Front. Energy 2022, 16(1): 9–18
https://doi.org/10.1007/s11708-022-0818-8

PERSPECTIVE

Sijie CHEN, Jian PING, Zheng YAN, Jinjin LI, Zhen HUANG

Blockchain in energy systems: values, opportunities, and limitations

Abstract The structure of a power energy system is becoming more distributed than before. It becomes challenging to manage such a system in a centralized way, because a central authority may not exist or may not be trusted by all parties. Blockchain is a promising tool to address this challenge, by enabling trusted collaboration in the absence of a trusted central authority. Its use in the energy sector has been pioneered by several pilot projects. However, to date the energy sector has not seen large-scale deployment of blockchain, partly because the founders of those pilot projects, the public, and utilities have not reached consensus on the values and limitations of blockchain in energy. This perspective aims to bridge this gap. First, the philosophy and unique values of blockchain are discussed. Second, some promising blockchain-based applications in energy systems are presented. Third, some common misunderstandings of blockchain in energy are discussed. Last, some frequently-asked questions from utilities are discussed. Hopefully this perspective can help advance large-scale deployment of blockchain in energy systems.

Keywords blockchain, immutability, energy trading, energy management, data synchronization

Received Dec. 23, 2021; accepted Jan. 14, 2022; online Mar. 10, 2022

Sijie CHEN, Jian PING, Zheng YAN
Key Laboratory of Control of Power Transmission and Conversion (Ministry of Education), Shanghai Jiao Tong University, Shanghai 200240, China

Jinjin LI (✉)
Key Laboratory for Thin Film and Microfabrication (Ministry of Education), Department of Micro/Nano-electronics, Shanghai Jiao Tong University, Shanghai 200240, China
E-mail: lijinjin@sjtu.edu.cn

Zhen HUANG (✉)
Key Laboratory for Power Machinery and Engineering (Ministry of Education), Shanghai Jiao Tong University, Shanghai 200240, China
E-mail: z-huang@sjtu.edu.cn

1 Introduction

Power energy systems are experiencing a structural change in recent years. On the one hand, with deregulation of the energy industry and cost drops of renewable energy technologies, a number of emerging players are entering energy systems. These players include photovoltaics (PVs), battery storages, smart buildings, virtual power plants, electric vehicle (EV) charging stations, etc [1,2]. On the other hand, synergy and coordination across multiple energy carriers, multiple energy balancing areas, and multiple organizations are increasing [3,4]. These changes lead to a more distributed structure of a power energy system [5,6], where multiple self-interested parties are expected to collaborate with each other. It can be challenging to manage such a system in a centralized manner. In some cases, a central authority may not exist and is unlikely to be established. In other cases, even if a central authority can be established, it may not be trusted and accepted by every participating party.

Blockchain brings an opportunity to address the above challenges. Instead of placing authority in a central entity, authority is given to participants in a collaboration network [7–9]. By letting multiple participants jointly run and oversee the collaboration network, blockchain enables trusted and transparent collaboration in the absence of a trusted central authority.

Blockchain has been used in several industries such as finance, commerce, and logistics. Its use in the energy sector has also been pioneered in a number of articles and pilot projects. However, to date the energy sector has not seen large-scale and influential implementation of blockchain-based applications. This is partly because some pilot projects use blockchain just for marketing purposes rather than to meet real demand, partly because the public has unrealistic expectations of blockchain, and partly because the deployment of blockchain does not have the support from utilities. This perspective aims to bridge this gap and advance large-scale implementation of blockchain in energy systems. To do so, the philosophy and unique values of blockchain are first discussed. Second, some promising blockchain applications in energy systems are presented. Third, some common misunderstandings or limitations of blockchain in energy are discussed. Last, some frequently-asked questions from utilities are answered, hoping to address utilities' concerns in deploying blockchain.

2 Philosophy and feature of blockchain

2.1 Unique features of blockchain: democracy, immutable rules, and immutable data records

Blockchain is aimed at limiting the power of a central authority, by letting participants jointly govern a collaboration network and mutually oversee and balance each other. The right to rule and lead is not placed in one central authority but distributed to all validating nodes. Validating nodes consist of those participants who are willing and able to govern the collaboration network. Each validating node has a chance to be a temporary leader in the collaboration network. This temporary leader is unable to impose its decisions but has to win the support from other validating nodes for its decisions.

Blockchain is unique in that it makes rules and data records of a collaboration network immutable if the majority of validating nodes are honest. A validating node is honest if it accepts those actions that follow the rules and rejects those actions that violate the rules. If some temporary leader manipulates the rules or data records, the majority of validating nodes will vote against its actions. An action without the support of the majority of validating nodes will not be finalized on blockchain. This makes the states, rules, and data on blockchain resistant to manipulation by any single participant.

2.2 Less unique features of blockchain: information sharing and transparency, tokens, and automatic enforcement

Blockchain features information sharing and transparency among participants. This feature is necessary to enable participants to oversee and counterbalance each other. Notably, a central authority can also have this feature, such as cloud storage.

Some blockchains (mostly public blockchains [10]) reward those temporary leaders in the form of cryptocurrencies (also called tokens [11]) to incentivize them to enforce rules honestly. Examples of such cryptocurrencies are Bitcoin [12] and Ether [13]. Notably, a central authority can also offer tokens, such as airline travel points.

In blockchain, once a participant sends a request that triggers the execution of rules (recorded in the form of smart contracts [4]), one or more temporary leaders will respond to the request by executing smart contracts. Usually, the temporary leaders do so for token rewards. From this participant's point of view, its request can be processed automatically, timely, and fairly. Notably, a central authority can also automate the response to participant requests, such as Google search.

