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In the Context of China's Mineral Resource Scarcity: How Does Digitalization Promote Low-carbon Transformation of Corporate Energy?

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Abstract

In the context of growing global energy demand and advancing climate change, digital technologies offer opportunities for a low-carbon energy transition. Through such technologies, including big data, artificial intelligence and the internet of things, digitalization enables intelligent optimization, flexible management and efficient operation of energy systems, access to renewable energy, and reducing both energy consumption and carbon emissions. Grounded in the data

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of listed companies from 2011 to 2020, this study discusses the influence of enterprise digitalization on the low-carbon energy transition. The results show that enterprises' digital development will boost their low-carbon energy transformation effectively. Digitalization promotes enterprises to achieve this transformation by aiding them in improving green technology innovation, optimizing supply chains and improving internal control level. In addition, a heterogeneity analysis of environmental regulation shows that in regions with strong environmental regulation, the promotion effect of enterprise digitalization on low-carbon energy transformation is more significant. The regional heterogeneity in the results suggests that eastern and central enterprises have a stronger promotion effect on enterprise energy low-carbon transformation in digital transformation. Therefore, such transformations should be regarded as important, and they should be incorporated into environmental protection policy. This would include promoting low-carbon technology innovation, combining environmental protection regulation with carbon emission reduction and implementing suggestions for reducing carbon emissions and sustainable development goals.

Keywords: Mineral resources, digital technology, digital transformation of enterprises, carbon emission reduction, low-carbon energy transformation

JEL Classification: Q51, C33, O44

1. Introduction

In the 21st century, we are living in an era full of transformation and challenges. Across the globe, economic structures, methods of production, ways of life and modes of thinking are undergoing profound changes. One of the driving forces behind this transformation is the rapid development and widespread application of digital technology. Digital transformation has become an inevitable trend in the development of all sectors, and at the same time, the concept of sustainable development is increasingly taking root in people's hearts. As it stands, China is still in a period of scarcity of resources and energy, and the issues of endless mining and wasting of mineral resources are becoming apparent. To meet the growing demand for minerals as society develops, miners can only continuously extract a large amount of mineral resources. However, due to the use of relatively backward mining technology in China, this has led to a significant wasting of resources, putting China in a dilemma where it can neither continue to exploit on a large scale nor meet the needs of development. At the moment, the world is holding high the banner of sustainable resource development. Mining companies have also realized that the old mine management model and outdated mining technology can no longer meet the current development needs, and innovation in management is urgent. Therefore, enterprises should implement the concept of sustainable development by focusing on improving mining technology and innovating the mine management model and taking the path of environmentally friendly resource utilization. Against this backdrop, exploring the relationship between digitalization and the low-carbon transformation of energy is of great theoretical and practical significance for us to understand the future direction of economic and social development, as well as to achieve a harmonious coexistence between the development and utilization of mineral resources and environmental protection.

In fact, digital technology is becoming increasingly integrated into every aspect of our economic, political, cultural, social and ecological life. This is happening through implementing new ideas, formats and models, and has been having a profound and extensive impact on production and daily life. Digitalization is important, both as actual content and as a symbol of the information revolution. Moreover, a profound and lasting impact has been made by the accelerating advancement of digital technology on the economy, society and culture around the world. Digital technologies are seen as an important driver of economic growth and innovation. They provide enterprises with more efficient production methods, broader markets and more accurate data analysis, thereby enhancing their competitiveness. Such technology is considered a crucial element in advancing social progression and enhancing lifestyle standards. Because of digital technology, people can more conveniently access information, communicate and participate in social activities. However, despite such technology having been widely used and recognized around the world, there are still significant gaps in development and presence among countries. In this regard, China, being one of the world's foremost internet markets, has emerged as an essential player and advocate in the realm of digital innovation. In China's "14th Five-year Plan", accelerating the digitalization and building a "digital China" are the country's core strategies. Its foundational aim is to promote the development of a healthy digital ecological environment by developing a digital economy (*DE*), a digital society and a digital government. Nowadays, digital transformation (*DT*) has indeed become the primary driver of the daily operation of today's enterprises. Enterprises apply digitalization to business management and the production process through artificial intelligence, cloud computing, big data, internet of things (IoT) and other advanced technologies, all of which can improve production efficiency, reduce costs (Sun *et al*., 2022) and enhance user satisfaction (Calvo-Porral *et al*., 2017). According to the China Academy of Information and Communication Technology's White Paper on the Development of China's Digital Economy, the magnitude of China's digital economy is projected to escalate to 39.2 trillion yuan in 2020, representing a significant 38.6% of the nation's GDP. So far, according to the Government Work Report delivered at the first session of the 14th National People's Congress, the *DE* has been growing; furthermore, the added value of emerging sectors, novel forms of business and innovative models has accounted for more than 17% of GDP. As such, *DT* has clearly become an irreversible trend, but it is simultaneously a crucial strategic choice: digitalization has emerged as a pivotal driver in China for fostering superior social (Neligan *et al*., 2022) and economic growth. This is reflected in promoting innovation and upgrading technology, encouraging the reform of advanced industrial structure, rationalizing industrial structure (Hao *et al*., 2023), expanding the scale of the consumer market, enhancing international competitiveness and supporting employment and talent training (Jacob *et al*., 2023).

Digitalization is widely perceived as a viable strategy for mitigating greenhouse gas emissions and fostering sustainable economic progress (He and Xie, 2022). Not only can it improve enterprises' total productivity (L. Wang *et al*., 2022; Su *et al*., 2023) and reduce management costs (M. Chen and K. Wang, 2023; K.-H. Han *et al*., 2023), but it can also be conducive to promoting information construction (W. Chen, 2023), energy conservation, emission reduction (H. Zhang, 2023) and a green development strategy (Hoyk *et al*., 2022). Through widespread utilization of digital technology, innovation and upgrading can be promoted in various fields, something that has already profoundly affected society, the environment and culture. Therefore, accelerating *DT* is not only inevitable for enterprise development, but it also constitutes a crucial initiative towards fostering exceptional growth in China.

