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The energy effect of blockchain technology innovation in the Industry 5.0 Era : From the perspective of carbon emissions

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Abstract. In the era of Industry 5.0, innovation in blockchain technology is expected to have a significant impact on energy efficiency and carbon emissions, especially in hybrid energy systems. This paper has obtained the innovation data on the blockchain patent of listed companies in China from 2010 to 2022 by machine learning and text analysis methodology of the large language model. On this basis, the relationship between the enterprises' blockchain technology innovation and the intensity of fossil energy consumption has been discussed. The study found that (1) the enterprises' blockchain technology innovation is able to reduce the intensity of fossil energy consumption, and this conclusion remains valid via controlling for endogeneity and upon the completion of the robustness test. (2) In terms of the mechanism, the enterprises' blockchain technology innovation can achieve energy transition by reducing the cost of internal control, strengthening external supervision, improving the efficiency of resource allocation, and strengthening the channels of supply chain management. (3) Further research has found that the energy effects as a result of blockchain technology innovation help to improve operational efficiency and lower the level of carbon emission. Our research provides scientific support for breaking the "technological energy paradox" in the field of energy economy while providing empirical evidence of "blockchain carbon reduction" for technologies such as blockchain BaaS alliance, cross-operator network spectrum, and shared base stations that will be applied on a large scale in the Industry 5.0 Era.

Keywords: Blockchain technology, Energy consumption, Industry 5.0 Era, Machine learning, Large language model.

1 Introduction

According to the World Meteorological Organization's recent "*State of the Global Climate 2023*" report, the records with respect to greenhouse gas levels, land surface temperatures, ocean heat and acidification, sea level rise, and the retreat of Antarctic-ocean ice sheets and glaciers have reached a new high (UN 2024)[1]. Fossil energy consumed in industrial production serves as an important cause of greenhouse gas emissions and global warming [1]. Global industrial carbon emissions were estimated to be 9.2 Gt in 2022, 25% of total emissions (International Energy Agency 2023)[2]. Industrial carbon emissions reduction mainly depends on the use of clean energy, carbon capture, carbon storage, and reducing fossil energy consumption as well. However, most developing countries are still in the early stages of the energy transition [2]. The supply of clean energy is unstable, and the technology related to carbon capture and carbon storage is not mature. In such a context, it is critical to reduce fossil energy consumption, accelerate the development of new energy technologies and industrial applications, especially innovative technologies such as renewable energy, new energy storage, and electricity digitalization, and promote the establishment and integration of distributed energy systems [3]. The rise of blockchain technology can bring radical changes in the Industry 5.0 Era. Enabling new energy production activities, optimizing distributed energy trading mechanisms, and promoting the sustainable development of enterprises serve as the solution to the mismatch of supply and demand in the space and time dimension of energy, fluctuations of energy price caused by geopolitical risks, and

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[1] The United Nations. https://news.un.org/zh/story/2024/01/1125667

[2] International Energy Agency, China Data Explorer (2023). [2023-04-14]. https://www.iea.org/countries/china.

environmental pollution as a result of excessive consumption of fossil energy [4].

Blockchain technology ensures the immutability and transparency of process data on energy production, consumption, and so on through distributed ledger technology and cryptographic algorithms in the Industry 5.0 Era. It can set up mutual trust among various entities in the complex system [5], improve the efficiency of spot transactions, and promote a sound development of the energy market. In addition, it can realize the digital traceability of energy assets and improve the transparency of data on energy consumption [6]. As a result, it is useful to change the energy demand curve of the regional energy system, and realize the rational use of fossil energy and clean energy, thereby reducing fossil energy consumption. However, some scholars show concerns, namely that the large-scale application of blockchain technology will lead to increased output, which will subsequently increase fossil energy consumption and total carbon emissions. The reason for this phenomenon is the proof of work (PoW) mechanism used by blockchain technology. The PoW mechanism requires a lot of computing power and power resources, and miners compete to perform calculations to solve complex hash functions that confirm transactions and generate new blocks. This results in extremely high energy consumption and carbon emissions, which are not conducive to sustainable development, that is, the "rebound effect" of fossil energy consumption will be generated [7, 8]. This has also led to the discussion of the "technological energy paradox" in the energy economy. As the main trading body of the energy market, enterprises bear the responsibility of optimizing the energy structure and achieving carbon and pollution reduction. What is the impact of blockchain technology innovation from enterprises on the intensity of fossil energy consumption? What is the underlying mechanism?

According to existing studies, scholars have identified the important role of blockchain technology in the energy market. Blockchain technology has transitioned from the underlying technology of distributed ledger to smart contract and decentralized technology and then developed into fragment cross-chain technology. Fragmentation cross-chain technology provides data sharing and value exchange among various energy platforms, as well as promotes energy diversity and cooperation. Meanwhile, fragmentation cross-chain technology enables direct peer-to-peer energy trading, eliminates middlemen, improves transaction efficiency, and allows for more flexible and efficient participation of small-scale renewable energy in the market. Boumaiza [9] proposed the idea of a distributed energy trading system based on blockchain technology. The system uses residential photovoltaics as energy producers and assesses value fluctuations in the energy trading market by forecasting energy data for the housing community. Bokkisam *et al.* [10] introduced a virtual proxy based on blockchain technology, which eliminates the need for fossil energy from third-party institutions, builds a community-based self-sufficiency system, and alleviates citizens' dependence on a public utility-based power grid. In this system, energy transactions become more efficient and reliable through the application of blockchain technology. Ali *et al.* [11] proposed a system that can reduce the cost of electricity consumption with the help of blockchain technology. The system can convert each user's electricity consumption into specific parameters according to a certain algorithm without sharing sensitive information. The verifier of the blockchain is determined based on the parameter value so as to encourage producers and consumers to reduce the demand for energy.

