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The development of energy blockchain and its implications for China's energy sector

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ABSTRACT

With technology progressing and the decreasing cost of renewable energy, consumers require energy supply to be smarter, cleaner, and more sustainable than before. By providing a decentralized trading mechanism, blockchain technology can facilitate sustainable energy consumption and achieve a circular economy. This study analyzes how China can employ blockchain technology to reform its energy sector. We survey the progress of blockchain technology in the energy sector and explore typical cases of energy blockchains in the world. We discuss the advantages and disadvantages of applying blockchain to China's energy sector. China's monopoly market structure in energy supply impedes the application of blockchain technology, but the expansion of clean energy provides a huge opportunity for it. Although China's technological level is lagging, the biggest obstacle is not technology but rather policy. We conclude that China should loosen its regulatory environment, amend the relevant laws, and balance the conflict between management and innovation.

1. Introduction

As the world's largest energy consumer, China emits roughly 30% of the world's total carbon emissions (Wu et al., 2019). To achieve sustainable development and a circular economy, China is upgrading its traditional industries and reforming its energy sector. The energy sector worldwide is becoming increasingly intelligent owing to the appearance of smart devices and related software, and the decreasing cost of renewable energy. A consumer-oriented energy transition is advancing rapidly, and users often require energy supply and management to be smarter, cleaner, and more sustainable than before. However, traditional energy companies in China are beset by centralization and poor market liquidity. China's electricity industry is monopolized by a few power giants, which usually built power plants far from urban areas. Long-distance electricity transmission drives up prices. Existing systems cannot manage increasingly complex transaction requests. Business models and profit models are no longer suitable for the demand of sustainable development and circular economy.

By providing greater convenience for consumers, the application of blockchain technology in the energy sector would have a significantly positive impact on the energy sustainable consumption. In the energy sector, blockchain technology can be applied to energy financing, distributed trading, and clean energy popularization. In particular, in the financing process of energy projects, blockchain technology can help reduce transaction costs and promote efficiency (Zhang and Hao, 2017). In the energy wholesale trading process, blockchain technology can provide security protection for transactions. In the energy retail trading process, blockchain technology can provide clearing and settlement systems. In the consumption process, it can facilitate public participation in new energy consumption and carbon emission reduction (Ruben et al., 2017). Blockchain technology is expected to change the energy sector significantly in the future.

Against a background of energy sector reform, blockchain technology may become a catalyst for industrial transformation and a new engine for sustainable growth. However, there are still many limitations to the application of blockchain technology in China's energy sector. At present, China's blockchain technology has been applied in some fields such as the finance. In theory, the blockchain technology can be combined with all parts in the energy sector chain, especially for new energy and its related distributed power generation. However, such a combination is greatly influenced by energy regulation policies and other kinds of energy policies. China's blockchain technology cannot be

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incorporated into the existing regulatory framework, and there is a contradiction between the regulation of energy and innovation motivated by blockchain, which has further slowed down blockchain's development. Overall, energy blockchain technology remains in the pilot test phase and there are no typical innovative applications in China so far. Therefore, exploring this issue is of great theoretical and practical interest. This study attempts to determine how China can employ blockchain technology to reform its energy sector. To the best of our knowledge, there are few existing studies focused on this topic so far, especially for China.

In Section 2, we first survey the progress of blockchain technology and its application in the energy sector. There are many areas in which blockchain technology can be applied, including finance (Treleaven et al., 2017), logistics (Dobrovnik et al., 2018), and medical treatment (Kuo et al., 2017), but the energy sector is drawing increasing attention. In Section 3, we present typical cases of energy blockchains in the world. The goal is to summarize the practical experience globally for the development of energy blockchain in China. Then, in Section 4, we discuss the advantages and disadvantages of applying blockchain in China's energy sector. It is difficult to support the application of blockchain technology in the energy sector, owing to its monopoly market structure, but the expansion of clean energy provides a huge opportunity for energy blockchain technology. Finally, in Section 5, we analyze issues related to technology and policy in energy blockchain. Although China's technological level lags that of developed countries, the biggest obstacle to applying blockchain technology in the energy sector may be policy rather than technology. China should loosen its regulatory environment, amend the relevant laws, and balance the conflict between management and innovation.

2. Literature

2.1. Blockchain technology

"Blockchain" emerged as a new term with the establishment of bitcoin, which achieved big success after it appeared. Nakamoto (2008) first introduced the blockchain in his paper "Bitcoin: A Peer-to-Peer Electronic Cash System." However, a blockchain can exist as a distributed data structure for any cryptocurrency, not necessarily bitcoin. It is generally believed that the blockchain and not only bitcoin will profoundly affect the world. Robinson (2014) said, "There are fewer people using bitcoins to buy goods and services than there are members enrolled in Kuwait Airways frequent flyer program. And yet … the blockchain technology behind bitcoin, is brilliant and will absolutely change the world." Mattila et al. (2016) mentioned that blockchain is widely referred to or in relation to digital consensus architecture as well as the algorithms or application domains on which it is built. The basis of blockchain is the distributed information storage system. In one sense, blockchain is a database whose information is saved and written. Due to the equal rights and obligations of blockchain nodes, the information is not managed centrally by a single organization, but by all nodes. When new information is written, each node can obtain complete data, without copying from others. Once the information is verified and added to the blockchain, it is permanently stored. Sometimes, blockchain can be regarded as a ledger in which transactions are saved (Chan, 2016; Condos et al., 2016; Nikic, 2018). Unless more than 51% of the nodes in the system can be controlled at the same time, the modification of the ledger on a single node is invalid. Therefore, blockchain has the following advantages: decentralization, persistency, anonymity, and auditability. These advantages have been aided by a series of new technologies, such as cryptographic hash, digital signature, and distributed consensus mechanism (Zheng et al., 2016). According to a 2016 development white paper on Chinese blockchain technology and application development (MIIT, 2016), blockchain technology is a kind of new distributed infrastructure and computing paradigm. It uses the blockchain data structure to verify and store data and it uses the distributed node algorithm to generate and update data. All the data are manipulated and programmed by smart contract, consisting of automated script code. In this process, cryptography is adopted to ensure data transmission and access security. It is generally believed that the smart contract on the blockchain platform is a computer program jointly developed and recognized by multiple users. It can verify information about the transaction according to the trigger conditions, and then automatically execute it and notify users after reaching a consensus. In fact, the smart contract predates and does not necessarily rely on blockchain technology. In 1996, Nick Szabo, an interdisciplinary legal scholar, first proposed the term "smart contract" (Szabo, 1996). It refers to "a set of promises, specified in digital form, including protocols within which the parties perform on these promises." However, due to the decentralization and the data tamper-proof characteristic of blockchain, smart contracts are more suitable for implementation in blockchain. The biggest advantage of smart contracts is the use of algorithms to replace human arbitration. The computer code itself explains the relevant obligations of the participants. It allows transactions to be executed without a third-party guarantee, greatly reducing manual participation in the transaction process. Because of multiple information sources, the blockchain technology provides a platform for operation management and decision making, also opening a new research field for operation management researchers (Babich and Hilary, 2019).