2.3 Scenarios where blockchain is useful

2.3.1 Blockchain is useful when a central authority does not exist

Blockchain is particularly useful to enable collaboration among participants who are equal and do not trust each other. In this case, they usually do not endorse any single participant to lead and dominate the collaboration network. By using blockchain, these participants can jointly manage the collaboration network in a democratic way. Examples of such collaboration networks in the real world include the United Nations Security Council and rotating presidency of the European Council. By comparison, blockchain enables democracy in the digital world.

2.3.2 Blockchain is useful when a central authority exists but is not trusted by all participants

Blockchain is also useful to improve collaboration where a central authority exists but is not trusted by all participants. In this case, the central entity can deploy blockchain to let interested parties oversee part of rules and data. The use of blockchain seems to limit the power of the central entity. However, thanks to this, the central entity becomes more trustworthy and gains a competitive advantage in attracting new customers, meeting regulatory requirements, and improving relations with partners. The blockchain platform developers themselves are examples of such central entities. These developers make all codes open source so that users can examine the codes at any time. On the one hand, open source prevents the developers from adding any backdoors or tricks in the codes. On the other hand, open source makes the blockchain platforms trustworthy and attractive to users and application developers.

3 Promising blockchain applications in the energy sector

3.1 Energy trading

Energy trading is a typical form of collaboration in energy systems. Profit-seeking market players always require reliability and fairness of market operation. Blockchain, as a trust enabler, shows great potential in energy trading. Blockchain can digitize market rules, remove the trust barrier among market participants, reduce the likelihood of disputes, and thus boost energy trading.

3.1.1 Example: peer-to-peer (P2P) bilateral energy trading

P2P bilateral energy trading is widely used in energy systems. It refers to direct trading between a buyer and a seller without any intermediators [14]. P2P bilateral trading includes wholesale market trading between large energy suppliers and consumers [15], retail market trading between energy retailers and small consumers [16], and distributed energy resource (DER) trading between prosumers [17]. The bilateral contracts in P2P trading are usually customized and complex, leading to uncertainties and possible deviations in contract execution and settlement. Lack of a trusted third-party regulator further increases the possibility of contract manipulation by any participant and increases the difficulty in handling disputes.

Blockchain can be used to facilitate P2P bilateral energy trading. By programming the bilateral contracts into blockchain smart contracts, interested parties can organize P2P energy trading autonomously. The bilateral contracts are executed, settled, and validated by multiple parties. Manipulation and violation of bilateral contracts will be rejected by other validating nodes [18,19]. In addition, historical trading results are recorded on blockchain in an immutable way [20]. These immutable and trusted trading information can also be accessed by an energy system operator for network management (such as network reconfiguration) [21].

Among various P2P bilateral trading applications, blockchain-based DER trading between prosumers has been the focus in both academia and industry [22,23]. Believers argue that DER trading and blockchain share similar philosophy. However, to date there has been only pilot demonstration but not large-scale implementation of blockchain-based DER trading. This is partly because P2P energy trading without any intermediators may not be supported by current regulation (e.g., the Brooklyn microgrid project run by LO3 Energy [24]), partly because the benefits of P2P energy trading have been limited due to low penetration of DERs, and partly because the role of a distribution system operator (DSO) is unclear. A well-designed blockchain-based DER trading mechanism should make Pareto improvement without hurting the interest of a DSO or jeopardizing the reliability of a distribution network. Specifically, a DSO can serve as a client node on blockchain. It does not execute and verify those bilateral contracts, but only accesses transaction information on blockchain for system operational purposes, such as power supply reliability, network usage charge, and imbalance settlement. With increasing penetration of DERs and the support of regulation, blockchain-based DER trading can play a more influential role in future energy systems.

3.1.2 Example: international and interregional energy exchange

The characteristics and costs of energy resources in different countries or regions are different and can complement each other. Energy trading across the borders of countries and regions can improve overall social welfare, boost asset utilization rates, and facilitate large-scale renewable energy integration. However, it is usually difficult to form a super-sovereign market operator above multiple national or regional market operators. Participating nations or regions may have to spend considerable time on negotiating which nation or region should coordinate the trading schedules, lead the trading center, and resolve possible disputes. In addition, the rules of national or regional energy markets can be different from each other, which complicates international or interregional trading.

Blockchain is promising in facilitating international or interregional energy trading (see Fig. 1). Energy trading mechanisms and algorithms such as transmission capacity allocation, market clearing, congestion management, and imbalance settlement are programmed as smart contracts. Participating regional market operators naturally serve as validating nodes, who jointly enforce smart contracts to ensure fairness and jointly resolve possible disputes by voting on blockchain. The trading records are immutable on blockchain, which is useful for handling disputes.

3.2 Energy management

Traditionally, energy management rules and processes are in a black box and are accessible only by an operator. Participating energy resources and regulatory agencies are unable to access these processes, let alone oversee these processes. Blockchain is a promising tool to make the energy management process more trustworthy and transparent.

3.2.1 Example: virtual power plant (VPP) operation

A VPP aggregates and controls a number of flexible demand-side resources and participates in the bulk power system like a power plant. Specifically, a VPP operator first collects the operational preferences and limits of all resources. It then determines a load curtailment plan involving all resources when being required to supply electricity to the bulk power system [25,26]. However, the algorithm for load curtailment is usually hidden in a black box. A dishonest VPP operator has the motivation and ability to manipulate the load curtailment algorithm, the resulting plan, and the compensation for curtailed load resources [27]. This can reduce the willingness of load resources to provide flexibility.

