An Energy Trade Framework Using Smart Contracts: Overview and Challenges

Moayad Aloqaily, Azzedine Boukerche, Ouns Bouachir, Fariea Khalid, and Sobia Jangsher

Abstract

The increasing demand for clean, sustainable and reliable energy sources that are secure and stable requires the integration of renewable and edge energy products with the existing power grid. With the introduction of technological advancements and distributed resources, energy users (aka prosumers) can now generate, store and manage their energy requirements, and share their resources with others. BC is a promising technology that can provide secure and verifiable transactions for P2P energy trading, and promote energy conservation. This article recognizes the best practices for sustainable energy, and highlights the benefits of BC and smart contracts in the energy sector. A distributed trading framework and smart contracts are proposed for future versions of BC and integration with other energy products, and potential solutions are suggested.

Introduction

Preserving energy is a major factor in the development of sustainable resources in cities, and Blockchain (BC) technology has attracted interest from the energy sector due to its ability to enable residents to sell surplus energy to one another or to the main energy grid [1]. BC-based energy technology and BC technology for P2P energy trading will benefit both producers and consumers, and drive the growth of a global electricity trading market. As well as transforming our cities from energy consumers to producers, this state-of-the-art energy model will generate revenue for individuals, businesses and governments.

BC is an efficient, low-cost system due to its incorporation into microgrids, which provide users with significantly lower energy costs than conventional systems. Though this decentralization approach mitigates single point of failure problems, data is somewhat more vulnerable to privacy attacks and authentication issues. BC is a system ledger that is available to every node in a network, and it includes stored assets and transfers user information. The advantage depends on the type of industry (e.g., bitcoin or energy tokens in energy trading). The main feature of BC is the security and accountability of transactions due to its immutable ledger, which reduces P2P central authority costs and ensures transparency [2].

The conventional energy exchange system is changing rapidly, due to the growth of distributed energy resources (DERs) such as solar cells, wind energy, biofuel and hydro power. The main features of BC technology for P2P energy sharing/trading provide the potential to transform the energy sector by reducing costs, latency and environmental pollution. In a P2P energy trading system, BC can store and track the electricity being traded and its source and destination among users at the grid level, while at the user level it can provide accurate and transparent records of energy transactions that can be verified by any user in the network.

With BC, users are represented by their public key and diverse encryption algorithms to ensure their identities are not accessible, thus providing privacy and digital signatures that secure the integrity of prosumer data. Moreover, smart contracts, also known as crypto-contracts, are algorithms that control the transfer of digital currencies or assets between parties under certain conditions. Crypto-contracts are stored on BC technology to provide security and accountability.

Though this effective technology has typically been used for financial currency and payment transactions, it has recently attracted experienced interest from other domains, including the energy sector. There have also been implementations on a smaller scale, to explore the benefits for energy trading and supply chain management. The basic framework of BC in energy trading using an energy router indicates that secure energy trading has been developed [3]. The compatibility of BC to the energy Internet and its various challenges has not yet been explored.

An overview of main energy BC stakeholders is presented in Fig. 1. As shown, the integration of consumers and prosumers will be through smart contracts and BC. Consumers can be individuals, governments or wholesale markets with crypto-contracts to collect information about participants and manage the load automatically, while prosumers can range from individuals willing to maintain their own energy (for electric vehicles and smart homes for example), to larger communities such as factories and high-rise buildings. The concept presented in Fig. 1 saves energy by identifying those consumers capable of participating in energy production, and fields that BC can be applied to other than financial transactions, such as Bitcoins.

The differences between the proposed P2P energy trading based on blockchain and the smart grid network can be summarized as:

- Basic consumers such as residential, industry and electric vehicles, in the smart grid network can serve as both prosumers and consumers at the same time in the proposed platform. They can produce their own ener-

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gy, and sell any excess via peer-to-peer with no need to rely on a third party (i.e., conventional power networks).
- Using BC provides trust, privacy and secure financial transactions that can encourage participants to apply the platform and increase the benefits.

The contributions of this article are as follows:
- Surveys verifying the importance of BC in the energy sector
- Overview of the research challenges, issues and potential solutions for successful development of BC in energy systems, particularly P2P
- A proposed distributed energy trade framework using BC smart contracts.

