.92	0.598
Seller	Offering price (CNY/(kW·h))	Amount (kW·h)	R	$Rank_{seller}$
a	0.43	90	0.65	0.1505
b	0.47	100	0.8	0.094
c	0.46	110	0.73	0.1242
d	0.45	70	0.9	0.045
e	0.42	130	0.65	0.147
f	0.48	50	0.74	0.1248

TABLE 6. **User sealing quotation (Scenario 2: Seller's reputation is better than buyer's).**

Buyer	Offering price (CNY/(kW·h))	Amount (kW·h)	R	$Rank_{buyer}$
A	0.63	100	0.9	0.567
B	0.68	80	0.8	0.544
C	0.62	120	0.73	0.4526
D	0.7	50	0.65	0.455
E	0.66	90	0.65	0.429
F	0.65	110	0.74	0.481
Seller	Offering price （CNY/(kW·h))	Amount (kW·h)	R	$Rank_{seller}$
a	0.43	90	0.9	0.043
b	0.47	100	0.87	0.0611
c	0.46	110	0.95	0.023
d	0.45	70	0.8	0.09
e	0.42	130	0.89	0.0462
f	0.48	50	0.92	0.0384

The matchmaking will sort the selling order and the buying order lists according to $Rank_{seller}$ and $Rank_{buyer}$ respectively. For comparison, the results of matching and clearing based on traditional double auctions are shown in Figure 3. From Table. 5, Table. 6 and Figure 3, it can be seen that in the matching process, buyer *D* has the highest bid, so. he is given priority in the traditional double auction mechanism, but he is ranked last in scenario 1 due to his poor reputation, similarly, seller *e* has the lowest bid, but he is ranked fifth and fourth in scenarios 1 and 2 respectively under this transaction mechanism. The trading mechanism we proposed takes the

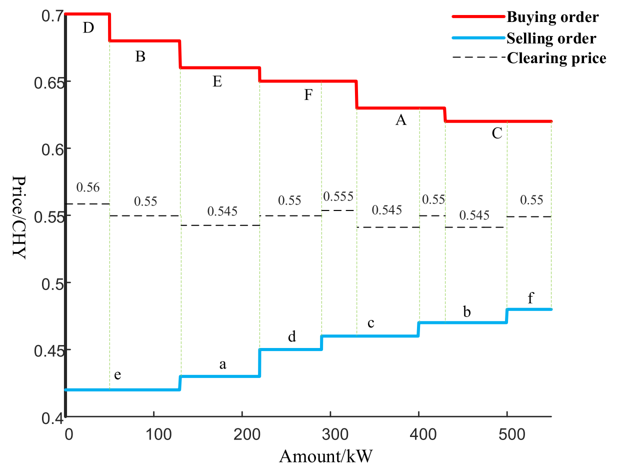

FIGURE 3. **Ranking and clearing price results of the traditional double auction.**

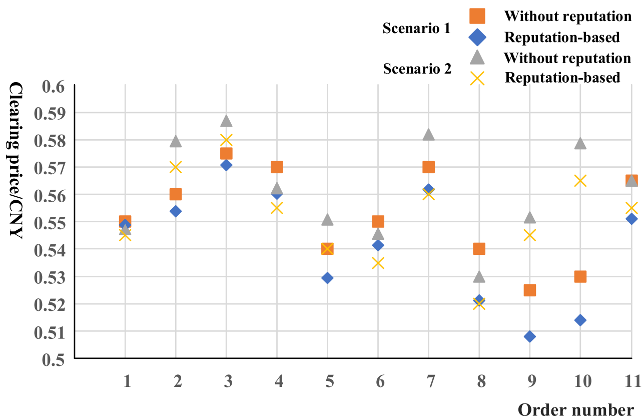

FIGURE 4. **Comparison of clearing price of different clearing mechanisms in two scenarios.**

reputation factor into account so that the user with the better offer and reputation will get priority

The matchmaking will sort the selling order and the buying order lists according to $Rank_{seller}$ and $Rank_{buyer}$ respectively. For comparison, the results of matching and clearing based on traditional double auctions are shown in Figure 3. From Table.5, Table. 6 and Figure 3, it can be seen that in the matching process, buyer *D* has the highest bid, so he is given priority in the traditional double auction mechanism, but he is ranked last in scenario 1 due to his poor reputation, similarly, seller *e* has the lowest bid, but he is ranked fifth and fourth in scenarios 1 and 2 respectively under this transaction mechanism. The trading mechanism we proposed takes the reputation factor into account, so that the user with the better offer and reputation will get the priority.

Figure 4 shows the comparison results of the clearing mechanism designed in this paper with that of the traditional double auction. In Scenario 1, the buyer's reputation is generally higher than the seller's, so the buyer's purchase price is lower compared with that of the traditional double auction.