On a blockchain-based VPP operation platform, the load curtailment algorithms of a VPP are programmed into smart contracts. VPP participants who voluntarily act as validating nodes can oversee the decision-making process of load curtailment. Other participants can also view the algorithms, their curtailed load volumes, and the

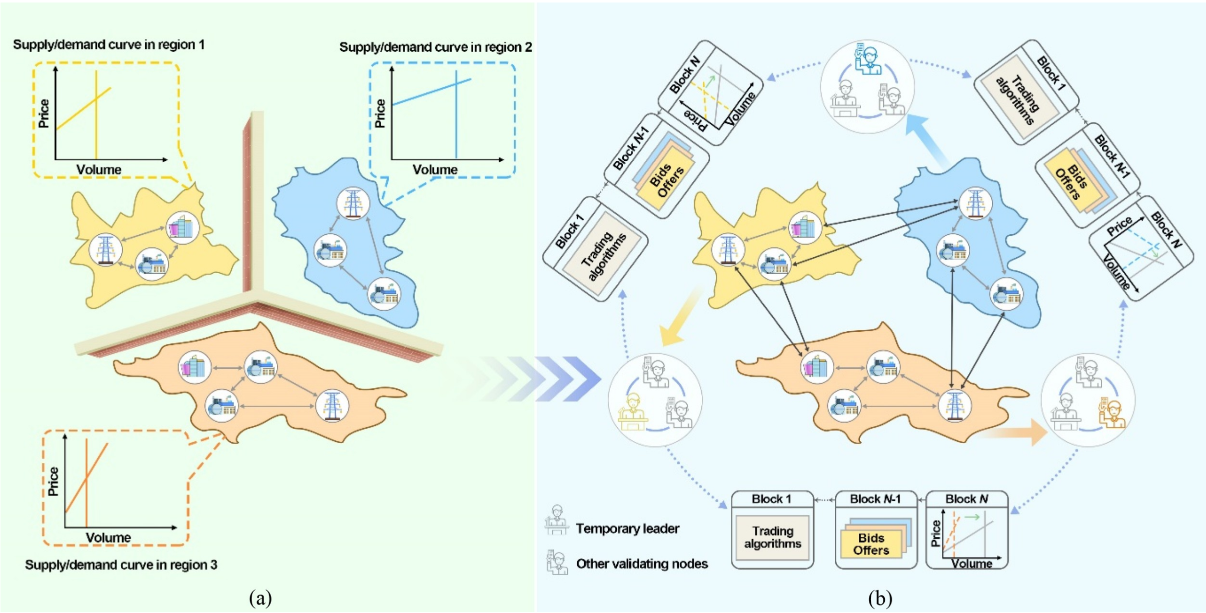


Fig. 1 Value of blockchain in interregional energy trading.

(a) Interregional energy trading without blockchain (Without a trusted super-sovereign market operator, only intraregional but not interregional energy trading can be organized); (b) interregional energy trading with blockchain (Blockchain enables an interregional energy market. Regional market operators serve as validating nodes on blockchain, who jointly operate and oversee the interregional energy market.).

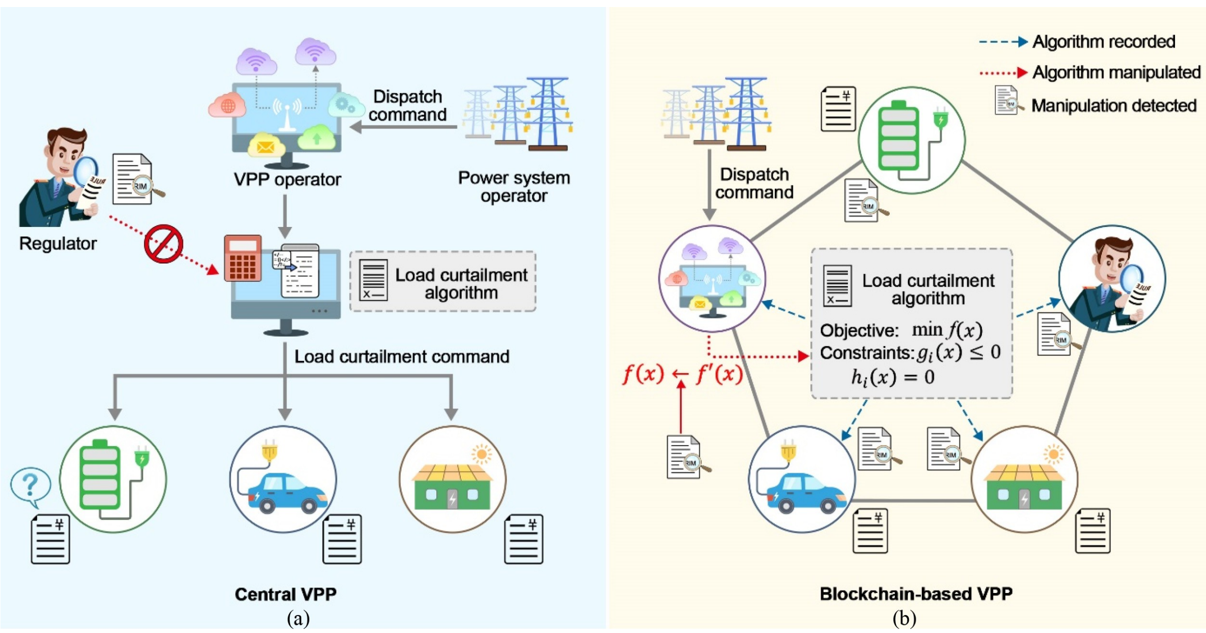


Fig. 2 Value of blockchain in VPP operation.

