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RBT: A distributed reputation system for blockchain-based peer-to-peer energy trading with fairness consideration ☆

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ABSTRACT

It has been proved by recent works that reputation can help to improve the efficiency of blockchain and enhance the fairness of energy trading markets. However, the application of distributed reputation in the energy field has not been fully studied yet. In this paper, we design a distributed reputation system to simulate real-world trust in blockchain-based peer-to-peer energy trading. It is a comprehensive reputation system in the sense that reputation scores are decided by the behavior of participants as consensus nodes, energy buyer, and energy sellers. Its implementation relies on blockchain, especially the smart contract technology, to achieve distributed and automatic reputation management. The distributed reputation system in turn helps to implement a delegated consensus algorithm for blockchain and a reputation-based k-double auction matchmaking scheme for peer-to-peer energy trading. In addition, we define a fairness indicator to capture the reputation-based average benefits and costs when considering reputation as the contribution to the peer-to-peer energy trading market. By simulating the comprehensive system, the numerical results demonstrate the effects of distributed reputation in improving the efficiency of blockchain and balancing fairness indicators between sellers and buyers during peer-to-peer energy trading. As far as we know, this paper is one of the few works to provide a formal method of evaluating the fairness of the peer-to-peer energy trading market.

1. Introduction

There have been a large number of research works and practical projects on blockchain-based energy trading since the advent of the blockchain technology in 2008 [1]. A blockchain system maintains a linked list of blocks with data, and any modification to the blockchain needs to be approved by participants, or nodes for simplicity, via a distributed consensus algorithm before it takes effect [2]. As a significant improvement of Blockchain 2.0 compared with Blockchain 1.0, smart contracts are a kind of programmable scripts that can run automatically once the predefined execution conditions are satisfied [3], which further expands the application scope of blockchain. Some favorable properties of blockchain are summarized as follows:

Decentralization. The system is not owned, operated, or controlled by any centralized individual or group. This is helpful to eliminate human error and manipulation [4]. Moreover, in transaction-related scenarios, decentralization can also help to circumvent extra intermediate transaction fees [5].

Transparency. In order to approve blocks by consensus, blocks needs to be disseminated among all participants. Data transparency can prevent the corruption and make the system more trustworthy [6].

Traceability and immutability. The chained data structure makes all historical data accessible by tracing previous blocks. In addition, the modification of a block requires the consensus among participants, making it more difficult for any individual to tamper with blockchain data. These two properties are of great importance to the mutual trust between participants and service providers [7].

Automation. The automation of blockchain is supported by smart contract technology, which automatically run when predefined conditions

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Nomenclature

χ_{CN}	Characteristic coefficient for R_{CN} when calculating R
χ_{EB}	Characteristic coefficient for R_{EB} when calculating R
χ_{ES}	Characteristic coefficient for R_{ES} when calculating R
ℓ	Leader node in consensus
BFI	Buyer fairness indicator
bp	Bidding price of a demand order
$bp_{\max}$	Maximum bidding price allowed
$bp_{\min}$	Minimum bidding price allowed
$C(r)$	Voting committee for request r
$cost$	Total cost in P2P energy trading
E_{buy}	Total amount of energy purchased in P2P trading
E_{sell}	Total amount of energy sold in P2P trading
FF	Fairness factor of the P2P trading system
$income$	Total income in P2P energy trading
op	Offering price of a supply order
$op_{\max}$	Maximum offering price allowed
$op_{\min}$	Minimum offering price allowed
R	The comprehensive reputation score
r	Consensus request
$r(R, FI)$	The correlation coefficient of reputation score R and buyer/seller fairness indicator FI
R_C	Average reputation score of committee C
$R_{\min}$	Trust lower bound for R
R_{CN}	The consensus node reputation score
R_{CN}	The energy buyer reputation score
R_{CN}^{+}	Reputation increase of consensus nodes
R_{CN}^{-}	Reputation decrease of consensus nodes
$R_{CN}^{L,+}$	Additional reputation reward of leader
$R_{CN}^{L,-}$	Additional reputation penalty of leader
R_{EB}^{+}	Reputation increase of the buyer for a successful transaction execution
R_{EB}^{-}	Reputation decrease of the buyer due to the failed consumption of a transaction
R_{ES}	The energy seller reputation score
R_{ES}^{+}	Reputation increase of the seller for a successful transaction execution
R_{ES}^{-}	Reputation decrease of the seller due to the failed supply of a transaction
$rank_{buy}$	Buying rank of a demand order
$rank_{sell}$	Selling rank of a supply order
SFI	Seller fairness indicator
tp	Trade price of a transaction
w_{CN}	Weight factor for R_{CN} when calculating R
w_{EB}	Weight factor for R_{EB} when calculating R
w_{ES}	Weight factor for R_{ES} when calculating R
CN-x	Rule x for consensus nodes
EB-x	Rule x for energy buyers
ES-x	Rule x for energy sellers

are satisfied. In addition to enhance efficiency, it can also eliminate unintended mistakes or malicious manipulation caused by human labor [8].

With the extensive deployment of renewable energy power generation devices, more and more energy systems are implemented in distributed ways. The concept of energy Internet has been put forward to encourage the deep integration of energy technologies and information and communication technologies [9]. There is no consensus on the specific definition of energy Internet, but its scope is usually broader than smart grid or microgrid. In more detail, an energy Internet system could also be natural gas or transportation systems in addition to power systems, and its energy forms includes electric energy, thermal energy, and so on. Moreover, users are more involved as energy Internet encourages the wide-area coordination of distributed energy systems in addition to local consumption [10].

As one of the most extensively studied information and communication technologies, blockchain has widely promoted distributed energy systems in various scenarios, for example, decentralized energy trading [11], energy cryptocurrency [12], automatic metering and billing [13], green certificate trading [14] and carbon emission trading [15], and automatic energy management [16]. According to the statistics in [8], decentralized energy trading accounts for 33% among 140 blockchain-based studies in energy field surveyed, making it the most popular energy scenario of blockchain.

The decentralized nature of blockchain can be applied to avoid the manipulation of centralized individuals and additional intermediate cost during distributed energy trading [17]. The transparency, traceability, and immutability of energy transaction records are helpful to enhance mutual trust between users and the service [18]. Furthermore, automatic energy trading enabled by smart contracts can prevent human error or manipulation and improve trading efficiency [19].

In blockchain, consensus is used as a subprotocol to prevent the behavior of consensus nodes from deviating from the prescribed protocols in a decentralized environment [20]. Although consensus is a classical problem in distributed computing, improving the scalability of consensus algorithms has always been a very difficult problem [21]. As a result, many existing blockchain systems are difficult to be applied on a large scale in practice [22]. In essence, consensus is a way to distributedly establish oblivious trust. Without the access to the history of previous consensus instances, this oblivious trust needs to be established for every new consensus instance, resulting in the heavy burden of computing or information transmission.

In recent years, more and more research works start to introduce reputation (or credit) to resemble real-world trust that is generally recordable, cumulative, and dynamic. A general reputation system records a reputation value that evaluates the trustworthiness of each node based on historical record [23]. One of the major uses of reputation in distributed systems is to enhance the efficiency of blockchain via delegated consensus. By delegating consensus decisions to nodes with higher reputation values, consensus can be reached much faster because the number of message transmissions required is reduced, with only a little sacrifice in decentralization [24]. Since low-reputation members are less likely to get involved into the consensus process, reputation mechanisms are also helpful in regulating the behavior of consensus participants [25].

In the meanwhile, reputation also plays an important role in the scenario of energy trading. With the promotion of distributed energy trading, the uncertain, untrusted, or selfish behavior of sellers or buyers makes the violation of trading contracts more common [26,27]. Using reputation mechanisms to evaluate the behavior of transaction users can effectively improve the reliability and fairness of energy trading [28].

1.1. Motivations

Although many works have introduced reputation in consensus, blockchain, or energy trading, most implementation manners of their reputation mechanism are either omitted or centralized (e.g., [29–31]). In contrast, a distributed reputation system can eliminate the manipulation of reputation records, thus enhancing the credibility of the reputation system [32]. As a matter of fact, implementing a reputation system in a distributed way is a difficult problem. For one thing, the recording and management of user reputation should not depend on a centralized authority. For another, the results provided by the distributed reputation system should be admitted by users.

Similar to energy trading, distributed reputation systems can also benefit from blockchain. In fact, there are other scholars studying distributed reputation management based on blockchain. The traceability and immutability of blockchain can improve the reliability of a distributed reputation system, and any update occurs to reputation can be tracked and cannot take effect unless it is approved by the majority. Blockchain-based reputation management has been applied to many different fields, for example, supply chain [33], vehicular network [34], intelligent transportation [35], and machine-to-machine application service [36].

In the energy field, reputation can be applied in many ways. The simplest way of applying reputation in the energy field is to improve the efficiency of the consensus subprotocol of energy blockchain [37]. Beyond that, reputation can also become a factor for transaction matchmaking [31] or an incentive for demand response [38]. However, as far as we are concerned, the application of distributed reputation in energy systems has not been fully explored yet. With the popularization of distributed energy systems, how to purposefully design and implement distributed reputation is worth studying.

Moreover, many works claim to bring fairness to energy trading. However, there is no consensus on what "fairness" is, and how fairness is assessed is rather vague. Some works believe that fairness eliminates the discrimination in benefit allocation among prosumers [39] or demand response among consumers [40]. The fairness is literally interpreted in [31] as "equity", i.e., distributing permit, compliance cost, and reduction responsibility based on reputation. Still, there is a lack of a scientific method to evaluate this equity.

1.2. Related works

In recent years, there have been a lot of works using reputation to improve the efficiency and scalability of consensus and blockchain. Proof-of-Reputation (PoR) [41] is a consensus for blockchain where the node with the highest reputation value becomes the block generator, and top 20% nodes become the verifiers of blocks. It stores reputation values in sub-blocks integrated into normal blocks that hold transaction information. In [42], a scheme called Proof-of-Reputation-X (PoRX) is proposed. It includes a reputation module to improve PoX, i.e., consensus algorithms similar to Proof-of-Work (PoW) and Proof-of-Stake (PoS). The basic idea derives from [43] that different difficulty levels of solving consensus puzzles are assigned to different nodes according to their reputation values.

In spite of this, most existing works focus more on applying reputation to distributed systems than specifying implementation details of their reputation mechanisms. As a result, their implementation manners are either omitted or centralized. ReCon [29] is a reputation module that can be integrated with any consensus algorithm. A public committee that makes consensus decisions is probabilistically selected based on the reputation values of nodes. However, how reputation values are maintained and how the selection of the committee is admitted by non-committee members are not explained. Dynamic-reputation Practical Byzantine Fault Tolerance (DBFT) is a consensus algorithm similar to PoR, which only allows the first 60% nodes to participate in consensus according to the ranking of credit values [37]. To complete multiple critical tasks including calculating credit values and selecting leader nodes, a centralized monitoring node is nonetheless indispensable.

Similar to many other distributed systems, distributed reputation management system can also be accomplished by blockchain. Tang et al. [44] carry out a trust-based framework to enable cross-platform collaboration in Internet-of-Things (IoT) scenarios. In this framework, the trust information is shared between different domains through a global blockchain. The trust-based credits can also serve as incentives to IoT collaboration engagement. Similarly, [36] shows that the machine-to-machine application services provided by peers can also be evaluated by blockchain which stores credibility information. They also provides an elaborate and comprehensive trust evaluation framework. In addition, [45] provides a systematic assessment of literatures on blockchain-based trust and reputation management.