The organization of this article is as follows. The following section provides an overview of the general structure of BC, including its advantages and the importance of different BC consensus algorithms in BC. We then present the use of BC technology in energy systems, while the applications of future BC energy systems are discussed following that. We then describe the proposed energy trade framework, and highlight the open issues and challenges that delay BC development in the energy sector. The final section presents potential solutions to the main issues in BC energy, followed by the conclusion.

An Overview of Blockchain

BC is a list of user transactions/data in the form of blocks, which are encrypted and timestamped. The header of each block contains hash, which is an encryption function that prevents users from manipulating the data in any previous block. The blocks are linked together, hence the name blockchain, and the first block is called the genesis block because it has no parent block, while the others do have parent blocks, as shown in Fig. 2.

BC has several advantages and benefits, and in this section we discuss the most relevant.

Integrity: The integrity of the data is maintained, and in a P2P network the complete ledger is distributed across the entire user network. Thus, every user has a copy of all transactions that take place in the network, and if a user attempts to manipulate the data in a block the change can be detected, since other users have a copy of the ledger. To add a transaction, the data must go through several verification processes, after which the record of that change cannot be edited or deleted. In addition, the blocks are linked by the hash of the previous block.

Censorship Resistance: In BC, no one can block, remove or alter a transaction; it is a tamper-proof environment.

Cost Effective: The use of BC eliminates the need for third parties, thereby lowering costs.

Efficiency: As BC users communicate with each other directly, rapid transactions are ensured. However, with a large number of nodes, traditional systems such as Visa and ATM are more scalable than BC-based transactions, since there is a limit to the block size (e.g., 1MB) in Bitcoin and every block requires 10 minutes for verification.

Transparency: As the ledger is accessible to all users, the authentication procedures for identifica tion and transactions is relatively simple.

Robustness: Since BC is a distributed model, there is no single point of failure.

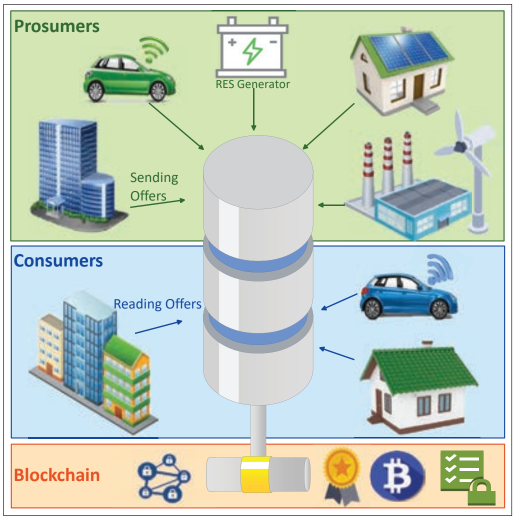

FIGURE 1. Overview of energy BC stakeholders.

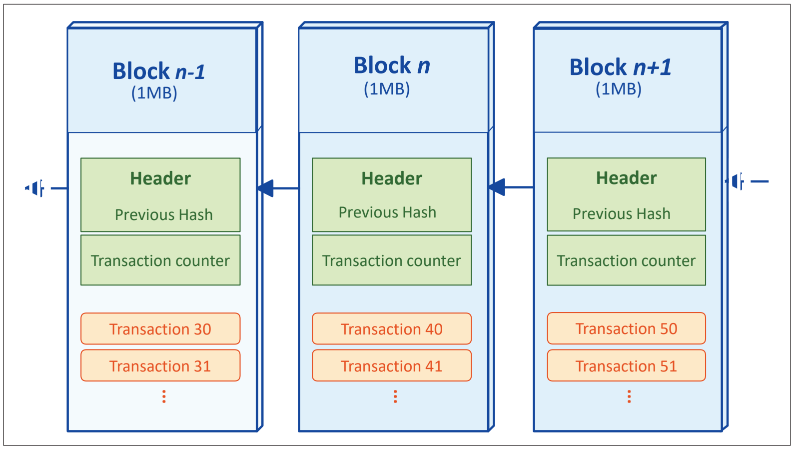

FIGURE 2. Blockchain structure.

Blockchain in Energy

This section examines energy integration with BC technology. The high demand for clean and sustainable sources of energy requires the integration of renewables with conventional energy in the existing power grid. As discussed earlier, the advantages of BC will lead to efficient energy trading in P2P, since all users can sell, buy or share energy independently. Using renewable energy sources (RES) such as solar panels, prosumers can independently produce and use energy, and sell any excess to consumers, whereas consumers can only purchase it. A comparison of BC-based and conventional energy systems is shown in Table 1, which clearly indicates the advantages of BC energy over conventional energy systems.

