Exploring the Potential of IoT-Blockchain Integration Technology for Energy Community Trading: Opportunities, Benefits, and Challenges

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***Abstract*—The integration of blockchain technology with energy community trading represents a promising frontier in the energy sector, offering innovative solutions to challenges in energy trading and management. This review conducts a systematic investigation of the potential benefits, applications and challenges of blockchain in facilitating multi-level energy trading for energy communities. Firstly, the background information of the blockchain and Internet of Things (IoT) is provided, along with an elucidation of their integration architecture for energy communities. Building on this foundation, the applications of blockchain in transactive energy communities are analyzed from three perspectives: community-level energy trading, regional-level energy trading, and grid-level energy trading. Following that, the currently known projects and pilots on blockchain-based transactive energy are comprehensively summarized. Finally, key challenges in implementing blockchain-based energy trading for local energy communities are discussed, providing guidance for future research.**

***Index Terms*—Blockchain, energy community, energy trading, Internet of Things.**

I. Introduction

SEVERAL energy and climate targets (e.g., EU 2030 framework [1] and the Peak Carbon Emissions and Carbon Neutrality [2]) have been proposed to promote the transition towards a low-carbon energy sector for the purpose of addressing climate change and achieving sustainable development. To achieve these ambitious goals, a fundamental restructuring of the power sector is imperative, transitioning towards decentralized renewable-based systems where citizens actively participate in energy consumption, production, trading, and supply endeavors [3].

Within this context, three challenges necessitate a fresh assessment of the consumer's role. First, the rapid development of distributed wind and photovoltaic (PV) power generation has transformed demand-side users into prosumers who can both generate and consume electricity. Second, the distributed renewable energy, characterized by its intermittency, is injected into the grid in a stochastic manner, requiring management by the grid, storage providers, or consumers themselves [4]. Third, there is a rapid growth of distributed energy resources (DERs), encompassing generation, storage, and devices located behind the end-user meters. These DERs will require pivotal user investment decisions and subsequent modifications in their behavior patterns.

Energy communities offer a viable approach to address these challenges by providing a potential institutional framework that organizes community energy reliant on distributed resources and energy systems. Energy communities act as collective actors, bringing together local users and energy market participants. Within the electricity market environment, these communities possess a natural advantage in aggregating and managing various flexible resources within their regions [5]. At the community level, peer-to-peer (P2P) energy trading, emerging among prosumers within the community. The trading mode enables users with surplus energy to engage in trades with those in need, fostering a balanced energy supply across the community and reducing transmission losses. At the consortium level, an energy community can exchange energy with neighboring communities while maintaining autonomous balancing, referred to as "community-to-community (C2C) energy trading", emerges as a prominent solution, enabling efficient utilization of renewable energy and further reducing community peak power demand and carbon emissions [6]. At the grid level, by interacting with external energy networks, energy communities can either balance and distribute surplus or deficit power or provide ancillary services to the grid. This trading approach is known as community-to-grid (C2G) energy trading. The multi-level energy trading framework enhances the energy efficiency of the community, reduces operational costs, and enhances the flexibility of the local energy market,

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promoting a win-win situation for all stakeholders, including energy enterprises, communities, and users.

However, the multi-level energy trading market of energy communities faces significant challenges. Firstly, it is essential to consider not only matching individual demands but also maintaining balance across the entire energy system, which includes infrastructure of various sizes. Secondly, public support from end users plays a crucial role in guiding energy trading. This support is driven by their awareness and active participation, but incentives are necessary to encourage involvement while ensuring security and privacy. Finally, the multi-level energy trading of energy communities encompasses various kinds of participants, ranging from individual households to diverse aggregators, including community managers, system operators, and market operators operating at various market levels.

To address these challenges, it is important to consider the privacy concerns of diverse participants, interoperability among different marketplaces, and the promotion of secure energy trading within existing market structures. Therefore, additional building blocks are needed to facilitate the engagement of multi-level market participants through digitalization and decentralization. This can be achieved through two principal areas: energy digitalization with the Internet of Things (IoT) and decentralized energy trading with blockchain technology.

IoT serves as a crucial link between the physical world and the cyber realm of computing systems, enabling the generation and management of vast quantities of data through the connection of energy suppliers, consumers and grid infrastructure [7]. The accessibility of real-time data not only assists policymakers in establishing clear and concise targets but also benefits stakeholders in unlocking value-added services through novel business models.

With the advancement of information and communication technology (ICT), energy-aware data can be gathered throughout the entire energy chain and distributed across all sectors within the energy landscape [8]. Blockchain, a decentralized distributed ledger technology, provides communities with an open, transparent, fair, reliable, and cost-effective trading platform. Firstly, blockchain, through its decentralized consensus mechanism, enables a transaction to occur and be authenticated in a mutually untrusted system, eliminating the need for a trusted third-party intervention. Secondly, the transactions recorded in the blockchain are essentially immutable because each node in the network preserves a complete record of all committed transactions. Additionally, cryptographic mechanisms ensure the tamper-proof nature of all transaction records [9].

The application of blockchain technology in energy communities can effectively address issues arising from transactions with other grid participants, ensuring fair, trustworthy, secure, and reliable information throughout the transaction process. In recent years, research on blockchain technology and its challenges has expanded significantly, attracting scholars to explore its technical nuances. To provide a comprehensive understanding of this area, several review papers have been published, each with its unique scope and focus. In [10]–[15], numerous reviews have been published pertaining to blockchain-enabled energy systems or smart grids, extensively elaborating the basic concepts, network architecture, enabling technologies, prevalent research challenges, and prospective future research directions. The studies [16]–[18] focus more specifically on the application of blockchain technology in the realm of P2P energy trading. Furthermore, the mutual integration of blockchain and IoT has also been thoroughly investigated by multiple studies [9], [19], [20]. Most importantly, the integration of blockchain and IoT can provide a virtual trading layer with a variety of energy trading services and applications. A few of literature [21], [22] have summarized and reviewed the topic of joint utilization of blockchain and IoT for energy trading. However, these aforementioned works only consider energy trading at the P2P level. To the best of our knowledge, none of the existing surveys have comprehensively investigated this popular topic, particularly few research emphasized the simultaneous deployment of blockchain and IoT for multi-level energy trading in energy communities. Comparisons between this study and other relevant research are illustrated in Table I.

TABLE I
SUMMARY AND COMPARISON OF EXISTING STUDIES ON BLOCKCHAIN

Reference	Blockchain application scenarios	IoT for blockchain	Multi-level energy trading
[10], [11]	Energy sector	No	Limited
[12]	Energy system	No	Limited
[13]	Power system	No	Limited
[14]	Smart grid	No	No
[15]	Smart grid	No	Limited
[16], [17]	P2P energy trading	No	Limited
[18]	P2P carbon trading	No	No
[9], [19], [20]	A number of industrial applications	Yes	No
[21]	P2P energy society	Yes	Limited
[22]	Energy community with positive buildings and interactive electric vehicles	Yes	Limited
This paper	Transactive energy community	Yes	Yes

This paper aims to fill the current knowledge gap by exploring the role of energy communities, IoT, blockchain, and their synergistic interaction in addressing the challenges and fostering innovations associated with the multi-level energy trading. Through the cutting-edge research analysis, it comprehensively summarizes how blockchain can facilitate multi-level and decentralized marketplaces to enable the development of sustainable energy communities. The main contributions of this paper are outlined below:

1) Presenting a systematic overview of the integration of blockchain and IoT for transactive energy community, where the IoT facilitates energy digitalization, while blockchain enables decentralized energy trading.

2) Presenting a comprehensive analysis of the utilization of blockchain technology in the transactive energy community from the perspectives of P2P, C2C and C2G energy trading.

3) Presenting a thorough survey on the industrial projects and pilots in blockchain-enabled transactive energy application.

4) Presenting an extensive discussion on challenges and future research directions in terms of market mechanism

under network constraints of distribution network, lightweight blockchain, and policy and regulation.

The remainder sections of this paper are organized as follows. Section II introduces IoT-Blockchain integration for transactive energy community. Section III summarizes the applications of blockchain technology in the transactive energy community. Section IV provides a survey of blockchain-based transactive energy projects and pilots. Section V discusses the research challenges and outlines the corresponding avenues/suggestions for future research directions. Finally, this review paper is concluded in Section VI. The architecture of this paper and the relationship of various sections are graphically represented in Fig. 1.