Therefore, can digital transformation reduce corporate carbon emissions? What is its mechanism of action? Can enterprise digital transformation promote carbon emission reduction in companies? Delving into these issues is of great significance for exploring effective paths for low-carbon transformation of enterprises and aiding in the achievement of China's "dual carbon" goals. Through a literature review, it has been found that digital transformation is of great importance for enterprises to achieve green development. However, existing research into digitalization and carbon emission reduction is mainly at the macro-regional level (Khan *et al*., 2020; Cui a Cao, 2024) with insufficient evidence at the micro-level of economic entities, namely individual companies. Particularly for China, the focus on carbon emission reduction has a short perspective, lacking sufficient micro-level corporate carbon emission data, which has restricted the conduct of related research. Therefore, we select micro-enterprises as the subject and studies the impact of enterprise digitalization on corporate carbon emission intensity and its mechanism of action, which can further expand the understanding of digital transformation and enrich the research into the paths of digital transformation and carbon emission reduction for the market and enterprises.

Based on the above discussion, as the micro subject of energy consumption and carbon emissions in the production process, the influence of enterprises' *DT* on carbon emission reduction has not yet been fully tested. The significant contribution of this research is encompassed in three main facets:

(1) This study examines the influence of digital transformation at the enterprise level on carbon emissions from a micro perspective, in the context of scarce mining resources. This enriches the academic and practical understanding of digital transformation and carbon emission reduction from the viewpoint of micro-structural entities. Reducing carbon emissions at the enterprise level can make a substantial contribution to environmental protection. Secondly, the widespread application of digital technology in various industries is bringing about fundamental changes to corpo-

rate management, production and operational models. Digital transformation offers many innovative solutions and tools that can effectively optimize energy utilization, reduce carbon emissions and promote the achievement of sustainable development goals.

(2) Based on the research framework of "theoretical analysis-empirical analysis", this study not only fully tests the influence of enterprise *DT* on carbon emission intensity (*CEI*) but also conducts a mechanism analysis and test based on the following three aspects: the internal control effect, innovation effect and green supply chain optimization effect, all of which enrich the existing theoretical research.

(3) Based on the characteristics of corporations and their areas, we investigate the heterogeneous effect of enterprises' *DT* on carbon emission reduction. As such, we offer a more comprehensive reform path for China's *DE* to propel the realization of carbon emission reduction goals. Including the heterogeneous outcomes can provide a scientific basis and practical experience for achieving a low-carbon economy and sustainable development goals, thereby promoting the synergetic development of society, economy and environment.

The rest of this study is organized as follows: Section 2 presents the literature review and theoretical hypotheses, Section 3 details the data source and variable selection, Section 4 is comprised of the empirical analysis, and the final part discusses the conclusion and policy recommendations.

2. Literature Review and Theoretical Hypotheses

2.1 Literature review

The pervasive adoption of digital technology fosters the digital metamorphosis of corporations and augments the efficiency of innovative technological advancements. (T. Li *et al.*, 2022). For traditional companies, "digital technology" is applied to life and work scenarios and the business model is optimized through data-driven business growth and guidance (Kaur *et al.*, 2023). The intent is to improve the efficiency and convenience of an enterprise's operation. The progress of enterprise technology will generate business innovation (Ramdani *et al.*, 2022). On the one hand, digitalization provides new technical means for enterprises' green development. In terms of utilizing digital technology. In the context of digital technology application, numerous scholars have demonstrated that *DT* can significantly enhance energy utilization efficiency and reduce pollutant emissions. Meanwhile, the low-carbon driving mechanism of digital economy (*DE*) has spatial heterogeneity at the level of regional technology accumulation (D. Han *et al.*, 2022). On the other hand, for corporations, *DT* promotes carbon emission reduction, especially for those needing to adhere to strong environmental regulation, facing fierce industry competition or focusing on *DT* at the production end. Employing time-series data of Chinese publicly listed manufacturing corporations, Wen *et al*. (2022) performed an empirical study and contended that clean energy and digitalization were the principal paths of the new industrial revolution. Furthermore, they concluded that environmental regulation could promote enterprises' *DT*. For example, Cao *et al*. (2021) discovered that digital finance demonstrably enhanced energy and environmental performance, particularly when corporations endeavoured towards energy conservation and emission mitigation. They also found that environmental pollution was significantly reduced. The existing literature focuses on enterprise technology innovation (B. Lin and Zhu, 2019), environmental regulation (T. Zhang *et al*., 2022), and carbon emission trading policy (Wei *et al*., 2022; B. J. Wang *et al*., 2019), each evaluating enterprises' emission reductions. Among them, some indicate that the cooperation effect of technological advancement is positive for carbon emission curtailment (X. Jiang *et al*., 2021). Q. Xu *et al*. (2023) demonstrated that in regions with strong environmental regulation, *DT* more significantly affected the environmental performance of resource-dependent companies. From the standpoint of carbon emission privileges, C. Zhang and J. Lin (2022) maintained that the *DE* has progressively emerged as a vital impetus for regional low-carbon development.

Simultaneously, given the increasing seriousness of global climate change and environmental problems, reducing carbon emissions has become a vital task set before the world today. Because they are such an important environmental indicator, carbon emissions are not only limited by policies and the formulation of new standards, but they also (either directly or indirectly) affect brand image, risk and sustainable development (Yu and Tsai, 2018). Enterprises reduce carbon emissions through *DT*, which not only aligns with social responsibility, but also can enhance credibility and attractiveness for sustainable development and, sometimes, obtain more investment.

According to the literature review, there are many ways that digital technologies can affect corporate carbon emissions:

(1) *DT* helps promote enterprise energy conservation and emission reduction; it can not only optimize enterprises' technological innovation capability but also achieve energy conservation and emission reduction by promoting enterprises' structural optimization of production and operations (Ma and B. Lin, 2023).

(2) Digital technology can be used to improve firms' efficient use resources and energy (B. Lin and Huang, 2023). When enterprises achieve improved production scale and efficiency through *DT*, this translates into fewer carbon emissions.

(3) Enterprises can realize a green and low-carbon supply chain via intelligent logistics and other technologies. The realization of such a green supply chain would require effective measurement, monitoring and improvement of each link by optimizing the supply chain process, corresponding data analysis, IoT sensors and other means, so as to reduce unnecessary logistics de-

mand, driving time, inventory management and so on, as well as to contribute to reducing carbon emissions (R. Zhao *et al*., 2017; Bai *et al*., 2019).

(4) *DT* helps enterprises achieve immediate interaction and complementary advantages in innovation, break through barriers, reduce carbon emissions, optimize production and reduce energy and material consumption (Quito *et al*., 2024) and lower waste discharge; this is done through data analysis, automating control and other digital technologies (L. Liu *et al*., 2022).