Blockchain technology plays a key role in the sustainable development of enterprises and provides a critical approach for them to transform and upgrade [12]. First, blockchain technology plays an important role in supply chain management [13], process tracking [14], and data sharing [15]. By means of whole-process tracking from production to delivery, blockchain technology can improve supply chain transparency and efficiency, reducing delays and moral hazards [16]. Second, the smart contract-automatic execution characteristic that comes with blockchain enables blockchain to greatly reduce the cost of collecting, recording, and disseminating data in a variety of environments [17]. Finally, blockchain technology also promotes cooperation and win-win results among enterprises. By building a blockchain-based alliance chain or public chain, enterprises can realize data sharing and collaborative work across organizations, break free from information isolated island, as well as achieve decentralized decision-making [18, 19] and decentralized governance [20] to improve overall operational efficiency. However, other studies have pointed out that the application of blockchain technology innovation to enterprises is still young and faces challenges in terms of technology maturity, security, regulations and policies as well [21].

The findings mentioned above serve as the foundation for the study in this paper. However, no study has paid attention to the impact of enterprises' blockchain technology innovation on the intensity of fossil energy consumption and the potential impact mechanism. Against the backdrop of global geopolitical risks along with the aggravation of competition in the energy market, it is required to give play to the advantages of blockchain fragmentation cross-chain technology, to achieve reasonable mixed use of energy sources of all kinds, and to improve energy utilization efficiency. As the main trading body of the energy market, enterprises bear the responsibility of optimizing the energy structure and reducing the consumption of fossil energy. China ranks first in the world in the number of patent applications in digital technologies such as big data and blockchain[3]. Based on the characteristics of blockchain technology such as high threshold, high cost, and imitability [22], how to apply blockchain technology innovation to reduce the intensity of fossil energy consumption by enterprises, and to reduce carbon with the help of blockchain has become an urgent issue for the industry and academia community [23].

Considering the findings mentioned above, this paper manifests itself in three key tasks. First, based on the text information from the patent application documents of the listed companies, the text analysis method by means of

[3] Cyberspace Administration of China: Digital China Development Report (2020).

machine learning has been utilized to identify the blockchain technology patents, and thus analyze the relationship between blockchain technology innovation and fossil energy consumption. Second, the impact mechanism between blockchain technology innovation and fossil energy consumption has been analyzed according to the practical application of blockchain technology innovation. Third, the potential economic and environmental consequences caused by the energy utility as a result of the enterprises' blockchain technology innovation have been further examined.

Our findings show that first, the enterprises' blockchain technology innovation is able to reduce the amount of fossil energy consumed by the enterprises, and such reduction remains robust when the core variables and fixed effects are subjected to changes. Second, blockchain technology innovation is able to reduce the intensity of fossil energy consumption and achieve energy transition by reducing the enterprises' internal costs, strengthening external supervision, improving the efficiency of resource allocation, and strengthening supply chain management as well. Finally, further research has found that the application of blockchain technology innovation to energy consumption can improve the efficiency of business operations and reduce carbon emissions.

The paper delivers marginal contribution in three aspects as follows: first, the academic community gives priority to "carbon reduction by blockchain technology" in their research. Previous studies in this field are mainly based on theoretical derivation [24], literature review [25, 26], and case study [27], most of which support the view that blockchain technology innovation is able to improve energy efficiency. However, it is challenging for the current theoretical research to bridge the gap between real data and theoretical speculation. This paper has examined the impact of the enterprises' blockchain technology innovation on the intensity of fossil energy consumption by enterprises in the Industry 5.0 Era, gives another outlook on the energy effect from the enterprises' blockchain technology innovation, and provides theoretical support for the promotion of sustainable development of enterprises by blockchain technology innovation in addition to providing a reference for the design of subsequent relevant researches.

Second, with increasing applications of blockchain technology in the Industry 5.0 Era, it is essential to gain a clear picture of the impact mechanism of "carbon reduction by blockchain technology". This paper manages to shed light on how blockchain technology innovation affects fossil energy consumption by enterprises through such channels as management empowerment, supervision empowerment, and operation empowerment, which helps guide enterprises in strengthening internal control, improving external supervision, enhancing resource allocation efficiency, and organizing supply chain management so as to reduce the enterprises' fossil energy consumption. Reducing fossil energy consumption by enterprises can reduce the dependence on fossil fuels and reduce carbon emissions at the source. Our findings can be promoted to other countries around the world. Using the characteristics of blockchain technology, namely decentralization, security and data transparency, rational use and ubiquitous interaction among multiple energy sources can come true. As a result, solutions are available to attain global net zero emissions.

Third, in the era of big data, the abundance of and easy access to data makes it possible to make decisions based on data. In the energy sector, energy management and optimization can be carried out more efficiently through real-time access to various energy-related data. Previous studies may not have adequately addressed the quality and accuracy of energy consumption data. For example, Wang *et al.* [28] pointed out that basic energy consumption data fell short in precision and accuracy, and some departments are careless in statistical services, which results in inaccurate basic data. These issues can affect the reliability of energy consumption analysis based on big data. Therefore, the deep-seated application of big data technology in the field of energy bears pivotal significance. This paper has combined machine learning with blockchain technology to expand the application of big data technology in the literature on energy economics. Using machine learning to extract useful information from blockchain data for analysis allows for more pinpointing energy demand and supply of energy. Thus, this will help enterprises and governments to make more scientific energy planning and layout, and provide intelligent decision support for energy management.

2 Theoretical analysis and research hypotheses

2.1 The Enterprises' blockchain technology innovation and the intensity of fossil energy consumption

According to Schumpeter's theory of innovation and endogenous growth, technological progress realized by research, development, and innovation activities is an endogenous factor of economic growth [29]. The "creative destruction" as a result of these R&D and innovation activities promotes technological progress, which in turn promotes endogenous economic growth [30]. Such new generation of information technologies as big data, cloud computing, mobile Internet, Internet of Things, artificial intelligence, and blockchain are regarded as the innovation fields with the most extensive innovative elements and the broadest development and application prospects, which exerts a deep-seated impact on all kinds of current social and economic activities. Blockchain plays a role in the integration of distributed networks, encryption technology, smart contracts, and other technologies. With the extensive application of blockchain technology in enterprises, the external environment of the enterprises' fossil energy consumption has also been changed. The innovation of blockchain technology has endowed the enterprises' supply chain with new features such as network sharing, intelligent collaboration, and big data support [17], and restructured the energy consumption chain with the logic of "digitalization – information sharing – efficiency improvement – decision optimization". This is mainly reflected in the following two aspects. First, blockchain technology innovation improves the transparency of energy supply chain data, eases such issues as information asymmetry and data tampering, improves the operational efficiency and product quality of the supply chain, as well as reduces production waste. Second, according to signal theory, each company's decision imposes externalities on other companies active in the economy, allowing the overall information provision to end up with a complex coordination game. Strategic alliances built through blockchain have an impact on managers' decisions, enabling the participants in blockchain to make more informed energy input decisions [31]. Based on this, this paper proposes:

Hypothesis 1: Blockchain technology innovation helps reduce the intensity of the enterprises' fossil energy consumption.