Figure 3 shows a framework of future energy markets implemented with a BC [3]. The larger generating station has two energy sources: conventional and renewable (e.g., solar). In the conventional system, the amount of energy produced is recorded on a spreadsheet and sent for auditing and verification by a government authority, which then issues a certificate. This process is very time consuming and prone to human error. In the case of BC, the generated energy is tracked by a smart meter and directly recorded on the BC, with other consumers in the network providing verification. An energy token is generated for

Characteristics	Conventional energy system	Blockchain based energy System
Power flow	Flow only from grid to the consumers	Flow in both directions, Consumers and Prosumers can inject energy into the grid.
Role of grids	Responsible for energy maintaining (e.g. outages) and distribution	Responsibility of peak load management through DERs and Congestion control.
Decentralization	Single grid distributes the energy	Every user consumes its own energy as well as able to sell to other users.
Storage	Single repository that stores the users' data for validation and transaction information	The transactions are stored by multiple users in the network
Autonomy	The nodes are managed by a single bank for transactions and verification therefore, dependent on a central entity	The interconnection of nodes provides security and allows every node to read and write transactions
Open access	Only registered users can avail energy services	Open to any user willing to trade/share energy
Intelligence	Transactions executed third parties, which involves additional costs	Automated transactions using smart contracts
Renewable energy	Does not facilitate the use of RES	Promotes and encourage the use of RES
Trust	The users trust a single entity for transactions, which if compromised or turn malicious causes all the data at great risk	BC enforce users to trust each other anonymously. In case if any node is compromised the data can be recovered from other nodes
Cost	The energy generation and transmission is costly and timely.	The generated energy is stored on the public ledger which doesn't require additional costs.

TABLE 1. Comparison of Blockchain energy and conventional energy system.

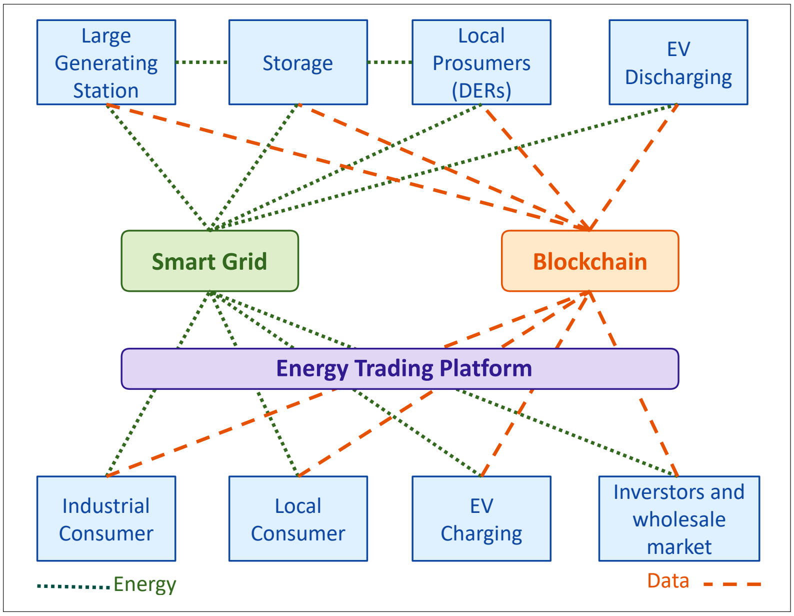

FIGURE 3. Perspective future energy system integrated with Blockchain.

every specified amount of energy produced and stored. This information can be acquired using energy trading software based on BC, which is available to all consumers, prosumers, investors and wholesale markets connected to that BC.

Consumers can purchase tokens for less than the cost of conventional energy, and buy energy from any local prosumer or wholesale market in exchange for energy tokens or bitcoins. They can also sell their tokens to other consumers, who could then sell them when their market value increases, thereby earning profit. Wholesale markets buy renewable energy and sell it to companies who want to use clean energy at lower cost. Other forms of energy such as gas or heat can also be monitored, traced and verified by storing the meter data in a BC based server that is accessible to gas and heat suppliers. This reduces the time and cost of cross validation.