(5) Improving enterprises' internal control can be achieved through *DT* and carbon emissions can be reduced by means of real-time monitoring, strengthening internal management, promoting green production technology and other aspects (Shang *et al*., 2023). Some examples include strengthening internal management and conducting carbon emission audits and assessments. Additional measures include setting up an internal audit organization with full functions, grasping the company's carbon emission status and trends, discovering and correcting problems in a timely manner, ensuring environmental compliance and adhering to regulatory requirements. Companies can use digital means to assess carbon emissions, identify the main sources and contributions of their carbon emissions and reduce emissions by heightening energy efficiency (Usman *et al*., 2024), reducing waste and other measures.

2.2 Theoretical mechanism

Firstly, from the perspective of energy supply and demand, *DT* aids in integrating digital technologies into the production and logistics processes of enterprises, thereby improving the efficiency and precision of energy supply. Not only does this provide the technical foundation for upgrading resource flow and supply, but it also makes it possible for enterprises to utilize energy more efficiently when information is incomplete (Duch-Brown and Rossetti, 2023), thereby reducing carbon emissions and *CEI*. Secondly, *DT* is grounded in the perspective of energy consumption structure. Indeed, research reveals that *DT* promotes energy transformation (Fan *et al*., 2022). Thirdly, *DT* is based on energy regulation. During the epoch of traditional industrial digital evolution, using digital technology can more accurately and efficiently capture the data and information of each production or operational link. Then, based on that information, management can make more advantageous decisions shortly. From the perspective of external regulation, the energy market can operate better under the supervision of external regulatory agencies, and data analysis can be conducted with the utilization of digital technology to achieve remote supervision (Sepasgozar, 2021). Based on the above, we formulate the following hypothesis:

Hypothesis H_1: The digital transformation of enterprises can promote carbon emission reduction.

Grounded in the dimension of enterprise green and low-carbon technology exploration, enterprise *DT* can minimize the expenditure on eco-friendly technological advancement while augmenting the development rate of low-carbon solutions. Flyverbom *et al*. (2018) showed that the process of *DT* and digitalization fundamentally reshaped the way information was produced, distributed and given meaning. Digitalization provides new technical means for enterprises' green development, increases environmental governance costs and strengthens a company's awareness of environmental governance (Wen *et al*., 2022). Together, all of these help enterprises save energy and reduce carbon emissions. When enterprises carry out a significant degree of low-carbon technology innovation, they will go from a quantitative change to a qualitative one.

Chinese traditional enterprises in the post-industrial era have undergone several technological upgrades and their digital technologies can significantly optimize production efficiency and reduce costs (Zhao *et al*., 2024). Moreover, the technological capability of corporations is the basis for green technology innovation, which is the essential issue regarding continuous competition with peers. By supporting collaborative breakthroughs among corporations, improving the degree of information sharing and enhancing knowledge sharing capability, the extent of eco-friendly technological advancement can support achieving the ultimate goal of corporate carbon emission reduction (Zhao *et al*., 2022). *DT* and green technology innovation are positively correlated with carbon emission reduction in enterprises which invest heavily in environmental protection and follow strong environmental regulation, according to Men *et al*. (2023). Li *et al*. (2021) analysed the innovation data of new energy listed companies to build a green innovation network and proved the innovation effect of digital technology in improving new industries. Moreover, a favourable market environment can play a guiding role in encouraging competition and market demand. For instance, carbon trading can stimulate corporate innovation by utilizing the market supply and demand mechanism, as pointed out by Wei *et al*. (2022). This leads to the advancement of innovative digital technology solutions, fostering proactive digital innovation among enterprises and thereby reducing carbon dioxide emissions. Based on this, we put forward the following hypothesis:

Hypothesis H_2: Corporate digital transformation can promote corporate carbon emission reduction by promoting green technology innovation.

The following is based on the perspective of enterprise green supply chains. Corporate carbon emissions come mainly from processes such as production, transportation and storage (Amina *et al*., 2019; Chelly *et al*., 2019). By using digital technology to oversee low-carbon supply chain management in the lifecycle, enterprises can quickly evaluate the impact factors of carbon emissions in each procedure; this helps enterprises better understand the carbon footprint of the lifecycle of products and services (Wassmann *et al*., 2023). Additionally, coordinated supply chain actions can be taken to lower carbon emissions in the entire supply chain. Using digital technology and platforms can help enterprises quickly obtain information about each production and operational link, shorten response times to changes in the external circumstances and address the issues of information asymmetry and information islands in traditional supply chains, so as to promote supply chain circulation speed. In the production process, *DT* promotes competitive advantage and improves energy efficiency and utilization rates, thereby enhancing awareness and strengthening determination of enterprises regarding supply chain *DT*. By optimizing the supply chain, the efficiency of information transmission, the accuracy of information matching in each link and competitive advantages can be improved. For example, by means of environmental regulation and consumers' green preference, supply chain optimization can significantly support enterprises in implementing green supply chain innovation (Huo *et al*., 2022). Finally, optimizing the supply chains can encourage corporations to economize energy and diminish carbon emissions. Based on this, we present the following hypothesis:

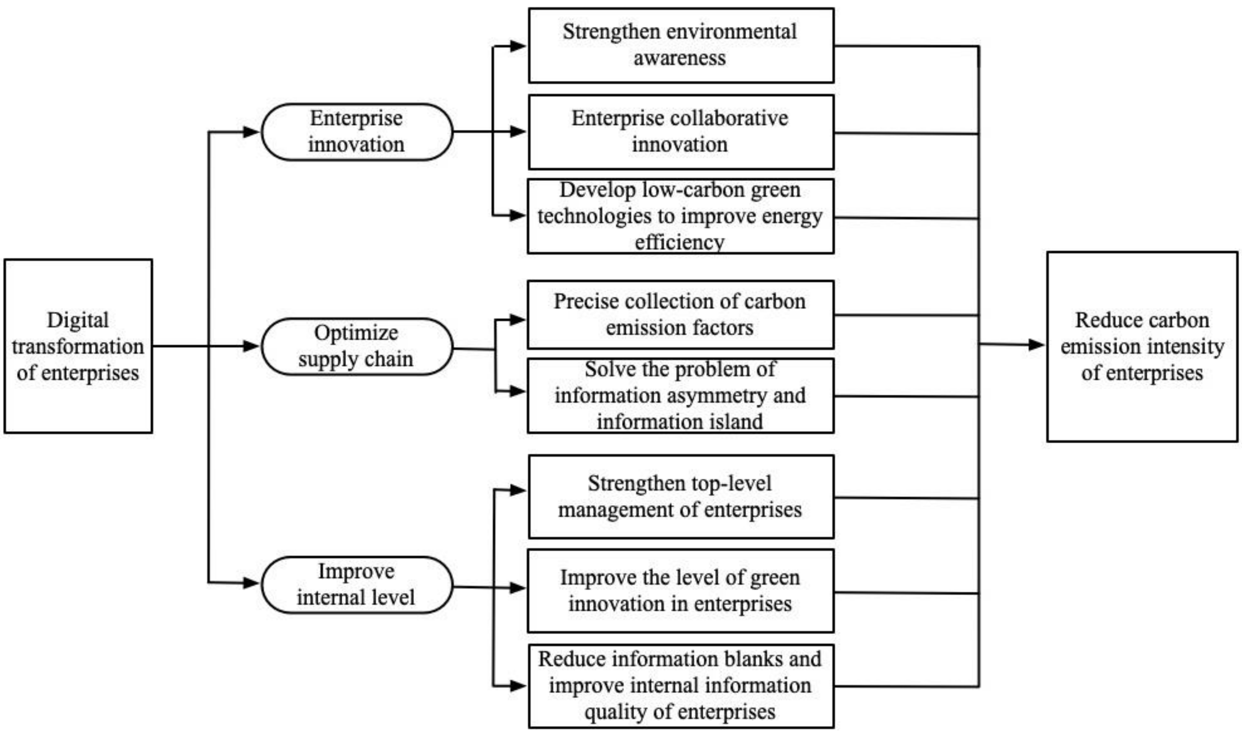
> **Hypothesis H_3**: Corporate digital transformation can promote corporate carbon emission reduction by optimizing the supply chain.

Based on the dimension of corporate internal control level, the following can be presented. Firstly, there are risks involved in internal control, which can seriously affect implementing internal work (Cheng *et al*., 2018). In traditional enterprises, and given the continuous advancement of corporations, the lack of internal control risk management is a critical factor restricting efficient management. When an enterprise reaches a certain stage in its development, internal control will gradually become the cornerstone of its management and code of conduct. Such transitions ensure the company's stable operation and sustainable development. K. Jiang *et al*. (2022) deemed that through *DT*, the corporations' level of internal control can be improved, thereby strengthening top-level management. To achieve the goal of indirectly reducing a firm's carbon emissions, therefore, it is vital to establish a sound internal control system as soon as possible and to optimize its management mechanism continuously. Secondly, good internal control is of great practical significance for improving operational efficiency (D. Li *et al*., 2020) and for promoting development. Strengthening internal control is the objective requirement of the modern enterprise system, and it is also an important guarantee for the smooth operation of enterprises. By establishing an effective internal control mechanism, enterprises can better identify, assess and manage risk, thus reducing possible losses and uncertainties. This helps improve an enterprise's stability and sustainability, as well as provide a good environment for their ongoing development. Moreover, improving the effect of internal control can greatly improve innovation performance (D. Li *et al*., 2020). Furthermore, internal control can advance green innovation by lowering corporate risk, alleviating financing constraints and enhancing the rationality of innovation investment. Finally, with the assistance of digital technology, stakeholders can share information more easily, thus reducing information gaps, improving the authenticity of corporate financial reports, operating results and risk control, and enhancing the information quality of internal supervision (Kuang *et al*., 2022).

In addition, relevant regulatory authorities should increase supervision of corporate carbon emissions and energy supply. By using digital technology, regulatory authorities can quickly and accurately observe the degree of change regarding carbon emissions on the market (Antil *et al*., 2023). Then, based on these data, they can regulate the energy supply of enterprises so that carbon emissions and energy consumption can meet the established standards. Doing so will reduce enterprises' carbon emissions. Furthermore, improving the level of internal control can strengthen top-level management, enhance labour productivity and efficiency and indirectly reduce carbon emissions. In addition, strengthening external supervision can also directly promote low-carbon energy transformation among enterprises. Based on the above, we offer the following hypothesis:

Hypothesis H_4: Corporate digital transformation can improve the level of corporate internal control and promote corporate carbon emission reduction.

Figure 1: Framework of theoretical mechanism



Source: Authors' own elaboration

3. Research Design

3.1 Study area

This study focuses on listed companies in China to explore the impact of digital transformation on corporate carbon emissions. Through in-depth analysis of the digitalization process and carbon emission data of companies during this period, the study aims to reveal how *DT* affects the intensity of corporate carbon emissions and the linear relationship that exists between the two. The research sample covers multiple industries, including manufacturing, mining, high-tech industries and others, to comprehensively examine the widespread impact of digital transformation on carbon emissions across various types of enterprises.

3.2 Sample data

The data in this study are obtained from the CSMAR database, and the samples are screened by the following standards: (1) exclude the samples of ST (Special Treatment), ST*, suspended listing and delisted companies; (2) eliminate all samples belonging to the financial industry; (3) eliminate samples with missing key variables and control variables; (4) eliminate the influence of sample outliers. Regarding the latter, the specific method is to take 1.2 times the 99% quantile of the variable as the maximum value and sample values greater than this value are reduced to this value; 0.8 times the 1% quantile is taken as the minimum value and sample values less than this value are increased to this value. In addition, the annual reports required by this paper are retrieved from the official websites of Shanghai Stock Exchange and Shenzhen Stock Exchange, and the remaining financial data are obtained from the CSMAR database.

3.3 Variable selection

The explained variable is corporate carbon emission intensity (*CEI*). This study relies on the practice of Chapple *et al*. (2013). An enterprise's *CEI* (*Intensity*) is described by the ratio of the calculated corporate carbon dioxide micro emissions (*Carbon_DR*) to its operating income (*firm_i*). The corporate carbon dioxide micro emissions are estimated according to the total energy consumption of the industry (*TECI*), and the calculation method is as follows. The enterprise's main business costs is *firm_c* and the primary costs of the industry as a whole are *Industry_c*. The data regarding the principal operating cost of the industry and the total energy consumption of the industry are obtained from the China Statistical Yearbook of Industrial Economy and China Energy Statistical Yearbook, respectively. The specific calculation formula is as follows:

$$Intensity = \frac{Carbon\_DE}{firm\_i \times 1{,}000{,}000} \tag{1}$$

$$Carbon\_DE = \frac{firm\_c}{Industry\_c} \times TECI \times 2.493 \tag{2}$$

The core explanatory variable is enterprise *DT* (*digital_tran*). We use Python web crawler to download the annual reports of all listed companies from 2011 to 2020 and text analysis to measure the degree of enterprise *DT* (Wu *et al.*, 2022). First, referring to the extant literature, the keywords about digitalization are summarized and categorized. Afterwards, the total word frequency and total number of sentences in the annual report are extracted through Python text analysis, and then 1 is added to the original word frequency and the original number of sentences. Finally, the word frequency of digital keywords is used as a proxy index of enterprise *DT* (*digital_tran*).