2.2 Enterprise blockchain technology innovation and internal control

According to the theory of organizational innovation, innovation enables enterprises to organize management and lower internal control costs [32]. The immutability and decentralization of blockchain technology can effectively set up mutual trust among various entities in a complex system. On the one hand, within the enterprises' organizations, blockchain technology is often embedded into the operational architecture at the business level as an auxiliary module [33], which can lower the chance for personnel to be involved in the production and operation process. As a result, this will reduce the manipulable space of the enterprises, lower the external supervision costs, and promote the reduction in internal control costs and the improvement in production efficiency [34]. On the other hand, in view of agency problems existing in internal operations, blockchain technology innovation encourages enterprises to realize real-time and transparent key activities such as production processes, R&D processes, and financial control, thereby reducing the supervision costs of enterprises in various business processes and reducing the efficiency loss caused by agency problems [35]. In addition, blockchain technology is able to embed compliance rules into the blockchain to detect whether business operations comply with regulations in real-time or not and ensure the compliance of the enterprises. By monitoring the compliance risks of enterprises in real time, potential risks can be discovered in time and early warnings can be made. By establishing a sound internal control system, enterprises can more accurately monitor and manage the use of energy, including procurement, storage, distribution, and use of energy. In this way, enterprises can detect and get rid of energy waste and inefficiency in a timely manner, thereby reducing energy consumption and improving economic efficiency. Based on this, this paper proposes:

Hypothesis 2: Blockchain technology innovation is able to reduce the intensity of the enterprises' fossil energy consumption by strengthening the enterprises' internal control.

2.3 The enterprise's blockchain technology innovation and external oversight

In the energy market, information asymmetry may be manifested as an imbalance among suppliers, consumers, regulators, and other parties in the acquisition, transmission, and processing of information. This imbalance may lead to distortion of market price, low transaction efficiency, unreasonable allocation of resources, and other problems as well, and thereby damage the fairness and efficiency of the market. Stakeholder theory points out that the managers of enterprises need to balance the interests of various stakeholders in their daily operations. Blockchain technology can completely record the entire process of energy production and consumption, realize the digital traceability of energy assets, and improve the transparency of energy consumption data [6]. In addition to blockchain technology, such traditional technologies as cloud computing, automation, and ERP systems can also be used to improve processing efficiency and establish transparent communication mechanisms among stakeholders. Compared to these traditional technologies, blockchain features advantages as follows: it is particularly suitable for coordinating different stakeholder groups, as well as it guarantees the security and immutability of information and value transactions. On the one hand, the energy information chain can provide external regulatory channels for the stakeholders of the enterprises. For example, the power industry establishes an energy data sharing mechanism and an efficient regulatory system through blockchain technology innovation so as to promote the rapid development of the renewable energy industry [36]. Linking financial information can improve the efficiency of energy companies in the financial market [37] and improve their financial performance [38]. On the other hand, as a restraint mechanism, external supervision can prompt credit rating agencies to provide more accurate ratings, thus alleviating information asymmetry in the energy market. In addition, external supervision is conducive to stimulating the self-iterative power of enterprises, pushing them to continuously improve green technology, improve energy utilization efficiency, and reduce the intensity of fossil energy consumption. Based on this, this paper proposes:

Hypothesis 3: Blockchain technology innovation is able to reduce the intensity of the enterprises' fossil energy consumption by strengthening the enterprises' external supervision.

2.4 Enterprise blockchain technology innovation and resource allocation efficiency

The theory of resource allocation is mainly focused on how to optimize resource allocation and allocate various resources (including human, material, and financial resources, etc.) in economic activities to different uses with limited resource supply, so as to minimize macroeconomic waste and maximize social welfare. With the rapid development of information technology, blockchain technology, as a revolutionary innovation, is gradually penetrating into the daily operation and decision-making process of enterprises.

First of all, blockchain technology can help enterprises achieve optimal allocation of resources. Through smart contracts and automatic execution mechanisms, enterprises can track and manage the use of resources in real-time, ensuring that resources are fully utilized. This can not only reduce the operating cost of enterprises but also improve the efficiency of resource utilization, thus improving the efficiency of resource allocation [39]. Second, blockchain technology promotes collaborative innovation. Blockchain technology can remove information barriers among enterprises and promote collaborative innovation. Through the blockchain platform, enterprises can share R&D results, technical resources, and market information, and strengthen cooperation and exchanges. This collaborative innovation mode helps enterprises to quickly acquire new technologies and new knowledge, improve innovation ability, and thereby improve the efficiency of resource allocation. Finally, blockchain technology can strengthen enterprises' risk management capabilities. By means of real-time monitoring and early warning mechanisms, enterprises can find potential risks in time and take effective measures to cope with them. This will help reduce the operational risks and market risks of the enterprises, ensure the stable development of the enterprises, and improve the efficiency of resource allocation. The improvement in resource allocation efficiency will help optimize energy consumption structure and improve energy utilization efficiency [40]. At the same time, the improvement in resource allocation efficiency can also promote the shift of energy consumption toward cleaner and low-carbon energy, thus reducing the risk of environmental pollution and ecological damage. Based on this, this paper proposes:

Hypothesis 4: Blockchain technology innovation is able to reduce the intensity of the enterprises' fossil energy consumption by improving the enterprises' resource allocation efficiency.