In the energy field, reputation mechanisms have also been applied in different energy scenarios. Khaqqi et al. [31] first consider the impact of reputation on trading prices in their emission trading system. The system will calculate a priority value based on both seller/buyer reputation and offering/bidding price for each order, which decides the visibility of the order during the matchmaking process. In the demand response mechanism provided by [38], the blockchain-based reputation system evaluates the quality of end-users and load aggregators, which affects the priority when matching with a user or aggregator in a similar way. With the help of smart contract, this reputation system accomplishes automatic reputation calculation.

1.3. Contributions

In the context of energy Internet, this paper designs a distributed reputation system for blockchain-based peer-to-peer (P2P) energy trading, named Reputation for Blockchain-based energy Trading (RBT). This reputation system has the following features:

1. Its design relies on the blockchain technology. Reputation scores are stored in blockchain, making reputation traceable and tamper-proof. In addition, smart contract is used to achieve automatic reputation management. Although there is a reciprocal relationship between reputation and blockchain, existing researches mainly focus on improving the efficiency of blockchain through reputation or achieving distributed reputation management through blockchain, but few of them have both.
2. This reputation system analogize the universality of real-world trust in the sense that it is used in both blockchain consensus and energy trading. On the one hand, reputation improves the efficiency of blockchain by implementing delegated consensus, and it also improves the fairness of energy trading by involving the reputation scores of both sellers and buyers in matchmaking. On the other hand, the behavior of users during blockchain consensus or energy trading will be reflected in their future reputation scores.
3. In particular, the P2P energy trading system uses a reputation-based k-double auction matchmaking strategy. Different from the original k-double auction in [46], our reputation-based k-double auction decides trade prices that are more beneficial to buyers and sellers with higher reputation scores. The purpose is to balance the fairness indicator among participants, which is defined as the average income by reputation for sellers and the average cost by reputation for buyers. This intuitively makes reputation an incentives in P2P energy trading. As far as we are concerned, the fairness indicator in our paper is the first to provide a formal way to conceptualize and evaluate fairness in P2P energy trading.

In order to evaluate the performance of RBT, we simulate a comprehensive system consisting of a reputation system, a blockchain system, and a P2P energy trading system. The simulation shows the improvement in the efficiency in blockchain and the fairness of the trading strategy.

The rest of this paper is organized as follows: Section 2 describes the framework of our blockchain-based distributed reputation system; Section 3 provides details of designing delegated consensus based on our reputation system; Section 4 explains a P2P energy trading strategy

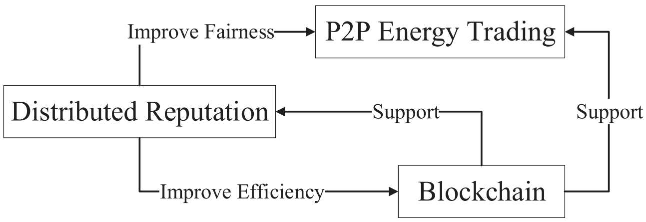


Fig. 1. The interconnected relationship between distributed reputation, blockchain, and P2P energy trading.

that also considers seller/buyer reputation; Section 6 briefly outlooks future research directions; Section 5 evaluates the performance of the entire system by simulation; Section 7 concludes this paper.

2. RBT: A distributed reputation system

In this section, we describe Reputation for Blockchain-based energy Trading (RBT), a blockchain-based distributed reputation system that can be applied in the scenario of blockchain-based P2P energy trading. Specifically, the reputation system is comprehensive in the sense that it can improve the efficiency of blockchain and the fairness of energy trading. The relationship between reputation, blockchain, and P2P energy trading is depicted in Fig. 1.

2.1. Reputation framework

The most direct purpose of RBT is to maintain a reputation score that comprehensively evaluates the behavior of each participant as different roles according to the prescribed rules. As shown in Fig. 2, the framework of RBT consists of three modules: role, rule, and reputation. We will explain each module in detail.

2.1.1. Role

The role module defines three different roles that each participant can play:

- **Consensus Node.** The energy trading system uses blockchain to record transactions (see more details in Section 3). Participants can choose to become a consensus node and join the process of transaction validation to receive extra reward. In more detail, consensus nodes will receive requests of adding transaction records into the blockchain from clients. Then consensus nodes generate corresponding blocks and initiate consensus instances for approval. Once consensus is reached, blocks will be added to the blockchain.
- **Energy Seller.** Energy users with power generation devices, e.g., household rooftop photovoltaic panels, can play the roles of energy sellers (or prosumers). They can make a profit by releasing surplus energy on the P2P trading platform for sale.
- **Energy Buyer.** Any participant can be an energy buyer (or consumer) during energy trading. Energy buyers can purchase energy on demand from the P2P trading platform.

New members are energy buyers by default, and they can also play the roles of consensus nodes and energy sellers at the same time.

2.1.2. Rule

Real-world trust systems usually have rules to regulate people's behavior. Similarly, RBT also has a rule module that defines rules for each role to regulate the behavior of participants. These rules are implemented as the criteria to calculate and update reputation scores. Following these rules helps to build up the reputation scores while violating these rules could result in a deduction in reputation scores.

As shown in Fig. 2, rules for consensus nodes (CN) are represented by CN-1, CN-2, …, rules for energy sellers (ES) are represented by ES-1, ES-2, …, and rules for energy buyers (EB) are represented by EB-1, EB-2, …. The rules for different roles are independent. For example, CNs only contain rules for consensus activities and will not affect the energy buyer reputation or the energy seller reputation.

2.1.3. Reputation

In RBT, reputation scores are stored as a 4-tuple:

$\langle R, R_{CN}, R_{ES}, R_{EB}\rangle$.

Among them, $R \in [0,1]$ is called the comprehensive reputation score. This reputation score is calculated based on:

- R_{CN}: the consensus node reputation score;
- R_{ES}: the energy seller reputation score;
- R_{EB}: the energy buyer reputation score.

Note that R_{CN}, R_{ES}, and R_{EB} are also numbers from $[0,1]$ that are calculated based on the rules prescribed in the rule module (see Sections 3.3, and 4.2 for more details). For new participants, $R_{CN} = R_{ES} = R_{EB} = 0.5$ by default.

The comprehensive reputation score R can be calculated differently according to the requirements of the practical system. For simplicity, this paper defines R as a linear combination of R_{CN}, R_{ES}, and R_{EB}:

$$R = \frac{w_{CN}\chi_{CN}R_{CN} + w_{ES}\chi_{ES}R_{ES} + w_{EB}\chi_{EB}R_{EB}}{w_{CN}\chi_{CN} + w_{ES}\chi_{ES} + w_{EB}\chi_{EB}}, \tag{1}$$

where $w_{CN}, w_{ES}, w_{EB} > 0$ are significance factors, and $\chi_{CN}, \chi_{ES}, \chi_{EB}$ are characteristic coefficients defined as:

$$\chi_{CN} = \begin{cases} 1 & \text{participant is a consensus node;} \\ 0 & \text{otherwise;} \end{cases}$$

$$\chi_{ES} = \begin{cases} 1 & \text{participant is an energy seller;} \\ 0 & \text{otherwise;} \end{cases}$$

$$\chi_{EB} = \begin{cases} 1 & \text{participant is an energy buyer;} \\ 0 & \text{otherwise.} \end{cases}$$

Note that the significance of the reputation score for each role can be changed by adjusting the corresponding significance factor according to actual needs. For example, putting more emphasis on the regulation of consensus behavior can be achieved by increasing the value of w_{CN}. Without the loss of generality, we set $w_{CN} = w_{ES} = w_{EB} = 1$. In addition, there is no worry about the divide-by-zero case because each participant is an energy buyer by default and $\chi_{EB} = 1$.

Finally, we define a trust lower bound $R_{\min}$. The participant with a comprehensive reputation score under $R_{\min}$ is seen as untrusted. The reputation score of an untrusted participant can no longer automatically restore to above $R_{\min}$ unless it is manually recovered with the acknowledgment of other participants. Here we set $R_{\min} = 0.2$.

2.2. Distributed implementation

There are several essential points in implementing a reputation mechanism in a distributed way. First, the reputation system should not be owned, maintained, or manipulated by any minority. This helps to regulate the behavior of participants if everyone has the competence to monitor the good and bad behavior of others. Second, any update in reputation scores should be seen, admitted, and shared by all participants. This could effectively prevent possible tampering with reputation scores. Third, the problem of data redundancy of the distributed system will be more serious as the number of participants increases. There is an urgent need for an effective way to store these reputation scores.

As shown in Fig. 3, the implementation of RBT includes three main components:

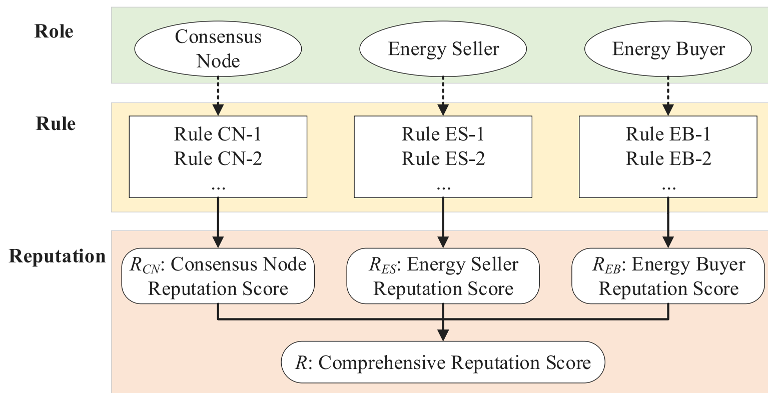


Fig. 2. Three modules of RBT framework work interdependently. The system defines different roles, and the reputation score of each role is calculated according to corresponding rules.

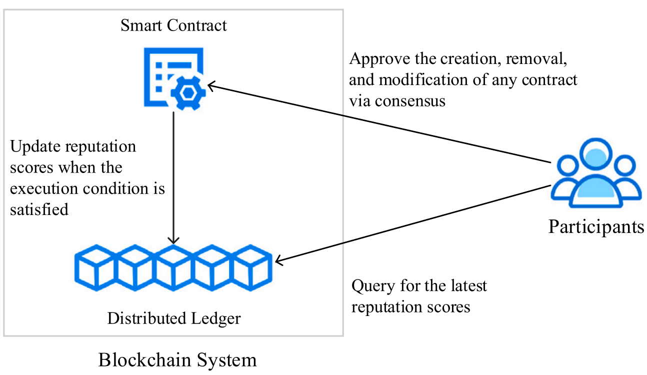


Fig. 3. Blockchain-based implementation of RBT. Reputation scores stored in the distributed ledger are automatically updated by smart contracts when reputation rules are applicable. Participants can edit reputation rules by modifying corresponding smart contracts.

- **Distributed Ledger**. Reputation scores are stored in a distributed ledger maintained by the blockchain system. Any update of the reputation scores can be viewed by all participants. This makes the reputation system more transparent and more robust to malicious tampering with reputation scores. Moreover, the linked list structure of blockchain makes reputation changes more traceable.
- **Smart Contract.** The rules in the rule module of the reputation framework are implemented as the scripts in smart contracts supported by the blockchain system. Once some 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.
- **Participants.** Participants can query the distributed database for reputation lookup. In addition, when a change of the smart contracts is received, participants will run a distributed consensus protocol to decide whether to approve or deny the change.

3. Reputation-based blockchain

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, which is why we consider implementing a blockchain-based energy trading system. We use RBT to improve the efficiency of the blockchain by implementing delegated consensus. Delegated consensus is an effective way to reduce the client-side latency and improve server throughput of a consensus algorithm by reducing the number of consensus nodes. Since reaching consensus needs massive message communication, reducing the participants of consensus required can reduce the workload of message processing in consensus nodes, thus raising the speed of reach consensus. Moreover, enhancing the efficiency of blockchain-based reputation system is also of great importance. If reputation scores are not updated in time, more consensus instances and transaction records may fail.