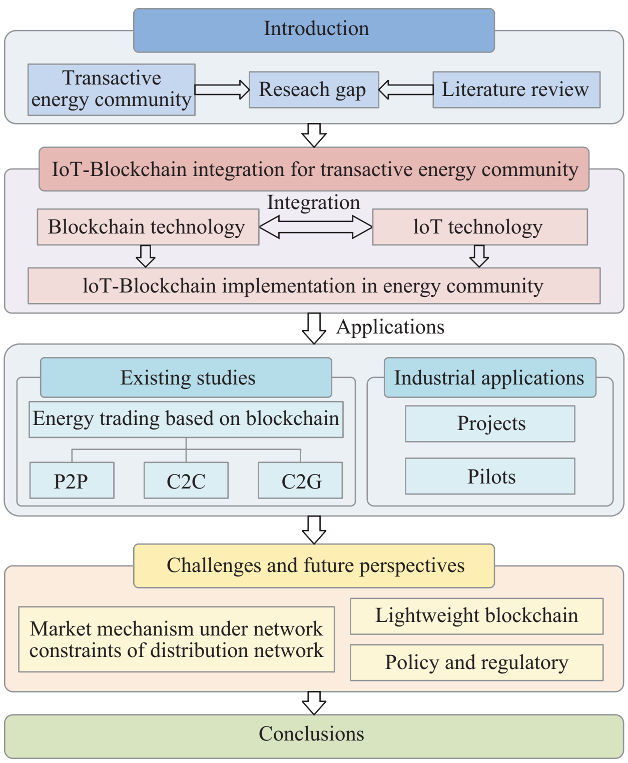


Fig. 1. Architecture of the paper.

II. IoT-Blockchain Integration for Transactive Energy Community

In this section, we will provide layered frameworks of blockchain and IoT technologies, followed by the implementation architecture of integrating blockchain with IoT in the energy community.

A. Definition and Overview of Blockchain

Blockchain, a booming distributed ledger technology, revolutionizes the way energy transactions by shifting the trading model from a centralized framework to a decentralized one [23]. A detailed description of blockchain from the perspective of layered frameworks [24], [25] is presented in the following.

1) Data Layer

The data layer is the foundation of blockchain. In a blockchain, data is stored in interconnected blocks linked by hash pointers, and every participant possesses a replica of the ledger. Fig. 2 depicts the structure of a basic block, which comprises a block header and a block body.

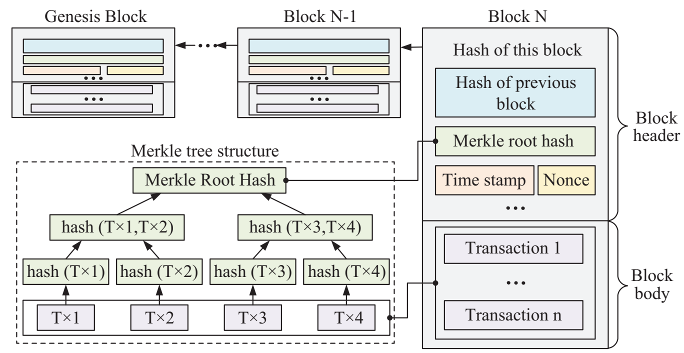


Fig. 2. Structures of basic blocks and Merkle tree.

2) Network Layer

The network layer, where participants engage in peer-to-peer broadcasting and verification of transaction blocks. Its key technologies include propagation protocols, overlay routing and verification mechanisms. Through these technologies, the network layer establishes the foundation for data privacy and network security in the blockchain [26].

3) Consensus Layer

The consensus layer establishes regulations to ensure the consistency of distributed ledgers across all participants [16], with various consensus algorithms being the core technology in this layer. Currently, the main consensus algorithms include Proof of Work (PoW), Proof of Stake (PoS), Practical Byzantine Fault Tolerance (PBFT), and so on.

4) Incentive Layer

The incentive layer is pivotal for accurate blockchain updates, leveraging issuance and distribution mechanisms. In public blockchains, it incentivizes participants to contribute resources for verification and mining, while penalizing malicious participants.

5) Service Layer

The service layer automates blockchain business processes, which includes smart contracts, wallets, and certificate authorities [23]. Smart contracts, the key technology in this layer, are essentially agreements converted into executable code in the blockchain, triggering autonomous execution upon fulfillment of preset conditions.

B. Architecture of Blockchain Integration with IoT

To harness the potential of active citizens and drive the transition towards clean energy, it is crucial to establish user-centric digitized networks that facilitate the deployment of multi-level trading services. IoT plays a pivotal role in bridging the gap between the physical world and the cyberspace of computing systems. Leveraging IoT-based digitalization enables the creation of real-time monitoring and management systems for home area networks, effectively bridging the gap between individual participation in the physical energy realm and the digital information domain [8].

Nevertheless, overcoming the limitations of large-scale integration and interoperability is essential to achieve greater energy flexibility while ensuring user-centric security and privacy. Blockchain provides new opportunities to enhance the interoperability of IoT systems while simultaneously strengthening privacy and security measures [19]. Fig. 3 illustrates the energy trading automation framework resulting from the integration of the IoT platform with blockchain architecture. An overview is provided below, focusing on the layered integration perspective of blockchain and IoT systems.

1) Perception and Actuation Layer

The layer is responsible for the identification, recognition, comprehension, and control of heterogeneous devices. The primary components within this layer include sensors that monitor and collect data on consumption and production metrics from the physical world, as well as actuators and controllers capable of interacting with or modifying the environment.

2) Communication Layer

The layer is in charge of integrating diverse wireless and wired communication networks that adhere to various protocols. In this layer, various kinds of wireless and wired devices can connect to IoT gateways, WiFi access points (APs), small base stations (BSs), and macro BSs, thereby constructing an industrial network. Connectivity is enabled by communication protocols such as low-power wide area networks [27], mobile field networks, wire/wired field networks, and wireless field networks [23].

3) Middleware Layer

The layer serves as a vital intermediary bridge facilitating interaction between IoT devices and cross-domain services and applications. The blockchain is deployed in this layer, and its detailed structure has been comprehensively illustrated in Section II-A. The design of the IoT system integrating with blockchain has two advantages. It offers an abstraction from the underlying layers of IoT, effectively masking their heterogeneity (encompassing the perception and actuation layer as well as the communication layer). In addition, it provides users with blockchain-based services that function as application programming interfaces to support a diverse range of applications [9].

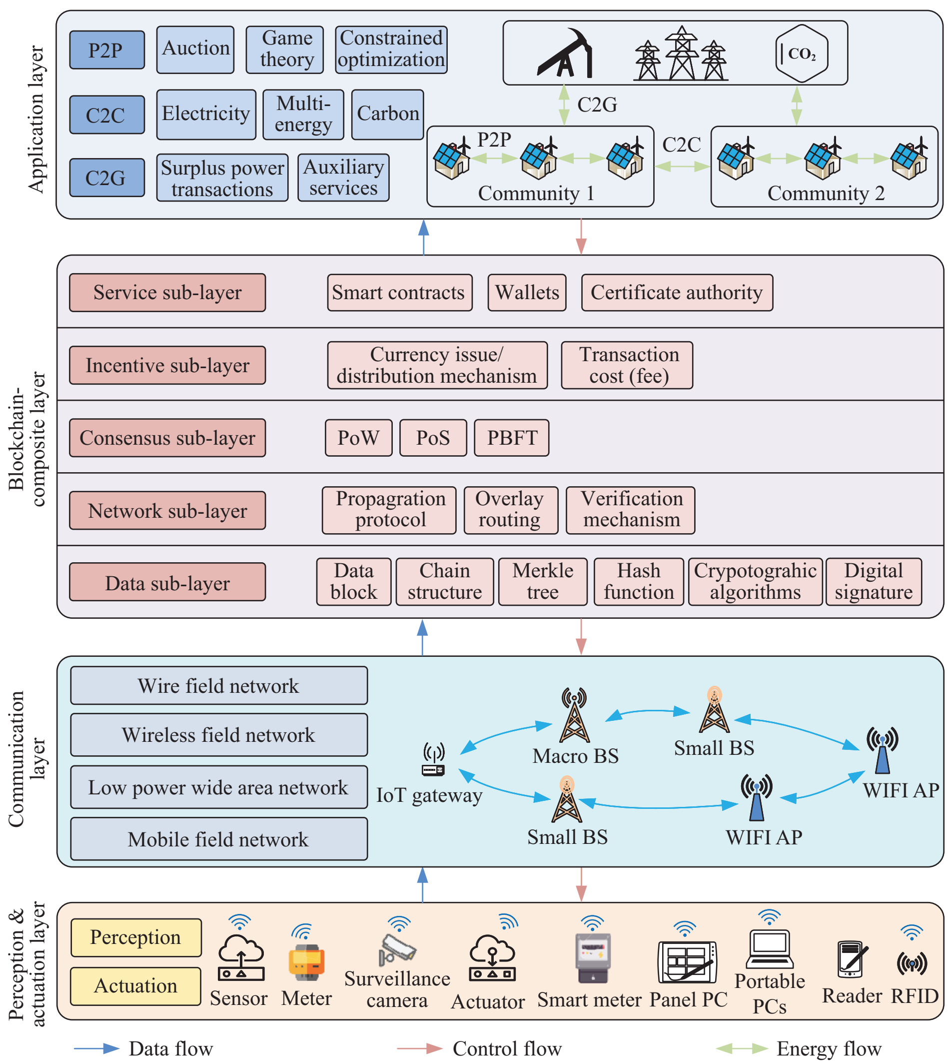


Fig. 3. The energy trading automation framework derived from the integration of IoT platform with blockchain architecture.