2.5 The enterprise's blockchain technology innovation and supply chain management

In the traditional supply chain, it is difficult for enterprises to accurately grasp the real-time status of enterprises upstream and downstream owing to the opaque information and poor communication. First of all, blockchain technology can record and share information on all links in the supply chain in real-time by a private chain or alliance chain technology so that enterprises can always understand the source of goods, transportation, warehousing, and other conditions, so as to improve the transparency and traceability of the supply chain. Chod *et al.* [41] show how high-quality companies can leverage the proposed blockchain-enabled verifiability of physical commodity transactions to more efficiently fund their supply chain operations by indicating their operational capabilities through inventory orders. Second, by strengthening the collaboration and information sharing of blockchain technology, enterprises can better respond to emergencies and market changes, and enhance the resilience and risk resistance of the supply chain. Strengthening supply chain collaboration and information sharing helps enterprises make structural adjustments in the supply chain and delivers a more flexible operation mode. In the face of emergencies or market changes, the enterprises can quickly adjust suppliers, production plans, and logistics routes to ensure the continuity and stability of the supply chain. This flexibility allows enterprises to better adapt to the complex and changing market environment. In addition, by recording and managing the carbon emissions, energy consumption, and other information with respect to enterprises upstream and downstream in the supply chain, enterprises can develop more scientific environmental protection strategies and reduce the negative impact on the environment [42]. Blockchain technology can also be used to trace the source of raw materials and production processes of products and to calculate the carbon emissions implied in trade, which is conducive to fair trade and sustainable development of the supply chain. Based on this, this paper proposes

Hypothesis 5: Blockchain technology innovation is able to reduce the intensity of the enterprises' fossil energy consumption by improving the management of the supply chain.

3 Variables and methods

3.1 Variables

3.1.1 Blockchain technology innovation

Blockchain Technology innovation (*lnBC*) can be defined as the innovative activities initiated by enterprises in the field of blockchain technology, with a goal to improve, optimize or develop new blockchain technology solutions so as to meet the specific needs of enterprises or to promote the development of the industry. Adding up the frequency of keywords with respect to the enterprises' blockchain technology innovation which is acquired from patent specifications has been realized by using the text mining method of machine learning in this paper [5], followed by digital processing of the sum in order to obtain *lnBC.*

3.1.2 The intensity of the enterprises' fossil energy consumption

The intensity of fossil energy consumption (*lnEC*). It is generally measured by the energy consumed per unit of output value of an enterprise [43]. In the pollution database, the enterprises' energy consumption contains a variety of different types of subdivided energy. Based on the practice of Wei *et al.* [44], this paper converts various energy consumption of enterprises (coal, oil, and natural gas) into standard coal according to *the Conversion Coefficient of Standard Coal* published by the Ministry of Industry and Information Technology, as well as adds them up to obtain the total energy consumption. Then, the logarithmic value of the ratio between total energy consumption and total industrial output value of enterprises is used as the proxy variable of energy consumption intensity for regression.

Table 1. Descriptive statistics.

Variables	N	Mean	Std	Min	Max
lnEC	28,907	0.9579	13.9469	0	2357.347
lnBC	28,907	0.0080	0.1002	0	3.2189
Lev	28,321	0.4254	0.2125	0.0474	1.0359
ROA	28,321	0.0319	0.1063	−0.5576	0.2896
Cashflow	28,321	0.0490	0.0872	−0.2578	0.3374
Top1	28,321	0.3329	0.1504	0	1.7776
ListAge	28,321	2.1553	0.7300	0.6931	3.5223

3.1.3 Control variables

According to the study of Fang *et al.* [45], the control variables are shown as follows: asset-liability ratio (*Lev*) defined as the ratio of total liabilities to total assets at the end of the year; Return on assets (*ROA*) defined as the ratio of net profit to the average balance of total assets; The cash flow ratio (*Cashflow*) is measured as the ratio of net cash flows generated from operating activities to total assets; The shareholding ratio of the largest shareholder (*Top1*) is defined as the ratio of the number of shares held by the largest shareholder to the total number of shares; Enterprise age (*ListAge*) is defined as the natural logarithm of the number of years from the date of establishment of an enterprise to the current year where statistics occurs. Descriptive statistics of variables are shown in Table 1.

3.2 Data sources

Given that 2010 is the year in which the *China Securities Regulatory Commission* (*CSRC*) promulgated "Rule No. 15 on the Compilation and Reporting of Information Disclosure of Companies that Issue Securities Publicly – General Provisions for Financial Reporting". This represents the minimum requirement for financial reporting disclosure. In order to avoid the impact of the differences between the old disclosure standards and the new ones, this paper chooses the year 2010 as the starting point of the sample interval, takes the annual financial reports of all A-share companies in Shanghai and Shenzhen stock markets from 2010 to 2022 as the initial research sample. The annual financial report documents of listed companies are from CNINFO, and other research data are from the CSMAR database. The observed values of any companies that are of financial and insurance, ST, ST*, and those of the companies that are less than 2 years old have been eliminated. In order to avoid the influence of extreme values, samples with severe missing financial data were eliminated in this paper, and 28,908 samples were finally obtained.

The processing steps of blockchain text mining are as follows: using cutting-edge machine learning methods and Large Language Model (LLM), this paper constructs a set of blockchain technology innovation indicators based on the patent text of China A-share listed companies from 2010 to 2022 and comprehensively reflects the actual use of blockchain technology in enterprises. Specifically, the measurement of blockchain technology innovation is divided into four steps: the first step is to sort out the patent texts of listed companies, which are collected by crawlers and WinGo financial text data platform, and to convert PDF documents into TXT documents while eliminating forms, text boxes, pictures, and missing files. In the second step, the relevant text is divided into sentences according to the period and semicolon to form a sentence base to be predicted. The third step is to simultaneously extract relevant texts and texts containing keywords on a random basis in order to form a sentence library to be marked, and manually mark the marked sentence library to determine whether the enterprise has carried out blockchain technology innovation or not. The fourth step is to use the Chinese general dictionary Jieba and financial dictionaries such as "*English and Chinese Dictionary of Modern Finance and Accounting*" to segment the patent text and remove the stop words, so as to convert the unstructured text data into word vectors for storage, and finally build a new set of enterprise blockchain technology innovation indicator.

3.3 Regression model

3.3.1 Baseline regression model

The baseline model is designed as follows:

$$lnEC_{it} = \beta_0 + \beta_1 ln1BC_{it} + \beta_2 \text{Controls} + \mu_t + \theta_n + \varepsilon_{it} \quad (1)$$

where i indicates the enterprise and t indicates the year. *lnEC* represents the enterprises' intensity of fossil energy consumption, *lnBC* represents the enterprises' blockchain technology innovation, and *Controls* are model control variables. And μ_t and θ_n represent year and industry fixed effects respectively. ε_{it} represents a random error term. In addition, we control the year and industry fixed effects and cluster the standard errors at the firm level.