When a new block containing transaction records is generated, it needs to be approved by distributed nodes in the peer-to-peer network through consensus before it can be added to the chain. The consensus algorithm is used to prevent double-spending transactions, where the same assets are spent in multiple transactions. Different from common consensus algorithms, an instance of delegated consensus will not involve all consensus nodes. Usually, delegated consensus will form a voting committee that contains consensus nodes with higher reputation scores, and the consensus process to approve transactions is only reached among committee members. Similar to [37], we use our reputation framework to implement delegated Practical Byzantine Fault Tolerance (PBFT) for the blockchain system. Non-committee nodes only participate in the consensus to approve changes in smart contracts.

3.1. Delegated PBFT

Each consensus instance begins with a client submitting a request to consensus nodes. In the blockchain-based energy trading system, adding energy transactions to the blockchain can be seen a consensus request. The original PBFT consensus completes in three main stages: pre-prepare, prepare, and commit [47].

1. In the pre-prepare stage, if the request is valid, then a pre-selected consensus node, called the leader, will broadcast a pre-prepare message that contains the request to all the other nodes. This stage makes sure the request received by all nodes are the same.
2. In the prepare stage, the nodes that have received a valid pre-prepare message broadcast a prepare message, which shares the pre-prepare message received from the leader. This stage makes sure that all nodes are participating the same consensus instance.
3. In the commit message, each node votes for the valid request by broadcasting a commit message. The commit message is also sent to the client. The request is committed and consensus is achieved if the commit messages from more than 2/3 nodes are received.

In order to relieve the pressure in message transmission, prepare and commit messages only include the hash of the original requests. PBFT has a quadratic message complexity because three stages require message broadcasting. In other words, if the total number of consensus nodes is n, then the number of message transmission to complete a consensus instance has the order of n^2. This brings significant workload to the system as the number of consensus nodes increases. As illustrated

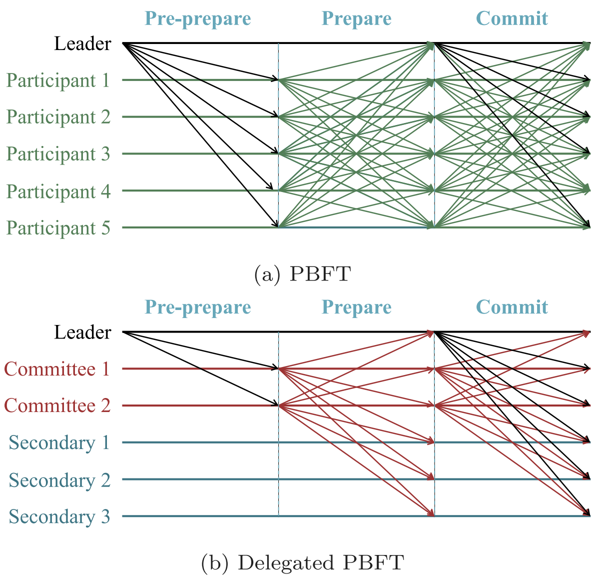


Fig. 4. Message flow of PBFT and delegated PBFT. The communication pattern of delegated PBFT is visibly simplified as it circumvents the all-to-all broadcast required by PBFT.

by Fig. 4, with the help of the reputation mechanism, delegated PBFT can effectively reduce its message complexity. We will describe the details of delegated PBFT in the next.

Delegated PBFT also has a distinguished leader node ℓ. Suppose leader node ℓ receives a request r. Leader ℓ need to generate a pre-prepare message as long as request r is valid. Different from the pre-prepare message of PBFT, the pre-prepare message of delegated PBFT need to specify a voting committee $C(r)$ which includes the information of the consensus nodes that will participate the prepare and commit stage.

In theory, any node other than ℓ with a comprehensive reputation score $R \geq R_{\min}$ may be selected as a committee member. Although we do not require the reputation scores of committee members to be at the top, it is recommended that committee $C(r)$ has a high average reputation (see Section 3.3). In order to effectively enhance the efficiency of delegated PBFT, the size of the committee should be much smaller than n when n is very large, and at least 4 nodes are needed to reach consensus.

After receiving the pre-prepare message, committee members in $C(r)$ as well as ℓ will continue with the prepare and commit stages as the original PBFT, which excludes non-committee nodes (or secondary nodes). Non-committee nodes only receive the prepare messages and the commit messages passively. The consensus is successful if more than 2/3 committee members approve the request by broadcasting commit messages.

3.2. Offline verification

Delegated consensus is a means to quickly respond to the client. It delegates the consensus tasks to participants with higher reputation scores. However, consensus decisions of the committee are not necessarily correct. Therefore, offline verification carried out by non-committee members is needed to ensure the final correct of the blockchain, which will also provide evidence for subsequent reputation updates. In our system, an offline verification subprotocol is designed to prevent double spending and conspiracy. Note that the term "offline" means that the verification of a consensus result is asynchronous with the consensus instance, so offline verification should not have a dramatic impact the efficiency of consensus.

3.2.1. Double spending

Double spending, one of the main aims of attacks on blockchain systems, is a kind of malicious behavior that attempts to spend the same assets in different transactions [48]. For example, leader ℓ can first send a request of transaction #1 to committee C_1. Before transaction #1 gets approved and takes effect, leader ℓ can send a different transaction #1′ to a disjoint committee C_2. This will cause forking in the blockchain, i.e., the inconsistency in the copies of blockchain data in different consensus nodes. Although only one of transaction #1 and #1′ will eventually be approved, the asynchrony in message transmission, consensus decision, and transaction execution provides the buyer a chance of spending the same assets in different transactions.

The longest-chain rule is a common way to deal with double spending [49]. In more detail, the blockchain system will periodically check the longest subchain. Then the system will keep the longest subchain and discard other subchains when forks exist. The intuition behind the longest-chain rule is that longer subchain has higher confidence to be seen by the majority [50].

3.2.2. Conspiracy

On the other hand, conspiracy refers to the case where a successful consensus instance approves an invalid request (also called forgery in [29]). In order to carry out a conspiracy, a malicious leader ℓ needs to specify a voting committee with the majority being Byzantine. As non-committee nodes only receive prepare and commit messages without the original requests, they are not able to tell the validity of the approved requests. They have to trust the consensus decision of the committee during the commit stage (this is where reputation-based trust is involved). As we have mentioned in Section 3.1, the voting committee is recommended to have a high average reputation in order to discourage conspiracy.

In offline verification, however, non-committee nodes are responsible for auditing the results of previous consensus instances. They can query about the content of old requests and check the validity, and an invalid request with a successful consensus indicates conspiracy. Once conspiracy is detected, the block containing the invalid request will be removed from the blockchain. Moreover, the leader and committee members that participate in a conspiracy will be subject to reputation penalties (see Section 3.3).

3.3. Rules for consensus nodes

Now we specify the rules of reputation update of consensus nodes:

1. **CN-1.** When a consensus instance for request r succeeds, the reputation of the leader ℓ changes by:

$$R_{CN}(\ell) \leftarrow \min\{\max\{R_{CN}(\ell) + R^{+}_{CN}(\ell) + R^{L,+}_{CN}(\ell), 0\}, 1\}, \tag{2}$$

and the reputation of a committee node $i \in C(r)$ changes by:

$$R_{CN}(i) \leftarrow \min\{\max\{R_{CN}(i) + R^{+}_{CN}(i), 0\}, 1\}, \tag{3}$$

where:

- $R^{+}(i)$ is positively related with the success rate of all consensus instances i has participated, and it is negatively related with the time duration since the last drop in $R_{CN}(i)$ and the current value of $R_{CN}(i)$;
- $R^{L,+}_{CN}(\ell)$ is positively related to the average reputation score of the committee C:

$$R_C(r) = \frac{1}{|C(r)|} \sum_{i \in C(r)} R(i). \tag{4}$$

2. **CN-2.** When a consensus instance for request r fails, the reputation of the leader ℓ changes by:

$$R_{CN}(\ell) \leftarrow \min\{\max\{R_{CN}(\ell) - R^{-}_{CN}(\ell) - R^{L,-}_{CN}(\ell), 0\}, 1\}, \tag{5}$$

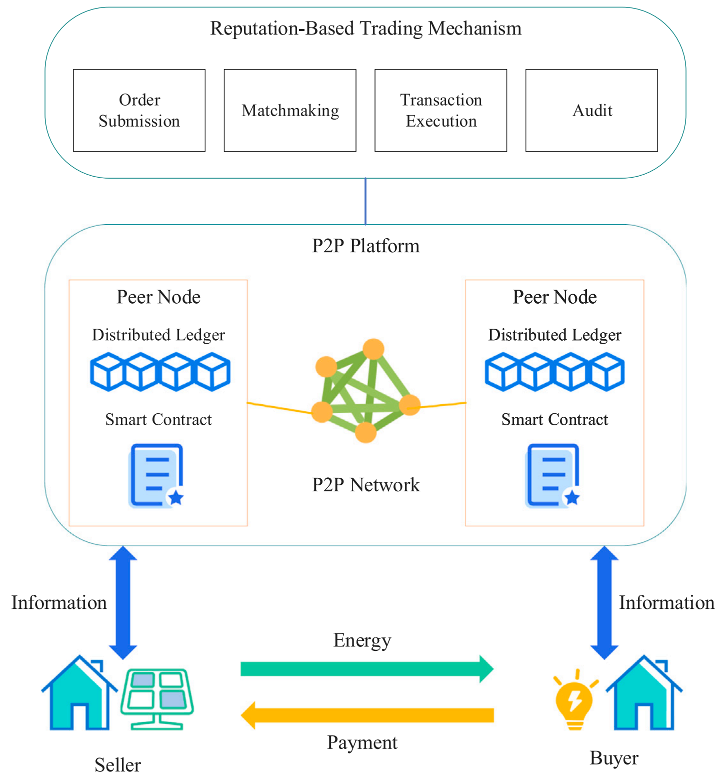


Fig. 5. Architecture of P2P energy trading system based on blockchain and reputation. Transaction records are stored in distributed ledger, and the reputation-based trading process can be programmed as smart contracts. Except for physical delivery, other trading steps rely on the blockchain platform.

and the reputation of a committee node $i \in C(r)$ changes by:

$$R_{CN}(i) \leftarrow \min\{\max\{R_{CN}(i) - R^{-}_{CN}(i), 0\}, 1\}, \tag{6}$$

where:

- $R^{-}(i)$ is positively related with the failure rate of all consensus instances j has participated and the time duration since the last drop in $R_{CN}(i)$, and it is negatively related with the time duration since the last drop in $R_{CN}(i)$ and the current value of $R_{CN}(i)$;
- $R^{L,-}_{CN}(i)$ is negatively related to R_C, the average reputation score of the committee C.

3. **CN-3.** The reputation score $R_{CN}(\ell)$ of the leader ℓ is cleared to 0 if double spending or conspiracy during the consensus process is discovered.

Note that CN-1 and CN-2 will be triggered once the consensus instance has finished, regardless of the result of offline verification. Conspiracy can be discovered during the verification right after the consensus, and double spending can be detected when the longest-chain rule is applied. These rules only change the reputation of the leader ℓ and committee nodes $i \in C(r)$, and reputation scores of non-committee nodes are not changed.