4) Application Layer

The layer facilitates a range of energy-conscious applications, such as P2P energy trading within an energy community, C2C energy trading within a region, ancillary services, and so on. These advancements not only enhance the value of data but also offer innovative energy solutions for diverse stakeholders, including consumers, prosumers, utilities, and other relevant parties.

By integrating blockchain technology, the IoT platform can collaborate with metering infrastructure to offer metering and automated billing services to all end-users, ultimately reducing overall administrative costs [28].

C. IoT-Blockchain Implementation in Energy Community

The proposed IoT-blockchain implementation architecture for energy trading in energy communities is presented in Fig. 4. The architecture is mainly composed of an IoT-based smart home, middleware for integration of IoT and blockchain, multi-level market participants in the transactive energy community, and a blockchain network.

In an IoT-based smart home, sensors and actuators are strategically deployed to connect the physical appliances to the digital network. The heterogeneous sensors and actuators employ different communication protocols, thus IoT gateways with specific acceptable protocols serve as the network processor to converge and bridge various sensor networks. The middleware is presented as a standard software service, bridging the integration of IoT systems and blockchain technology. It offers a set of heterogeneous integration enablers, including IoT-blockchain adaptors for plug-and-play interfaces, and blockchain gateways that enable multi-level market participants with specific certificated identities to gain access to the blockchain network. The multi-level market participants, such as consumers/prosumers, community operators and distributed system operators (DSO), participate in the multi-level energy trading through the blockchain network. The blockchain network connects grid-edge IoT networks to form a platform allowing diverse energy market participants to engage in multi-level energy trading in a transparent and fair manner. A peer can be a node that executes smart contracts, endorses transactions and stores records through a distributed ledger. The smart contract can trigger energy services, achieving the automation of multi-level energy trading of energy communities introduced in Section III, including P2P, C2C and C2G energy trading.

III. Blockchain for Multi-Level Energy Community Trading

Energy trading for energy communities can be categorized into three distinct types based on their trading objectives: P2P, C2C, and C2G energy trading. The three trading modes form vertically the multi-level energy trading market of the energy community, as presented in Fig. 5. Intra-community trading involves P2P energy trading among consumers within the community, while inter-community trading refers to C2C energy trading between communities. Under the C2G mode, energy communities collaborate with external energy market entities such as the grid, gas utility, and carbon center to engage in multi-energy trading.

There is a rapidly growing interest in researching and applying blockchain-based energy trading. In this section, we will focus on the application of blockchain in energy communities. This section first presents the blockchain-based energy trading process and then discusses recent advancements in P2P, C2C, and C2G trading.

A. Blockchain-based Energy Trading Process

The execution process for energy trading in energy com-

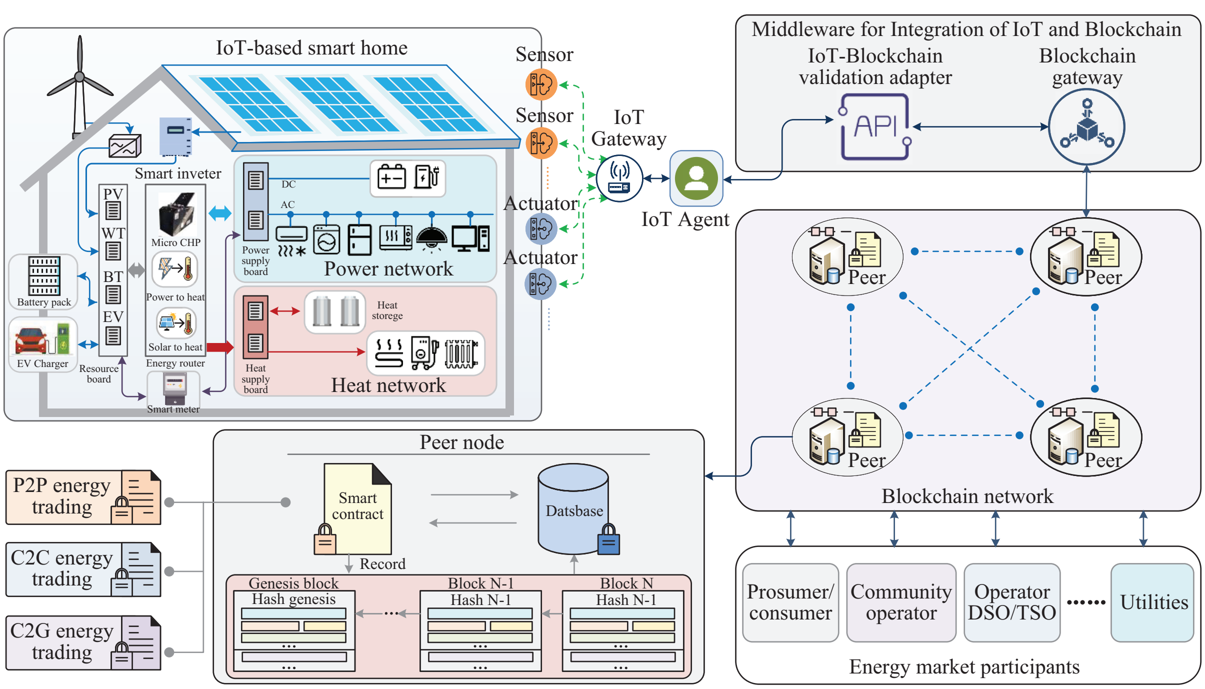


Fig. 4. IoT-blockchain implementation architecture for energy trading in energy communities.

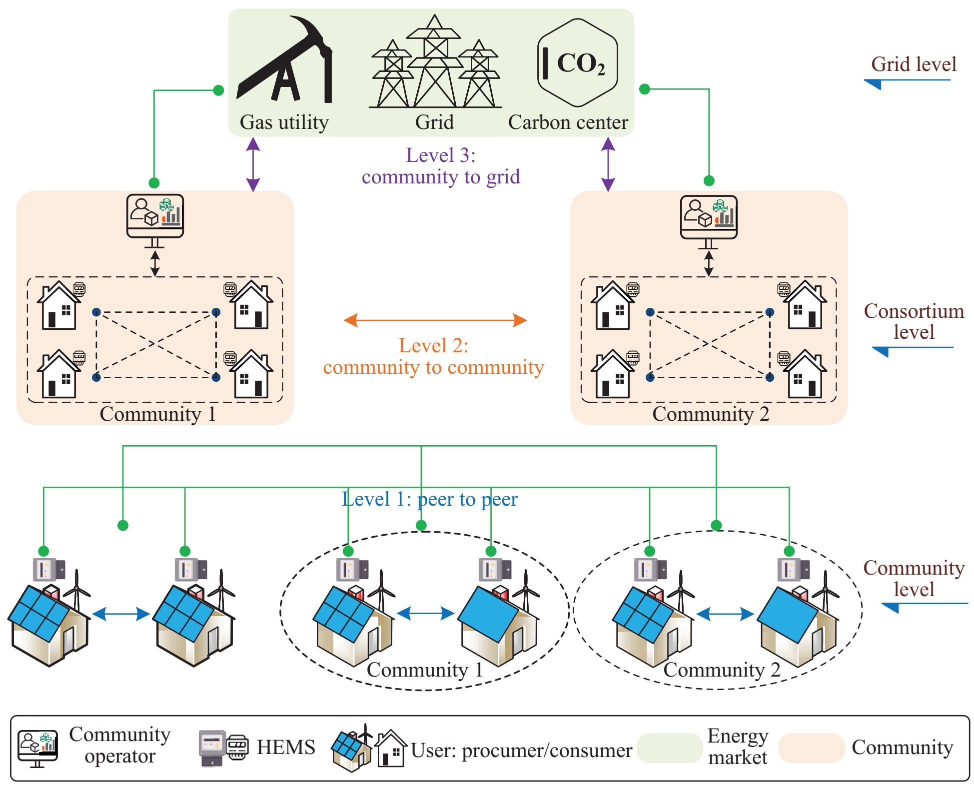


Fig. 5. Multi-level energy trading market of energy community.

munities based on blockchain technology is shown in Fig. 6. 1) Initialization of energy market participants: Each market participant registers on a trusted authority, subsequently obtaining a unique private key, a corresponding public key, and a wallet address. Specifically, the public key is a unique identifier that enables the addressability of each participant in the blockchain network. The private key serves as a digital signature to authenticate the identity of each participant. The utilization of a pair of public and private keys enables secure interactions among participants in the blockchain network [29]. Following this initialization, participants can engage in energy trading through the blockchain.