(a) A centralized VPP (The decision-making process of a central VPP operator is in a black box. The operator can disobey load curtailment algorithms without being detected by participants and the regulator. A VPP participant may therefore distrust the load curtailment plan and compensation); (b) a blockchain-based VPP (Participants and the regulator voluntarily serve as validating nodes. Any attempts to manipulate load curtailment algorithms are detected and rejected by the majority of validating nodes.).

compensation they should receive. Although making the algorithms and data immutable may limit the power of a VPP operator in the short run, it can help a VPP attract new participants and comply with regulation in the long run. Figure 2 demonstrates the value of blockchain in VPP operation. Specifically, blockchain improves the credibility of a VPP operator and gives VPP participants and the regulator the right to oversee the operation process.

Blockchain can also enable demand-side resources to form and run a VPP in the absence of a central VPP operator [1,28]. In this case, demand-side resources both participate in and jointly operate the VPP. The operation rules are approved by all participants and recorded in smart contracts. Such a fully autonomous scheme no longer needs a third-party operator, which further reduces administrative costs.

3.2.2 Example: multi-energy system synergy

Co-optimization of a multi-energy system unlocks the synergy among electricity, gas, heat, and cooling. The dynamics of gas, heat, and cooling systems are significantly slower than electricity systems, therefore they can serve as energy storages to help electricity systems maintain instantaneous supply-demand balance and absorb volatile renewable energy generation [29]. Given that the co-optimization spans multiple energy carriers, a central operator or coordinator usually does not exist. Similar to international energy exchange, it is challenging for participants to agree on who should lead and dominate the multi-energy system. Unlike international energy exchange, mechanisms and algorithms for multi-energy system co-optimization are more complex. This increases the difficulty for participants to detect or disable any manipulation by a central operator, if there is one.

Blockchain can be used to coordinate the operation of a multi-energy system. To do so, the mechanism, model, and algorithm of multi-energy system operation is recorded on blockchain. Validating nodes can be comprised of operators of electricity, gas, heat, and cooling systems, or operators of multi-energy communities. These validating nodes counterbalance each other and jointly determine and verify the operation pattern. With blockchain, participants can willingly reach consensus on an operation pattern covering multiple energy carriers in the absence of a superior operator.

3.3 Energy data synchronization

Tremendous data are generated, transmitted, and recorded in a modern energy system. Each participating organization keeps some data, which overlap with each other. It is common that the same data kept by several organizations become inconsistent, which may cause disputes on the true version of the data. This is probably because some parties have manipulated the data, but others lack evidence of data manipulation. The risks of data loss and data manipulation will bother interested parties and even result in biased decisions. Blockchain can synchronize the data across interested parties, ensure data immutability, and enhance participant trust of data.

3.3.1 Example: renewable energy asset management

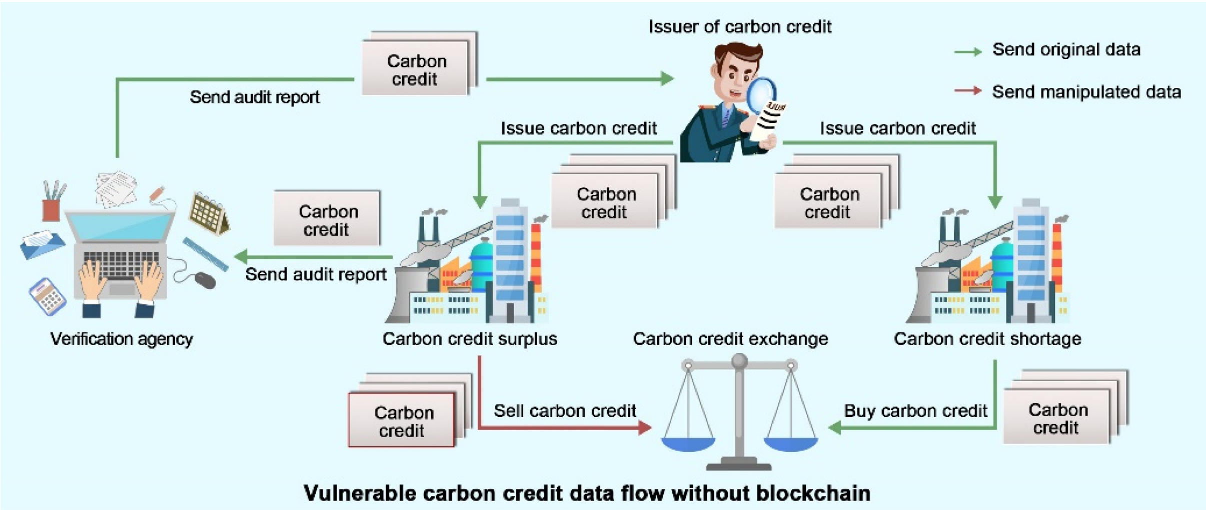
Renewable energy resources, such as PV stations and wind power plants, are expensive and even risky to build. Crowdfunding becomes a practical solution for renewable energy investors [30]. However, investors may not trust each other. In addition, the investors and operator of a renewable energy resource are usually different. This results in a typical principal-agent problem. That is, the operator usually acts in a way contrary to the best interests of the investors. Lack of trust among the investors and the operator lowers the investors' willingness to invest.

Blockchain can facilitate crowdfunding. The financing and operating statues and records of a renewable energy asset are digitized on blockchain. These data are immutable and consistent across all the investors and the operator. With these trustworthy data, investors can view the construction progress of the renewable energy resource and monitor its operating status. This forces the operator to construct and operate the renewable energy resource as contracted. Otherwise, the data records on blockchain are evidence for violation of contracts. In this way, blockchain builds trust among the investors and the operator and lowers the barrier of crowdfunding.