Advances in the technology have created several ways to integrate DERs into the energy system which, as shown in Fig. 4, can be integrated with BC energy. Household storage and energy management is also becoming popular, due to the costly infrastructures of current energy systems [4]. As indicated in Fig. 4, the future of BC energy is at the prosumer level where it could be used for a house or building in a community, or by a farmer who is able to produce and sell energy to other consumers in his locale, with all transaction information stored in BC. DERs allow the production and sharing of electricity, heat and gas, and the integration of BC with these resources means they can be shared securely while providing authenticity and transparency. Though there is currently minimal research being conducted into integrating BC into gas and heat trading, it is highly likely these will be included in the future. The following explain the technologies expected to be used in energy BC [3, 5]:

Smart Contracts: BC applies smart contracts to execute transactions. A smart contract is similar to a conventional contract in that its conditions are known to the network users, and they are written in a programming language. Smart contracts execute automatically once the conditions are met, after which they are stored in the public ledger and cannot be changed or deleted.

Distributed Storage: All users have the copy of the entire ledger, which means the data is resistant to a single point of failure.

Consensus: This is used to avoid forks or double spending by users in the system. Each consensus mechanism has its own advantages and trade-offs.

Encryption: Asymmetric key cryptographic algorithms are used to provide users with security and privacy, and a Hashing function with digital signatures is used to ensure data integrity. There are various encryption algorithms used by BC, the most common being the *elliptic curve* algorithm for asymmetric key cryptography and the *SHA-256* for hashing.

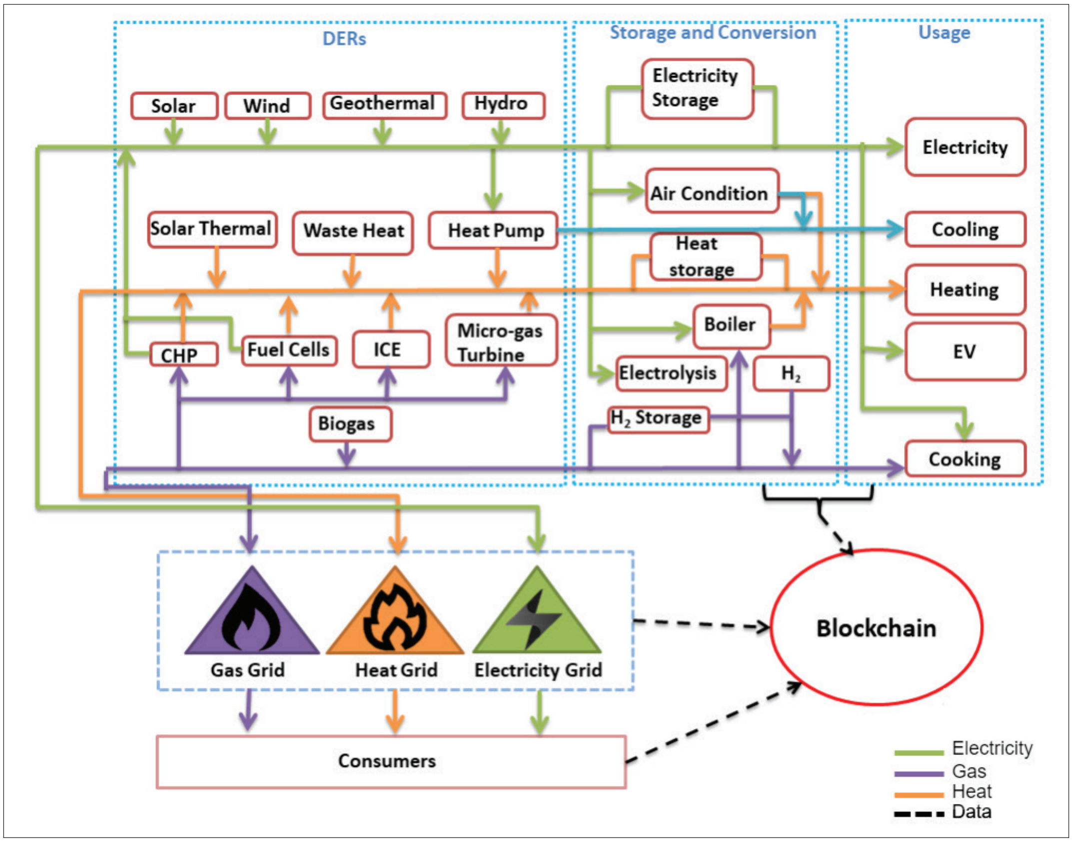

FIGURE 4. DERs in energy Blockchain.