2) Energy trading: In the blockchain, participants submit their trading information, which is subsequently exchanged over the peer-to-peer communication network to achieve market clearing. The specific trading processes exhibit variability, stemming from the diverse market players involved, the chosen trading mechanisms, and the adopted market-clearing methods. The following three subsections will describe the various trading processes in detail.

3) Transaction results to chain: After the energy trading, the determined trading results are stored as data blocks. These data blocks are then appended to the blockchain upon successful validation and confirmation through the consensus mechanism.

4) Transaction execution: Once the trading results are recorded on the blockchain, it triggers all participants to automatically execute the market clearing results. In addition, the blockchain implements rewards or punishments for players based on whether their execution fulfills their commitments.

B. Community Energy Trading/P2P

The market clearing technique for P2P energy trading varies depending on factors like network topology and market rules, and it can be classified into auction approaches, game theoretic approaches, and constrained optimization approaches.

In the auction approach, multiple players express their willingness to purchase or sell energy by submitting bids and offers to the network. In [30], a double auction-based P2P energy trading model leveraging blockchain technology was developed for prosumers within a community. Similarly, [31] presented a P2P trading model that incorporates iterative double auction mechanisms with blockchain technology, aiming to maximize social welfare. Furthermore, [32] introduced a transactive energy framework based on auction theory, implemented in a blockchain environment.

The realization of auction-based P2P energy trading on the blockchain is shown in Fig. 7. In the beginning, prosumers summit their selling/buying bids which are encrypted and packaged into blocks. Then, these blocks are disseminated through the P2P network, achieving consensus and backup among all network nodes. Upon receiving bids from all agents within a defined timeframe, the smart contract autonomously executes a double auction algorithm [31], or a clearing and pricing mechanism [33]. Once the algorithm converges or the system reaches market equilibrium, a contract script containing transaction volumes, corresponding prices, and digitally signed signatures is generated. After the completion of the transaction, the corresponding information will be broadcast across the entire network and stored in the blockchain.

The game theoretic approach utilizes strategic thinking to

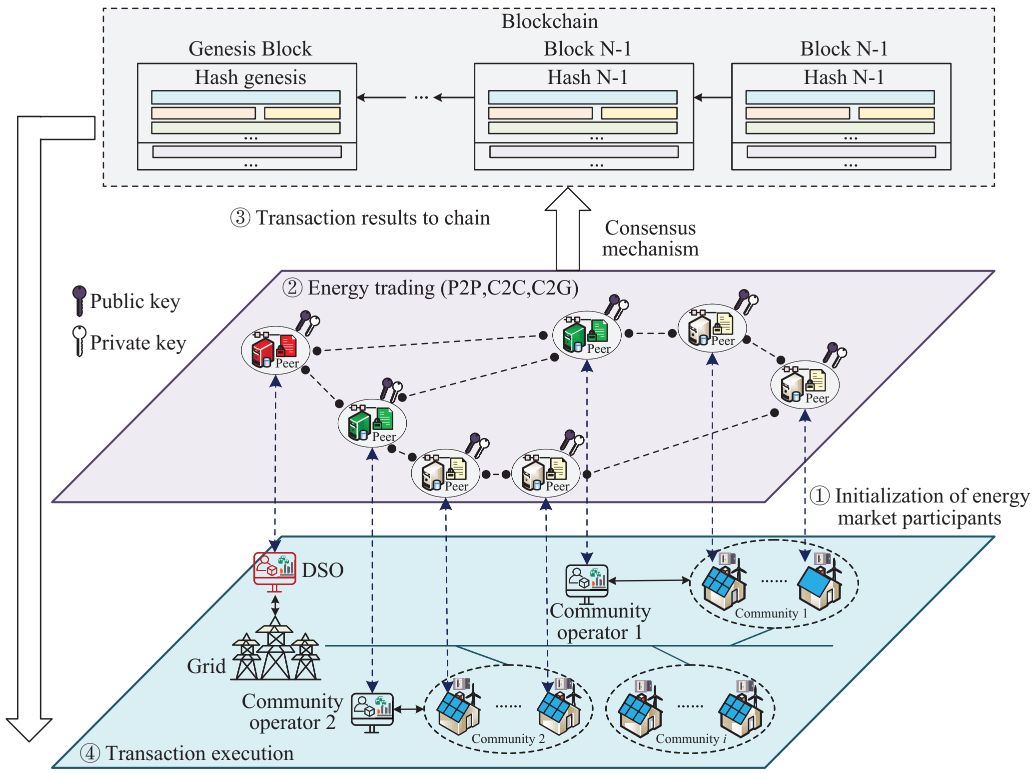


Fig. 6. A simplified diagram of energy trading process using the blockchain.

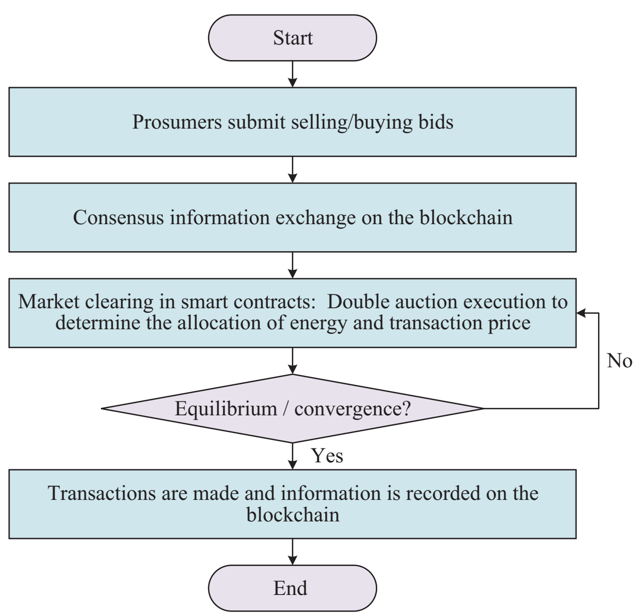


Fig. 7. Flowchart of auction-based energy trading on the blockchain.

organize multiple autonomous entities with unified or conflicting interests, which effectively mitigates selfish behaviors and ensures fair cost allocation among players. In [34], a P2P energy trading model combining cooperative game and blockchain technology was presented for prosumers within local communities. In [35], a pricing model based on non-cooperative game theory was introduced within a localized PBFT-based Consortium blockchain framework, aiming to facilitate decentralized energy trading. The game-based energy trading process implemented on the blockchain is similar for P2P and C2C, and the specific details are described in Section III-C.

The constrained optimization approach employs mathematical programming techniques to establish optimal trading results, taking into account operational security constraints and trading considerations. Due to the risk of privacy exposure and heavy computational complexity of centralized optimization, distributed optimization approaches, including dual decomposition [36], [37] and alternating direction method of multipliers (ADMM) [38]–[40], have gained widespread popularity in the existing literature. The inherent decentralized attribute of blockchain enables the optimization of energy trading through decentralized algorithms, enhancing information privacy and computational efficiency [41]. In [42], a decentralized Ant-Colony optimization approach was proposed to facilitate the clearing of the energy market, effectively safeguarding the privacy of participants in energy trading. Additionally, [43] presented a blockchain-based energy trading framework with a decentralized optimization algorithm operating within the blockchain system. Similarly, [44] introduced an architecture leveraging blockchain and smart contracts for the decentralized optimization and control of DERs within microgrid networks, solving the decentralized optimization problem using ADMM technique. Furthermore, [45] presented a blockchain-enabled platform designed to facilitate decentralized energy trading activities among end-users within a virtual power plant, and employed the ADMM technique to establish a decentralized optimization model.

The frameworks discussed in the literature above, which integrate blockchain technology with decentralized optimization, demonstrate significant consistency. In these frameworks, blockchain serves to decentralize the system by distributing the role of a central operator among all users. This ensures fair energy trading, eliminating the need for reliance on a utility company or central operator. Specifically, ADMM, as referenced in [43]–[45], is a popular decentralized algorithm frequently integrated with blockchain.