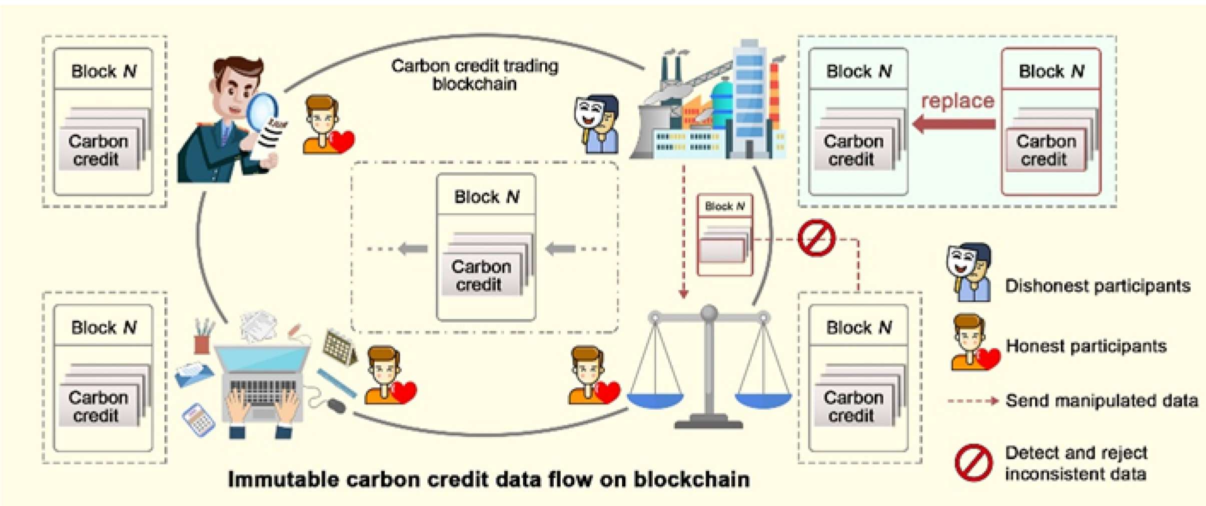
3.3.2 Example: carbon credit issuance and trading

Carbon credit is widely used to quantify the value of renewable energy resources and capture the environmental impacts of fossil energy sources. Traditionally, the responsibility for metering, issuing, trading, and verifying carbon credits belongs to different organizations. Data are not effectively synchronized among these organizations and can be tampered with, which can potentially trigger disputes.

To ensure data consistency and immutability, the issuance authority, the carbon market regulator, the carbon credit exchange, and carbon emission verification agencies can together establish a carbon credit blockchain. The information about carbon credit issuance, consumption, and trading are recorded on blockchain permanently [31]. Carbon market participants can verify the integrity of carbon credit during trading [32]. The verification agencies can easily audit the carbon credit of



(a)



(b)

Fig. 3 Value of blockchain in carbon credit issuance and trading.
(a) Vulnerable carbon credit data flow without blockchain (Traditionally, a participant can temper with or delete some carbon credit data, causing data inconsistencies among interested parties); (b) immutable carbon credit data flow on blockchain (On blockchain, each validating node synchronizes the carbon credit data. Anyone's attempt to manipulate the data are detected and denied by others.).

all participants. Figure 3 demonstrates the value of blockchain in carbon credit issuance and trading.

Different from the above asset management application, carbon emission is not just about an organization or an energy system, but about the public good and everyone. The carbon emission data of an organization or an industry should not be kept with itself, but be accessible and overseen by the whole society. In the long run, blockchain provides a means for the public to oversee the carbon emission data uploaded on blockchain. The public can also oversee the carbon emission of an organization in the physical world and report any apparent inconsistency between its actual emission and its on-chain emission record. On-chain and off-chain public scrutiny can together incentivize an organization to truthfully report its carbon emission.

4 Misunderstandings of blockchain in energy

Blockchain is a powerful tool in enabling trust in the digital world. However, its value and capacity are sometimes exaggerated. Such exaggeration does no good to the blockchain community or the energy industry, because unrealistic expectations of blockchain may lead to frustration and disappointment to the technology and further prevent its use. This section discusses some common misunderstandings or limitations of blockchain in energy, by taking power energy trading and exchange as an example.

4.1 Is it necessary to replace a trusted central authority by blockchain?

There is no need or advantage of replacing a trusted central authority by blockchain. The unique value of blockchain lies in enabling trust by democracy. Democracy can efficiently limit the power of a dictator, but its decision-making process is less efficient than dictatorship. If a central authority exists and participants trust that the central authority will not abuse its power, the use of blockchain is unnecessary. Other benefits of blockchain such as transparency and automation can also be delivered by a central authority.

For example, blockchain is useful as a coordinator for international or interregional electricity trading and dispatch. In these scenarios, it is unlikely to establish a central coordinator trusted and endorsed by every interested party. But for intraregional electricity trading, it is common that a regional market operator already exists and is endorsed by the regional government. In this case, the trust added by blockchain may not compensate for the efficiency lowered by blockchain.

4.2 Is blockchain able to ensure trust outside the digital world?

Blockchain itself can only build trust in the digital world but not the physical world. This is because blockchain is only an information and communications technology, comprising computer programs and databases. As a result, blockchain can only ensure trust for those data uploaded on blockchain and those rules executed on blockchain. It is beyond the capacity of blockchain if any data or rules are manipulated outside blockchain.

In the electricity trading example, any dispatch and trading rules enforced on blockchain are reliable. Any electricity trading arrangements recorded on blockchain are reliable. But blockchain itself cannot ensure that the actual energy production or consumption of each participant strictly follows the trading arrangements. To ensure so, not only must the trading arrangements be reliable, but also must the sensor or meter readings of each participant be reliable. To ensure data reliability both on chain and off chain, blockchain must be combined with other technologies, such as internet-of-things technologies. Blockchain itself is also unable to detect or disable collusion. For example, some electricity sellers can collude to withhold capacity and sell electricity at a higher price. Such collusion happens outside blockchain and does not break any rules recorded on blockchain. In this case, some collusion mitigation mechanisms prior to the advent of blockchain should be used, such as increasing the number of market players.