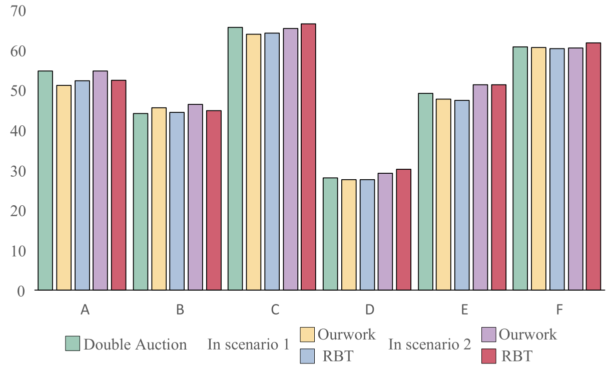

FIGURE 5. Comparison of buyer's cost under three mechanisms.

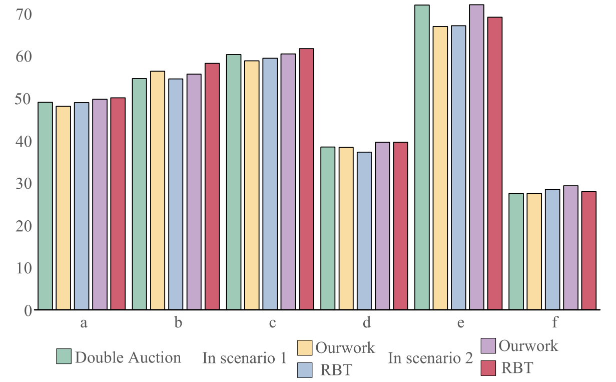

FIGURE 6. Comparison of seller's revenue under three mechanisms.

In Scenario 2, the seller's reputation is generally higher than the buyer's, so the seller's selling price increases relatively.

Figure 5 and Figure 6 show the cost and revenue of both sides under three trading mechanisms respectively. In general, both our designed trading mechanism and RBT enable buyers and sellers with better reputations to profit from the transaction. However, the mechanism designed in this paper can protect the revenue of high-reputation users, in Scenario 1, buyer *A* will spend less and the buyer with a relatively poor reputation like buyer *B* will spend more compared with RBT. For the sellers, our mechanism still can guarantee higher income for sellers with good reputations like the seller d.

C. SIMULATIONS OF DPOR PERFORMANCE

To verify the performance of the consensus mechanism designed in this paper, we compare the performance of the proposed DPoR, PoW, and PBFT. Thereafter, we set up a situation where an honest node continuously commits malicious behavior during the consensus process to verify the security of the DPoR mechanism. Then, the voting-based selecting scheme is considered to show the decentralization of DPoR.

The first 50 nodes are set to satisfy the reputation threshold to enter the candidate pool, and the addresses are replaced by node1-node100. It is assumed that all participating nodes have the same computer configuration and that the results of ANs based on two selecting schemes are the same. According to the random selection results, the auditing order will be: [node4, node24, node27, node25, node11, node21].

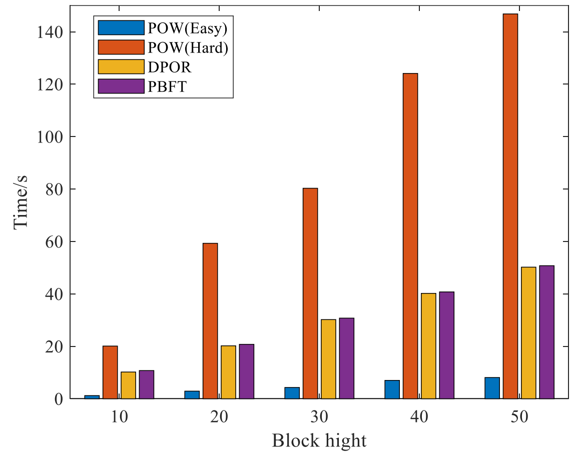

FIGURE 7. Block time of POW, PBFT, and DPoR.

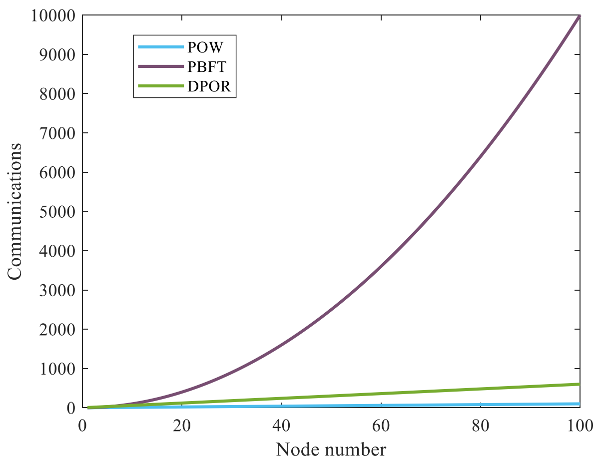

FIGURE 8. Comparison about communication times of DPoR, PBFT, and PoW.