Blockchain itself is a distributed ledger system (Wattenhofer, 2017). Therefore, banking, securities, and insurance, among other issues related to the ledger can use blockchain to improve efficiency. Blockchain can guarantee the immutability and integrity of documents (Beck et al., 2016). Davidson et al. (2018) considered blockchain as an example of institutional evolution and an economics breakthrough enabling analysis of a new general-purpose technology. It can be used to provide notarization services while its Internet properties make it more convenient and quicker than a traditional service. In conclusion, blockchain is a kind of distributed architecture in which the individuals can interact each other without central authority (Xu et al., 2016).

2.2. Studies on energy blockchain technology

Blockchain technology can be introduced to many fields, including finance (Treleaven et al., 2017), logistics (Dobrovnik et al., 2018), and medical treatment (Kuo et al., 2017). Hegadekatti (2017) considered the technology to be so important that it would alter the evolution of the entire economy. Among other fields of application, the energy sector has drawn the attention of more and more researchers. Mihaylov et al. (2014) conducted a study on the application of blockchain technology in the energy field, in which a virtual currency was introduced to energy markets based on information provided by smart meters. Sikorski et al. (2017) studied the applications of blockchain technology in an electricity market scenario involving two electricity producers and one electricity consumer. In addition, the authors explored the application feasibility of blockchain to Industry 4.0 and concluded there is great potential for blockchain in the energy market. Noor et al. (2018) introduced blockchain technology to a demand-side management model in the context of rapidly growing energy demand and intermittent renewable source supply. Their model demonstrated how demand-side management based on blockchain technology could be useful during an energy transaction. Similar to Noor et al. (2018), Pop et al. (2018) designed an approach to distributed demand-side management based on blockchain technology that could match the demand for and production of energy. Thakur and Breslin (2018) employed a blockchain mechanism to develop distributed algorithm microgrid energy trade. Their solution had an advantage over the existing literature in that it addressed the security issues of computation. Aitzhan and Svetinovic (2018) introduced blockchain into anonymous negotiation and trading transactions in a decentralized energy trading system. The authors also studied security and evaluated performance when elicited security and privacy requirements were a matter of concern. The results showed that a combination of blockchain would be a promising direction. Su et al. (2018) designed a scheme based on energy blockchain to secure charging services for electric vehicles in the smart community. Through their mechanism, renewable energy sources could be allocated effectively to electric vehicles. Wu and Tran (2018) surveyed the application of blockchain to the energy Internet and studied their compatibility. The authors considered that blockchain technology was highly compatible with the energy Internet and would provide a good opportunity for the future of the energy Internet. Fan et al. (2018) also pointed out that the conflicts among high capital requirement, low cost, and high efficiency have hindered the development of the energy Internet. However, the energy blockchain could help to solve this problem, because it can eliminate the information asymmetry in transactions, restrain oligopoly behavior, and establish a pricing model, etc. Mengelkamp et al. (2018b) designed a decentralized market platform whereby prosumers and consumers could trade local energy using blockchain. Based on 100 residential households, they simulated and evaluated their blockchain-based market, showing that it could reduce the potential cost. Similarly, Andoni et al. (2019) investigated 140 blockchain research projects and startups, and analyzed the potential impact on the operation of energy companies. They found that blockchain technology significantly reduced transaction costs, such as information processing, communication, and verification, which made the market accept small and distributed generators. As the blockchain technology changed the energy market structure, it would hurt the interests of traditional energy utilities.

Overall, the blockchain technology in the energy sector is applied mainly in energy financing, energy trading, smart distribution and sale for power, the energy Internet, and collaborative power dispatching system, among others. Of these, the application to clean energy is the focus of blockchain technology. The energy blockchain can improve the efficiency of the energy sector from the following three aspects. First, the combination of blockchain technology and the micro grid can bring small clean energy suppliers into the energy market. This would reduce the monopoly power of the energy sector and lower the energy cost, which are advantages enjoyed by consumers. Second, an important reason for the slow change of the traditional energy sector is the uncertainty in product price and supply. Meanwhile, blockchain technology and smart contracts can help to achieve stability of energy supply and predictability of energy prices, which can reduce such uncertainty. Third, the distributed ledger system of blockchain can help regulators to record details of energy transactions, which makes it easier to audit and supervise carbon emission quotas and improve the transparency of carbon emissions.