4. Blockchain-based peer-to-peer energy trading with reputation

Our system considers the distributed energy trading in a regional energy Internet. The architecture of the P2P energy trading system based on blockchain and reputation is shown in Fig. 5. The P2P platform will allocate a peer node to each buyer or seller during energy trading. The peer node is mainly used to publish supply or demand orders. It can also become a consensus node to record transactions into the blockchain and approve any change in smart contracts. Peer nodes are usually implemented in smart meters. The platform can stores transaction records into the distributed ledger. The reputation-based trading has 4 stages: order submission, matchmaking, transaction execution, and audit. The trading mechanism can also be implemented as smart contracts to achieve automation. Similarly, any changes to the trading mechanism should be approved by consensus.

In this section, we will go into more details about the reputation-based P2P trading mechanism.

4.1. Reputation-based peer-to-peer trading mechanism

In this paper, we consider the day-ahead energy trading. In other words, the energy delivery plan of a day is determined in the previous day through order submission and matchmaking. The transaction execution takes place on the energy delivery time specified by transactions. The audit will be carried out once the execution finishes. The workflow of the P2P energy trading stages is depicted in Fig. 6. The P2P energy trading system is connected to the main grid to tackle unmatched orders (see Section 4.1.2 for more details). Since the delay of real-time energy trading is expected to be within 5 minutes [51], our system has no essential difficulty to be extended to the real-time energy trading scenario (given the performance analysis in Section 5). We choose the day-ahead trading only for the purpose of illustration.

4.1.1. Order submission

In the first stage of energy trading, sellers need to submit supply orders while buyers need to submit demand orders. A supply order includes information about the time of energy supply, the amount of energy supply, and the *minimum* acceptable selling price (called the offering price). A demand order includes information about the time of energy demand, the amount of energy demand, and the *maximum* acceptable buying price (called the bidding price). Due to the consideration of user privacy protection, blockchain uses the account addresses of order submissions to correspond to the identities of prosumers or consumers instead of unique identifiers.

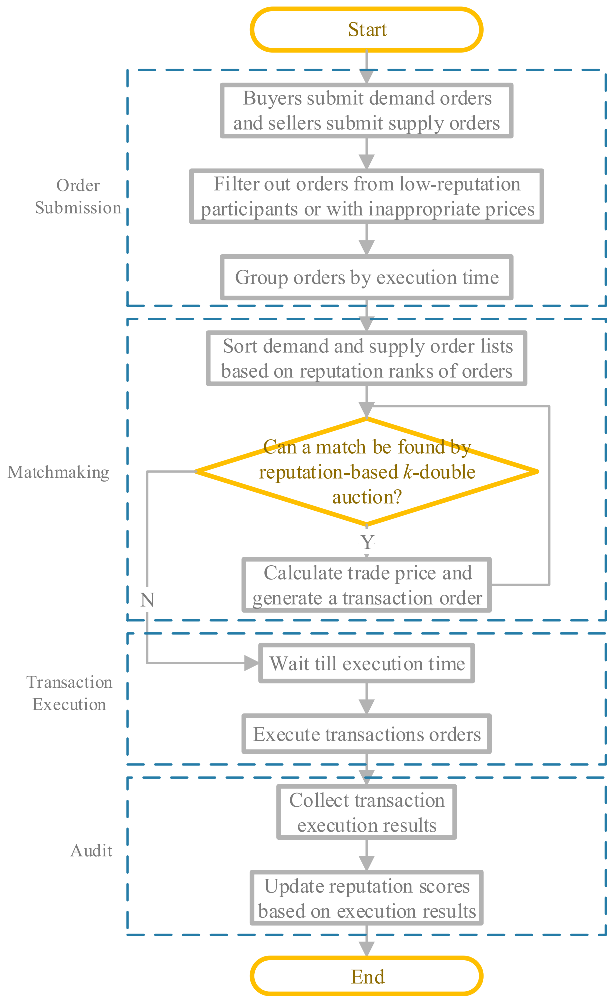


Fig. 6. Workflow of reputation-based P2P energy trading.

In order to prevent the seller from raising the price maliciously and the buyer from lowering the price maliciously, the system will provide reference price ranges for both parties. In more detail, we define $bp_{\min}$, $bp_{\max}$, $op_{\min}$, and $op_{\max}$ as the minimum bidding price, the maximum bidding price, the minimum offering price, and the maximum offering price allowed by our trading mechanism. A buying order with a bidding price out of $[bp_{\min}, bp_{\max}]$ or a selling order with an offering price out of $[op_{\min}, op_{\max}]$ will be removed. In addition, orders submitted by participants with reputation scores lower than $R_{\min}$ will also get filtered. Then supply and demand orders will be grouped by the time of supply or demand (collectively referred to as the transaction execution time) since orders cannot get matched if they are supposed to take place at different time periods.

4.1.2. Matchmaking

Before applying matchmaking between sellers and buyers, many existing systems will sort supply orders in ascending order of offering price and demand orders in descending order of bidding price [52]. This strategy is to maximize the profits of sellers and minimize the expenses of buyers. In our reputation-based energy trading mechanism, we consider the reputation-based profit and expense.

Similar to the credit defined in [53], reputation scores can also be regarded as an indicator of the contribution of a participant in P2P energy trading. A fairer approach could be to increase the profits of high-reputation sellers and decrease the expenses of high-reputation buyers. To achieve this, we define the reputation-based rank for supply and demand orders similar to the priority value in [31].

In more detail, the buying rank of a demand order from buyer b is defined as:

$$rank_{buy} = \frac{bp}{1 - R(b)}, \tag{7}$$

where bp is the bidding price of the demand order, and $R(b)$ is the comprehensive reputation score of buyer b. Similarly, the selling rank of a supply order from seller s is defined as:

$$rank_{sell} = \frac{op}{R(s)}, \tag{8}$$

where op is the offering price of the supply order, and $R(s)$ is the comprehensive reputation score of seller s. Once the ranks of orders are calculated, supply orders will be sorted in ascending order of $rank_{sell}$, and demand orders will be sorted in descending order of $rank_{buy}$. As we can see from (7) and (8), when two supply/demand orders have the same offering/bidding price, the one from a higher-reputation seller/buyer has a smaller/larger rank and will be in a higher position.

We then use a reputation-based k-double auction method to decide the trade price. In more detail, the matchmaking between sellers and buyers will start from the top of the supply and demand order lists. A matching is found when it comes across a bidding order from buyer b and an offering order from seller s with $bp \geq op$. Then the trade price is calculated by:

$$tp = k \cdot bp + (1 - k) \cdot op, \tag{9}$$

where k is calculated by:

$$k = \frac{R(s)}{R(b) + R(s)}. \tag{10}$$

Different from the k-double auction method in [46] where k is a constant, the trade price in our reputation-based method is decided by not only the prices of the supply order and the demand order, but also the comprehensive reputation scores of both the buyer b and the seller s. Note that the trade price is closer to the price submitted by the participant with lower reputation. This strategy will in turn increase the profit of the seller or decrease the expense of the buyer with a higher reputation in a transaction.

Finally, a transaction order will be formed, which specifies the buyer's address, the seller's address, the transaction execution time, the amount of energy delivery, and the trade price.

Note that some order, or part of an order, may not be able to find a match after reputation-based k-double auction. In order to keep a balance between supply and demand, the main grid acts as the seller or buyer of the transaction. The trade price will be the unified purchase or sale price.

4.1.3. Transaction execution

Upon the execution time of a transaction, the energy and currency transfer will take effect according to the transaction order. Note that the transaction execution may fail if the seller refuses to transfer the prescribed amount of energy or the buyer refuses to pay the prescribed price.

4.1.4. Audit

The audit stage will review the execution of transactions and then update reputation scores according to the reputation rules for energy buyers and energy sellers. A successful execution of a transaction will enhance the reputation of both parties, while the reputation scores of those who failed to fulfill their transaction contracts will be reduced.

4.2. Rules for buyers and sellers

The update in the reputation scores of P2P energy trading participants are as follows:

- **ES-1.** When the supply of a transaction order is successfully executed, the reputation of the seller is changed by:

$$R_{ES}(i) \leftarrow \min\{1, \max\{0, R_{ES}(i) + R^{+}_{ES}(i)\}\}, \tag{11}$$

where $R^{+}_{ES}(i)$ is positively related to the ratio of total successful supply amount to the number of successful transaction execution and the duration since last reputation drop.

- **ES-2.** When the supply of a transaction order fails, the reputation of the seller is changed by:

$$R_{ES}(i) \leftarrow \min\{1, \max\{0, R_{ES}(i) - R^{-}_{ES}(i)\}\}, \tag{12}$$

where $R^{-}_{ES}(i)$ is positively related to the ratio of total failed supply amount to the number of failed transaction execution, and is negatively related to the duration since last reputation drop.

- **EB-1.** When the consumption of a transaction order is successfully executed, the reputation of the buyer is changed by:

$$R_{EB}(i) \leftarrow \min\{1, \max\{0, R_{EB}(i) + R^{+}_{EB}(i)\}\}, \tag{13}$$

where $R^{+}_{EB}(i)$ is positively related to the ratio of total successful energy consumption to the number of successful transaction execution and the time duration since last reputation drop.

- **EB-2.** When the consumption of a transaction order fails, the reputation of the buyer is changed by:

$$R_{ES}(i) \leftarrow \min\{1, \max\{0, R_{ES}(i) - R^{-}_{ES}(i)\}\}, \tag{14}$$

where $R^{-}_{ES}(i)$ is positively related to the ratio of total failed consumption amount to the number of failed transaction execution, and is negatively related to the duration since last reputation drop.

These rules can also be implemented as smart contracts to achieve automation and avoid mistakes or tampering during manual calculation.

4.3. Fairness of peer-to-peer energy trading

Many existing works advocate to bring fairness to energy trading, but few of them has a clear measure of fairness. In this paper, we propose a formal definition of fairness indicator to evaluate a possible fairness for the P2P energy trading system.

In general, trading markets aim to eliminate discrimination and balance the average income of each seller and the average cost of each buyer [39,40]. Different from the notions of fairness in most existing works, the fairness in this paper considers reputation as a way to quantify the contribution of a participant to the P2P energy trading system. In this case, a fair trading system by intuition can be friendlier to the participants with more contribution, making average income/cost more relevant to the reputation of the seller/buyer.

Formally, the seller and buyer fairness indicators are defined as follows:

- For sellers, the seller fairness indicator (SFI) is defined as:

$$SFI(s) = \frac{income(s)}{E_{sell}(s) \cdot R(s)}, \tag{15}$$

where $income(s)$ is the total income of s during a trading period, and $E_{sell}(s)$ is the total amount of energy sold by s;

- For buyers, the buyer fairness indicator (BFI) is defined as:

$$BFI(b) = \frac{cost(b)}{E_{buy}(b) \cdot R(b)}, \tag{16}$$

where $cost(b)$ is the total cost of b during a trading period, and $E_{buy}(b)$ is the total amount of energy purchased by b.

If we regard the reputation score as a kind of contribution to the P2P energy trading system, then fairness indicators can be seen as the average income and average cost per contribution. Balancing fairness indicators among sellers and buyers can increase the average incomes of high-reputation sellers and reduce the average costs of high-reputation buyers. The balance or fairness can be mathematically evaluated by the following fairness factor (FF):

$$FF = \frac{1}{|r(R, FI)|}, \tag{17}$$

where $r(R, FI)$ is the correlation coefficient of comprehensive reputation score R and buyer/seller fairness indicator FI. The more balanced BFIs and SFIs are, the closer to zero $r(R, FI)$ is, and the greater FF is. This intuition achieves a kind of fairness as it is more friendly to the participants with high cumulative contribution. It also helps to use reputation as incentives due to its favor to participants with high reputation scores.

5. Evaluation

In this section, we evaluate the performance of our comprehensive system by simulation, which consists of a reputation system RBT, a blockchain system, and a P2P energy trading system. We implement the entire system in Go language (GoLand 2020.3.1 x64). The simulation experiments are executed on a computer with Intel® Core™ i7-6500U CPU at 2.50 GHz and 12 GB RAM. Each experiment is run 10 times, and each graphs in this section is plotted with the average data collected from these 10 runs.