In the next, a brief description of P2P energy trading within a local energy community based on the application of blockchain coordinated with the ADMM approach is presented. In this example, the optimization objective is to minimize the overall operational cost of the system, which can be expressed as follows.

$$\min \sum_{i\in\mathcal{I}} f_i(x_i, y_{ij}) \tag{1a}$$

$$\text{s.t.}\quad y_{ij} = -y_{ji} \tag{1b}$$

$$x_i \in \mathcal{X}_i \tag{1c}$$

where f_i denotes the operational cost of user i, x_i denotes the decision variables, and y_{ij} denotes the trading variables between user i and user j. Constraint (1b) ensures that the energy trading market is balanced. $\mathcal{X}_i$ denotes the feasible set.

The standard ADMM algorithm is capable of decomposing the original problem (1) into a lower-level problem and an upper-level problem by introducing auxiliary variables $\hat{y}_{ij}$. The local lower-level problem is solved independently by each user, as shown in (2a). The upper-level problem is executed in the blockchain through a smart contract, as shown in (2b). The solution approach to the problem involves the following iteration process.

$$x_i^{k+1}, y_{ij}^{k+1} = \arg\min_{x_i\in\mathcal{X}_i} f_i(x_i, y_{ij}) + \sum_{j\in\mathcal{N}_i} \frac{\rho}{2}\left\| y_{ij} - \hat{y}_{ij}^k + \frac{\lambda_{ij}^k}{\rho}\right\|_2^2 \tag{2a}$$

$$\hat{y}_{ij}^{k+1} = \arg\min_{\hat{y}_{ij}=-\hat{y}_{ji}} \sum_{i\in\mathcal{I}}\sum_{j\in\mathcal{N}_i} \frac{\rho}{2}\left\| y_{ij}^{k+1} - \hat{y}_{ij} + \frac{\lambda_{ij}^k}{\rho}\right\|_2^2 \tag{2b}$$

$$\lambda_{ij}^{k+1} = \lambda_{ij}^k + \rho(y_{ij}^{k+1} - \hat{y}_{ij}^{k+1}) \tag{2c}$$

where λ_{ij} is the Lagrange multiplier vector, and ρ is the penalty parameter.

The implementation process of the blockchain-based sequential ADMM update is illustrated in Fig. 8. This algorithm iteratively alternates between addressing the lower-level problem (handled by users' smart meters) and the upper-level problem (executed by the smart contract) until convergence is reached. In each iteration, users individually address the lower-level problem on their meters, determining their energy scheduling and exchanges, and subsequently updating the latter value on the smart contract. Once the smart contract receives the energy exchange values from all users, it automatically resolves the upper-level problem, generating auxiliary variables that are then sent to users for the next iteration. The iterative process terminates when the convergence error falls below a predefined threshold, at which point users obtain the optimal scheduling for their respective devices. Ultimately, users execute the optimized energy scheduling as per the obtained results.

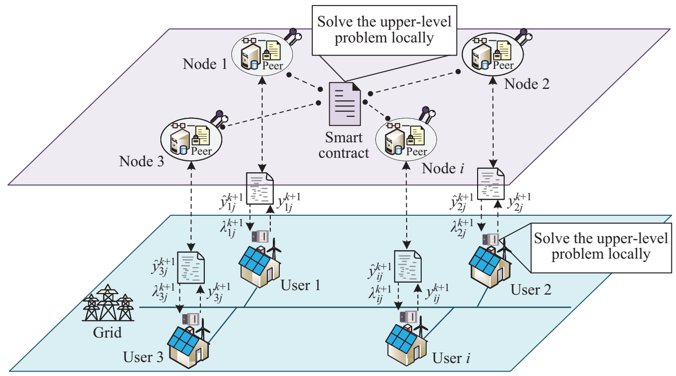


Fig. 8. The implementation of the blockchain with sequential ADMM update.

Each participant in the market is equipped with IoT devices capable of performing three primary tasks:

1) Calculation: Each intelligent device solves its operational subproblems to obtain its own energy scheduling decisions, aiming to minimize users' costs while taking into account known external conditions. The updated variables are subsequently transmitted to the corresponding nodes, and each blockchain-enabled device securely stores its digitally signed information on the blockchain, ensuring its immutability and accessibility across the entire system.

2) Communication: IoT devices exchange boundary information with other participants through the communication layer. Once consensus is reached among peers regarding the market solution, it is securely recorded on the blockchain, ensuring its immutability and widespread accessibility to all participants.

3) Actuation: After the market clearing finishes, each intelligent device reads the optimization results and promptly adjusts both its consumption and generation patterns accordingly.

In this framework, users are not obliged to reveal the optimization process for their trading decisions. This preserves the sensitivity and privacy of local energy information for each household, including PV generation and energy consumption, ensuring it remains private and inaccessible to the network. However, the ADMM algorithm mentioned above follows a sequential solution process that depends on centralized communication and computation within the smart contract. The method is partially decentralized rather than fully decentralized, resulting in a compromise in computational efficiency.

In [46], a fully P2P energy trading optimization model implemented on the blockchain was proposed, where parallel ADMM was employed to solve the model in a fully decentralized manner. The update strategy of the parallel ADMM is formulated as follows.

$$x_i^{k+1}, y_{ij}^{k+1} = \arg\min_{x_i\in\mathcal{X}_i} f_i(x_i, y_{ij}) + \sum_{j\in\mathcal{N}_i} \frac{\rho}{2}\left\| \frac{y_{ij}^k - y_{ji}^k}{2} - y_{ij} + \frac{\lambda_{ij}^k}{\rho}\right\|_2^2 \tag{3a}$$

$$\lambda_{ij}^{k+1} = \lambda_{ij}^k - \frac{\rho}{2}(y_{ij}^{k+1} + y_{ji}^{k+1}) \tag{3b}$$

The implementation process of the blockchain-based parallel ADMM update is shown in Fig. 9. In each iteration, each user utilizes its local smart meter to solve its operational problem. Subsequently, the updated boundary information, which includes the trading variables, is sent to the corresponding nodes. This information is then propagated across the blockchain P2P network, allowing each user to retrieve it. Based on the updated boundary information, each user updates its multipliers accordingly. The smart contract in this case has the exclusive role of collecting the trading quantity and distributing it to the relevant trading participants.

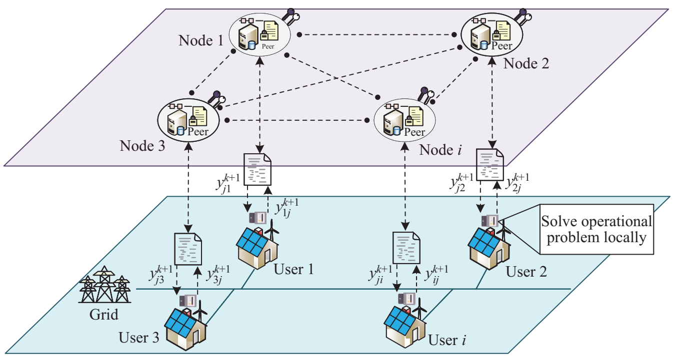


Fig. 9. The implementation of the blockchain with parallel ADMM update.

It is noted that each iteration requires on-chain and off-chain collaboration when combining the ADMM decentralized optimization algorithm with the blockchain. As shown in Figs. 8 and 9, the users' operation problems are done off-chain while the updated boundary information is exchanged in the blockchain. Importantly, sensitive privacy information is kept local and is not uploaded to the blockchain, ensuring user data protection. The on-chain and off-chain collaboration not only addresses the resource consumption challenge but also enhances the scalability, security, and efficiency of blockchain for distributed energy trading.

However, the reference [46] does not explicitly demonstrate how blockchain can defend against malicious actions. In existing decentralized optimization approaches, all participants exchange information to make decisions. The underlying assumption is that mutual trust exists among all participants [38]–[40], [47]–[49]. However, dishonest participants or malicious attackers may spread incorrect information, potentially misleading the remaining participants and compromising the overall security of the community system. Therefore, it is crucial to safeguard the security of information exchange among decentralized users to mitigate the risks posed by such potential malicious behaviors [50].

Blockchain can effectively address this challenge by facilitating secure interactions among participants. Rather than relying on a central entity for trust and authority, authority is distributed evenly among all participants. All transactions and interactions are governed by predefined smart contracts—self-executing agreements that are automatically enforced and continuously verified by the network. Consensus among the participants, achieved through a consensus mechanism, is required for any action to be implemented. This system relies on majority agreement among honest participants, with built-in checks and balances to deter malicious activities and maintain protocol integrity. Consequently, it incentivizes all parties to behave honestly, thereby preserving trust within the system [51]. For instance, in [52], a blockchain equipped with a state machine replication (SMR) consensus algorithm was utilized to provide a trustworthy environment for information exchange among individual users.