We choose PoW and PBFT as the comparisons for simulation testing. Besides, the block-out process of 50 blocks is simulated with the same input. The block time of every 10 blocks is recorded, and the statistical results are shown in Figure 7. It is worth noting that the block time of PoW is related to the difficulty of mining these blocks. Thus, we set the 2 different situations for PoW for the difficulty of mining. From Figure 7, we can observe the block time for 3 consensus mechanisms. Although PoW under easy difficulty can reach the minimal block time, it is impractical in the utilization of the real world, such as Bitcoin. Consequently, the proposed DPoR mechanism can mitigate the block time significantly compared with the mainstream consensus mechanisms.

From the perspective of communication time, we select PBFT and PoW as the comparisons. PBFT consensus mechanism is less scalable because its communication complexity grows exponentially with the increase of nodes. The PoW consensus mechanism has an advanced scalable ability,

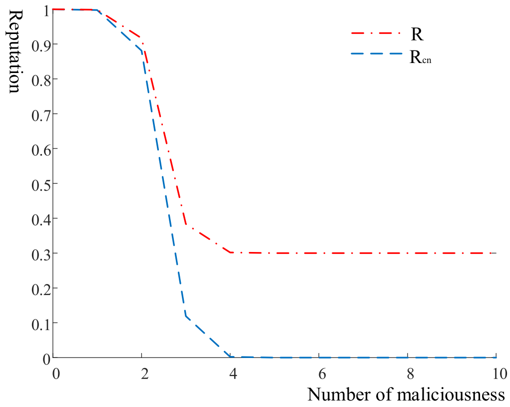

FIGURE 9. Reputation penalty of malicious nodes.

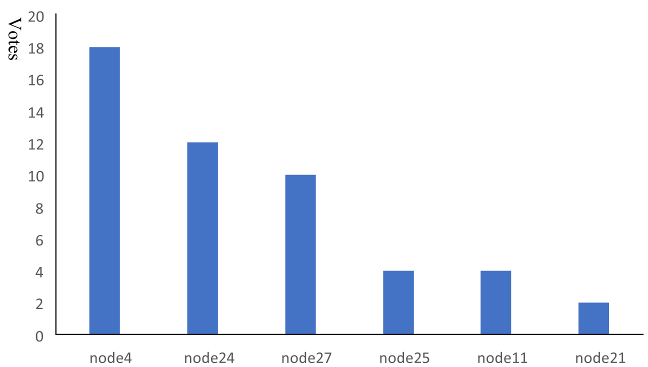

FIGURE 10. Voting results are based on the voting-based AN selection scheme.

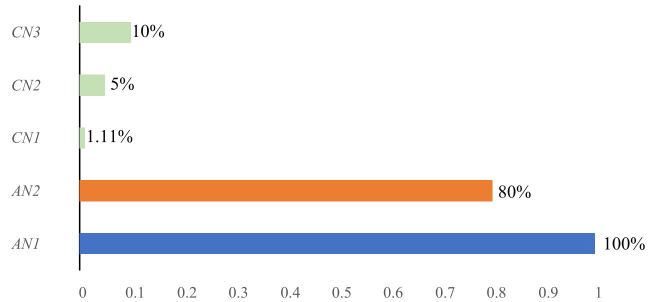

FIGURE 11. Rewards distribution for each block under two different audit node selection schemes.

specifically the communication complexity can be considered as $O(n)$. The DPoR consensus mechanism designed in this paper controls the number of audit nodes, which greatly reduces the communication complexity. In the case of this section, the number of audit nodes designed is 6, so the communication complexity of DPoR can be considered as $O(6n)$, which greatly reduces the communication complexity of the energy blockchain network compared with $O(n^2)$ of PBFT, and makes DPoR scalable and can adapt to the future development trend of distributed energy trading under massive data.

Figure 8 shows the number of communications required for the block-out process for two different algorithms with different numbers of nodes. Compared with PBFT consensus, the performance of which will decrease significantly with the increase of nodes, DPoR consensus controls the number of audit nodes by using delegate consensus. Although its communication time is relatively higher compared with PoW consensus, we comprehensively consider the block time and communication time to select the DPoR mechanism as a trade-off. Thus, the blockchain system designed in this paper can always ensure efficient operation under the scenario with increasing nodes.

As shown in Figure 9, it visualizes the decrease in reputation due to the malicious behavior of the audit node during the consensus process. Under the reputation update rules for AN, a small number of malicious behaviors will be tolerated, but if the node continues to perform maliciously, its reputation will drop rapidly, and if it is less than the set reputation threshold, the node will be automatically kicked out of the AN list and cannot continue the audit work, which guarantees the stable operation of the energy blockchain.