5.1. RBT reputation scores

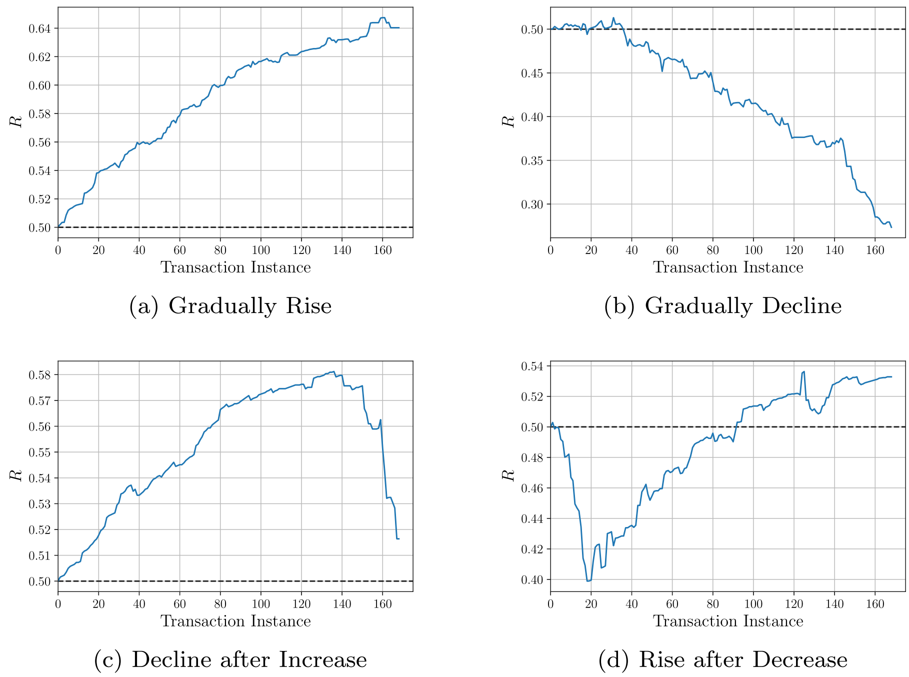
In order to test the effect of RBT, we need to specify example formulas according to the reputation update rules described in Sections 3.3, 4.2. The details of the formulas are described in Appendix. Fig. 7 simulates 4 typical trends of comprehensive reputation scores with 168 transaction instances: gradually rise, gradually decline, decline after increase, and rise after decrease. These trends, also reflected by the results in [54], intuitively simulate the changes of real-world trust.

5.2. Reputation-based delegated PBFT

We then evaluate the performance of the blockchain system that implements reputation-based delegated PBFT. We compare it with a blockchain system with the original PBFT algorithm [47] as its consensus mechanism. All the graphs here will use red curves to represent our reputation-based blockchain system and blue curves to represent PBFT-based blockchain system. Link latencies between consensus nodes are randomly drawn from a uniform distribution with an average of 200 ms. Communication messages between nonfaulty nodes are guaranteed to be delivered within 20 s (since it has been proved that deterministically reaching fault-tolerant consensus is impossible with indefinite message delay [55]). Moreover, the time to generate a new block is no longer than 20 s. Transaction records are submitted by the client application in a speed that follows a Poisson process at an average of 2 requests per second [56].

We carry three experiments to compare the performance of reputation-based blockchain and PBFT-based blockchain: server scalability, client scalability, and fault tolerance. In these experiments, client-side latency and server-side throughput are the two performance indicators of the blockchain system that are commonly evaluated in related works [57]. Client-side latency, or latency for short, captures the elapsed time from request submission to corresponding reply reception by clients. Server-side throughput, or throughput for short, is calculated as the average number requests servers can process per second.

Table 1 provides comparative data of the three experiments, where the average is taken among the data used to plot the corresponding figures. We will go through each experiment in the next.



(a) Gradually Rise (b) Gradually Decline

(c) Decline after Increase (d) Rise after Decrease

Fig. 7. Four typical trends of comprehensive reputation scores.

Table 1
Performance comparison between reputation-based and PBFT-based blockchains.

Experiment	Metric	Reputation-based	PBFT-based	Change
Server scalability	Average latency	1.68	3.95	−57.47%
	Average throughput	9.39	5.27	+78.18%
Client scalability	Average latency	11.46	23.66	−51.56%
	Average throughput	8.62	0.84	+926.19%
Fault tolerance	Average throughput	3.36	1.73	+94.22%

5.2.1. Server and client scalability

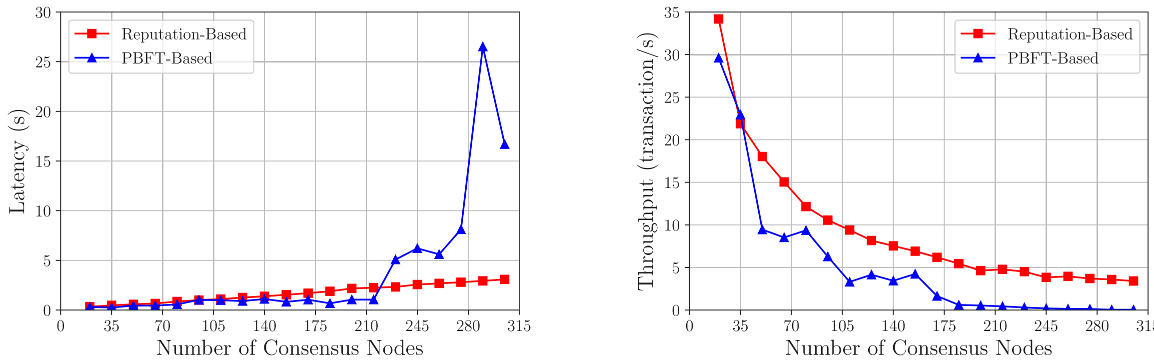
The scalability of the blockchain system largely depends on the scalability of its underlying consensus algorithm. Scalability usually has two aspects: server scalability and client scalability [58]. Server scalability reflects the ability to handle the workload caused by the increase in the number of servers (consensus nodes), while client scalability reflects the ability to handle the workload caused by the increase in the number of clients. In this paper, scalability is evaluated by average client-side latency, the average time for clients to wait for consensus results, and average server-side throughput, the average number of succeeded consensus instances, as the number of servers or clients increases. For a system with higher scalability, the latency increases and the throughput decreases at relatively slower speeds as the system scale increases [57].

As we have mentioned in Section 3.1, the quadratic message complexity of PBFT is the main obstacle to its (server) scalability. Our delegated PBFT alleviates this problem by only involving committee members in consensus. In the server scalability experiment, we fix 20 clients and 20 committee members. We can see from Fig. 8(a) that the change in the latency of reputation-based blockchain is very small, compared to the sudden increase in the latency of PBFT-based blockchain after the number of consensus nodes passes 216. In Fig. 8(b), both curves fall as the number of consensus nodes rises, but the red curve has a slower decreasing speed. The performance degradation of reputation-based blockchain is because that the growth in the total number of consensus nodes slows down the process of offline verification, although the size of the committee does not increase. These two graphs indicate the improvement in server scalability of reputation-based blockchain compared to that of PBFT-based blockchain.

Client scalability evaluates the capability of handling the pressure from the increasing number of client requests. When the request submission speed exceeds the speed of server processing, the accumulation of client requests will significantly reduce the system efficiency. To test the client scalability of our reputation-based blockchain, we subsequently fix 100 servers, 20 of which could become committee members. As shown by Fig. 9(a), although both curves are on the rise, the red curve is more often below the blue curve. The latency of PBFT-based blockchain has a significant rise after the number of clients exceeds 136. Fig. 9(b) shows a great increase in the throughput of reputation-based blockchain. The throughput of PBFT-based blockchain is almost 0 after the client number passes 100, while the throughput of reputation-based blockchain does not have a dramatic decrease until the client number passes 240. The great gap between these two curves could result from the slow and complicated panic and view change subprotocols of PBFT, which try to tolerate faulty nodes. Delegated PBFT avoids this slowdown by allowing the failure of consensus to fast push request processing. These two figures indicate the better client scalability of reputation-based blockchain compared to that of PBFT-based blockchain.

5.2.2. Fault tolerance

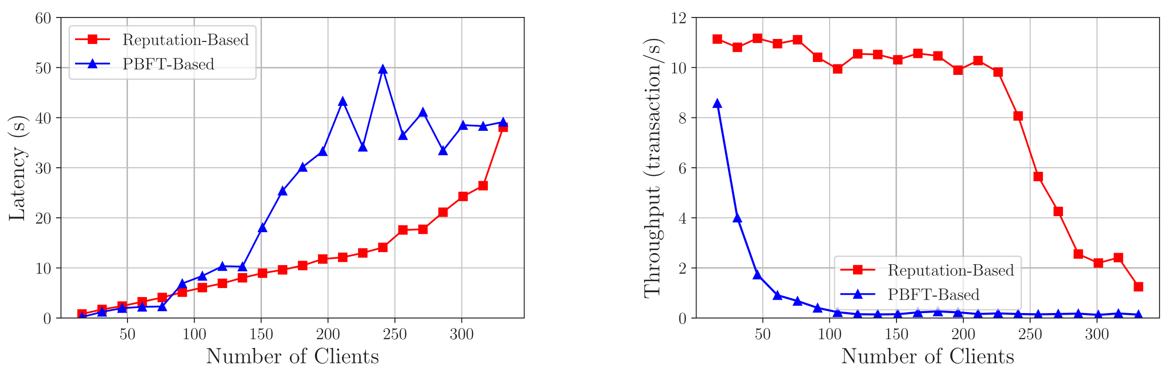
Fault tolerance is the capability of eventually reaching consensus in the presence of Byzantine faults. It can be measured by the change of throughput as the Byzantine fault rate, or the proportion of the consensus nodes with Byzantine faults, increases [59]. It has been proved that PBFT cannot reach consensus if the Byzantine fault rate is greater than 1/3 [60]. Consequently, the throughput of PBFT will fall to zero (or extremely close to zero) when the Byzantine fault rate passes 33%.



(a) Latency vs. Server Number

(b) Throughput vs. Server Number

Fig. 8. Performance comparison between delegated PBFT-based blockchain with reputation and PBFT-based blockchain as the number of consensus nodes (servers) increases from 20 to 305.



(a) Latency vs. Client Number

(b) Throughput vs. Client Number

Fig. 9. Performance comparison between delegated reputation-based blockchain with reputation and PBFT-based blockchain as the number of clients increases from 1 to 331.

In contrast, delegated consensus only reach consensus within the committee. As time goes on, the reputation scores of nodes with Byzantine faults will be lower and lower due to the penalty of consensus failure, double spend, and conspiracy. The rules for consensus nodes described in Section 3.3 nonetheless encourages leader ℓ to select a voting committee with higher average reputation. As a result, there is still a chance to reach consensus and achieve a nonzero throughput when benign nodes are the majority in the committee, even if the Byzantine fault rate is greater than 1/3.

This point can be confirmed by Fig. 10. The location where the throughput becomes zero indicates the limit of fault tolerance. We can see that the throughput of PBFT-based blockchain falls down to almost 0 when the Byzantine fault rate passes 30%, while the throughput of reputation-based blockchain does not converge to 0 until the Byzantine fault rate passes 80%. This indicates an improvement in the fault tolerance capability of reputation-based blockchain compared to that of PBFT-based blockchain.