C. Regional/Local Energy Trading/C2C

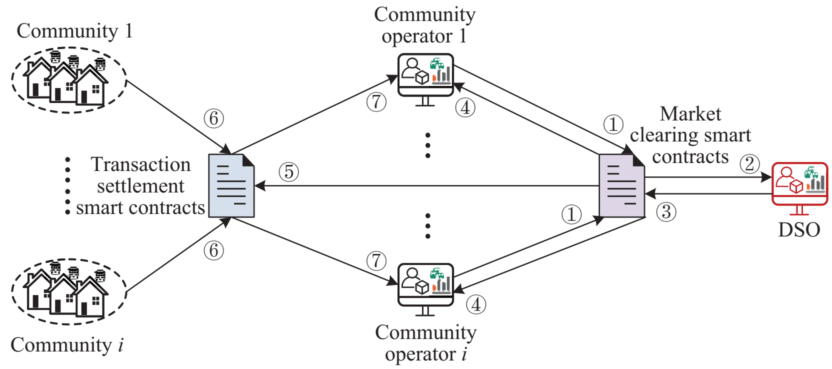
There exist notable similarities between P2P and C2C energy trading, as both can be regarded as point-to-point decentralized trading conducted within their respective network levels [53]. P2P energy trading operates at the community level, facilitating collective energy balance and self-consumption among its members. C2C energy trading operates at the consortium level, enabling cooperative self-sufficiency and self-consumption among various communities [8].

The main distinctions between P2P and C2C energy trading can be attributed to the entities involved and the types of trading conducted. In P2P energy trading, the participants mainly consist of prosumers or consumers operating within a specific community. On the other hand, C2C energy trading involves larger entities such as communities and energy aggregators operating within a designated region. Additionally, while P2P energy trading focuses primarily on the exchange of electricity, C2C energy trading encompasses a broader range of commodities, including electricity, heat, carbon allowances, and more [53].

In one study, blockchain techniques were applied to empower networked community microgrids, enabling them to adopt a more proactive approach in transactive energy trading [54]. Another research work introduced a blockchain consensus mechanism called proof of solution (PoSo), aiming to safeguard the security of information exchanged within decentralized energy management and trading [55]. PoSo has shown effectiveness in mathematical optimization-based tasks with continuously differentiable objective functions and constraints. However, its application remains limited when addressing challenges related to integer programming, leaving a gap in its utility for certain types of complex optimization problems. Furthermore, other studies have explored the utilization of blockchain in the energy and carbon allowance joint transactive market in interconnected microgrids. The integration of blockchain has improved the security, transparency, and efficiency of transactions within this market [56], [57].

Subsequently, a concise overview of the C2C energy trading process, facilitated by the integration of blockchain technology and the cooperative game approach, is presented. In the cooperative game framework, participants initially cooperate to form a grand coalition and maximize the overall coalition payoff. Then, the coalition payoff is allocated fairly to each participant. In the blockchain-based framework, the cooperative game is achieved with the help of two types of smart contracts. The detailed energy trading process of the blockchain with the cooperative game is illustrated in Fig. 10.

Firstly, the market-clearing smart contracts provide a public interface for all communities to submit their trading data.



① Community operators send trading data to market clearing smart contracts.
② Market clearing smart contracts send trading data to the DSO.
③ The DSO clear markets and sends clearing results to the market clearing smart contracts.
④ Market clearing smart contracts send clearing results to the community operators.
⑤ Market clearing smart contracts send clearing results to the transaction settlement smart contract.
⑥ Transaction settlement smart contracts query smart meters for real-time data.
⑦ Transaction settlement smart contracts settle payment for each community operator.

Fig. 10. The implementation of the blockchain with cooperative game.

These smart contracts have a predefined schedule for data submission, ensuring the prompt delivery of trading data to the DSO. Once all communities have provided their trading data, the DSO proceeds to clear the market. This process involves calculating the optimal schedule and payoff allocations among the communities. After market-clearing, the market-clearing smart contracts broadcast the clearing results to all participating communities and the transaction settlement smart contracts. Subsequently, the transaction settlement smart contracts query smart meters to acquire real-time data which is then compared with the market-clearing outcomes facilitated by the market-clearing smart contracts. If communities fulfill their market commitments, the transaction settlement smart contracts will settle the payments automatically. Otherwise, the transaction settlement smart contracts will invoke a predefined penalty framework, imposing additional charges on non-compliant communities [58].

D. Grid Energy Trading/C2G

In addition to facilitating P2P and C2C energy trading, blockchain technology holds huge potential in managing network operations about ancillary services, such as voltage and voltage regulation, peak shaving, and so on. For P2P and C2C trading, blockchain technology aims to simplify and incentivize energy trading among users by limiting the involvement of third parties. However, in the provision of ancillary services, these third parties, including grid operators and balancing responsible parties, can engage in trades directly with prosumers. In this scenario, a hybrid blockchain that combines the strengths of public and private networks is imperative. The core advantage of blockchain technology lies in its ability to establish a secure platform for various markets focused on the provision of ancillary services, while simultaneously easing market entry for smaller devices integrated into the network. As critical infrastructures, the grids are subject to numerous rules and regulations, ensuring that entities involved in the provision of ancillary services adhere to their contractual obligations with network operators. However, due to the intricacies of these regulations, small prosumers often refrain from offering ancillary services, despite having the theoretical capacity. Blockchain technology, through the utilization of smart contracts, can bridge this gap by digitizing the existing regulatory framework for ancillary services provision [13].

In this study, [59] proposed a blockchain-powered microgrid architecture to encourage increased user participation in the market by providing reactive power ancillary services. However, the architecture overlooks the crucial role of user selection in transactions, which can lead to potential issues. In situations where a user fails to meet the demand, this oversight not only increases the burden on data processing but also poses a threat to the stability of the grid. To address this issue, [60] proposed a methodology for evaluating the economic value of users' services within the blockchain-based ancillary service market. This approach enables a more accurate assessment of contributions to voltage regulation and facilitates the selection of high-quality users capable of effectively responding to service demands. However, the reliance on a fixed user rating system limits opportunities for certain users to fully address service demands, as their response capabilities are not fully leveraged. In related work, [61] introduced a blockchain-based transactive energy system that incentivizes agents to offer voltage regulation services. Within this framework, a reputation rating system was established for each user, and ratings were dynamically adjusted by the successful or unsuccessful implementation of service contracts. This approach demonstrated the potential of market users to respond to a broader range of ancillary service demands. However, the discussion in this research lacks a clear focus on the consensus mechanism, which is essential for ensuring the integrity and security of transactions within the blockchain-based transactive energy system.

On the demand side, users generally engage in peak-shaving ancillary services through demand response. In [62], blockchain technology was employed to facilitate real-time price-driven demand response programs in uncertain environments. Through the utilization of blockchain with a smart contract, users can receive information and execute demand response actions in a near-real-time manner. [63] proposed a demand response approach in the blockchain-based ancillary service market. This approach leverages an energy storage capacity competition framework implemented using the Proof of Capacity (PoC) consensus mechanism. By utilizing this mechanism, the research aimed to enhance the responsiveness and efficiency of ancillary service providers. In [64], a blockchain-enabled demand response management for a community-based peer-to-peer energy trading was presented, where the non-cooperative game-based demand response mechanism was proposed by dynamic pricing. The smart contract acts as a community coordinator to guarantee the integrity and non-repudiation for both the pricing models and the data storage.

In summary, the aforementioned references provide valuable insights into the application of blockchain technology in the ancillary service market. However, there is scope for further research to address the issues related to user selection, rating systems, consensus mechanisms, and the optimization of service responsiveness and efficiency. These areas of investigation are crucial for the successful implementation and operation of blockchain-based ancillary service markets in the energy sector.

In the following, a consumer aggregation system for demand response services based on blockchain is described [65]. This scenario involves a grid operator requiring users to modify consumption patterns to meet peak demand regulation requirements. In this case, the baseline is the user's typical consumption profile, which allows for assessing whether any observed consumption changes are attributable to demand response indicators. The difference between baseline and actual consumption quantifies individual user performance during demand response events. The availability profile is employed to quantify the flexibility of each user in adapting their behaviors. This profile represents the user's willingness to respond to the operator's requests. Notably, the availability profile is recalculated in each subsequent demand response event, factoring in the user's previous performance.