3. Case analysis of blockchain application in the energy sector

Energy financing, energy trading, energy consumption, and the energy Internet are the four main applications of blockchain technology in the energy sector, although there are other applications in this area. For example, blockchain technology can be applied to energy regulations to better regulate energy transactions. However, owing to the lack of typical cases and scenarios, these applications are not the focus of this study.

3.1. Energy financing

Despite the stable return on investment in the energy sector, there are often financing difficulties owing to the huge initial investment and non-transparent asset information (Wamba et al., 2017). In fact, energy investment in many countries is treated as infrastructure investment, and only a few consortia or state-owned enterprises can afford the high construction costs. Blockchain technology can aid the financing and operating of energy assets. Whether for the securitization of energy assets or development of green energy carbon assets, blockchain technology can be used in asset registration, traceability, and circulation, which can greatly improve efficiency and reduce transaction costs (Manolas et al., 2017). Only in combination with a smart contract can the potential of blockchain be exploited (Bhargavan et al., 2016). Self-enforcement and being tamper-proof are the most distinctive features of the smart contract, through which the contract terms are written in the computer system, making intermediaries in the financing process redundant. Duchenne (2018) considered that blockchain and smart contracts could help address challenges related to elements of the lifecycle of energy attributes (e.g., renewable energy credits), including issuance, financing, and trading. There are many applications of blockchain in energy financing. For example, in sub-Saharan Africa, where power access remains a huge challenge, the finance company Sun Exchange aims to supply solar power to schools, factories, and nature reserves via installations financed by blockchain technology to encourage international investment (Seelaus, 2017). Investors can purchase solar cells and lease them to the users of power. Sun Exchange pays investors using bitcoin or local currency. The annual return on investment rose to around 10% in 2017. The key point is that Sun Exchange has adopted blockchain-based smart contracts, although the scheme does not involve distributed energy trading.

In another example, the China Energy Blockchain Laboratory launched the green ABS (asset securitization) cloud platform in 2016, which uses blockchain technology to register the number of generators and their output, making the production process visible and the return predictable. While providing production monitoring, this platform has reduced investment risk for investors and solved financing difficulties.

3.2. Energy trading

Blockchain has the properties of flexibility, openness, and decentralization. It helps stakeholders connect with each other to realize automatic energy transactions, including auction, bidding, and payment. Each node in blockchain negotiates a spot price, transmission path, and transaction priority allocation in a time sequence. In this process, a kind of new energy digital currency, NRGcoin, which is generated by injecting energy into a smart grid, is widely used to ensure the effectiveness of real-time transactions (Mihaylov et al., 2014). Blockchain technology also provides new solutions for the transaction execution and information security of distributed energy owing to the distributed storage, integrity, and traceability of data. Park et al. (2018) illustrated a power trade system between prosumers and consumers of smart homes, which allowed a more transparent, trustworthy, and secure peer-to-peer (P2P) trading environment. Their simulation results show that a blockchain-based P2P energy-transaction platform would create a sustainable environment for energy transactions.

Transactive Grid, the world's first energy trading program based on blockchain, was built in New York in April 2016 by LO3 Energy and Consensus Systems (Zhao et al., 2018). LO3 Energy has another program, Brooklyn Microgrid, which closely cooperates with Transactive Grid to combine the payment system and distribution grid infrastructure. New York State often suffers from large-scale blackouts due to hurricane damage to the central grid, Transactive Grid's trading system attempted to solve the problem in line with the reform vision of New York State. In Brooklyn, many families depend on photovoltaic power generators installed on building roofs for power supply. Through the blockchain technology and smart contract, surplus electricity can be sold to neighboring units in the network. Thus, users can trade electricity energy without public power companies or a central grid (Mengelkamp et al., 2018a). LO3 Energy had hoped to prove that a local smart energy trading system is better than a traditional top–down centralized energy system. Although the facts show that Transactive Grid is not that smooth, it did promote the development of distributed power trading, and is regarded as a model for energy blockchain projects in the United States and beyond. The following Fig. 1 shows that an example total of five families participated in the project. On the supply side, three families install roof solar photovoltaic power generators. The

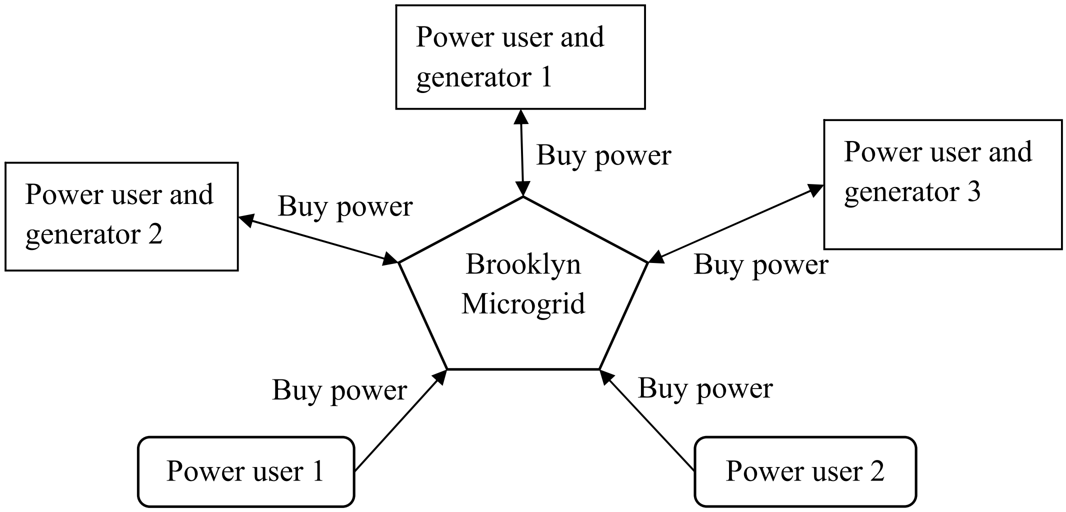

Fig. 1. Transactive grid in Brooklyn microgrid.

other two families are electricity-purchasing households.