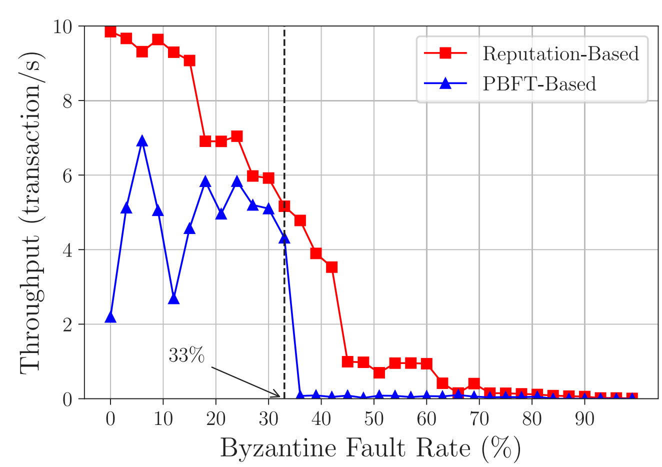


Fig. 10. Throughput comparison between delegated consensus-based blockchain and PBFT-based blockchain as the proportion of consensus nodes with Byzantine faults increases from 0% to 99%.

5.3. Practical concerns of reputation-based blockchain

Although blockchain has become one of the most influential information and communication technologies, practical concerns about blockchain are becoming more apparent, which include the complexity of implementation, difficulty in maintenance, compatibility problem between different versions and systems, and lack of unified evaluation criteria. In order to analyze the applicability, we adopt the administrative criteria in [61] to evaluate our reputation-based blockchain system (shown by Table 2). Note that the criteria of support and autonomy are not included as they are for open source blockchain platforms.

5.4. Case study for reputation-based peer-to-peer energy trading

In order to evaluate our reputation-based P2P energy trading system, we run a case study of a certain trading round for the same transaction execution time period. All data constructed for our case study are based on the experiments in [31,62]. Note that our system is designed in the context of energy Internet, where energy can be in the form of gas, cool, heat, and electric power [63]. Our case study

Table 2
Analysis of practical concerns according to the administrative criteria in [61].

Criterion	Evaluation	Note
Attack resistance	Average	Apart from default cryptographic algorithms and Byzantine fault tolerance, additional schemes are required to prevent denial-of-service attack and Sybil attack.
Ease to learn	Good	Developers need to learn about the reputation system in addition to common blockchain system.
Ease to develop	Average	The adoption of scenarios other than P2P energy trading needs to set the rule module differently.
Developers	Excellent	The development work was completed by a group of three software engineers.
Interoperability	Not applied	Our system is designed for distributed energy trading in a regional energy Internet, so the interoperation with other blockchain systems is not considered.
Maintenance	Good	Since the core of the reputation system, the rule module, is implemented by smart contracts that are programmable, the maintenance should not bring too many additional difficulties compared with existing blockchain platforms.
Ease to deploy	Good	
Backup/Restore	Good	
Automation	Excellent	The automation is high due to the extensive use of smart contracts.

Table 3
Supply orders for case study.

Seller	Amount (kW·h)	Offering price ($/kW·h)	Reputation score	$rank_{sell}$
A	53	2.24	0.7198	3.1120
D	32	1.82	0.5931	3.0686
E	60	1.63	0.5316	3.0662
F	26	2.34	0.4738	4.9388
H	35	1.62	0.2004	8.0838
J	33	1.69	0.6002	2.8157
K	38	1.82	0.6997	2.6011
Q	40	2.21	0.6046	3.6553
R	59	1.73	0.6815	2.5385
S	35	2.27	0.7414	3.0618
T	31	2.23	0.5875	3.7957
U	32	1.92	0.1680	11.4286
Y	59	2.30	0.6085	3.7798

Table 4
Demand orders for case study.

Buyer	Amount (kW·h)	Bidding price ($/kW·h)	Reputation score	$rank_{buy}$
B	31	1.78	0.6361	4.8888
C	59	2.25	0.6781	6.9854
G	28	1.64	0.7911	7.8431
I	27	2.26	0.6426	6.3199
L	51	1.87	0.5646	4.2929
M	60	2.04	0.3653	3.2131
N	28	2.39	0.6783	7.4247
O	25	2.13	0.2000	2.6618
P	40	1.94	0.7390	7.4273
V	33	2.31	0.4699	4.3560
W	28	1.64	0.1178	1.8586
X	27	1.95	0.5111	3.9869
Z	27	2.31	0.6590	6.7702

Table 5
Matchmaking results of reputation-based k-double auction.

Transaction	Buyer	Seller	Amount (kW·h)	Trade price ($/kW·h)
1	G	H	28	1.62
2	P	R	40	1.83
3	N	R	19	2.06
4	N	K	9	2.11
5	C	K	29	2.04
6	C	J	30	1.95
7	Z	J	3	1.99
8	Z	S	24	2.29
9	I	E	27	1.92
10	B	E	31	1.70
11	V	S	11	2.29
12	V	E	2	1.99
13	V	D	20	2.09
14	L	D	12	1.85
15	L	H	7	1.87
16	Grid	A	53	1.17
17	Grid	Q	40	1.17
18	Grid	Y	59	1.17
19	Grid	T	31	1.17
20	Grid	F	26	1.17
21	Grid	U	32	1.17
22	L	Grid	32	3.28
23	X	Grid	27	3.28
24	M	Grid	60	3.28
25	O	Grid	25	3.28
26	W	Grid	28	3.28

chooses electric power for illustrative purposes, but there should be no difficulty extending our system to other forms of energy. Moreover, the distributed energy trading in energy Internet has no restriction on participants. They can be residential, commercial, or industrial.

Tables 3 and 4 provide detailed information of the supply and demand orders respectively. The unified purchase price and sale price of the main grid are also provided. In order to encourage the participation in P2P energy trading, we choose a lower unified sale price of $ 3.28 per kW·h and a higher unified purchase price of $ 1.17 per kW·h.

The matchmaking will first filter out the orders from participants with reputation lower than $R_{\min} = 0.2$ (U and W), sort the supply order list and the demand order list according to $rank_{sell}$ and $rank_{buy}$ respective, and go through both lists from the top. The matchmaking results are shown in Table 5. We compare our trading strategy to the k-double auction with $k = 0.6445$ without considering reputation in [46], and the corresponding matchmaking results for the same supply and demand orders are shown in Table 6. Note that the seller of Transaction 11 and 12 in Table 6 is U with untrusted low reputation score 0.1680. The consequence of allowing these P2P transactions is that the success of their execution cannot be guaranteed, thus bringing the risk of loss to buyer M and X.

Fig. 11 compares the average income/cost of each seller/buyer in P2P energy trading between two trading strategies based on the trading results of the case study. We can see from the two figures that the average values of seller average incomes and buyer average costs of reputation-based k-double auction are both increased and their variances are both decreased, compared to that of k-double auction without reputation. Note that the figures only considers P2P transactions, so transaction 17–26 in Table 5 and transaction 13–25 in Table 6 are not counted.

Finally, we show the BFIs and SFIs of all participants based on the trading results of both trading strategies in Fig. 12. It can be seen from the scatter diagrams that the fairness indicators of reputation-based k-double auction are more concentrated and more balanced among different reputation scores. The slopes of the two regression lines have a drastic difference. In more detail, the slope of the regression line in Fig. 12(a), i.e., $r(R, FI)$ of reputation-based k-double auction, is closer to 0, which yields a greater fairness factor of 3.7615 (compared with the fairness factor of 1.1442 of k-double auction without reputation) according to (17). As we have mentioned in Section 4.3, a greater

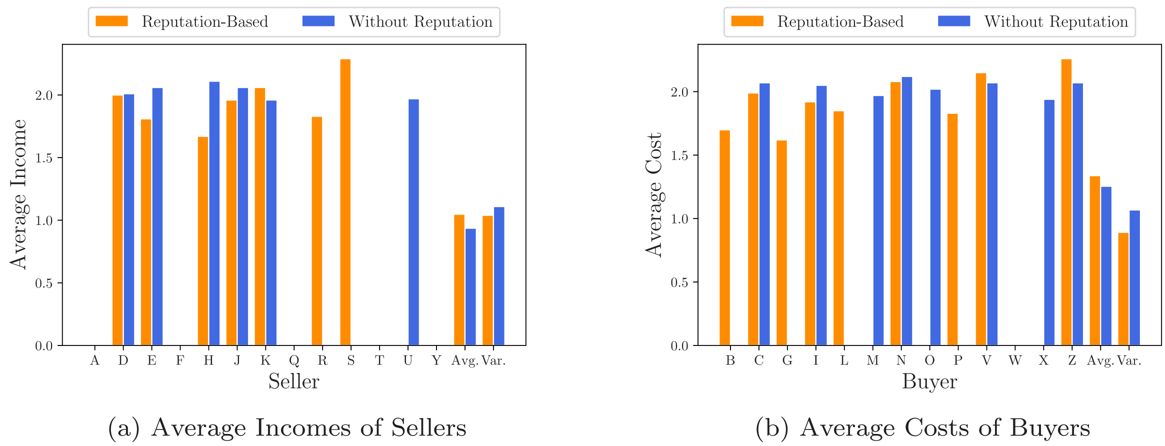


Fig. 11. Comparison of average incomes of sellers and average costs of buyers in P2P energy trading between reputation-based k-double auction and k-double auction without reputation. The data are calculated based on the matching results in Tables 5 and 6.

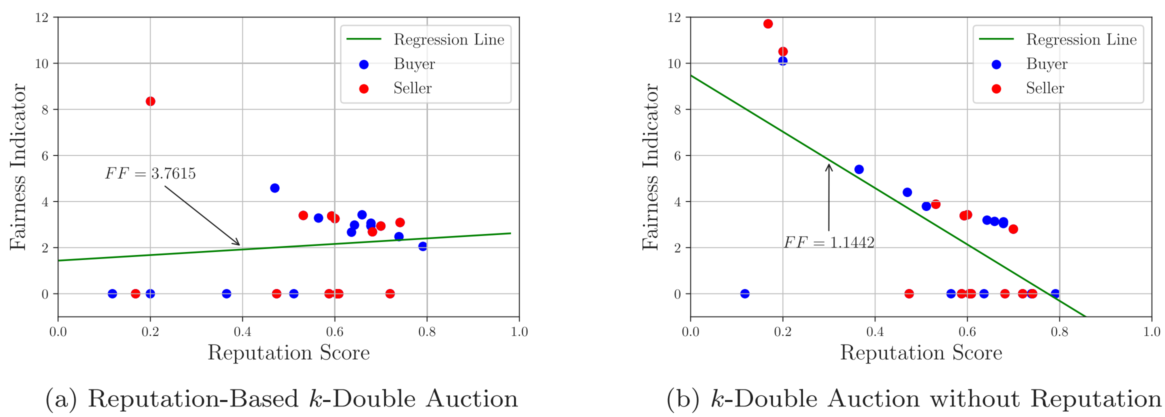


Fig. 12. Comparison of buyer/seller fairness indicators between reputation-based k-double auction and k-double auction without reputation. The data are calculated according to (15), (16), and (17). The fairness factors of both mechanisms are indicated by the slopes of their regression lines.

Table 6
Matchmaking results of k-double auction without considering reputation [46].