Energy Blockchain Applications

This section highlights the possible applications and scenarios of future energy systems based on BC using smart contracts.

Trading/Sharing of Renewable Energy

BC energy provides a power system that users can use to purchase electricity when required. In the case of a disaster or an outage, users in the BC based power system can operate independently by acquiring electricity from neighbors or a local source, without needing to wait for the conventional system to resume operations. Renewable electricity can be generated by solar, hydro, thermal power and other means. Users can purchase or send electricity directly from/to the grid, and the record is updated in the BC ledger.

Usage and Tracking of Green Energy BC: Using tradable green tokens, some organizations such as Greeneum incentivize and track users of green energy in order to increase its usage. BC can be used to store information related to buying green certificates from a prosumer, and a green certificate is issued to prosumers who produce energy from renewable sources. The certificate is issued by the government for a specific amount of green energy, thereby encouraging prosumers to produce clean energy and restrict CO_2 emissions into the environment [6]. The certificates can be sold to users who need clean energy, and the amount of energy equivalent to the certificate can then be sold to the wholesale market by the prosumers. Consumers send their certificates to the wholesale market and receive clean energy in return.

Trading of Renewable Gas and Heat: The local use of combinations of heat and power (CHP) units, solar thermal and bio-gas plants locally installed by the users, allows sharing of gas and heat with neighbors via BC. This application is currently being researched, and is in the potential future plans of numerous companies [5].

Oil Industries: BC can also improve the management, efficiency and security of transactions between suppliers and partners in the oil industries, since the hydrocarbon tracking at all phases of the supply chain enhances accountability. However, the complexity of the system increases quickly, particularly with regard to cross-border trading. IBM is one company using BC for oil transport.

Tokenization of Energy

Conventional energy is brought to end users through long transmission lines, and since the energy flows through the grids continually much of it is wasted. A BC based platform increases the efficiency and reduces the costs of retailers and supply companies by allowing consumers to connect to wholesale markets and other prosumers directly. A token is generated for a specific amount of power from a renewable source, then sold to consumers and wholesale markets on BC based platforms. Tokenizing enhances exchanges between suppliers and users. Non-sustainable energy can also be tokenized to reduce costs. *Wepower* and *Grid+* are two companies using energy tokens.

Metering and Billing

In a conventional energy system, a meter operator gets a meter reading and sends it to a transmission system operator (TSO) for planned running consump-

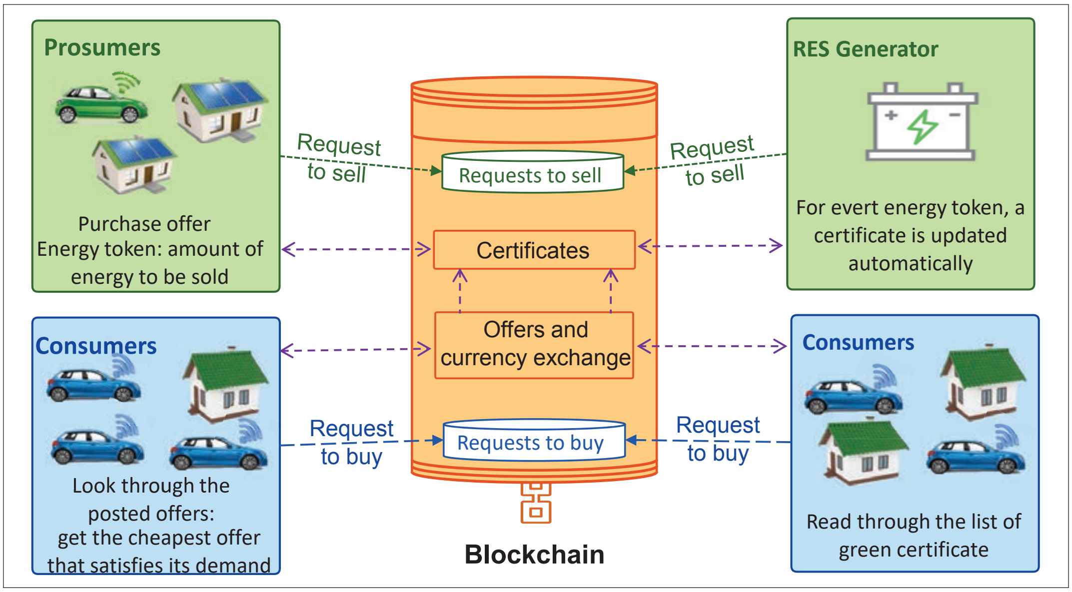

FIGURE 5. Framework of energy Blockchain.