According to the *Energy Roadmap 2050* (EU, 2012), the EU plans to reduced greenhouse gas emissions by 80%. Blockchain could play an important role in achieving this goal. The SCANERGY project is funded by EU to manage the electricity produced and consumed at the level of both neighborhoods and cities based on blockchain technology. This new technology can make simulations and predictions to ensure efficient allocation of energy in an area. Because there is no need for long-distance transmission lines, greenhouse gas emissions are reduced significantly. Based on the SCANERGY project, Mihaylov et al. (2015) proposed the NRG-X-Change mechanism for trading renewable energy in smart grids. Because all nodes in the blockchain system have the same rights and obligations, data storage, transmission, verification, and other processes are based on a distributed system structure. Data loss for any node does not affect the operation of the whole system. This is helpful for addressing the problem of integrity and credibility of data exchange in distributed energy transactions.

3.3. Energy consumption

At the energy consumption end, by adopting the blockchain and a smart contract, the transparency of energy consumption can be promoted. Once blockchain is applied, there is no need for active intermediaries in the market, significantly reducing transaction costs. Users have more options than before, which changes the demand curve of the energy system and makes great sense for efficient utilization of diverse sources of energy. In a short time, power users can always find the right energy suppliers to meet their diverse needs. Those who care about costs can choose low-priced suppliers while those who care about the environment can choose renewable energy (Dubey et al., 2017).

Typical applications of blockchain technology in energy consumption include the charging of electric vehicles, home energy consumption management, and transactions involving distributed energy over short distances. The German Share&Charge project, operated by MotionWerk, is an application of blockchain for charging stations (Vanrykel et al., 2018). Most of Germany's electric vehicle owners have their own charging stations, and 9 out of 10 families charge their electric cars at home. However, there are not enough public charging stations in Germany, which affects the market development of electric vehicles (Sierzchula et al., 2014). To address this issue, Share&Charge built a sharing platform by connecting the owner of a charging station and the owner of an electric vehicle based on blockchain technology (Plenter et al., 2018). Private owners of charging stations must register their stations with Share&Charge, after which they can share and rent the station on the Share&Charge platform by setting prices and other information (Goranović et al., 2017). The owners of electric vehicles can research the stations using Share&Charge's interactive map on a mobile app. They must pay tariffs not to Share&Charge but to the private owners of charging stations. After the charging process, the owner of the charging station pays a set fee of 15% of the tariff to MotionWerk. This project encourages the sharing of charging stations and helps address challenges related to the lack of charging infrastructure.

3.4. Energy Internet

Rifkin (2011) first proposed the term "energy Internet" in the book *The Third Industrial Revolution: How Lateral Power is Transforming Energy*, and predicted that humans would enter an era of combining renewable energy technology with information technology. Sun et al. (2015) proposed several types of architecture and frontiers for the energy Internet. Zhou et al. (2016) studied the energy Internet from the perspective of business, and introduced some key concepts, including prosumers (households that both produce and consume a product), microgrids (small networks of electricity users), virtual power plants (networks of decentralized, medium-scale power generating units), smart grids, and smart energy. Baležentis and Štreimikienė (2019) discussed smart grid technology and its development in China. Even though they considered the smart grid concept to have no strict definition, a lot of basic properties could be outlined, such as two-way communication, flexible pricing system, and better resource management. According to these authors, the energy Internet is an energy ecosystem comprising various energy networks and transport networks. Various energy sources are complementary at the horizontal level while generators, grid, loads, and storage are coordinated at the longitudinal level. The energy Internet is a sharing network that comprises a power system, the Internet, renewable energy, natural gas, and electric vehicles, among other elements. The most prominent feature of the energy Internet is access to renewable energy sources through storage device and management systems (Yang et al., 2017; Dubey et al., 2018). The major renewable energy sources adaptable to the energy Internet include solar energy, wind energy, geothermal energy, and biomass. Because of the diversity of energy forms and participants, and in particular, the randomness and volatility of wind and solar energy, the energy Internet is likely to become highly complex, requiring decentralized technology support. Blockchain technology, with its advantages of decentralization, persistency, anonymity, and auditability, is very suitable for the energy Internet. It can connect distributed energy acquisition devices, distributed energy storage devices, and various networks, such as power, oil, and natural gas networks. On this basis, the Internet can be introduced to reconstruct the traditional energy sector. After adopting blockchain technology, the energy Internet would become a strong energy supply and utilization system with greater flexibility, openness, and self-regulation. Many companies and projects focused on the energy Internet have emerged worldwide, including Tendril, FirstFuel, EcoFactor, and Bidgely.

4. The energy sector and blockchain technology in China

Considering China's conditions, the energy blockchain still has a lot of room for development, especially as China has made some progress in green and sustainable energy production. In the following subsections, we introduce the development environment of China's energy blockchain, including supply and demand structure of energy, the digital economy, and distributed generation.