Transaction	Buyer	Seller	Amount (kW·h)	Trade price ($/kW·h)
1	N	H	28	2.12
2	V	H	7	2.06
3	V	E	26	2.07
4	Z	E	27	2.07
5	I	E	7	2.04
6	I	J	20	2.06
7	C	R	59	2.07
8	O	D	25	2.02
9	M	D	7	1.96
10	M	K	38	1.96
11	M	U	15	2.00
12	X	U	16	1.94
13	Grid	J	13	1.17
14	Grid	Q	40	1.17
15	Grid	T	31	1.17
16	Grid	A	53	1.17
17	Grid	S	35	1.17
18	Grid	Y	59	1.17
19	Grid	F	26	1.17
20	X	Grid	11	3.28
21	P	Grid	40	3.28
22	L	Grid	51	3.28
23	B	Grid	31	3.28
24	G	Grid	28	3.28
25	W	Grid	28	3.28

fairness factor helps to make reputation a good incentive to participants in the P2P energy trading system.

6. Future outlook

Energy Internet appeals the collaborative trading mode of regional distributed energy and wide-area centralized energy. Compared to the conventional centralized trading mode, this collaborative mode can provide more autonomy and flexibility when considering the high heterogeneity of prosumers and customers in large-scale energy systems [64]. How a reputation mechanism gets adapted to this mode under different time scales will become an important research topic.

Apart from the idea proposed in this paper, there are many different ways and standards to conceptualize and evaluate the term "fairness" for energy trading. Our future work will keep finding different scientific and legitimate definitions of fairness for energy trading. We will also strive to achieve fairness through distributed reputation systems.

In addition to the trading market, trading supervision also plays a crucial role in practical energy trading systems. A reasonable reputation system should conform to the supervision mechanism. However, due to the fact that most of the energy trading systems are still centralized, the regulatory mechanism for distributed energy trading is not very consummate. Therefore, the requirements of distributed energy trading supervision on reputation rules need to be further explored.

With the continuous development of distributed energy systems, distributed reputation will become a promising research topic in this area. In the future, we could further extend the application of distributed reputation in other forms of trading in the energy fields, such as green certificate trading or carbon emission trading. Furthermore, distributed reputation mechanisms for non-trading related topics like secure energy data management [65] and service cross-platform collaboration [44] are also worth studying.

7. Conclusion

This paper studies the implementation of a distributed reputation system. The value of studying distributed reputation has two aspects. On the one hand, a distributed reputation mechanism can better match the requirement of removing centralized entities from modern distributed energy systems. On the other hand, distributed reputation for energy systems has not been fully explored by existing works.

Based on the performance evaluation of the comprehensive system RBT, we can find that blockchain is helpful to achieve the decentralization of the reputation and energy trading modules, and that reputation can enhance the efficiency of blockchain and the fairness of P2P energy trading. The definition of fairness indicator proposed in this paper regards reputation as the contribution to the system, which intuitively makes reputation a good incentive for trading participants.

CRediT authorship contribution statement

Tonghe Wang: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing - original draft, Visualization. **Jian Guo:** Writing - review & editing. **Songpu Ai:** Software. **Junwei Cao:** Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix. Formulas for reputation update rules

The formulas for reputation update rules chosen in our simulation in Section 5 are as follows:

1. Reputation increment for consensus nodes of a successful consensus instance in CN-1:

$$R^{+}_{CN}(i) = \begin{cases} 1-\pi^{ind_{CN}} & R_{CN} \geq R_{\min}, \\ 0 & \text{otherwise}, \end{cases} \tag{A.1}$$

where

$$ind_{CN} = -\alpha \frac{r^{+}_{CN}(i)\left(1-10^{-\beta t^{-}_{CN}(i)}\right)}{\left(100 R_{CN}(i)\right)^2}, \tag{A.2}$$

$r^{+}_{CN}(i)$ is the overall consensus success rate of i, $t^{-}_{CN}(i)$ is the elapsed time since last drop in $R_{CN}(i)$, and α, β, π are parameters;

2. Reputation reward for the leader of a successful consensus instance in CN-1:

$$R^{L,+}_{CN}(\ell) = \gamma R_C(r), \tag{A.3}$$

where γ is a parameter;

3. Reputation deduction for consensus nodes of a failed consensus instance in CN-2:

$$R^{-}_{CN}(i) = \begin{cases} base^{\rho}_{CN} & R_{CN}(i) \geq R_{min}, \\ 0 & \text{otherwise}, \end{cases} \tag{A.4}$$

where

$$base_{CN} = \alpha \frac{r^{-}_{CN}(i)\left(1-10^{-\beta t^{-}_{CN}(i)}\right)}{\left[100\left(1-R_{CN}(i)\right)\right]^2},$$

$r^{-}_{CN}(i)$ is the overall consensus failing rate of i, and ρ is a parameter;

4. Reputation penalty for the leader of a failed consensus instance in CN-2:

$$R^{L,-}_{CN}(\ell) = \gamma\left(1-R_C(r)\right). \tag{A.5}$$

5. Reputation increment for the seller of a successful supply execution of a transaction in ES-1:

$$R^{+}_{ES}(i) = \begin{cases} 1-\pi^{ind_{ES}} & R_{ES} \geq R_{\min}, \\ 0 & \text{otherwise}, \end{cases} \tag{A.6}$$

where

$$ind_{ES} = -\alpha \frac{r^{+}_{ES}(i)\left(1-10^{-\beta t^{-}_{ES}(i)}\right)}{\left(100 R_{ES}(i)\right)^2}, \tag{A.7}$$

$r^{+}_{ES}(i)$ is the ratio of total energy of all succeeded supply executions to total energy of all participated transactions of i, $t^{-}_{ES}(i)$ is the elapsed time since last drop in $R_{ES}(i)$;

6. Reputation deduction for the seller of a failed supply execution of a transaction in ES-2:

$$R^{-}_{ES}(i) = \begin{cases} base^{\rho}_{ES} & R_{ES}(i) \geq R_{min}, \\ 0 & \text{otherwise}, \end{cases} \tag{A.8}$$

where

$$base_{ES} = \alpha \frac{r^{-}_{ES}(i)\left(1-10^{-\beta t^{-}_{ES}(i)}\right)}{\left[100\left(1-R_{ES}(i)\right)\right]^2},$$

$r^{-}_{ES}(i)$ is the ratio of total energy of all failed supply executions to total energy of all participated transactions of i;

7. Reputation increment for the buyer of a successful demand execution of a transaction in EB-1:

$$R^{+}_{EB}(i) = \begin{cases} 1-\pi^{ind_{EB}} & R_{EB} \geq R_{\min}, \\ 0 & \text{otherwise}, \end{cases} \tag{A.9}$$

where

$$ind_{EB} = -\alpha \frac{r^{+}_{EB}(i)\left(1-10^{-\beta t^{-}_{EB}(i)}\right)}{\left(100 R_{EB}(i)\right)^2}, \tag{A.10}$$

$r^{+}_{EB}(i)$ is the ratio of total energy of all succeeded demand executions to total energy of all participated transactions of i, $t^{-}_{EB}(i)$ is the elapsed time since last drop in $R_{EB}(i)$;

8. Reputation deduction for the seller of a failed demand execution of a transaction in EB-2:

$$R^{-}_{EB}(i) = \begin{cases} base^{\rho}_{EB} & R_{EB}(i) \geq R_{min}, \\ 0 & \text{otherwise}, \end{cases} \tag{A.11}$$

where

$$base_{EB} = \alpha \frac{r^{-}_{EB}(i)\left(1-10^{-\beta t^{-}_{EB}(i)}\right)}{\left[100\left(1-R_{EB}(i)\right)\right]^2},$$

$r^{-}_{EB}(i)$ is the ratio of total energy of all failed demand executions to total energy of all participated transactions of i.

In the simulation, we choose $\alpha = 6$, $\beta = 0.02$, $\gamma = 0.05$, $\pi = 5$, $\rho = 0.48$.

References

[1] Nakamoto S. Bitcoin: A peer-to-peer electronic cash system. 2008, https://bitcoin.org/bitcoin.pdf. [Accessed 3 Feburary 2021].
[2] Vangulick D, Cornelusse B, Ernst D. Blockchain for peer-to-peer energy exchanges: Design and recommendations. In: 2018 power systems computation conference. IEEE; 2018, http://dx.doi.org/10.23919/pscc.2018.8443042.
[3] Dekhane S, Mhalgi K, Vishwanath K, Singh S, Giri N. GreenCoin: Empowering smart cities using Blockchain 2.0. In: 2019 international conference on Nascent technologies in engineering. IEEE; 2019, http://dx.doi.org/10.1109/icnte44896.2019.8946014.

[4] Burkov AV. Application of technologies of distributed ledgers (blockchain) in the management of a decentralized autonomous organization (DAO). J Adv Res Dyn Control Syst 2020;12(SP7):1337–45. http://dx.doi.org/10.5373/jardcs/v12sp7/20202234.

[5] Dorri A, Hill A, Kanhere SS, Jurdak R, Luo F, Dong ZY. Peer-to-peer EnergyTrade: A distributed private energy trading platform. 2018, arXiv:1812.08315.

[6] Martín C, Alba I, Trillo J, Soler E, Rubio B, Díaz M. Providing reliability and auditability to the IoT LwM2M protocol through Blockchain, unpublished, http://dx.doi.org/10.13140/RG.2.2.35363.68642.

[7] Wen S, Xiong W, Tan J, Chen S, Li Q. Blockchain enhanced price incentive demand response for building user energy network in sustainable society. Sustainable Cities Soc 2021;68:102748. http://dx.doi.org/10.1016/j.scs.2021.102748.

[8] Andoni M, Robu V, Flynn D, Abram S, Geach D, Jenkins D, et al. Blockchain technology in the energy sector: A systematic review of challenges and opportunities. Renew Sustain Energy Rev 2019;100:143–74. http://dx.doi.org/10.1016/j.rser.2018.10.014.

[9] Zobaa AF, Cao J, editors. Energy internet. Springer-Verlag GmbH; 2020, https://www.ebook.de/de/product/39269761/energy_internet.html.

[10] Hua H, Wei Z, Qin Y, Wang T, Li L, Cao J. Review of distributed control and optimization in energy internet: From traditional methods to artificial intelligence-based methods. IET Cyber-Phys Syst Theory Appl 2021. http://dx.doi.org/10.1049/cps2.12007.

[11] Esmat A, de Vos M, Ghiassi-Farrokhfal Y, Palensky P, Epema D. A novel decentralized platform for peer-to-peer energy trading market with blockchain technology. Appl Energy 2021;282:116123. http://dx.doi.org/10.1016/j.apenergy.2020.116123.

[12] Mihaylov M, Razo-Zapata I, Nowé A. NRGcoin—A Blockchain-based reward mechanism for both production and consumption of renewable energy. In: Transforming climate finance and green investment with blockchains. Elsevier; 2018, p. 111–31. http://dx.doi.org/10.1016/b978-0-12-814447-3.00009-4.

[13] Gür AÖ, Öksüzer Ş, Karaarslan E. Blockchain based metering and billing system proposal with privacy protection for the electric network. In: 2019 7th international Istanbul smart grids and cities congress and fair. IEEE; 2019, http://dx.doi.org/10.1109/sgcf.2019.8782375.

[14] Zhao F, Guo X, Chan WKV. Individual green certificates on blockchain: A simulation approach. Sustainability 2020;12(9):3942. http://dx.doi.org/10.3390/su12093942.

[15] He H, Luo Z, Wang Q, Chen M, He H, Gao L, et al. Joint operation mechanism of distributed photovoltaic power generation market and carbon market based on cross-chain trading technology. IEEE Access 2020;8:66116–30. http://dx.doi.org/10.1109/access.2020.2985577.

[16] Miglani A, Kumar N, Chamola V, Zeadally S. Blockchain for Internet of Energy management: Review, solutions, and challenges. Comput Commun 2020;151:395–418. http://dx.doi.org/10.1016/j.comcom.2020.01.014.