tion, then it proceeds to a distribution system operator (DSO) and the energy supplier for billing. This is a costly process, since all the entities charge for their services. With BC, all the work of the meter is done by the ledger and the role of meter operator is limited to providing reliable meters. The real time transactions are recorded, verified and performed by BC according to actual consumption. A server is installed with a smart meter that repeatedly records the energy consumption and production of a house [7].

Grid Related Transactions (Microgrids)

In traditional grids, energy is lost due to resistance and long transmission paths. A microgrid is an independent self-contained grid in a small community, with its own electricity supply that is not from a conventional grid. Using solar panels on prosumer rooftops in a local community of houses or buildings, users can get electricity far less expensively than conventional electricity. Prosumers can sell electricity directly to the grid, and consumers can buy it from the grid with a transaction initiated through smart contracts and recorded in the BC ledger. This application is being considered in the future planning of companies such as LO3 Energy and Drift, who currently use conventional grids for buying, selling and renewable energy.

Electric Vehicles

Electric vehicles (EVs) can be charged at charging points, or EV drivers can buy electricity from prosumers connected to the grid [8]. These transactions are also initiated by smart contracts and stored on a BC ledger. EVs can also be energy resources by selling their excess energy to other consumers to earn digital currency.

Energy Trade Framework using Smart Contracts

The BC energy trade framework using smart contracts is proposed in this section.

As shown in Fig. 5, a three-layer framework of BC, consumers and prosumers is proposed. The prosumers can be homes that are capable of producing renewable energy, as well as EVs that can sell their excess energy to a grid and, similarly, consumers can be both EVs and users of a housing community. Large scale communities such as buildings or neighborhoods can be integrated into the process of producing or consuming energy, and an aggregator between users and the grid can act as a coordinator between them. A prosumer introduces energy to be sold into the main grid via an aggregator, and the aggregator or an energy router broadcasts the energy sale offers (smart contracts) of all prosumers to the nodes. After verification by the miner nodes that perform validation and publish transactions on the BC ledger, the transactions are saved in the BC. A consumer can read the energy offers, and if one meets its requirements, send a purchase request with the payment and transaction fee to a prosumer. The request is made public after verification and saved in the BC, and an instruction message is then sent to the aggregator to release the energy to the consumer.

In a home network, a consumer EV can act in the same manner as discussed above. If it is charged from an external network the consumer enters the data in the external charging site software, which is then verified by the external supplier through the user's home supplier. Upon verification the transaction is initiated through the home supplier to the external supplier. The same procedure takes place when an EV intends to sell its excess energy, with the addition of a time period field since the vehicle is continually moving. The amount of time it is available is until the expiry time of the offer.

A consumer can send a purchase request, and if it is accepted after verification they can purchase a green certificate that they can use to acquire renewable energy from the wholesale market when available. Consumers can also sell the certificates to other consumers.

Advantages of the Proposed Framework:

The proposed BC energy trade framework using smart contracts offers several advantages to all participants (i.e., BC, Cloud, grid, consumers) and also helps the environment:

- All framework players are producers and beneficiaries at the same time.
- The use of blockchain encourages trust between peers which will eventually increase the adoption of the framework, and ultimately save energy.
- BC is an eco-friendly framework, since it encourages using less non-renewable resources and relying more on renewables such as wind and solar.
- New technologies, including electric vehicles and drones, can participate and benefit from the BC framework.

Open Issues and Challenges

According to the latest market research report by Technavio, the compound annual growth rate of the renewable energy trading market is expected to increase by at least 10 percent from 2019 to 2023. This growth will likely involve many issues and problems, including the nature of renewable energy, the energy sector's capability to scale up or down, energy storage systems, installation and maintenance, legalization and logistics and the cost associated with growth. Peer-to-peer renewable energy trading will help minimize the impact of these challenges, and overall have a positive impact on the energy markets.