3.3.2 Intermediate regression model

In order to examine the channels through which the enterprises' blockchain technology innovation affects the intensity of energy consumption, we take mediating variables as dependent variables and construct a mediating model. The specific construction model is shown in equation (2).

$$M_{it} = \alpha_0 + \alpha_1 lnBC_{it} + \alpha_3 X_{it} + \mu_i + \upsilon_t + \varepsilon_{it}. \quad (2)$$

Table 2. Baseline regression.

Variables	lnEC	
	(1)	(2)
lnBC	−0.3962** (0.1634)	−0.3872** (0.1964)
Lev		−0.8495 (0.5726)
ROA		−5.7994** (2.6586)
Cashflow		3.7315 (4.4168)
Top1		0.6105 (1.0765)
ListAge		0.0240 (0.1492)
Cons	0.6470*** (0.1256)	1.0546 (0.9151)
Year FE	Yes	Yes
Industry FE	Yes	Yes
N	28,907	28,321
R^2	0.0036	0.0051

Note: ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$, the results end at the fourth decimal place.

According to the research hypothesis, M_{it} represents all the intermediary variables. The intermediary variables are internal control, external supervision, resource allocation efficiency, and supply chain management respectively.

4 Results

4.1 Baseline regression

Table 2 reports the baseline regression results of the energy effects of blockchain technology innovation, where column (1) examines the relationship between blockchain technology innovation and the univariate of the enterprises' energy consumption. *lnBC* is significantly negative at the 5% level, indicating that there is a negative relationship between the two. In column (2), the negative relationship between blockchain technology innovation and the enterprises' energy consumption remains true when other conditions remain unchanged and control variables are added. This shows that blockchain technology innovation has improved the transparency and efficiency of energy transactions and reduced corporate energy consumption. On the one hand, through blockchain technology, enterprises can monitor their energy consumption in real-time, as well as identify and solve inefficiencies in energy use in a timely manner [46]; On the other hand, through blockchain's smart power grid and distributed ledger technology, enterprises can have better management and optimization of their use of renewable energy sources, such as solar and wind. This not only helps reduce their dependence on traditional fossil fuels but also reduces their energy costs and impact on the environment [47]. Test hypothesis 1.

4.2 Robustness tests

Considering that the treatment of variables may affect the reliability of the estimated results, we have conducted a robustness test. Table 3 reports the results of the robustness test. In column (1), the explained variable indicator is replaced with the non-logarithmic energy consumption intensity. Column (2), blockchain technology innovation has been extended to digital technology innovation, refer to [48], taking the explanatory variable as the natural logarithm of the digital technology innovation word frequency plus 1 in the Wingo platform patent text. In column (3), in order to mitigate the potential impact of unobservable factors at the city level, this paper has further added the fixed effect of cities on the basis of the fixed effect of controlling industry and year as the main test [49]. Through the above tests, it is found that the empirical results are still robust, and hypothesis 1 has been verified again.

4.3 Endogeneity test

Given limited data, there may be errors in the estimation of blockchain technology innovation and the enterprises' energy consumption, resulting in unobservable factors between the two and leading to the endogeneity of the estimated coefficient. In this paper, the instrumental variable method is used to further test the robustness of the estimation results. We choose the number of post offices (one hundred) of each prefecture-level city in 1984 multiplied by the number of blockchain patents with one period lag as the instrumental variable. On the one hand, considering blockchain technology as the continuation of traditional communication technology development, the local history of telecommunications infrastructure will affect the application of blockchain technology from the technical level as well as use habits and other factors; On the other hand, the impact of traditional telecommunications tools like post offices on economic development has gradually declined with the decline in the frequency of use, with exclusivity achieved. Since the basic sample of this paper is the data that changes with time and city in two dimensions, and the number of post offices in each prefecture-level city in 1984 is a variable that does not change with time. In order to make the instrumental variables meet the dynamic characteristics of the bidirectional characteristics of time and city, this paper refers to Nunn and Qian's [50] processing method of the two-dimensional instrumental variables, the number of blockchain technologies in the previous period so as to reflect the time variation of instrumental variables. In columns (1) and (2) of Table 4, the number of post offices (one hundred) in each prefecture-level city in 1984 was multiplied by the number of blockchain patents with a lag of one period as an instrumental variable for the endogeneity test. The regression results of the first stage show that instrumental variables are positively correlated with blockchain technological innovation. The regression results of the second stage show that after considering the endogeneity problem, there is still a significant negative relationship between blockchain technology innovation and the enterprises' intensity of fossil energy consumption. At the same time, the Cragg-Donald Wald F statistic is larger than the critical value of Stock-Yogo at the 10% significance level (16.38), that is, it passes the weak instrumental variable test. The K-Paaprk LM statistic rejects the null hypothesis at the 1% significance level, that is, the identifiable test is passed. The significance and direction of the coefficients

Table 3. Robustness test.

Variables	EC	lnEC	lnEC
	(1)	(2)	(3)
lnBC	−0.6145*** (0.2277)		−0.4363** (0.2196)
DigiInno	−0.7837 (2.8236)	−0.1118*** (0.0223)	−0.7673 (0.5860)
Lev	−6.5204 (5.0725)	−1.2999*** (0.1128)	−5.8690** (2.8036)
ROA	−8.9691 (7.5731)	−2.7268*** (0.3069)	3.7514 (4.3534)
Cashflow	−0.6739 (0.4747)	−0.6885*** (0.2267)	0.9236 (1.3587)
Top1	0.0819 (0.4393)	−0.2992*** (0.0932)	0.0497 (0.2032)
ListAge	−0.6145*** (0.2277)	−0.1915*** (0.0262)	−0.4363** (0.2196)
Cons	2.6261 (1.7283)	1.8386*** (0.0864)	0.3598 (0.7928)
Year FE	Yes	Yes	Yes
Industry FE	Yes	Yes	Yes
City FE	No	No	Yes
N	28,321	22,337	28,321
R^2	0.0199	0.2352	0.0088

Note: ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$, the results end at the fourth decimal place. Endogeneity test.

have not changed after adding the instrumental variables, which shows the reliability of the benchmark regression results in this paper.