4.3 Is blockchain able to ensure 100% trust?

Rules and data on blockchain are much harder to manipulate than in a centralized system, but they are not 100% immutable. In a centralized system, it is hard or even impossible for anyone to counterbalance the central authority. If the central authority manipulates some rules or data, it is difficult for other parties to disable or even detect such manipulation. On blockchain, participants counterbalance each other in a democratic way. Each validating node can vote for or against any actions in the collaboration network. An action is finalized if it is supported by the majority of validating nodes. However, similar to democracy in the real world, if the majority of votes are controlled by dishonest parties, these dishonest parties together can break blockchain rules or manipulate data records.

In the electricity trading example, the trading arrangements are unreliable if the majority of participants are dishonest. In this case, honest participants may detect but cannot disable such unreliable arrangements. The collaboration network will probably become divided, with honest parties trading with each other and not with any dishonest parties. Such a divided collaboration network is usually in nobody's interest, which motivates everyone to act honestly. Figure 4 shows some limitations of blockchain with an example of energy consumption metering.

4.4 Is blockchain able to protect privacy?

Blockchain is not good at protecting privacy. Bitcoin is known as protecting user privacy, but in the sense of disconnecting the blockchain identity and real-world identity of a user. The transaction details, including the bitcoin transaction volumes and the blockchain identities of the sender and the receiver, are public information accessible by every validating node. Notably, blockchain features transparency and information sharing, which usually conflict with user privacy protection.

In the electricity trading example, each validating node possesses a copy of the trading arrangements of all parties. If the trading arrangements are determined by some optimization-based pool market rules, complete information about the trading optimization model and parameters should also be accessible to each validating node. Such information includes the bids, offers, and operational constraints of each participant and network constraints. Luckily, several methods can be used along with blockchain to protect user privacy. In a hierarchical computational method, each participant only needs to provide border information or an aggregated equivalent model for validating nodes to derive the optimal trading arrangements [33–37]. In a differential-privacy-based method, each participant adds some noises to the submitted information [38,39]. In cryptographic methods such as hash functions, homomorphic encryption [40,41], and zero-knowledge proofs [42], the information sent to validating nodes is pre-encrypted by participants. For

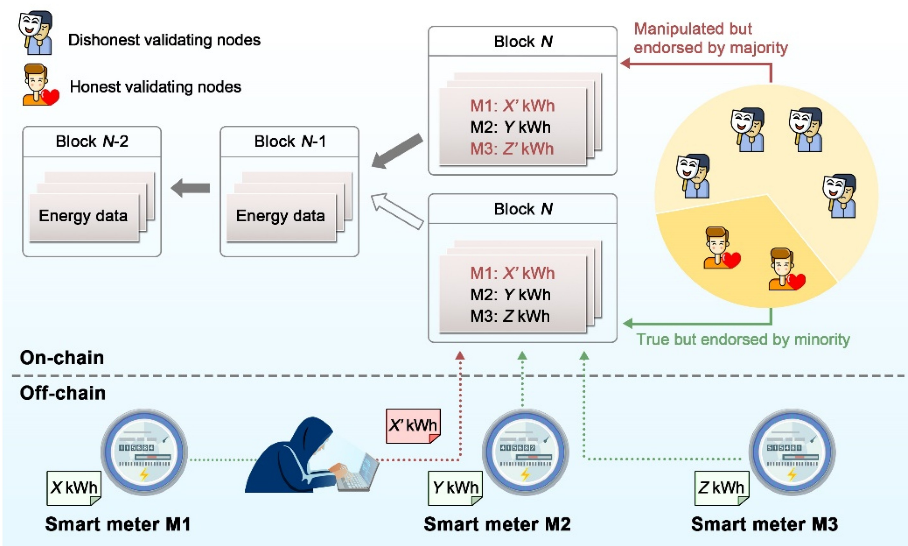


Fig. 4 Limitations of blockchain in energy consumption metering (The reading of smart meter M1 is manipulated in the physical world, which cannot be prevented by blockchain. In addition, the majority of validating nodes are dishonest, who delete the reading of smart meter M3 on blockchain. The rest honest validating nodes believe in the correct reading of M3. Blockchain is divided into two networks.).

example, participants can submit encrypted bilateral trading arrangements by using a hash function. Validating nodes can ensure immutability of the arrangements without knowing any details of the arrangements.

4.5 Are blockchain rules able to be upgraded?

Once collaboration rules are recorded on blockchain in the form of smart contracts, they are immutable. A participating party can also upgrade rules by releasing new smart contracts. However, other participants can choose to follow the old rules or the upgraded rules at wills. The two rule sets co-exist and compete with each other to attract users.

In the electricity trading example, a participant can release a new electricity trading rule, model, and algorithm on blockchain. Other parties can join the new rule or stay in the old one. If the majority of participants still follow the old rule, it becomes difficult for anyone to find counterparties in the new rule, which makes the new rule less attractive. Therefore, before releasing a new rule, this participant should negotiate with others, to let the majority of participants, if not all, accept the new rule.

5 Addressing the concerns of utilities when deploying blockchain

Utilities have played a central and dominant role in the energy industry in many countries, such as China. Energy users, regulators, and new entrants in the energy industry may be open and even delighted to see the use of blockchain, but utilities may see blockchain as a potential threat that challenges their dominance. However, it is vital to have the support from utilities to deploy blockchain in the energy industry. Our experience suggests that utilities frequently ask three questions when facing blockchain. To convince utilities to deploy blockchain, it is vital to answer these three questions.