The detailed sequence process of the demand response event on the blockchain is shown in Fig. 11. Firstly, the metering data of users' energy consumption is transmitted to the blockchain, where it is subsequently leveraged by smart contracts to compute baselines and availability profiles. Then, the DSO triggers a demand response event notification on the blockchain, prompting the smart contracts to distribute power reduction requirements among users. Users read load reduction provided by the smart contracts and participate in the DR service accordingly. During the event, the consumption data is recorded on smart meters and blockchain. At the end of the DR event, smart contracts evaluate users' compliance with the mandated demand reduction and reward consumers accordingly. Additionally, in IoT-based smart homes, the load reduction requirements received from the smart contracts can be integrated into HEMS [66], enabling the HEMS to autonomously adjust and schedule loads based on predefined parameters.

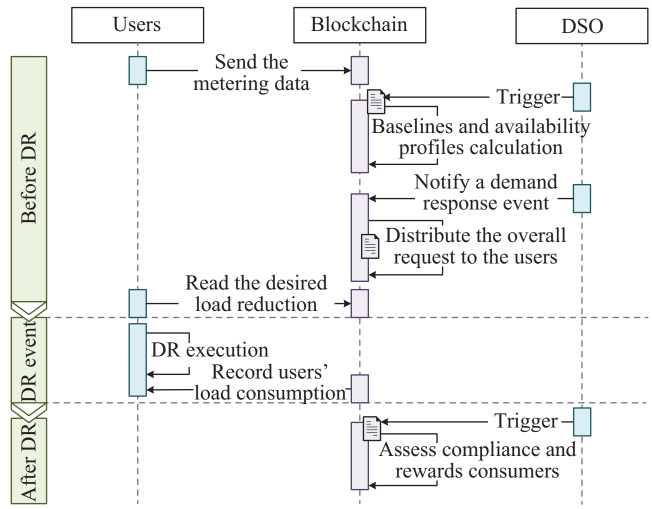


Fig. 11. Sequence diagram of the demand response event on the blockchain.

In this section, a series of blockchain applications in the domain of transactive energy communities have been introduced. These applications are categorized into three domains: P2P, C2C and C2G energy trading. A summary of all blockchain-based applications discussed in this section is outlined in Table II.

Based on the analysis of the above studies, it is found that the biggest difference among different trading modes is the utilization of smart contracts. The comparison of smart contract functions in blockchain-based applications is shown in Table III. It can be found that smart contracts always play a central role in financial transaction settlement in various blockchain-based trading mechanisms. However, the degree of involvement and specific functions of smart contracts vary during the process of market clearing. Specifically, in auction-based trading, smart contracts are responsible for comprehensively collecting and integrating the bidding information of all participants to facilitate market clearing. In the game-based, partially decentralized optimization-based and C2G trading modes, smart contracts assist in the calculation and verification of market clearing. Conversely, in fully decentralized optimization-based trading, smart contracts don't directly participate in the calculation process of market clearing, which provides an opportunity to shift the market clearing mechanism to off-chain execution, potentially significantly enhancing the overall efficiency of blockchain transactions.

IV. Industrial Projects and Pilots

Experts and scholars around the world have achieved preliminary research findings on the application of blockchain technology in the field of the energy sector. Based on these theoretical studies, several corresponding engineering applications have been implemented and operated globally. This section will focus on the state–of–the–art currently known projects and pilots in blockchain-enabled transactive energy applications. The respective focuses, contributions and limitations of these initiatives are listed in Table IV.

Based on the summary of typical industrial projects and pilots listed in Table IV, the following conclusions can be

TABLE II
SUMMARY OF BLOCKCHAIN-BASED APPLICATIONS IN TRANSACTIVE ENERGY COMMUNITY

Focus aspects	Reference	Trading content	Technical approach
P2P	[30], [32]	Electricity	Blockchain, auction theory
	[31]	Electricity	Blockchain, iterative double auction algorithm
	[33]	Electricity	Blockchain, double-auction, Vickrey-Clarke-Groves (VCG) mechanism
	[34]	Electricity	Blockchain, cooperative game
	[35]	Electricity	Localized PBFT-based Consortium blockchain, non-cooperative game theory
	[42]	Electricity	Blockchain, decentralized Ant-Colony optimization approach
	[43]	Electricity	Blockchain, modified PBFT consensus protocol, ADMM
	[45]	Electricity	Blockchain, smart contract, ADMM
	[46]	Electricity	Blockchain, ADMM
C2C	[52]	Electricity	Blockchain, optimality condition decomposition (OCD), SMR consensus algorithm
	[54]	Electricity	Blockchain, smart contract, auction theory
	[55]	Electricity	Blockchain, PoSo consensus mechanism
	[56]	Electricity and carbon allowance	Blockchain, smart contract, cooperative game
	[57]	Electricity and carbon allowance	Blockchain, smart contract, PoW consensus algorithm
C2G	[59]	Reactive power ancillary service	Consortium blockchain
	[60]	Voltage regulation service	Blockchain, smart contract
	[61]	Voltage regulation service	Blockchain, smart contract, reputation rating system
	[62]	Demand response service	Blockchain, PoS consensus mechanism, smart contract, robust fuzzy multi-objective optimization
	[63]	Demand response service	Blockchain, PoC consensus mechanism
	[64]	Demand response service	Blockchain, smart contract, non-cooperative game
	[65]	Demand response service	Blockchain, smart contract

TABLE III
COMPARISON OF SMART CONTRACT FUNCTIONS IN BLOCKCHAIN-BASED APPLICATIONS

Focus aspects		Smart contract functions	
		Market clearing	Transaction settlement
P2P/C2C	Auction	●	●
	Game	◑	●
	Partially decentralized	◑	●
	Fully decentralized	○	●
C2G	–	◑	●

○ = No, ◑ = Partially, ● = Fully

drawn.

1) European and American countries, which have embarked on blockchain initiatives earlier, boast a more robust experience in piloting blockchain-based projects. In contrast, China's explorations in this domain remain comparatively sparse.

2) Despite the promising results achieved in pilot projects, blockchain-based energy trading applications have not yet achieved large-scale commercialization.

3) The applications reviewed face a series of challenges. These range from technical issues, such as high concentration of computer power and limited capacity, as well as non-technical challenges, including policy support and regulatory frameworks.

4) The current blockchain projects in energy trading primarily focus on P2P trading within communities. However, limited interaction with third parties, such as network operators and utilities, suggests that there is potential for further exploration in C2C and C2G trading models.

V. CHALLENGES AND FUTURE PERSPECTIVES

Despite the advantages that blockchain offers to energy trading within energy communities, several obstacles still impede its widespread and practical implementation. This section discusses the challenges and future perspectives surrounding the exploitation of blockchain's potential to empower low-carbon, sustainable, and transactive energy communities.

A. Market Mechanism Under Network Constraints of Distribution Network

In the electricity market, energy transactions among participants are fundamentally linked to the physical operation of the power grid. However, there are still technical barriers that need to be overcome. For instance, when executing power transactions, it is critical to consider the physical topological constraints of the grid, which include power flow limit violations, line congestion, and voltage adjustments [79]. Ignoring these constraints in energy trading jeopardizes the security and stability of distribution networks.

In a centralized transactive energy market, market operators have comprehensive access to pertinent information, including the structure of the distribution network and market participant bids. This extensive knowledge facilitates the development of market-clearing solutions that seamlessly align with network constraints. However, in a decentralized market, market participants lack knowledge about the network's status and the trading activities of other participants [80]. Therefore, addressing network security constraints in a decentralized market has emerged as a significant research challenge.

Incorporating decentralized optimization and on-chain and off-chain collaboration into blockchain technology can potentially overcome these challenges. The initial focus is on exploring decentralized optimization methodologies that incorporate physical topological constraints. This approach effectively decouples the centralized problem into individual subproblems that can be optimized independently and eliminates the need for a consensus procedure. By leveraging decentralized optimization algorithms, the optimization process can be efficiently conducted off-chain to find the optimal solution.