As for the control variables, we employ the following control parameters in reference to previous articles: (1) enterprise size (ln *size*), the logarithm of the total assets at the end of the year; (2) whether it is a state-owned enterprise (*Soe*): if it is state-owned, the variable is defined as 1; otherwise, it is 0; (3) enterprise total asset turnover (*Turnover*), the ratio of operating income to average total assets; (4) the natural logarithm for the number of employees (ln *number*) and the natural logarithm of the total number of employees at the end of the year; (5) the shareholdings of the top five shareholders (*Pre_five*); and (6) equity balance (*Gqz*), the shareholding ratio of the second to fifth largest shareholders/shareholding ratio of the largest shareholder. In addition, we also control time (*time*) and industry (*Industry*) as fixed effects. The company's annual report and other financial data are sorted out in the CSMAR database.

3.4 Model setting

To test the influence of corporation digitalization on *CEI*, we construct the following model:

$$\begin{aligned} Intensity_{it} &= \alpha_0 + \alpha_1 digital\_tran_{it} + \alpha_2 Insize_{it} + \alpha_3 Soe_{it} + \alpha_4 Turnover_{it} + \\ &+ \alpha_5 Innumber_{it} + \alpha_6 pre\_five_{it} + \alpha_7 Gqz_{it} + \varepsilon_{it} \end{aligned} \tag{3}$$

where *i* denotes industry and *t* denotes time.

We employ a quantitative method to analyse the relationship between *DT* and carbon emissions, offering statistically significant empirical evidence that can be generalized across different industries and company sizes. By integrating a wide range of data sources, this research provides a comprehensive perspective on the *DT* process and its environmental impact. However, there are some limitations; the study relies on cross-sectional data, which may fail to capture the dynamic changes of *DT* and its impact on carbon emissions. Although this research identifies a correlation between digital transformation and carbon emissions, it may not fully explain the potential causal mechanisms by which *DT* leads to emission reductions.

4. Empirical Analysis

4.1 Descriptive statistics

We sequentially select data from Chinese listed companies from 2011 to 2022 for analysis, following the previously designed control variables, core explanatory variables and dependent variables. During the data processing, effective measures were taken, resulting in a final dataset of 18,076 entries. The descriptive statistical results are as follows.

Table 1: Descriptive statistics

Variable	*N*	Mean	St. dev.	Min	Max
Intensity	18,076	0.8194	1.3730	–1.1414	4.5125
digital	18,076	0.0176	0.0005	0.0005	0.1823
ln *size*	18,076	22.1818	1.3292	17.6413	28.6365
Soe	18,076	0.3509	0.4772	0.0000	1.0000
Turnover	18,076	0.6524	0.4982	0.0053	11.2744
ln *number*	18,076	8.0750	7.5930	1.0000	10.0156
Pre_five	18,076	55.1245	15.5251	0.8109	99.2300
Gqz	18,076	73.4792	62.0540	0.0000	400.0007

Source: Authors' own calculations

4.2 Benchmark regression analysis

Table 2 presents the results of the benchmark regression model, with column (1) showing a negative correlation between *DT* and corporate *CEI* without controlling for any variables. This indicates that *DT* can significantly reduce corporate *CEI*, providing preliminary support for the theme proposed in this article. However, in column (2), the regression analysis is repeated after the control variables are added and the coefficient of the core explanatory variable remains significantly negative (1%), which once again proves our core argument that *DT* can reduce corporate carbon emissions and achieve low-carbon energy transformation. Columns (3) and (4) respectively control for the year variable and the industry variable. The coefficients of the digital transformation indicator for both are negatively significant, further demonstrating the significant inhibitory effect of corporate *DT* on corporate carbon emission intensity. Grounded in the above explanation, hypothesis H_1 is proved, namely that *DT* can boost a reduction in enterprise *CEI*, which is conducive to low-carbon energy transformation.

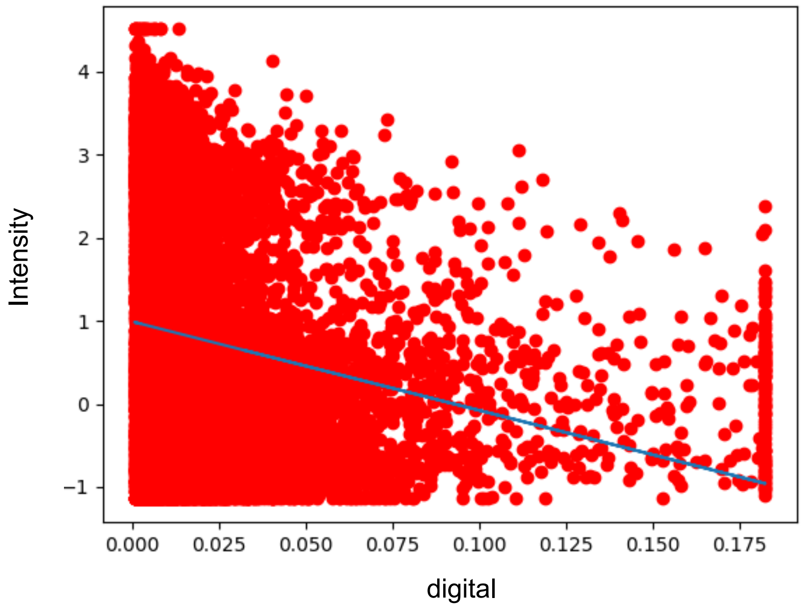
Table 2: Benchmark regression results

Variables	(1) *Intensity*	(2) *Intensity*	(3) *Intensity*	(4) *Intensity*
digital	−0.232*** (−3.00)	−0.422*** (−5.53)	−8.377*** (−26.28)	−2.309*** (−15.66)
ln *size*	–	0.011*** (5.44)	−0.014 (−1.59)	−0.040*** (−13.20)
Soe	–	0.080*** (15.17)	0.330*** (14.43)	0.181*** (21.68)
Turnover	–	0.120*** (17.61)	−0.039** (−2.56)	0.156*** (14.81)
ln *number*	–	0.000*** (4.23)	0.000 (0.84)	0.000*** (6.80)
Pre_five	–	−0.002*** (−13.80)	−0.001 (−1.12)	−0.002*** (−8.24)
Gqz	–	−0.000*** (−2.92)	−0.000 (−1.09)	−0.001*** (−9.68)
Cons	0.823*** (300.95)	0.582*** (13.16)	1.232*** (6.43)	1.698*** (25.97)
Industry fixed effects	Yes	Yes	No	Yes
Year fixed effects	Yes	Yes	Yes	No
N	18,076	18,076	18,076	18,076
R^2 adj.	0.951	0.954	0.121	0.891