4.4 Mechanism analysis

4.4.1 Internal control

Internal control is a series of methods and measures taken by enterprises to ensure the safety and efficiency of operation and management activities and is an important guarantee for enterprises to achieve goals, and improve efficiency and competitiveness [51]. Effective internal management is very important for the enterprises. It can not only ensure the effective operation of the internal control system but also help enterprises maximize economic benefits. In this paper, the natural logarithm of the Dubois internal control index plus one is used as the proxy index of the enterprises' internal control. On the one hand, blockchain technology can optimize the internal management mechanism of enterprises and lower internal costs. Through the decentralization and transparency of blockchain, enterprises can achieve data transparency and real-time sharing in all aspects of the supply chain. This not only helps to reduce information asymmetry and fraud but also reduces the waste of resources due to redundancies and errors in the supply chain. On the other hand, blockchain technology can simplify the procurement process, reduce manual operations, reduce labor costs, and indirectly reduce energy consumption associated with human operations [52]. Column (1) of Table 5 finds that blockchain technology can enhance the level of internal control in enterprises. This shows that blockchain technology innovation is able to reduce the enterprises' energy consumption by optimizing internal management and reducing internal costs. This not only helps to improve the economic efficiency and competitiveness of the enterprises but also helps to promote the sustainable development of the enterprises. Hypothesis 2 has been verified.

4.4.2 External oversight

External supervision mainly refers to the supervision and inspection of the economic activities, financial management, accounting behavior and others of enterprises by relevant institutions or actors [53]. First, blockchain technology provides a more transparent and reliable data recording mechanism for the external supervision of enterprises. This allows regulators, investors, and the public to have a more accurate picture of a company's operations and energy consumption, allowing for more effective monitoring. In addition, external supervision will make enterprises confront greater compliance pressure and social pressure. Then, the enterprises have more incentive to reduce the intensity of fossil energy consumption. Enterprises may take a series of measures to optimize the energy structure and improve energy efficiency so as to reduce the enterprises' intensity of energy consumption and reduce the consumption of fossil energy. In this paper, the natural logarithm of the number of companies concerned by analysts plus 1 is used to represent the external supervision of enterprises. Column (2) of Table 5 finds that blockchain technology can increase the level of external oversight. This shows that blockchain technology innovation strengthens the external supervision of enterprises by providing technical support and increasing the compliance pressure of the enterprises, thus reducing the energy consumption of the enterprises. Hypothesis 3 has been verified.

4.4.3 Resource allocation efficiency

Resource allocation efficiency refers to the ability of enterprises to maximize income under limited resources, which is embodied in the reasonable utilization of human

Table 4. Endogeneity test.

Variables	lnBC	lnEC
	(1)	(2)
IV	0.1088*** (0.0216)	
lnBC		−0.5605*** (0.1977)
Lev	0.0079* (0.0045)	−1.3997*** (0.1826)
ROA	0.0091 (0.0070)	−3.2507*** (0.4301)
Cashflow	0.0039 (0.0077)	−0.8382*** (0.2992)
Top1	−0.0012 (0.0062)	−0.5205*** (0.1196)
ListAge	0.0027 (0.0028)	−0.1535*** (0.0367)
Year FE	Yes	Yes
Industry FE	Yes	Yes
N	21,353	21,353
R^2	0.1236	0.0624
Cragg-Donald Wald F statistic		25.10
K-Paaprk LM statistic		***

Note: ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$, the results end at the fourth decimal place.

Table 5. Mechanism inspection.

Variables	ICI	Attention	TFP	ST5r
	(1)	(2)	(3)	(4)
lnBC	0.1483*** (0.0472)	0.0621*** (0.0178)	0.3592*** (0.1215)	−0.0367*** (0.0138)
Lev	−0.6470*** (0.0962)	−0.0518*** (0.0194)	2.0546*** (0.0874)	−0.0711*** (0.0152)
ROA	3.7122*** (0.2505)	−0.0109 (0.0235)	2.9287*** (0.1325)	−0.0988*** (0.0258)
Cashflow	−0.2735 (0.2337)	−0.0243 (0.0259)	0.1992 (0.1335)	−0.0803*** (0.0259)
Top1	0.1153 (0.0921)	−0.0631** (0.0304)	1.0034*** (0.1151)	0.0026 (0.0188)
ListAge	−0.0469** (0.0229)	0.2766*** (0.0094)	0.3655*** (0.0332)	−0.0050 (0.0057)
Cons	−0.6470*** (0.0962)	−0.0518*** (0.0194)	2.0546*** (0.0874)	−0.0711*** (0.0152)
Year FE	Yes	Yes	Yes	Yes
Industry FE	Yes	Yes	Yes	Yes
N	28,315	28,321	28,321	24,417
R^2	0.1859	0.5312	0.5311	0.1966

Note: ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$, the results end at the fourth decimal place.

resources, capital, materials, and other resources. In essence, it reflects the contrast between input and output in the process of resource allocation, and its goal is to maximize meeting the needs and objectives of social consumers while achieving the maximum benefit of the economy. On the one hand, in the traditional enterprise management mode, there are often problems such as asymmetric information and cumbersome processes in resource allocation, resulting in low resource utilization efficiency. Blockchain technology can record, verify and share business operation data in real-time, avoiding energy use decision-making errors and energy waste caused by opaque information [54]. On the other hand, the improvement of resource allocation efficiency helps to optimize energy consumption structure and improve energy utilization efficiency. With technological progress and industrial upgrading, enterprises are able to adopt more advanced production processes and equipment and promote the transformation of energy consumption to cleaner and low-carbon energy. In this paper, the Labor-based Leontief Method (LP) is used to calculate the total factor productivity of the enterprises. Column (3) of Table 5 finds that blockchain technology can improve the total factor productivity of enterprises. This shows that blockchain technology innovation affects the efficiency of enterprise resource allocation by optimizing resource allocation, improving management efficiency, and improving information transparency, thus reducing enterprise energy consumption. Hypothesis 4 has been verified.