TABLE IV
SUMMARY OF BLOCKCHAIN-BASED TRANSACTIVE ENERGY PROJECTS AND PILOTS

Project	Reference	Country	Focus	Activity/Contribution	Challenge/Limitation
Shekou Energy Blockchain Project	[11]	China	Smart contract based on blockchain to enable P2P energy trading	Simple operation on the user side Utilize electronic certificates to incentivize users to adopt clean energy	Insufficient incentives for participating users Low engagement from power grid Low user volume
Brooklyn Microgrid Project	[67]	US	P2P electricity trading among residents Microgrid energy distribution	Online P2P trading platform Near-real-time trading and information sharing Address the challenge of grid congestion stemming from the proliferating number of renewable energy sources and EVs Automatic energy trading	Technical issues of blockchain platform such as high concentration of computer power and limited capacity Lack of policy assurance for the legitimacy of P2P trading Low user volume
Quartierstrom	[68]	Switzerland	A decentralized P2P marketplace for locally generated solar energy for communities	Implement a double auction as a smart contract Employ a dynamic grid usage tariffs to align energy market incentives with grid stability interests	Regulatory framework barrier for P2P markets Optimal tariffs design issues for utility grid cost recovery and prosumer investment cost amortization
EnerPort	[69]	Irish	Blockchain-based P2P trading between microgrids	Online P2P trading platform Data monitoring and management Automated control and governance of trading Enhanced return on renewable energy investments Reduced energy bills	Current issues and limitations of blockchain technology Lack of specific regulations or policies High complexity Risk of low public acceptance
Hackney Housing Estate	[70]	UK	Blockchain-based platform P2P energy trading Operation and management of the system	Integration of Artificial Intelligence (AI) and blockchain Demand response Battery storage Reduced energy bills Preferred rates for energy selling	Technical issues Potential risk of public acceptance
Uttar Pradesh Rooftop Solar Project	[71]	India	Blockchain-enabled P2P solar power trading	Reduced energy prices for consumers Increased return on investment for prosumers Unified billing management platform Recommendations for regulators for policy making Localized demand-supply balancing benefits network operators Minimize need for additional transmission grid infrastructure for growing demand	Complexity of the system System errors Educating the public
Enerchain	[72]	Germany	Blockchain-based P2P trading platform for the wholesale enegy market	P2P wholesale trading between prosumers, DSO and aggregators End-to-end transaction in less than a second Market-based coordination of flexible schedule in Microgrid with storages and EVs	Technical issues of the system Lack of local market analysis or discussion Potential risk of public acceptance
Vicinity Centres multiple projects	[73]	Australia	Blockchain-based P2P energy trading between shopping centres and their neighbouring communities	Green energy benefits More competitive and beneficial energy prices Instantaneous switching between solar energy and national grid energy Advanced energy storage Decrease dependency on the national grid	Technical issues of blockchain technology Public acceptance Possible system errors
Nicheliving Connected Communities Energy Project	[74]	Australia	Blockchain-based platform for P2P trading	Full renewable energy via an embedded electricity network and solar PV and storage microgrid Reduced energy prices for consumers Deliver apartments with solar power and battery storage Additional income source for energy prosumer	Technical limitations Potential risk of public acceptance Risk associated with apartment sales
Tennet & Vandenbron	[75]	Netherlands	Blockchain-enabled grid management	Combine blockchain technology and vehicle-to-grid (V2G) Provision of balancing and ancillary services	Limited regulation capacity Small scale application
Brixton energy solar "Project Community" project	[76]–[78]	England	Blockchain-enabled platform for P2P trading Energy generation and storage	Usage of domestic batteries to store surplus energy for future trading Reduced energy bills for the housing estate Residents will benefit from cost savings through reduced service fees Promote renewable energy accommodation in small communities of high-density urban areas	Lack of dedicated regulations for P2P trading inside the housing estate Limited public acceptance Project highly depends on public investments

Under this paradigm, on-chain activities primarily focus on verifying the feasibility of transactions and accurately recording the exchanged energy and financial quantities upon successful completion. This approach not only enhances the efficiency of the transaction process but also ensures the secure and stable operation of the entire system. Decentralized optimization plays a crucial role in ensuring the information security of all participants, safeguarding their privacy and integrity.

The collaboration between on-chain and off-chain activities enhances the efficiency and scalability of blockchain applications, enabling them to handle large-scale and high-concurrency scenarios. Offloading certain transactional processes, such as computation processes, to the off-chain environment has the potential to significantly expedite blockchain throughput [15]. However, the intricate nature of data interaction requires careful consideration when designing information interfaces that seamlessly integrate on-chain and off-chain functionalities.

B. Lightweight Blockchain

With the increasing number of blockchain nodes participating in the market, the information stored within the blocks experiences a significant surge, ultimately leading to a decline in transaction performance and compromised scalability [81]. Moreover, given the dynamic nature of energy transactions and the constant real-time fluctuations in pricing, the data processing system must be capable of instantaneously handling massive volumes of transactions [82]. Due to the inherent limitations of the existing blockchain system, specifically its high security requirements and decentralized nature, blockchain-based solutions face significant challenges in achieving computational efficiency, thereby posing major obstacles to their widespread adoption in practical power system markets. [83]. The main obstacles stem from the challenges of resource-constrained devices. For instance, sensors and smart meters exhibit inferior computing capabilities, limited storage space, low battery power, and unreliable network connectivity [9].

To address these challenges, "lightweight" systems have been developed that aim to integrate blockchain technology into resource-constrained networks, while striving to minimize the complexity and resource-intensive requirements associated with blockchain [84]. When designing and implementing blockchain technology, it can be optimized for lightweight processing from five aspects: architecture [85], cryptography [86], consensus [87], storage [88], and authentication [89]. To illustrate the research directions in lightweight blockchains, the existing and potential research directions are summarized in Fig. 12 from the following five areas.

C. Policy and Regulation

In the European Union, there is broad consensus among institutions and authorities regarding the potential of blockchain technology [90]. As a strategic tool, blockchain could facilitate active participation of local or community-level consumers in electricity markets, enhancing market democratization and transparency.

However, in China, the widespread adoption of blockchain technology in energy community trading faces major obstacles primarily in the areas of policy and regulation [28]. The emerging trading modes such as P2P trading and C2C trading are still in the early stages of development in China, resulting in limited adoption at the moment. Furthermore, China has strict financial supervision policies that prohibit the issuance and circulation of various virtual cryptocurrencies like Bitcoin [91].

The inherent decentralization of blockchain technology also challenges China's centralized energy management paradigm, potentially disrupting the interests of central organizations to some extent [92]. It also poses significant challenges in establishing a clear regulatory authority throughout the entire blockchain transaction network [93].

To address these issues, it is suggested that regulatory bodies establish a comprehensive decentralized electricity trading market that supports dominant enterprises and encourages active participation of users in the new energy trading system. National energy and financial regulatory authorities should develop regulatory policies that incorporate energy blockchain technology into a reasonable and compliant regulatory framework [94]. Furthermore, government and blockchain companies should conduct standardization research on the application of blockchain in energy trading. This research should identify typical implementation scenarios and develop technical standards for setting up demonstration projects [95].

VI. Conclusion

This review paper proposes a systematic overview to investigate the IoT-blockchain integration framework to motivate the multi-level energy trading of energy communities. Firstly, the blockchain and IoT technologies are introduced in brief, along with a detailed exploration of the architecture for integrating blockchain with IoT in energy community. Then, based on the comprehensive survey of current research works, the

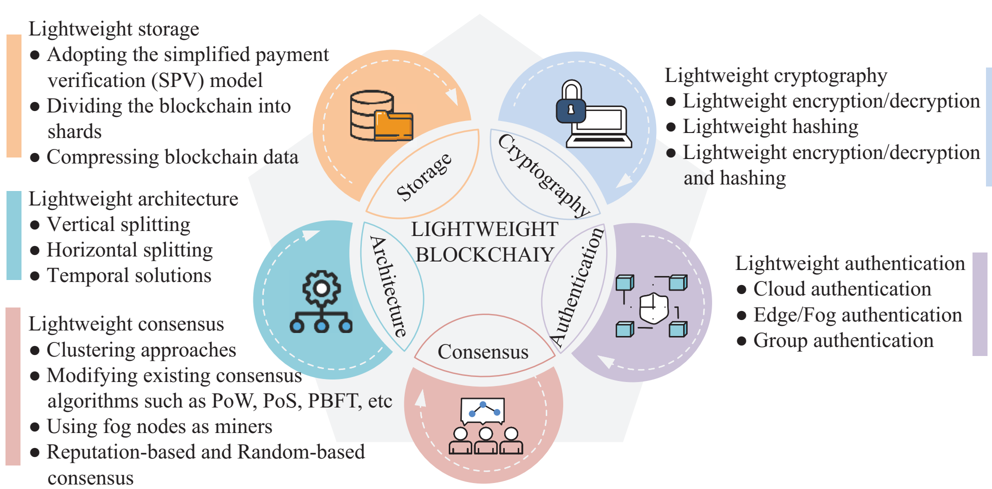


Fig. 12. Lightweight blockchain research directions in five areas.

co-creation of energy communities incorporating blockchain technology is explored with categorized aspects from P2P, C2C, and C2G energy trading respectively. Furthermore, a detailed review of selected blockchain-based transactive energy projects and pilots is conducted in terms of their focuses, activities/contributions and challenges/limitations. Finally, challenges and potential future research directions are discussed in terms of market mechanisms under network constraints of distribution network, lightweight blockchain, as well as policy and regulation.

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