4.1. Supply and demand structure of energy in China

At present, large state-owned enterprises dominate China's oil, natural gas, and power, and there are few private enterprises in the energy sector. The two biggest oil giants, China National Petroleum Corporation and China Petrochemical Corp., control most of the production, processing, and sales of crude oil and natural gas. Five state-owned power groups, China Huaneng Group Corporation, China Datang Group Corporation, China Huadian Group Corporation, China Electric Power Group Corporation, and China Electric Power Investment Group Corporation, monopolize most of the electricity production. There are only two enterprises, State Grid Corporation and the Southern China Grid Corporation, involved in power transmission and distribution. This excessive concentration of the energy market structure does not seem to aid the application of blockchain technology. The relationship between firm size and innovation behavior is a classical topic in economics (Zhang et al., 2017). Schumpeter (1942) considered that a highly decentralized market structure might not encourage innovation, because firms would be unable to capture monopoly rent. It is general believed that innovation is positively associated with size, but not in a linear form (Kamien and Schwartz, 1982; Evangelista et al., 1997). However, innovation that could challenge incumbent firms, like blockchain technology, is more likely to occur in a more competitive market (Seth et al., 2017; Belás et al., 2018; Figueiredo and Ferreira, 2019). There is no doubt that the combination of blockchain technology and new energy technology will significantly transform the energy sector into a distributed one, thereby threatening the centralized traditional energy suppliers. Arrow (1962) argued that competition could facilitate innovation, because innovation can help innovators defeat competitor. Even Schumpeter (1942) referred to innovation that can result in "creative destruction," or so-called disruptive innovation, at the expense of incumbent firms. Therefore, China's monopoly market structure might not be an advantage for energy blockchain.

China is the world's biggest consumer of fuel energy. Fig. 2 shows that coal remains the main energy source with a share of more than 70% in the past decade. However, the proportion of coal consumption in China has declined year by year. The relative cleaner energy sources of oil and natural gas have remained stable in China's energy structure, comprising 13% of total energy consumption. At the same time, the proportion of non-fossil energy consumption has continued to expand, although the total amount remains relatively low, accounting for only 17% of total energy consumption in 2017. Owing to this energy consumption structure, China accounts for about one-third of the total global carbon dioxide (CO_2) emissions. Since joining the Paris Accord in 2015, China has come under strong pressure to reduce emissions. It has pledged to reduce CO_2 emissions per unit of gross domestic product by 60–65% by 2030 from a 2005 base. There is only a little more than a decade remaining for China to meet this goal. Doing so would require a significant and quick transition in the structure of China's energy production and consumption.

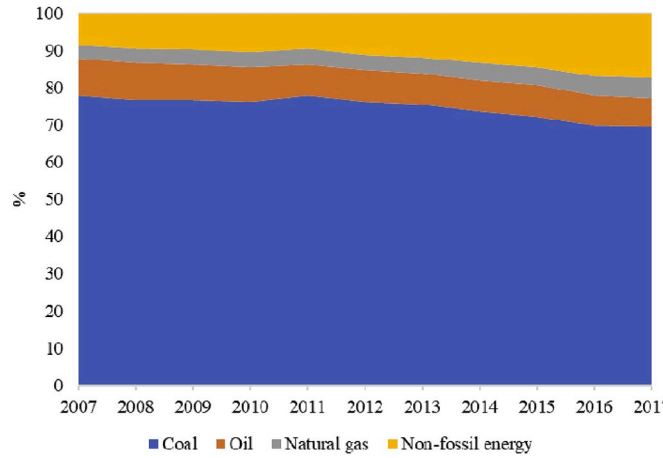

Fig. 2. The structure of energy consumption in China.
Source: China statistical yearbook.

China is presently trying to speed up the development of clean energy, such as wind and solar energy. In recent decades, the generation cost of new energy power has been decreasing owing to technological progress and scale expansion, providing huge opportunities for energy blockchain technology. Fig. 3 shows that the spot price trend of solar cells reflects the generation cost of new energy power. The price dropped most sharply before 2012; it was more than 0.7 dollars/watt in August and September 2011 but after 3 months, had dropped to less than 0.5 dollar/watt. Thereafter, it dropped continually, and reached 0.4 dollars/watt by the end of 2012. Between 2013 and 2016, the spot price ranged from 0.3 to 0.4 dollars/watt. After mid-2016, the price fell below 0.3 dollars/watt and fluctuated around 0.2 dollars/watt for almost 2 years. The latest price is 0.1 dollars/watt, and is expected to drop to at least half the current levels by 2030. Despite this drop, China's power grid does not actively absorb renewable energy owing to its dispersed location and instability. There is a high proportion of wind or solar power curtailment in north-western China. The apparent causes are the rejection of power grid enterprises and concern about employment by thermal power enterprises. The real reason is that the centralized operation mode for traditional energy cannot be applied to such distributed energy. Blockchain technology provides a decentralized trading mechanism, and perfectly suits the needs of wind and solar energy owing to reduced transaction costs.

4.2. Digital economy in China

Many blockchain operations are conducted on mobile platforms. The convenience of mobile Internet access can reduce the threshold of blockchain technology significantly, which is very important for its development. Services based on mobile platforms in China are increasingly used for work, life, consumption, and entertainment. China's mobile network information and industrial technology level have been catching up to those of some developed countries. As shown in Fig. 4, the number of mobile Internet users in China reached 753 million in 2017, accounting for more than half of the total population. The proportion of Internet users using mobile phones increased from 90.1% in 2015 to 92.5% in 2017. The progress in recent years is reflected not only by mobile platforms, but by the entire digital economy. China's digital economy had turnover of 27.2 trillion yuan with a growth rate of 20.3% in 2017, which is higher than China's GDP growth. The digital economy employed 171 million people in 2017, accounting for 22.1% of total employment (ISC, 2018). The development of mobile platforms and the digital economy has laid a solid technical foundation for the large-scale application of blockchain technology.