The first question is, does an application have to be deployed on blockchain and not on other platforms?

To answer this question, it is not enough to justify the use of blockchain by only stating that blockchain can ensure transparency, information sharing, or automation. Some centralized technologies also offer these features and are more efficient and mature than blockchain. The unique feature of blockchain is to enable trust, by ensuring that data and rules are immutable. If building trust is important to a utility in a use case, blockchain is a preferred choice.

The second question is, is it really in a utility's interest to use blockchain?

In the short run, a utility may benefit or profit from the ability to manipulate data and rules at its own will. But in the long run, trust is vital in establishing sustainable partnership with stakeholders. The use of blockchain can help a utility attract new customers, launch new businesses, partner with other utilities, and comply with regulation. For example, blockchain can help a utility do so when it serves as a VPP operator, as discussed in Section 3.2.1. More importantly, as the structure of an energy system is more distributed, it is unrealistic for a utility to be in the center of every use case. In some use cases that are not utility-centric, blockchain gives a utility a chance to be involved and not to be excluded.

The third question is, how can a utility convince its partners that it is truly using blockchain rather than just claiming that it uses blockchain?

In the last several years, for marketing purposes, a number of companies claim that they use blockchain but never truly deploy blockchain. To tell whether blockchain is truly used, the ideal way is to make the corresponding codes open source for everyone to check. However, a utility and its partners may not be experts in examining the open source codes. A simpler way is to let a utility and its partners run several tests on a blockchain-based application. In each test a node is set as offline or attempts to manipulate data records or rules. If such attempts fail, there is evidence of the use of blockchain. By visualizing such attacks and defenses, other interested parties are able to tell whether the application is deployed on blockchain.

Beyond the above three concerns, several studies also identified challenges that need to be overcome to advance the use of blockchain [7,9,10]. These challenges include the unsatisfactory speed, scalability, and privacy protection of blockchain, lack of standardization and flexibility of blockchain, and incomplete regulatory policies. These challenges are not energy-sector-specific and at present may not be the primary concerns of utilities when deploying blockchain. But these issues need to be addressed in the long run to advance the use of blockchain in energy.

6 Conclusions

The structure of a power energy system is becoming increasingly distributed, making it difficult to be managed in a centralized manner. Blockchain is promising to address this challenge, by enabling trusted collaboration in the absence of a trusted central authority. Promising blockchain applications in energy systems include energy trading, energy management, and data synchronization. With blockchain, participants can jointly run and oversee these applications, ensuring that rules are strictly enforced and data records cannot be manipulated.

There are some misunderstandings or limitations when deploying blockchain in the energy sector, which lead to two implications. First, blockchain should not be deployed in every case, but only those that demand trust, democracy, and immutability. Second, blockchain can be used along with some other technologies that address the weaknesses of blockchain.

It is vital to convince utilities when deploying blockchain in the energy industry. To do so, one needs to deploy blockchain in scenarios where building trust is important to utilities, to convince utilities that trust is vital for them in the long run, and to find a way to demonstrate that blockchain is truly deployed.

Acknowledgments The work was supported by the National Key R&D Program of China (No. 2021YFC2100100), the National Natural Science Foundation of China (No. 21901157), and the Shanghai Science and Technology Project of China (No. 21JC1403400).

References

1. Morstyn T, Farrell N, Darby S J, et al. Using peer-to-peer energy-trading platforms to incentivize prosumers to form federated power plants. Nature Energy, 2018, 3(2): 94–101
2. Parag Y, Sovacool B K. Electricity market design for the prosumer era. Nature Energy, 2016, 1(4): 16032
3. Liu X, Mancarella P. Modelling, assessment and Sankey diagrams of integrated electricity-heat-gas networks in multi-vector district energy systems. Applied Energy, 2016, 167: 336–352
4. Thomas L, Zhou Y, Long C, et al. A general form of smart contract for decentralized energy systems management. Nature Energy, 2019, 4(2): 140–149
5. Molzahn D K, Dorfler F, Sandberg H, et al. A survey of distributed optimization and control algorithms for electric power systems. IEEE Transactions on Smart Grid, 2017, 8(6): 2941–2962
6. Kargarian A, Mohammadi J, Guo J, et al. Toward distributed/decentralized DC optimal power flow implementation in future electric power systems. IEEE Transactions on Smart Grid, 2018, 9(4): 2574–2594
7. Andoni M, Robu V, Flynn D, et al. Blockchain technology in the energy sector: a systematic review of challenges and opportunities. Renewable & Sustainable Energy Reviews, 2019, 100: 143–174
8. Dong Z, Luo F, Liang G. Blockchain: a secure, decentralized, trusted cyber infrastructure solution for future energy systems. Journal of Modern Power Systems and Clean Energy, 2018, 6(5): 958–967
9. Ul Hassan N, Yuen C, Niyato D. Blockchain technologies for smart energy systems: fundamentals, challenges, and solutions. IEEE Industrial Electronics Magazine, 2019, 13(4): 106–118
10. Mollah M B, Zhao J, Niyato D, et al. Blockchain for future smart grid: a comprehensive survey. IEEE Internet of Things Journal, 2021, 8(1): 18–43
11. Lee J Y. A decentralized token economy: how blockchain and cryptocurrency can revolutionize business. Business Horizons, 2019, 62(6): 773–784
12. Satoshi N. Bitcoin: a peer-to-peer electronic cash system. 2008, available at the website of bitcoin
13. Wood G. Ethereum: a secure decentralised generalised transaction ledger. 2021-12-02
14. Tushar W, Saha T K, Yuen C, et al. Challenges and prospects for negawatt trading in light of recent technological developments. Nature Energy, 2020, 5(11): 834–841
15. Brehm P A, Zhang Y. The efficiency and environmental impacts of market organization: evidence from the Texas electricity market. Energy Economics, 2021, 101: 105359
16. Lu Q, Lü S, Leng Y. A Nash-Stackelberg game approach in regional energy market considering users' integrated demand response. Energy, 2019, 175: 456–470
17. Paudel A, Chaudhari K, Long C, et al. Peer-to-peer energy trading in a prosumer- based community microgrid: a game-theoretic model. IEEE Transactions on Industrial Electronics, 2019, 66(8): 6087–6097
18. Yang Q, Wang H. Blockchain-empowered socially optimal