This section explores some of the potential challenges caused by the use of BC energy. In addition to advantages for the energy sector, there are also various problems and open issues that will need to be addressed before it can be applied on a large scale [5]. There is the challenge of controlling scalability and costs while maintaining decentralization and security, as well as privacy issues and linking attacks that are not optimally addressed by BC energy. These include regulatory issues and optimization of digital and physical media in energy trading, a lack of public awareness and physical constraints such as the locations of solar and wind energy sources being too far from consumers, thereby wasting energy. Reliability, predicting RES and continuous real-time monitoring of smart meter data is critical for maximum output. The following discuss challenges of BC implementation in the energy sector:

Regulatory Issues: There are currently no governmental regulations regarding the implementation of BC in the energy sector. One reason for this is that BC is not sufficiently flexible in terms of changing data once it is stored; if a user decides to leave BC it can be difficult to remove their data and personal details from the ledger. Another reason is that there is no optimization mechanism between the physical transfer of energy and digital currency transfer, plus digital currency is banned or restricted in some countries.

Scalability: A scalable network means it can manage more work, such as managing large network nodes or high computational power. A number of factors affect scalability, including latency (the time to verify a transaction) and throughput (the number of transactions per second). Scalability is limited with BC energy, since it uses smart contracts rather than small cryptocurrency transactions [9] which can cause latency. In addition, a large volume of nodes in a network impacts the computational power, as each node increases latency. The size of a transaction also affects latency and throughput.

Storage: Since every BC user has a complete copy of the ledger, a sizable amount of memory is required, and this can slow the system or even halt transactions, particularly with a large number of nodes.

Energy Tokenization: Tokens are used to indicate that a specific amount of energy was produced from a renewable source, so it can be transferred from a prosumer to consumers using BC. New P2P algorithms are needed to determine the optimal amount of energy represented by a token. They must address several parameters, including the number of prosumers and consumers, the amount of energy available to be sold, the amount of energy available for sharing, the sales history, demand, consumption estimates and weather conditions (i.e., winter or summer).

Potential Solutions

This section proposes potential solutions to the above issues:

Anonymity: Anonymity provides user and transaction security by concealing the links between each transaction and its associated user [10]. There are a number of ways to achieve anonymity, such as using multi-signatures for transactional privacy [11], and authors having multiple pseudonyms [12] so they can send their data without linking attacks. In [13], the authors suggest that garlic routing and ring signatures are potential solutions for maintaining anonymity and avoiding linking attacks.

Data Hiding: User data can be hidden by combining it with a large data set [10]. The authors in [14] used a virtual powerplant between the aggregator and the consumer to avoid user data being revealed to the aggregator.

Side Chain: With respect to side chains, a traditional BC is broken down into smaller chains, so if a network is busy the side chain nodes can verify the transaction. This accelerates the process of transaction verification, reduces latency and scales up the network [15].

Block Size: Increasing block size allows more transactions in a block to be verified, and increases scalability. However, block size is a bottleneck, and increasing it also increases the verification time and probability of an orphan block. Also, though more transactions in a block can be verified and storage increased, the instability of the network also increases. Thus, the maximum block size that provides the highest level of scalability without affecting network stability must be defined.

Off-Chain Transactions: In the case of off-chain transactions, the money transfer process occurs outside the BC network and the equivalent amount of cryptocurrency is placed in the smart contract, and the validators can connect to the BC network and verify the transactions at any time [15]. Off-chain reduces BC transaction costs and increases speed, thereby providing anonymity.

Sharding: Sharding is dividing a large BC into smaller blocks that are linked to one another. The blocks contain a small portion of the data that is stored in the main BC. The dividing allows parallel transactions that can accelerate the process of verification and optimize scalability and storage. Sharding is currently being researched.

Conclusion

This article explains how BC can be useful in the energy sector. The typical centralized system that was once preferred now involves costs that many users cannot manage, and also makes huge demands on conventional power structures. Advances in technology and DERs allow consumers to switch to decentralized, less costly systems based on renewable energy. Researchers consider BC integral to maintaining the security and reliability of a decentralized system, and the framework for energy trading between consumers and prosumers via smart contracts. There are many challenges in the adoption of a BC-based energy system, including security vulnerabilities and efficiency. This article addresses the key issues, and suggests various solutions. BC energy is now in the initial stages of testing and implementation, and has been applied on a small scale. There are still areas that require further research, such as scalability, green BC and integrating it into other energy sources such as gas and heat.

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