China's blockchain industry has been developing rapidly at the levels of both business and government. In business, there were 434

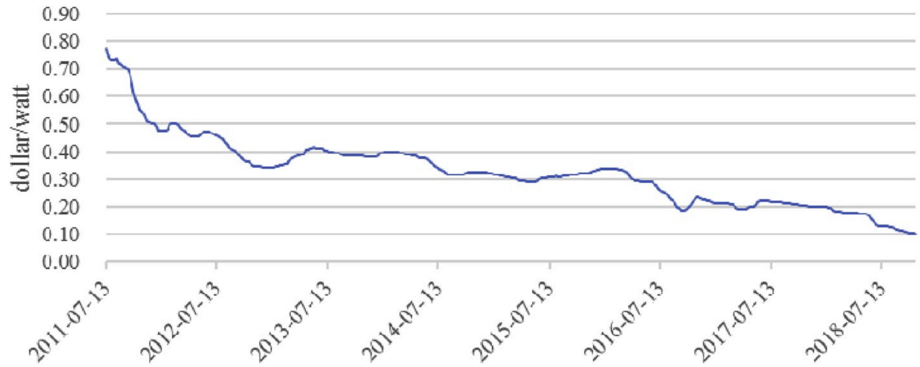

Fig. 3. The spot price of solar cell.
Source: Wind database.

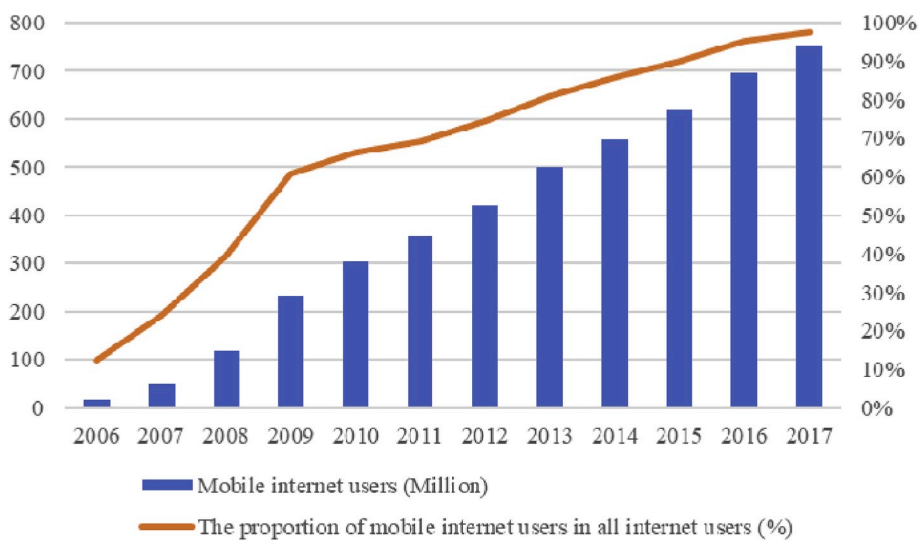

Fig. 4. The number and proportion of mobile Internet users in China.
Source: Wind database.

enterprises in China in 2017 specialized in blockchain. They are distributed in the following major cities: Beijing, Shanghai, Shenzhen, and Hangzhou. According to the World Intellectual Property Organization, there were 406 patents applied in the area of blockchain worldwide in 2017, of which 225 were from Chinese enterprises. At government level, China's State Council has repeatedly mentioned encouraging research into and application of blockchain technology in the following documents: "Notice on issuing a new generation of AI development plan," "Guiding opinions on further expanding and upgrading the potential of information consumption to continuously release domestic demand," and "Guiding opinions on actively promoting innovation and application of supply chain." In addition, most local governments are very interested in the application of blockchain. Some cities, like Beijing, Shenzhen, and Nanjing, have included blockchain in their 13th Five-Year Plan strategies for industry development, while other cities, like Guangzhou, Guiyang, Qingdao, Hangzhou, and Chongqing, have designated blockchain as an emerging industry for development and have issued a series of special policies for blockchain. The following Fig. 5 describes the number of blockchain companies and financing events, reflecting the development trend of blockchain industries in China. The number of companies rose at an annual growth rate of 100% between 2013 and 2017, indicating the popularization of the blockchain concept, which has drawn interest from many entrepreneurs. The number of financing events can better reflect the capital attracted by an industry better than the number of companies can. Since 2016,

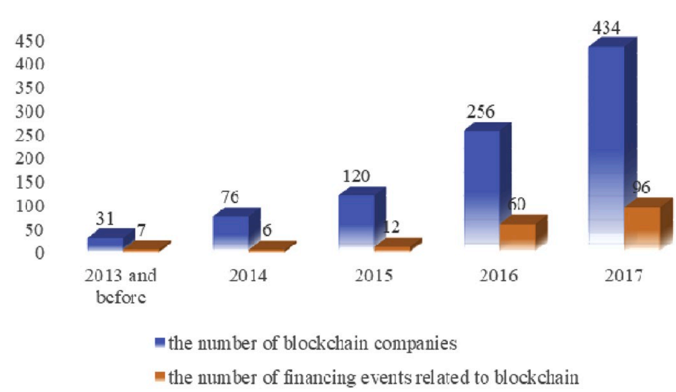

Fig. 5. The number of blockchain companies and financing events.
Source: White paper on China's blockchain industry in 2018.

investment in blockchains filed has increased significantly, with 60 financing events, or five times as many as in 2015. Blockchain financing peaked in 2017 when the number of financing events reached 96 (MIIT, 2018).