4.4.4 Supply chain management

Supply chain management is one of the key factors for enterprise management. Facing fierce market competition, the relationship between the upstream and downstream of the supply chain has become the source of the core competitive advantage of enterprises [55]. With the extensive application and deep integration of blockchain technology in the enterprises, the external environment of the enterprise supply chain configuration decisions has also been changed. Blockchain technology innovation has provided such new features as enterprise supply chain network sharing, intelligent collaboration, and big data support. First, blockchain technology can enhance the collaborative management of supply chains. The supply chain is a complex network, involving many subjects and links. Blockchain technology improves the operational efficiency of the supply chain and reduces energy waste through intelligent collaborative work. Second, blockchain technology can also promote greening and sustainable development in the supply chain. For example, enterprises can establish a green supply chain evaluation system to encourage suppliers to adopt more environmentally friendly production methods and energy consumption methods [56]. Meanwhile, blockchain technology can establish trading and incentive mechanisms for renewable energy, encouraging all links in the supply chain to adopt more renewable energy and reduce the consumption of fossil energy. This paper measures the supply chain management level by means of the average purchase proportion of the top five suppliers and the sales proportion of the top five customers. The findings in column (4) of Table 5 confirm that blockchain technology innovation reduces supply chain concentration, promotes diversification of supply chain configuration and supply chain management. Through its nature of decentralization, blockchain optimizes supply chain management and reduces intermediate links, thereby reducing energy consumption in logistics and warehousing. For example, the use of blockchain technology can track the full life cycle of a product, from raw material procurement to final sales, which helps companies predict demand more accurately and reduce overproduction and unnecessary transportation. Hypothesis 5 has been verified.

4.5 Heterogeneous effects

4.5.1 Marketization degree

In economic development, enterprises cannot achieve the ideal effect of energy saving and emission reduction without a good market environment. It is manifested in the full market competition, perfect market system, and so on. However, the Chinese market has a short board of uneven resource allocation. The highly competitive market forces distort the price signals in the product market and change the demand for factors, resulting in an unequal marginal output of factors and ultimately misallocation of resources. Based on this, this paper has examined the heterogeneity of energy effects of blockchain technology innovation at different marketization levels. As can be seen from Table 6, in regions with high marketization levels, blockchain technology innovation has reduced the level of energy consumption of enterprises. The high level of marketization means that the allocation of resources depends more on market mechanisms than governmental intervention. This helps guide enterprises in making energy consumption decisions according to market signals and achieving the optimal allocation of resources. Meanwhile, enterprises are motivated to carry out technological innovation and are more inclined to adopt energy-saving technologies and equipment to reduce energy waste and reduce production costs. In low-marketization areas, the energy effect of blockchain technology innovation is not significant. This shows that a high level of marketization can help deliver a better environment and higher efficiency to the development of enterprises [57]. However, enterprises also need to develop reasonable energy consumption strategies according to their own actual conditions and market environment and make full use of market means to support the green and low-carbon energy transformation [58].

4.5.2 Industrial character

Factors of production play an important role in the enterprises' operation and development. Rational use and allocation of production factors can not only improve production efficiency and product quality but also achieve sustainable development [59]. Based on this, this paper divides enterprises into labor-intensive ones, technology-intensive ones and capital-intensive ones, and has examined how the energy effects of blockchain technology innovation differ. As shown in Table 7, blockchain technology innovation has a more significant effect on reducing the intensity of fossil energy consumption in labor-intensive enterprises. In traditional labor-intensive enterprises, the recording and management of energy consumption data are often opaque and inaccurate. This is mainly caused by the backward data recording method and the non-standard data management. The introduction of blockchain technology can achieve real-time recording, immutable, and transparent management of energy consumption data. Enterprises can record every energy consumption data on the blockchain through the blockchain platform, forming an immutable data chain. In this way, enterprises can accurately analyze energy consumption according to these data, and find out the peak and low periods of energy consumption, so as to rationally arrange production plans and energy use plans to achieve the purpose of reducing the intensity of energy consumption [57].

4.6 Further analysis

As a distributed database technology, blockchain technology innovation is characterized by decentralization, transparency, and immutable data. As discussed above, enterprises can manage and track energy consumption more efficiently through blockchain technology innovation, so as to achieve optimal allocation of fossil energy and reduce fossil energy consumption. This section will delve into the economic and environmental consequences of applying blockchain technology innovation to reduce enterprises' fossil energy consumption.

Table 6. Heterogeneity test for the level of marketization.

Variables	High level of marketization	Low level of marketization
	(1)	(2)
lnBC	−0.2786*** (0.0699)	−0.3915 (0.4094)
Lev	−1.3870*** (0.2154)	−0.1842 (1.1914)
ROA	−3.2405*** (0.4782)	−13.5693 (10.5711)
Cashflow	−0.9118*** (0.3337)	13.5044 (13.6189)
Top1	−0.6751*** (0.1431)	2.3330 (2.5386)
ListAge	−0.1259*** (0.0478)	0.0247 (0.1768)
Cons	−0.2786*** (0.0699)	−0.3915 (0.4094)
Year FE	Yes	Yes
Industry FE	Yes	Yes
N	15,228	13,093
R^2	0.1684	0.0080

Note: ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$, the results end at the fourth decimal place.

Table 7. Heterogeneity test for production factors.

Variables	Labor-intensive	Technology-intensive	Capital intensive
	(1)	(2)	(3)
lnBC	−0.3315*** (0.0833)	−0.4462 (0.3099)	−0.0839 (0.2200)
Lev	−1.7613*** (0.3734)	−0.3913 (0.8692)	−1.4249*** (0.3092)
ROA	−3.4107*** (0.9352)	−7.2508* (4.2014)	−3.1887*** (0.6493)
Cashflow	−1.3192*** (0.5044)	7.0772 (7.3165)	−1.1347** (0.5650)
Top1	−0.7478*** (0.1898)	1.3878 (1.7759)	−0.1341 (0.2602)
ListAge	−0.1041* (0.0626)	0.0786 (0.2070)	−0.2905*** (0.0807)
Cons	2.2772*** (0.2591)	0.1400 (1.6414)	1.7148*** (0.2919)
Year FE	Yes	Yes	Yes
Industry FE	Yes	Yes	Yes
N	7,565	17,352	3,404
R^2	0.1578	0.0050	0.2394

Note: ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$, the results end at the fourth decimal place.