[17] Zielinska A, Skowron M, Bien A. The concept of the blockchain technology model use to settle the charging process of an electric vehicle. In: 2019 applications of electromagnetics in modern engineering and medicine. IEEE; 2019, http://dx.doi.org/10.23919/ptze.2019.8781739.

[18] Deshpande V, George L, Badis H, Desta AA. Blockchain based decentralized framework for energy demand response marketplace. In: NOMS 2020 - 2020 IEEE/IFIP network operations and management symposium. 2020.

[19] Yang W, Guan Z, Wu L, Du X, Lv Z, Guizani M. Autonomous and privacy-preserving energy trading based on redactable blockchain in smart grid. In: GLOBECOM 2020 - 2020 IEEE global communications conference. 2020.

[20] Lev-Ari K, Spiegelman A, Keidar I, Malkhi D. FairLedger: A fair blockchain protocol for financial institutions. 2019, arXiv:1906.03819.

[21] Slepak G, Petrova A. The DCS theorem. 2018, arXiv:1801.04335.

[22] Salimitari M, Chatterjee M. A survey on consensus protocols in blockchain for IoT networks. 2018, arXiv:1809.05613.

[23] Dedeoglu V, Jurdak R, Putra GD, Dorri A, Kanhere SS. A trust architecture for blockchain in IoT. In: Proceedings of the 16th EAI international conference on mobile and ubiquitous systems: Computing, networking and services. ACM; 2019, http://dx.doi.org/10.1145/3360774.3360822.

[24] Do T, Nguyen T, Pham H. Delegated proof of reputation. In: Proceedings of the 2019 international electronics communication conference. ACM; 2019, http://dx.doi.org/10.1145/3343147.3343160.

[25] Lei K, Zhang Q, Xu L, Qi Z. Reputation-based byzantine fault-tolerance for consortium blockchain. In: 2018 IEEE 24th international conference on parallel and distributed systems. IEEE; 2018, http://dx.doi.org/10.1109/padsw.2018.8644933.

[26] Cong LW, He Z. Blockchain disruption and smart contracts. Rev Financ Stud 2019;32(5):1754–97. http://dx.doi.org/10.1093/rfs/hhz007.

[27] Khorasany M, Paudel A, Razzaghi R, Siano P. A new method for peer matching and negotiation of prosumers in peer-to-peer energy markets. IEEE Trans Smart Grid 2020;1. http://dx.doi.org/10.1109/tsg.2020.3048397.

[28] Bhatti BA, Broadwater R. Distributed Nash equilibrium seeking for a dynamic micro-grid energy trading game with non-quadratic payoffs. Energy 2020;202:117709. http://dx.doi.org/10.1016/j.energy.2020.117709.

[29] Biryukov A, Feher D. ReCon: Sybil-resistant consensus from reputation. Pervasive Mob Comput 2020;61.

[30] Feng J, Zhao X, Lu G, Zhao F. PoTN: A novel blockchain consensus protocol with proof-of-trust negotiation in distributed IoT networks. In: Proceedings of the 2nd international Acm workshop on security and privacy for the Internet-of-Things. ACM Press; 2019, http://dx.doi.org/10.1145/3338507.3358613.

[31] Khaqqi KN, Sikorski JJ, Hadinoto K, Kraft M. Incorporating seller/buyer reputation-based system in blockchain-enabled emission trading application. Appl Energy 2018;209:8–19. http://dx.doi.org/10.1016/j.apenergy.2017.10.070.

[32] Battah A, Iraqi Y, Damiani E. Blockchain-based reputation systems: Implementation challenges and mitigation. Electronics 2021;10(3):289. http://dx.doi.org/10.3390/electronics10030289.

[33] Shahid A, Sarfraz U, Malik MW, Iftikhar MS, Jamal A, Javaid N. Blockchain-based reputation system in agri-food supply chain. In: Advanced information networking and applications. Springer International Publishing; 2020, p. 12–21. http://dx.doi.org/10.1007/978-3-030-44041-1_2.

[34] Iqbal S, Malik AW, Rahman AU, Noor RM. Blockchain-based reputation management for task offloading in micro-level vehicular fog network. IEEE Access 2020;8:52968–80. http://dx.doi.org/10.1109/access.2020.2979248.

[35] Hîrţan L-A, Dobre C, González-Vélez H. Blockchain-based reputation for intelligent transportation systems. Sensors 2020;20(3):791. http://dx.doi.org/10.3390/s20030791.

[36] Shala B, Trick U, Lehmann A, Ghita B, Shiaeles S. Novel trust consensus protocol and blockchain-based trust evaluation system for M2M application services. Internet of Things 2019;7. http://dx.doi.org/10.1016/j.iot.2019.100058.

[37] Cai W, Jiang W, Xie K, Zhu Y, Liu Y, Shen T. Dynamic reputation-based consensus mechanism: Real-time transactions for energy blockchain. Int J Distrib Sens Netw 2020;16(3). http://dx.doi.org/10.1177/1550147720907335.

[38] Liu L, Li B, Qi B, Qin Q, Sun Y, Chen S, et al. Reliable interoperation of demand response entities considering reputation based on blockchain. IEEJ Trans Electr Electron Eng 2019;15(1):108–20. http://dx.doi.org/10.1002/tee.23032.

[39] Jing R, Xie MN, Wang FX, Chen LX. Fair P2P energy trading between residential and commercial multi-energy systems enabling integrated demand-side management. Appl Energy 2020;262:114551. http://dx.doi.org/10.1016/j.apenergy.2020.114551.

[40] Wang H, Zhang JX, Li F. Incentive mechanisms to enable fair renewable energy trade in smart grids. In: 2015 sixth international green and sustainable computing conference. IEEE; 2015, http://dx.doi.org/10.1109/igcc.2015.7393723.

[41] Zhuang Q, Liu Y, Chen L, Ai Z. Proof of reputation: A reputation-based consensus protocol for blockchain based systems. In: Proceedings of the 2019 international electronics communication conference. ACM; 2019, http://dx.doi.org/10.1145/3343147.3343169.

[42] Wang EK, Liang Z, Chen C-M, Kumari S, Khan MK. PoRX: A reputation incentive scheme for blockchain consensus of IIoT. Future Gener Comput Syst 2020;102:140–51. http://dx.doi.org/10.1016/j.future.2019.08.005.

[43] Huang J, Kong L, Chen G, Wu M-Y, Liu X, Zeng P. Towards secure industrial IoT: Blockchain system with credit-based consensus mechanism. IEEE Trans Ind Inf 2019;15(6):3680–9. http://dx.doi.org/10.1109/tii.2019.2903342.

[44] Tang B, Kang H, Fan J, Li Q, Sandhu R. IoT passport: A blockchain-based trust framework for collaborative Internet-of-Things. In: Proceedings of the 24th ACM symposium on access control models and technologies. ACM; 2019, http://dx.doi.org/10.1145/3322431.3326327.

[45] Bellini E, Iraqi Y, Damiani E. Blockchain-based distributed trust and reputation management systems: A survey. IEEE Access 2020;8:21127–51. http://dx.doi.org/10.1109/access.2020.2969820.

[46] Angaphiwatchawal P, Phisuthsaingam P, Chaitusaney S. A k-factor continuous double auction-based pricing mechanism for the P2P energy trading in a LV distribution system. In: 2020 17th international conference on electrical engineering/electronics, computer, telecommunications and information technology. IEEE; 2020, http://dx.doi.org/10.1109/ecti-con49241.2020.9158275.

[47] Castro M, Liskov B. Practical Byzantine fault tolerance and proactive recovery. ACM Trans Comput Syst 2002;20(4):398–461. http://dx.doi.org/10.1145/571637.571640.

[48] Begum A, Tareq A, Sultana M, Sohel M, Rahman T, Sarwar A. Blockchain attacks, analysis and a model to solve double spending attack. Int J Mach Learn Comput 2020.

[49] Sankagiri S, Gandlur S, Hajek B. The longest-chain protocol under random delays. 2021, arXiv:2102.00973.

[50] Bu G, Gürcan Ö, Potop-Butucaru M. G-IOTA: Fair and confidence aware tangle. 2019, arXiv:1902.09472.

[51] Boogert A, Dupont D. On the effectiveness of the anti-gaming policy between the day-ahead and real-time electricity markets in The Netherlands. Energy Econ 2005;27(5):752–70. http://dx.doi.org/10.1016/j.eneco.2005.03.006.

[52] Lin J, Pipattanasomporn M, Rahman S. Comparative analysis of auction mechanisms and bidding strategies for P2P solar transactive energy markets. Appl Energy 2019;255:113687. http://dx.doi.org/10.1016/j.apenergy.2019.113687.

[53] Erdinç O, Taşcikaraoğlu A, Paterakis NG, Catalão JPS. Novel incentive mechanism for end-users enrolled in DLC-based demand response programs within stochastic planning context. IEEE Trans Ind Electron 2019;66(2):1476–87. http://dx.doi.org/10.1109/tie.2018.2811403.

[54] Gruhler A, Rodrigues B, Stiller B. A reputation scheme for a blockchain-based network cooperative defense. In: 2019 IFIP/IEEE symposium on integrated network and service management. 2019. p. 71–9.
[55] Fischer MJ, Lynch NA, Paterson MS. Impossibility of distributed consensus with one faulty process. J ACM 1985;32(2):374–82. http://dx.doi.org/10.1145/3149.214121.
[56] Bonniot L, Neumann C, Taïani F. PnyxDB: A lightweight leaderless democratic Byzantine fault tolerant replicated datastore. 2019, arXiv:1911.03291.
[57] Kuzlu M, Pipattanasomporn M, Gurses L, Rahman S. Performance analysis of a hyperledger fabric blockchain framework: Throughput, latency and scalability. In: 2019 IEEE international conference on blockchain. IEEE; 2019, http://dx.doi.org/10.1109/blockchain.2019.00003.
[58] Hill MD. What is scalability. ACM SIGARCH Comput Archit News 1990;18(4):18–21. http://dx.doi.org/10.1145/121973.121975.
[59] Abd-El-Malek M, Ganger GR, Goodson GR, Reiter MK, Wylie JJ. Fault-scalable byzantine fault-tolerant services. In: Proceedings of the twentieth ACM symposium on operating systems principles. ACM Press; 2005, http://dx.doi.org/10.1145/1095810.1095817.
[60] Martin J-P, Alvisi L. Fast Byzantine consensus. IEEE Trans Dependable Secur Comput 2006;3(3):202–15. http://dx.doi.org/10.1109/tdsc.2006.35.
[61] Saito K, Shiseki A, Takada M, Yamamoto H, Saitoh M, Ohkawa H, et al. Requirement analyses and evaluations of blockchain platforms per possible use cases. 2021, arXiv:2103.03209.
[62] You H, Hua H, Cao J. A smart contract-based energy trading strategy in energy internet. In: 2019 IEEE international conference on energy internet. IEEE; 2019, http://dx.doi.org/10.1109/icei.2019.00090.
[63] Yang Q, Ding T, Ma W, Zhang H, Jia Z, Tian W, et al. Decentralized joint power-gas-heat economic dispatch for global energy internet in Northeast Asia. In: 2018 IEEE power & energy society general meeting. IEEE; 2018, http://dx.doi.org/10.1109/pesgm.2018.8585805.
[64] Jing R, Wang M, Zhang Z, Wang X, Li N, Shah N, et al. Distributed or centralized? Designing district-level urban energy systems by a hierarchical approach considering demand uncertainties. Appl Energy 2019;252:113424. http://dx.doi.org/10.1016/j.apenergy.2019.113424.
[65] Duan J, Chow M-Y. A resilient consensus-based distributed energy management algorithm against data integrity attacks. IEEE Trans Smart Grid 2019;10(5):4729–40. http://dx.doi.org/10.1109/tsg.2018.2867106.