4.3. Blockchain and China's distributed power supply

The main problems on China's energy supply side include the monopoly structure, slow structural transformation, insufficient amount of clean energy, and irrational price. Distributed energy supply is more directly user oriented than is traditional centralized energy supply (Gunasekaran et al., 2017). The production amount of energy is adjusted according to users' needs. Blockchain technology can greatly assist distributed energy supply. One of its features is the distributed ledger mode, which can reduce transaction costs and support P2P transaction technology in a distributed energy market. Even though distributed energy in China started later than in the rest of the world, it has developed rapidly. At present, the main domestic distributed energy sources are natural gas, wind power, and solar photovoltaic power. Distributed generation project units can supply electricity to power users or grid enterprises by paying a certain fee. This electricity transaction must be conducted through the distributed generation market transaction platform. In a centralized trading mode, because power transactions involve power users, distributed generation, power grid enterprises, and power trading centers, among other main bodies, they inevitably have the disadvantages of high cost, low efficiency, low transparency, and high risk of information security. However, by using blockchain technology, market-oriented transactions for distributed generation can avoid these problems (Gao and Tong, 2018). Using blockchain technology, the power transaction process can be changed to a continuous and irreversible data record. This process has the advantageous characteristics of intelligence and automation, and does not require personnel, thereby ultimately reducing transaction costs.

Shekou Energy Blockchain Project is China's first community public service project applying blockchain. It connects four distributed clean power stations in Shekou district, Shenzhen city. Users can voluntarily participate in clean power transactions. They can obtain real-time information about the four power stations and can choose to purchase power through a mobile app. Once the user makes a purchase, blockchain generates smart contracts that match P2P transactions between power plants and users. Meanwhile, electronic certificates are generated to prove the utilization of clean energy (Xiao, 2018).

China's largest chemicals company, Sinochem, has achieved some progress in the application and development of energy blockchain. Sinochem fist conducted a pilot crude oil import project using blockchain at the end of 2017, based on its business importing crude oil from the Middle East. In March 2018, Sinochem used blockchain technology for another business exporting petroleum to Singapore. In May 2018, Sinochem finished its financing business based on blockchain technology. Sinochem also used blockchain technology to build the "small petroleum butler" platform, which has become China's largest online smart oil station platform. Other energy blockchain projects are performing well in China. A start-up, Energolabs, set up Energo, in an attempt to decentralize clean energy in 2016. Another technology start-up specializing in solar photovoltaics in Jiangsu province began to invest in an energy blockchain project in 2018. Shaanxi province has launched a pilot project in the field of the energy Internet that has entered the implementation stage. Overall, both research into and application of blockchain in China's energy sector are in the initial stage. In the long run, blockchain technology will be adopted in large scale, which will accelerate China's change from centralized to decentralized energy production.

5. Technology and policy issues in energy blockchain development

5.1. Energy blockchain: not a mature technology

There is no doubt that blockchain technology would be a revolutionary change for the energy sector. However, blockchain is not a panacea. For example, distributed energy producers can easily lower the power production cost relative to centralized producers. However, power or energy is mostly a homogenized product, which means that producers cannot achieve differentiation through branding and marketing. Thus, the introduction of too many entrants in a short time would lead to excessive competition. Blockchain technology itself is still not mature, not only in China but also globally. In general, blockchain is a data technology that requires software and hardware support. Although it can be decentralized or weakly centralized by P2P transactions to reduce transaction costs, its distributed ledger also requires huge data storage resources. An advantage of blockchain is transparency and traceability, as each transaction is recorded in the blockchain automatically. However, from another perspective, as more nodes participate in a transaction, participants may need to spend more time searching and verifying information; this may raise search cost, which is not good for real-time energy transactions. In energy blockchain, trades occur only between the nodes with fastest response speed. Thus, the power supplier may not be the nearest power generation in space, which obviously reduces resource allocation efficiency and leads to energy waste. An analogy can be drawn with online ride-hailing service, in which a driver who collects a passenger is not necessarily the one closest to the passenger but the one who responds fastest, thereby reducing efficiency. In energy blockchain, in addition to such waste, power suppliers that do not take orders also pay for transactions, which is a kind of unnecessary input. While blockchain technology can save transaction costs, the operating and power costs of blockchain supporting facilities cannot be ignored. Otherwise, the loss would outweigh the gain.

Truby (2018) referred to the high energy consumption of blockchain technology and identified fiscal policy to promote environmentally sustainable development when using blockchain technology. Dong et al. (2018) discussed problems of multiple data copies and redundant information in blockchain applications. Each node is unnecessarily involved in the process of every transaction, and nodes are likely to be targeted by computer viruses in the future. Blockchain creates multiple data copies on networked nodes, which can support secure data management in the gird. However, blockchain also generates redundant information. Individual nodes have to participate in every transaction's verification process, and thus, take extra storage space and consume more power. Moreover, it would be likely that cyber attackers launch a targeted cyber-attack on just one node in order to understand the whole network's dynamic information. There is reason to believe that blockchain-targeted computer viruses or attacks will emerge in future. Therefore, applying blockchain to future energy systems requires more effective technologies to resolve the information redundancy issue. Overall, energy blockchain is still in the exploratory period and relevant research in key technology areas is ongoing (Andoni et al., 2019). For China, although its technological level in blockchain lags that of developed countries, the gap is not in fact too big. A bigger obstacle than technology may be policies that are unadaptable to the business model of energy blockchain. In addition to pushing technology progress, China should pay more attention to how to improve relevant policies, develop new business models, and carry out pilot projects comprehensively.

5.2. Applicability of existing policies in China to energy blockchain

5.2.1. Stringent energy regulation environment

The development of an energy blockchain project requires a relatively loose regulatory environment. China's energy sector is regarded as a basic one closely related to the national economy and people's livelihood, the development of which is strongly affected by regulatory policy (Song and Wang, 2018). Without appropriate regulation policy environment, energy blockchain cannot achieve substantial development, even with feasible technology. For example, in the past 2 decades, China's electricity market reform has advanced slowly. There are still many strict regulations governing the generation, transmission, and distribution of electricity. In 2002, the Electric Power System Reform Program separated power generation enterprises from vertical integration. However, effective competition has not resulted. The electricity industry still has high barriers to entry, and prices are firmly controlled by the government. Therefore, to create the conditions for promoting the energy blockchain, electricity system reform needs to be deepened further, with a further loosening of relevant regulations.