transactive energy system: framework and implementation. IEEE Transactions on Industrial Informatics, 2021, 17(5): 3122–3132
19. Christidis K, Sikeridis D, Wang Y, et al. A framework for designing and evaluating realistic blockchain-based local energy markets. Applied Energy, 2021, 281: 115963
20. Luo F, Dong Z Y, Liang G, et al. A distributed electricity trading system in active distribution networks based on multi-agent coalition and blockchain. IEEE Transactions on Power Systems, 2019, 34(5): 4097–4108
21. Shahidehpour M, Yan M, Shikhar P, et al. Blockchain for peer-to-peer transactive energy trading in networked microgrids: providing an effective and decentralized strategy. IEEE Electrification Magazine, 2020, 8(4): 80–90
22. Tushar W, Saha T K, Yuen C, et al. Peer-to-peer trading in electricity networks: an overview. IEEE Transactions on Smart Grid, 2020, 11(4): 3185–3200
23. Tushar W, Yuen C, Saha T K, et al. Peer-to-peer energy systems for connected communities: a review of recent advances and emerging challenges. Applied Energy, 2021, 282: 116131
24. Mengelkamp E, Gärttner J, Rock K, et al. Designing microgrid energy markets: a case study: the Brooklyn Microgrid. Applied Energy, 2018, 210: 870–880
25. Al-Awami A T, Amleh N A, Muqbel A M, et al. Optimal demand response bidding and pricing mechanism in distribution network: application for a virtual power plant. IEEE Transactions on Industry Applications, 2017, 53(5): 5051–5061
26. Kong X, Xiao J, Liu D, et al. Robust stochastic optimal dispatching method of multi-energy virtual power plant considering multiple uncertainties. Applied Energy, 2020, 279: 115707
27. Ping J, Yan Z, Chen S, et al. Coordinating EV charging via blockchain. Journal of Modern Power Systems and Clean Energy, 2020, 8(3): 573–581
28. Yang Q, Wang H, Wang T, et al. Blockchain-based decentralized energy management platform for residential distributed energy resources in a virtual power plant. Applied Energy, 2021, 294: 117026
29. Liu X, Wu J, Jenkins N, et al. Combined analysis of electricity and heat networks. Applied Energy, 2016, 162: 1238–1250
30. Lam P T, Law A O. Crowdfunding for renewable and sustainable energy projects: an exploratory case study approach. Renewable & Sustainable Energy Reviews, 2016, 60: 11–20
31. Woo J, Fatima R, Kibert C J, et al. Applying blockchain technology for building energy performance measurement, reporting, and verification (mrv) and the carbon credit market: a review of the literature. Building and Environment, 2021, 205: 108199
32. Khaqqi K N, Sikorski J J, Hadinoto K, et al. Incorporating seller/buyer reputation-based system in blockchain-enabled emission trading application. Applied Energy, 2018, 209: 8–19
33. Yang Q, Wang H. Privacy-preserving transactive energy management for IoT-aided smart homes via blockchain. IEEE Internet of Things Journal, 2021, 8(14): 11463–11475
34. Chen S, Zhang L, Yan Z, et al. A distributed and robust security-constrained economic dispatch algorithm based on blockchain. IEEE Transactions on Power Systems, 2022, 37(1): 691–700
35. Chen S, Shen Z, Zhang L, et al. A trusted energy trading framework by marrying blockchain and optimization. Advances in Applied Energy, 2021, 2: 100029
36. Ping J, Yan Z, Chen S. A two-stage autonomous EV charging coordination method enabled by blockchain. Journal of Modern Power Systems and Clean Energy, 2021, 9(1): 104–113
37. Chen S, Xu C, Yan Z, et al. Accommodating strategic players in distributed algorithms for power dispatch problems. IEEE Transactions on Cybernetics, 2021, online, https://doi.org/10.1109/TCYB.2021.3085400
38. Gai K, Wu Y, Zhu L, et al. Privacy-preserving energy trading using consortium blockchain in smart grid. IEEE Transactions on Industrial Informatics, 2019, 15(6): 3548–3558
39. Hassan M U, Rehmani M H, Chen J. DEAL: differentially private auction for blockchain-based microgrids energy trading. IEEE Transactions on Services Computing, 2020, 13(2): 263–275
40. Xu D, Zhou B, Chan K W, et al. Distributed multi-energy coordination of multimicrogrids with biogas-solar-wind renewables. IEEE Transactions on Industrial Informatics, 2019, 15(6): 3254–3266
41. Shen M, Tang X, Zhu L, et al. Privacy-preserving support vector machine training over blockchain-based encrypted IoT data in smart cities. IEEE Internet of Things Journal, 2019, 6(5): 7702–7712
42. Pop C D, Antal M, Cioara T, et al. Blockchain and demand response: zero-knowledge proofs for energy transactions privacy. Sensors (Basel), 2020, 20(19): 5678