Notes: *, **, *** indicate significance at the 1%, 5% and 10% levels, respectively. The *t*-stat value is in parentheses.
Source: Authors' own calculations

Python is used to draw the scatter diagram of enterprise *CEI* and *DT*. The horizontal axis represents the degree of *DT* and the vertical one represents *CEI*. However, the non-parametric estimation based on a scatter plot cannot statistically verify the significance of this negative relationship; thus, more comprehensive measurement approaches will be used to demonstrate it in the following section.

Figure 2: Scatter diagram of enterprise *DT* and *CEI*



Source: Authors' own elaboration

4.3 Mechanism test

In order to measure enterprises' green innovation levels, we use the logarithm of the number of green patents in the current year plus one (*envtapr_sum*). In addition to eliminating other unobservable factors, this relative index can mitigate issues related to endogeneity. The green patent list identifies patentable innovations, including inventions, utility models and design patents, based on IPC codes. We consider only invention patents and utility model patents, which include four patent types: (1) the amount of green inventions obtained independently in the present year, (2) the total green utility models gained independently in the present year, (3) the tally of green inventions secured jointly in the present year and (4) the green utility models obtained jointly in the current year. The results presented in Table 3 demonstrate the following: column (1) shows that enterprise *DT* can significantly reduce enterprises' *CEI*; column (2) suggests that enterprise *DT* can significantly improve firms' level of green technology innovation; and column (3) illustrates that *DT* can also significantly lower companies' *CEI* by enhancing green technology innovation. Thus, hypothesis H_2 is proved.

Table 3: Test results of enterprise innovation mechanism

Variables	**(1)** ***Intensity***	**(2)** ***Envtapr_sum***	**(3)** ***Intensity***
digital	−0.436*** (−5.70)	1.193*** (4.63)	−0.427*** (−5.60)
Envtapr_sum	–	–	−0.008*** (−2.91)
Control variable	Yes	Yes	Yes
Industry fixed effects	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes
Cons	0.559*** (12.02)	−4.714*** (−24.17)	0.554*** (11.91)
N	17,634	17,634	17,634
R^2 **adj.**	0.955	0.230	0.955

Notes: *, **, *** indicate significance at the 1%, 5% and 10% levels, respectively. The *t*-stat value is in parentheses.
Source: Authors' own calculations

We employ enterprise supply chain concentration (*SCC*) as a mediating variable to test whether *DT* diminishes enterprise *CEI* by optimizing the supply chain. We also conduct stepwise regression analysis. Column (1) illustrates that enterprise digitalization can significantly reduce enterprise *CEI*. Column (2) demonstrates that enterprise digitalization can significantly diminish the supply chain concentration. After the intermediary variable is added to the regression analysis in column (3), the absolute value of the coefficient of a corporation's *DT* index (*digital*) decreases. Therefore, it can be argued that enterprise *DT* contributes to a reduction in *CEI* by optimizing the supply chain. Against the backdrop of the increasingly obvious trend of environmental protection becoming stronger in both society and industry, the green supply chain has become a vital tool for achieving sustainable development. By implementing green supply chains, enterprises can reap the beneficial effects, such as cost reduction, brand promotion and image building. In the future, as enterprises give more focus to sustainable development, the green supply chain will become the inevitable direction for enterprises and, indeed, the whole industry. Thus, hypothesis H_3 is proved.

Table 4: Testing the supply chain mechanism

Variables	(1) *Intensity*	(2) *SCC*	(3) *Intensity*
digital	−0.481*** (−6.28)	−1.475*** (−8.23)	−0.436*** (−5.76)
SCC	–	–	0.030*** (6.71)
Control variable	Yes	Yes	Yes
Industry fixed effects	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes
Cons	0.398*** (7.01)	6.575*** (63.48)	0.356*** (6.51)
N	16,856	16,856	16,856
R^2 adj.	0.956	0.336	0.956

Notes: *, **, *** indicate significance at the 1%, 5% and 10% levels, respectively. The *t*-stat value is in parentheses.
Source: Authors' own calculations

The present study employs the natural logarithm of the enterprise internal control index (ln *inner*) as a mediating variable. In the process of data processing, the missing values are replaced by the median of the sample, thereby mitigating the influence of outlier values. In Table 5, the following is detailed. Column (1) illustrates the results of enterprise digitalization at the level of enterprise internal control, indicating that *DT* significantly reduces *CEI* and promotes low-carbon energy transformation. Column (2) shows the regression effects of an enterprise's internal level (ln *inner*) on enterprise digitalization. The proxy index of enterprise *DT* is significantly positive, a degree that effectively improves the level of internal control. Column (3) adds mediating variables to the benchmark regression and the proxy indicator of enterprise digital transformation (*digital*) is significantly negative. Enterprises can optimize the business process through digital means, reduce managers' earnings behaviour and reduce potential internal control risk. Additionally, improving internal control will decrease *CEI* by establishing a good supervision mechanism, improving labour productivity and preventing excessive pollution. Therefore, hypothesis H_4 is proved.

Table 5: Test results of internal control level mechanism

	(1) *Intensity*	(2) ln *inner*	(3) *Intensity*
digital	−0.410*** (−5.11)	0.320*** (2.72)	−0.386*** (−4.85)
ln *inner*	–	–	−0.075*** (−11.42)
Control variable	Yes	Yes	Yes
Industry fixed effects	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes
Cons	1.064*** (17.89)	5.677*** (100.00)	1.054*** (17.76)
N	15,943	15,943	15,943
R^2 adj.	0.956	0.037	0.956

Notes: *, **, *** indicate significance at the 1%, 5% and 10% levels, respectively. The t-stat value is in parentheses.
Source: Authors' own calculations

4.4 Robustness analysis

The following section pertains to replacing core explanatory variables. We summarize the number of sentences in listed companies' annual reports and reconstruct the key explanatory variable (*digital_2*). The digital word frequency of a corporation's annual report is divided by the aggregate count of sentences, thereby re-estimating the model. As illustrated in Table 6, column (1), the coefficient value of enterprise *DT* (*digital_2*) remains negative, indicating that the research results have not changed.