5.2.2. Outdated legal system

For a long time, China has adopted a license management system for power supply. China's Electricity Law requires that only one electricity supplier can operate in an electricity-supplying area for supply safety and to avoid unfair or excessive competition. However, this means that selling electricity based on a blockchain grid is illegal. In a deeper sense, incumbents have become vested interest groups in the process of reform. To some degree, these laws were made to protect the interests of incumbents. While energy blockchains can promote the utilization of clean energy, they also have a negative impact on incumbents in the electricity industry. The latter may have little motivation to adopt such a new technology. According to current technological and economic conditions, development of the energy blockchain requires incumbents' existing power grid. In China, distributed electricity market transactions adopting the blockchain technology require access to the power grid run by local power supply enterprises. However, there are no laws or regulations to force local power supply enterprises to provide such fair access. One such case has already arisen in China. A power supply company in Shandong argued that its jurisdiction was not suitable for distributed solar photovoltaic power plants because of security issues and absorption capacity.

5.2.3. Conflicts of management and innovation

Although blockchains can achieve P2P transactions and reduce the possibility of energy waste, they cannot solve the problems of intermittency and volatility. It threatens sustainable energy supply, which is treated as an important part of national economic security (Irani et al., 2017). When using blockchain technology to develop new energy sources, it is necessary to combine it with traditional energy to ensure sustainability of energy supply. Therefore, the energy blockchain involves not only market transactions in new energy, but also the integration of traditional energy to form a complementary and comprehensive energy blockchain. However, the old management system in traditional energy may be contrary to the spirit of innovation required for energy blockchains. The conflict between management and innovation must be addressed when promoting such integration. For instance, to implement energy trade through blockchain, each household must install smart meters with software for the energy blockchain. Smart meters then connect with each other to form the blockchain network. The user can broadcast a smart contract about energy deals using a mobile app. However, existing meters installed in households belong to power supply enterprises, which in practice have management authority. Because power supply enterprises are also traditional energy suppliers, they may refuse to install new smart meters. Alternatively, power supply enterprises could install smart meters but be unwilling to share the data with electricity producers and consumers. This would inhibit the innovation activities of blockchain companies. As an indispensable part of energy blockchain, an energy transaction platform needs to be evaluated and audited by different government departments. Such oversight should include whether the consumption condition is sufficient and how to access the distribution network. To ensure platform construction and innovation, the government should simplify the management steps as well improve the management level and efficiency.

6. Conclusion

With the appearance of smart devices and related software, as well as the decreasing cost of renewable energy, energy consumers require energy supply to be smarter, cleaner, and more sustainable than before. This requirement is perfectly met by blockchain technology, which provides a decentralized trading mechanism that helps to achieve sustainable consumption of energy and the development of a circular economy. This study attempted to answer how blockchain technology could be used by China's energy sector. Presently, large state-owned enterprises significantly dominate China's energy market, which does not seem to aid the application of blockchain technology. However, the generation costs of new energy sources have been decreasing dramatically, providing huge opportunities for energy blockchains. Nevertheless, China continues to face many technical and policy issues. The blockchain technology itself is still not mature—not only in China but also around the world. The energy blockchain is still in the exploratory phase. However, a bigger obstacle than technology may be policy, which is unadaptable to the business model of energy blockchain. To create conditions for promoting the energy blockchain, electricity system reform needs to be further deepened. Specifically, the following policy suggestions should be considered by policymakers.

First, China should support enterprises, universities, and research institutes to establish relevant research platforms to study blockchain technology. The key study areas include encryption technology, distributed algorithms, and risk assessment. The focus of the research should be on finding solutions based on real problems in China. Although there are some applications of blockchain technology in China, at present, the number of self-developed blockchain platforms in China is still relatively small. Most of them have developed by imitating the research of foreign open source communities.

Second, China should promote the construction of household distributed power generation. China's household distributed power generation lags that of developed countries. Household distributed power generation is conducive to the massive application of blockchain technology in the energy field. Smart meters connected to blockchain are used to record the power flow between household appliances, photovoltaic cells, etc. Redundant generated power can be sold to adjacent power users and can achieve mutual power assistance among household users. Furthermore, distributed power generation can guide users to participate actively in the production of clean power and reduction of carbon emissions.

Third, relevant regulations governing the energy sector need to be loosened. Currently, Most of China's energy projects need to be approved by a policy, or companies must purchase qualifications, licenses, etc. to implement a project. As an important catalyst for the energy sector, energy blockchain companies should not be restricted by too many rules of access and licensing. China should amend its outdated Electricity Law to make individuals and private companies eligible to be electricity suppliers. When necessary, new laws should be introduced to ensure access to the power grid and fairness of transactions. In addition, regulators should promote smart supervision by applying the blockchain technology itself in regulating energy blockchain companies. Overall, to protect innovation in energy blockchains, the government should simplify the management steps as well as improve the management level and efficiency.

Declaration of competing interest

This manuscript has not been published or presented elsewhere in part or in entirety and is not under consideration by another journal. The authors have approved the manuscript and agreed with submission to your esteemed journal. There are no conflicts of interest to declare.

CRediT authorship contribution statement

Shuai Zhu: Writing - original draft, Software. **Malin Song:** Data curation, Formal analysis. **Ming Kim Lim:** Conceptualization, Methodology. **Jianlin Wang:** Resources, Investigation. **Jiajia Zhao:** Writing - original draft, Supervision, Validation, Writing - review & editing.

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