4.6.1 The enterprises' operation efficiency (TQ)

In traditional energy trading, the costs in transaction costs and time tend to be high due to the asymmetry of information and the complexity of the transaction process. Blockchain technology can enable direct transactions of energy and speed up the execution of transactions and reduce transaction costs. The smart contract function of blockchain enables automated transaction execution and payment, which not only eliminates intermediary links but also saves labor costs. For example, Electrify, a Singapore-based energy company, has adopted an energy trading platform developed with blockchain technology, which allows it to trade directly with energy suppliers, thus improving the transparency of transactions and the efficiency of business operations [60]. The results in column (1) of Table 8 show that the enterprises' applying blockchain technology to reduce fossil energy consumption can improve operational efficiency.

4.6.2 The enterprise's carbon emission

The comprehensive tracking and monitoring of the supply chain can be realized through blockchain technology, including the procurement of raw materials, production, transportation, and other links. By optimizing supply chain management, enterprises can reduce unnecessary energy consumption and waste, thereby reducing carbon emissions [61]. At the same time, blockchain technology can ensure the authenticity and immutability of carbon emission data. Every carbon emission data is permanently recorded on the blockchain and cannot be modified or deleted. This provides a reliable database for enterprises to understand their carbon emissions more accurately and develop

Table 8. Economic and environmental consequences.

Variables	Eff	Carbon
	(1)	(2)
lnEC*lnBC	0.0209** (0.0100)	−0.3233*** (0.0960)
Lev	0.0055 (0.0068)	0.2021 (0.2530)
ROA	0.0197** (0.0097)	0.6288** (0.2795)
Cashflow	−0.0087 (0.0109)	0.8844* (0.4987)
Top1	−0.0019 (0.0096)	−0.1016 (0.2358)
ListAge	0.0323*** (0.0033)	−0.1362* (0.0821)
Cons	0.0525*** (0.0078)	1.9747* (1.0761)
Year FE	Yes	Yes
Industry FE	Yes	Yes
N	21,791	27,666
R^2	0.1158	0.0466

Note: ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$, the results end at the fourth decimal place.

corresponding emission reduction strategies [62]. The results in column (2) of Table 8 show that enterprises applying blockchain technology to a reduction in fossil energy consumption can reduce the amount of carbon emissions.

5 Conclusion and discussion

In the Industry 5.0 Era, the major countries in the world are accelerating the development of blockchain technology, and the application of blockchain technology has been extended to digital finance, the Internet of things, intelligent manufacturing, supply chain management, digital asset trading, and other fields. Blockchain can coordinate industrial integration, innovate business models, and promote green, low-carbon, and sustainable development. This paper establishes a theoretical analysis framework for the impact of blockchain technology innovation on energy consumption and uses the data of listed companies in China to verify the energy effect of blockchain technology innovation and its impact mechanism. The study found that blockchain technology innovation reduces the enterprises' intensity of energy consumption. In terms of the impact mechanism, the enterprises' blockchain technology innovation can achieve energy transition by reducing the cost of internal control of the enterprises, strengthening the degree of external supervision, improving the efficiency of resource allocation and strengthening the channels of supply chain management. Further research has found that the energy effects of blockchain technology innovation help to improve the efficiency of business operations and reduce carbon emission levels.

Combined with the above research's conclusions, this paper puts forward the following policy implications. First, policymakers should actively promote the development of decentralization of blockchain technology by establishing distributed energy trading platforms to enhance the convenience of direct peer-to-peer energy transactions between various participants of renewable energy sources, nets-charge-storage. This not only helps to improve the substitution of renewable energy sources for fossil energy sources but also helps to improve the safety, flexibility and stability of renewable energy systems. The government is also able to support enterprises to carry out blockchain energy management projects by setting up special funds or providing preferential policies such as tax breaks for enterprises with blockchain technology [63]. Second, enterprises should combine the characteristics of blockchain technology, optimize internal management processes, improve the efficiency of resource allocation, and ensure the effective integration of technology and business in the Industry 5.0 Era [64, 65]. Enterprises should take a comprehensive look at their internal management processes and identify key processes that are closely related to energy consumption and the application of blockchain technology. By integrating and optimizing these processes, enterprises can ensure the docking of blockchain technology with existing business processes to improve energy management efficiency and reduce energy consumption. Finally, enterprises should establish a blockchain energy monitoring system to identify external systemic risks in a timely manner, such as energy policy changes, market fluctuations, and technical security risks. At the same time, dynamic real-time monitoring shall be applied to the economic and environmental consequences of the enterprises during the process of energy transition. The response plans shall be formulated, as well as the risk response strategies and measures shall be clarified in order to ensure rapid response when risks occur and to reduce the impact on enterprise energy consumption and operations. In the face of technical security risks, enterprises should develop safer and more efficient blockchain technology solutions. Through technological innovation, the stability and security of blockchain technology shall be improved in order to reduce the risk of the enterprises during the application. Overall, blockchain technology eliminates the high fees and inefficiencies caused by intermediaries through a decentralized energy trading platform, enabling energy suppliers and users to directly conduct peer-to-peer energy trading. This trading mode not only reduces the transaction cost but also improves the flexibility and efficiency of the transaction. All energy transactions will be recorded on the blockchain, which can be queried by anyone, greatly improving the transparency of transactions. This transparency helps regulators to regulate energy markets more effectively and prevent energy waste and abuse.

As for the problem that the PoW mechanism of blockchain technology requires a large amount of computing power and power resources, some new consensus mechanisms need to be proposed in the future. For example, large-scale application of Proof of Stake (PoS) and proof of authority (PoA). These consensus mechanisms do not require a lot of computing power but instead rely on verification nodes that hold a certain amount of digital currency or have a specific identity to confirm transactions and generate new blocks. In this way, energy consumption and carbon emissions can be reduced, thus making it more low-carbon and environmentally friendly.

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Conflicts of interest

The authors declared no potential conflicts of interest with respect to the research, authorship, and publication of this article.

Data availability statement

The datasets used and analyzed during the current study are available from the corresponding author upon reasonable request.

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