This segment also pertains to eliminating the impact of policies. On 29 October 2011, the National Development and Reform Commission of the PRC, launched an experimental project of carbon quota trading in Beijing, Shanghai, Shenzhen, Chongqing, Guangdong, Tianjin and Hubei. By the end of 2013, all the pilot provinces and cities had essentially completed the building of carbon emission trading markets. To eliminate the interference of this policy with carbon emission reduction, we deleted samples dated earlier than 2014 and conducted a regressive analysis again. The estimated results are illustrated in Table 6, column (2). The analysis outcomes illustrate that the core conclusion, namely that corporate *DT* helps diminish corporate *CEI*, has not changed.

The core explanatory variables are lagged by one period. Given the implementation effect of *DT* having a certain lag effect, we conduct a one-period lag treatment on the explanatory variables and administer a regression analysis again. The estimated results are illustrated in Table 6, column (3), indicating that our core arguments have not changed.

Industry and year fixed effects are independently controlled. With the control variables unchanged, year and industry fixed effects are separately controlled. The analysis outcomes are illustrated in Table 6, columns (4) and (5), and the coefficients of the *DT* indicators are significantly negative, showing that our research results have not changed.

Interactive fixed effects are considered. We also include the interaction fixed effects of industry and year to control for any omitted variables that may affect the research outcomes. As illustrated in Table 6, column (6), the coefficient of enterprise *DT* remains negative and the significance level is stable, indicating that our research results have not changed.

Table 6: Results of robustness analysis

	Substitution of variables	**Eliminate policy factors**	**One period lag**	**Industry and time control effects are gradually controlled**		**Interaction term for time and industry is considered**
	Intensity (1)	***Intensity*** (2)	***Intensity*** (3)	***Intensity*** (4)	***Intensity*** (5)	***Intensity*** (6)
digital	–	−0.335*** (−4.41)	−0.537*** (−6.32)	−8.892*** (−27.76)	−2.428*** (−16.16)	−0.380*** (−5.75)
digital_2	−0.290*** (−4.94)	–	–	–	–	–
Year fixed effects	Yes	Yes	Yes	Yes	No	Yes
Industry fixed effects	Yes	Yes	Yes	No	Yes	Yes
Control variable	Yes	Yes	Yes	Yes	Yes	Yes
Industry year Interaction fixed effects	No	No	No	No	No	Yes
N	18,076	14,394	15,208	18,076	18,076	18,071
R^2 adj.	0.954	0.960	0.953	0.109	0.883	0.968

Notes: *, **, *** indicate significance at the 1%, 5% and 10% levels, respectively. The *t*-stat value is in parentheses.
Source: Authors' own calculations

4.5 Heterogeneity analysis

This segment addresses heterogeneity based on the intensity of environmental regulation. For enterprises with diverse degrees of environmental regulation in different provinces, there are also differences regarding the influence of *DT* on their *CEI*. In this paper, the median of environmental regulation intensity of all provinces in China is taken as the dividing line; those greater than such are said to have strong environmental regulation and those less than the dividing line are considered as having weak environmental regulation. The results are illustrated in Table 7, columns (5) and (6). From this, it can be seen that, for enterprises with strong environmental regulation in their provinces, *DT* has a greater influence on emission intensity, while for those with weak regulation, digitalization has a smaller influence on emission intensity. In cases of greater emphasis placed on environmental protection, enterprises are more inclined to participate actively in green innovation; this aligns with the aforementioned theoretical appraisal. We also introduce the cross term of digitalization index and environmental regulation degree index into the benchmark model; the results are illustrated in Table 7, column (1). The coefficient of digitalization indicator (*digital*) is significantly negative and the regression coefficient of the cross term (*digital*envir*) is significantly positive. Such findings indicate that, when compared to enterprises in regions with weak environmental regulation, *DT* reduces emission intensity to a lesser extent.

Heterogeneity based on region is discussed in this section. For enterprises in different regions, the influence of digitalization on *CEI* also differs. We classify the listed companies into three groups per region and compare the influence of *DT* on emission intensity in diverse regions by means of group regression. The grouped regression results are illustrated in Table 7, columns (2) to (4). It can be seen that, for enterprises in the eastern and central regions, the regression coefficient of the *DT* index (*digital*) is significantly negative at 1%. These data indicate that digitalization significantly affects *CEI* reduction in the eastern and central regions. However, for enterprises in the western regions, the degree of improvement in terms of an enterprise's *DT* does not exert a substantial influence on *CEI*.

Table 7: Estimation results of effect of heterogeneity

	(1)	(2)	(3)	(4)	(5)	(6)
Variable	**Term of interaction**	**The East**	**Central region**	**The West**	**Strong environmental regulation**	**Weak environmental regulation**
digital	−0.417*** (−5.45)	−0.415*** (−4.92)	−0.697*** (−3.07)	−0.186 (−0.62)	−0.572*** (−5.40)	−0.300*** (−2.71)
digital*envir	0.073*** (11.26)	–	–	–	–	–
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Industry fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Control variable	Yes	Yes	Yes	Yes	Yes	Yes
Cons	0.538*** (12.13)	0.348*** (6.94)	0.937*** (7.39)	1.525*** (10.37)	0.540*** (8.28)	0.569*** (9.26)
N	17,873	12,660	3,056	2,157	8,962	8,910
R^2 adj.	0.955	0.957	0.954	0.949	0.954	0.955

Notes: *, **, *** indicate significance at the 1%, 5% and 10% levels, respectively. The *t*-stat value is in parentheses.
Source: Authors' own calculations