Figure 10 shows the voting results based on the voting-based AN selection scheme. Figure 11 shows the distribution of billing rewards for each block under two different audit node selection methods. AN1 is randomly selected by a trusted third-party institution from the candidate pool, so it gets all the transaction fees in the block it audits as the reward. Since all nodes are assumed to have the same power configuration, the total amount of transaction fees contained in the block is the same when the total number of transactions to be audited is sufficient.

AN2 is selected by CNs voting under the voting-based audit node scheme, so according to equation (9) and (10), 80% of the transaction fees in the block will be used as the billing reward, and the remaining 20% will be used as the voting incentive for the CNs. For example, the voting incentive received by CN1 corresponds to the incentive received by the CN voting for node 4, CN2′s reward corresponds to the incentive received by the CN voting for node 25, and CN3′s reward corresponds to the incentive received by the CN voting for node 21.

Under the selection scheme of a voting-based audit node, if all candidate nodes vote centrally, it will lead to a significant reduction in the revenue they receive; if candidate nodes vote randomly, the node they choose does not become an AN then they won't have any revenue, which limits the randomness of candidate node voting and does not lead to over-centralization of the system.

VII. CONCLUSION

In this paper, considering the inherent characteristics of distributed energy trading, the analytics for energy blockchain are proposed, including the node model and consensus mechanism. We introduce the concept of reputation into the node model, so the distributed control of reputation in the energy blockchain is realized, and a reputation-based optimal

TABLE 7. Criteria of the AHP evaluation.

Scaling (a_{ij})	Meaning
1	Compared with the two elements, they have the same importance
3	Compared with the two elements, the former is slightly more important than the latter
5	Compared with the two elements, the former is obviously more important than the latter
7	Compared with the two elements, the former is more important than the latter
9	Compared with the two elements, the former is extremely important than the latter
2,4,6,8	The median value of the above adjacent judgment
$1/a_{ij}$	Comparing the two elements, the latter is more important than the former

TABLE 8. Criteria of the AHP evaluation.

n	1	2	3	4	5	6
RI	0	0	0.58	0.89	1.12	1.26

TABLE 9. Criteria of the AHP evaluation reputation verification. (Scenario 1: Buyer's reputation is better than seller's).

Buyer	R_{cp}	R_{bd}	R_{cd}	R	Seller	R_{cp}	R_{bd}	R_{cd}	R
A	1	0.7	0.72	0.9	a	0.7	0.57	0.56	0.65
B	0.9	0.7	0.87	0.87	b	0.77	1	0.78	0.8
C	1	0.9	0.85	0.95	c	0.83	0.63	0.5	0.73
D	0.83	0.66	0.8	0.8	d	0.98	0.82	0.72	0.9
E	0.9	0.89	0.87	0.89	e	0.7	0.54	0.58	0.65
F	0.93	1	0.85	0.92	f	0.74	0.73	0.74	0.74

trading mechanism is designed to guide and motivate users to remain honest spontaneously. Considering that reputation is the quantitative assessment result of the trustworthiness of the participants in the market, reliable nodes are selected as audit nodes, which eliminates the competition for billing rights, makes the consensus process efficient and low energy consumption, and ensures scalability.

The reputation evaluation index for market players is complex and multifaceted, more metrics could be introduced in future studies. Additionally, blockchain technology has the well-known impossibility triangle. Decentralization, efficiency, and security of blockchains normally do not scale simultaneously with the number of participants in the network. The DPoR consensus mechanism designed in this paper combines low energy consumption and high efficiency while weakening the decentralized nature of the blockchain network. When designing the energy blockchain network in the future, how to weigh the decentralization, efficiency, and security of the system will be the key research direction of the energy blockchain.

TABLE 10. Reputation verification. (Scenario 2: Seller's reputation is better than buyer's).

Buyer	R_{cp}	R_{bd}	R_{cd}	R	Seller	R_{cp}	R_{bd}	R_{cd}	R
A	1	0.72	0.72	0.9	a	1	0.7	0.72	0.9
B	0.77	0.9	0.75	0.8	b	0.9	0.7	0.88	0.87
C	0.81	0.63	0.5	0.73	c	1	0.9	0.84	0.95
D	0.63	0.74	0.6	0.65	d	0.83	0.68	0.78	0.8
E	0.68	0.6	0.58	0.65	e	0.9	0.91	0.86	0.89
F	0.75	0.7	0.74	0.74	f	0.93	1	0.85	0.92

APPENDIX

$$CR = \frac{CI}{RI} \tag{17}$$

$$CI = \frac{\lambda_{\max} - n}{n - 1} \tag{18}$$

where λ_{max} is the largest feature root of the judgment matrix A, n represents the matrix order, RI stands for average random consistency index, and RI is obtained from the following Table 8.

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