5. Study Implications and Conclusion

5.1 Study implications

Firstly, against the backdrop of increasingly scarce mineral resources, studying the relationship between corporate *DT* and carbon emissions is particularly important. As global resources become increasingly scarce, the traditional resource-driven development model is no longer sustainable and businesses face an urgent need to transform and upgrade. In this context, digital transformation has become a key way for companies to improve resource efficiency and reduce dependence on mineral resources. Research has found that through digital technologies, companies can effectively manage production processes, optimize resource allocation, reduce energy consumption and lower carbon emissions, thereby alleviating environmental pressure while ensuring economic development. Secondly, it not only helps businesses discover new growth points and achieve sustainable development but also has significant meaning for promoting society towards a resource-conserving and environment-friendly development path. Through digital transformation, companies can more accurately grasp resource consumption and carbon emissions during production processes and then take effective measures to save energy and reduce emissions. In addition, digitalization can also promote transformation of enterprises towards low-carbon sectors such as the service industry and high-tech industries, reducing direct dependence on mineral resources and laying a solid foundation for long-term development of the economy. Finally, under such circumstances, governments and businesses should place greater emphasis on the role of digital transformation in reducing carbon emissions. Through policy guidance, financial support, technological innovation and other efforts, they can push companies further and more steadily along the path of digital transformation. This is not only an investment in the development of the company itself but also a responsibility to the future well-being of humanity and the ecological health of the planet. Therefore, studying the relationship between corporate *DT* and carbon emissions is of immeasurable value for achieving efficient resource utilization, environmental protection and sustainable development of the economy and society.

5.2 Conclusion

The influence of corporate *DT* on carbon emissions is a paramount issue of significant importance. Through a comprehensive understanding of *DT* and in-depth research into digital technology, corporations can better handle the multifaceted challenges posed by carbon emissions and realize the sustainable development of enterprises. With Chinese listed companies as our target audience, we carried out a theoretical analysis and an empirical test on the carbon emission effect of firms' *DT*. The empirical results are as follows:

Firstly, with the continuous development of science and technology and the wide application of information technology, enterprises can optimize and automate business processes, thus reducing energy consumption and carbon emissions. By adopting digital technologies, companies can use resources more efficiently and lower waste, thereby reducing carbon emissions. Additionally, the integration of digital tools can lead to more accurate monitoring of the carbon footprint across various business operations.

Secondly, corporate *DT* can significantly reduce *CEI* via three pathways: improving the level of corporation green technology innovation, optimizing the corporate supply chain and improving the level of corporate internal control. *DT* offers the opportunity to innovate and, by introducing green technologies and solutions, companies can effectively reduce adverse environmental impacts. In addition, corporate *DT* can diminish carbon emissions by strengthening supply chain management and by reducing energy consumption in logistics and transportation. At the same time, improving the level of internal control can effectively monitor and manage the carbon-emitting behaviour of enterprises and further reduce the carbon intensity.

Finally, for companies with strong environmental regulation and located in the central or eastern regions of China, the *DT* has a stronger inhibitory effect on the intensity of corporate carbon emissions. Thus, *DT* can help these companies better meet environmental requirements and reduce their carbon emissions. This is particularly relevant in regions where there is a higher awareness and pressure to conform to environmental standards. That is because the companies are subject to stricter environmental regulations. As a result, these firms are more likely to invest in advanced digital technologies that can help them comply with regulatory demands while also improving their competitive edge on the market.

The above conclusions show how, in the process of corporate *DT*, firms can diminish their carbon emissions and achieve sustainable development. This can be done by selecting appropriate digital technologies, adapting to the needs of different industries and analysing many factors in combination with specific scenarios. *DT* itself is only one way to improve production efficiency. How to give full play to its potential regarding environmental protection requires enterprises to adhere actively to their social responsibilities and make positive contributions to protecting the environment and promoting green development amid *DT*. In addition, on the whole, only when more enterprises recognize the importance of *DT* to environmental protection and sustainable development can they achieve more extensive and in-depth cooperation in environmental protection and sustainable development. Therefore, corporations engaging in *DT* need to combine their specific situation (from the perspective of overall development) with playing the due role in *DT* at the same time, if they are to achieve a more efficient and sustainable green office and production mode.

Future digitalization, both in China and worldwide, can adopt the following suggestions to further reduce carbon emissions and promote sustainable development:

(1) Incorporate environmental protection into the core goal of digitalization. In the course of digitalization, the compatibility of environmental protection, sustainability, social responsibility and other principles should be strengthened and incorporated into firms' core goals. That is, while striving to realize *DT*, companies' impact on the environment during the production process should be considered, as well as the efficient use of energy. Together, these efforts will promote enterprises' *DT* in the direction of sustainable development.

(2) It is important to promote low-carbon technology innovation. The government should vigorously support carbon-reducing technological advancement and encourage enterprises to invest in R&D, new energy technologies, other equipment and processes to promote green technology development. At the same time, preferential financial and tax policies should be provided to motivate corporations to invest in environmental protection and energy conservation.

(3) Promoting environmental protection supervision and corporate social responsibility is vital. It is suggested that the following measures be taken up: 1. strengthen environmental protection supervision and corporate social responsibility; 2. highlight the importance of environmental protection; 3. establish a sound environmental protection legal framework system; and 4. enhance environmental protection supervision of large enterprises. Furthermore, it should be advocated that enterprises give full play to their subjective initiative, formulate sustainable development goals, implement corporate social responsibility, strengthen investment in green technology promotion, engage in environmental protection measures and other aspects, while implementing *DT*. This should facilitate the synchronized advancement of economic growth and the social ecosystem.

(4) The following offers an overall consideration of digital ecosystem and carbon emission reduction. While reviewing firms' *DT* projects, the administrative body should evaluate and record statistics on the environmental impact and carbon emissions of the projects. The administrative body should also promote the construction of a green evaluation system, which would include the maximum environmental influence and the worst potential situation in the financial evaluation system pertaining to digitalization projects, reduce the carbon emissions of corporations and promote companies' transformations in the direction of sustainable development.

(5) The government should establish reasonable carbon emission fees and carbon emission trading mechanisms, encourage corporations to reduce their carbon emissions through cleaner production methods, improve their resource utilization efficiency, reduce their environmental protection costs and boost the advancement of carbon-efficient economy.

(6) Accelerate the coordinated development of digitalization and unleash the driving effects of digital transformation. Encourage the sharing of data resources between adjacent regions and industries along the supply chain. Strengthen the transfer of corporate resources and interactive communication, break down information barriers between different stages, jointly explore practical experiences in digital transformation and promote green and low-carbon development of the entire chain in highly energy-consuming industries.

Digitalization is an irresistible trend, but how to protect the environment and promote sustainable development, simultaneously, amid *DT* is a major problem faced by enterprises and governments alike. Therefore, substantial support from the government and all sectors of society is needed to jointly boost the coordinated advancement of digitalization and carbon output reduction, facilitate sustainable development and create a green and harmonious social environment.

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Availability of data and material

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

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