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Research on the carbon emissions reduction effects of China's digital economy: moderating role of the national big data comprehensive pilot zone policy

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The rapid expansion of the digital economy presents substantial opportunities for achieving the "dual carbon" objectives in China and globally. Understanding how the digital economy contributes to carbon emission reduction is essential for promoting high-quality economic growth. This study examines the mechanisms through which the digital economy affects carbon emissions, with a focus on the "production side" of the social reproduction process. Using panel data from 30 provincial-level regions in China between 2012 and 2022, this study employs a dual fixed-effects model and a mediation effect model to analyze the impact of the digital economy on carbon emissions. It explores three key channels–scale effects, structural effects, and technological effects. Additionally, a moderating effect model is applied to assess the role of the National Big Data Comprehensive Pilot Zone (NBDCPZ) policy in enhancing the carbon reduction effects of the digital economy. The findings indicate that: (1) The digital economy plays a significant role in reducing carbon emissions, with its effects being more pronounced in eastern regions and areas with abundant energy resources and higher levels of digital economic development. (2) On the production side, technological progress and structural upgrading mediate the reduction of carbon emissions, whereas scale expansion increases emissions. However, the combined effect of technological progress and structural upgrading outweighs the negative impact of scale expansion. (3) The moderating effect analysis reveals that the NBDCPZ policy amplifies the carbon reduction effects of the digital economy, further strengthening its prohibitive influence on emissions. As nations increasingly prioritize sustainable development, this study provides valuable insights into the mechanisms by which the digital economy contributes to emission reduction. The findings highlight the need for region-specific policies that leverage digital transformation to achieve carbon neutrality goals.

KEYWORDS

digital economy, carbon emissions, production-side, national big data comprehensive pilot zone policy, mediating effect, moderating effect

1 Introduction

The escalating global environmental crisis has made sustainable development a central concern for all nations, with climate changes because of the greenhouse effect, attracting worldwide attention. A series of changes of climate and environment such sea-level rise, glacier melting, global warming, and smog have shown us that the environmental changes caused by greenhouse gases are increasingly affecting our survival. This has grown into an urgent issue that countries around the world have to tackle now and in future (Li et al., 2022). Countries around the world are striving to tackle the dual challenge of reducing environmental degradation caused by climate change without sacrificing national economic growth (Bai et al., 2022). This dilemma has pushed nations to move from basic assumptions to innovative solutions, to balance economic development with environmental management. Since 2011, China has experienced rapid economic expansion, outpacing many nations. However, this progress has come at a significant cost, particularly in terms of environmental pollution, resulting in China becoming the world's largest carbon emitter (Zhang et al., 2022). In response, the Chinese government has prioritized addressing environmental problems associated with carbon emissions a top priority. During the 20th National Congress of the Communist Party of China, China's government has put forward the "double carbon" goal which called for a proactive and gradual approach to reaching carbon-peaking and carbon-neutrality. Currently, the Chinese economy continues to grow at a medium-to-high rate undergoing urbanization and industrialization, both of which are associated with serious energy consumption. The dependence of these processes indicates China's dependence on energy will continue for a long time. This implies that China is going to face a tremendous pressure to balance economic development with reducing carbon emissions for a long time. So, the digital economy has become a ray of hope due to its enormous potential in the context, providing China with a promising path to address this dilemma effectively. In the "14th Five-Year Plan and the 2035 Vision," China's government outlined plans to fortify the construction of a digital government and society, improve the digitizing of social governance and public service, speed up low-carbon and green development, continuously enhance environmental quality, and intensify the battle against pollution. The China's resolve to advance the digital economy, lower pollution levels, and enhance green governance is reflected in these policies. China's growing commitment to resolving environmental problems and advancing sustainable development is shown in the growing emphasis on the digital economy (Niu et al., 2024).

The new digital era is coming rapidly as a new round of industry transformation and digital technology revolution. A new economic form is emerging as a result of digital technology innovation and development, including the platform economy, sharing economy, and smart cities. China's digital economy has experienced significant growth. In 2005, its scale was 2.6 trillion yuan, and rose to the amount of 45.5 trillion in 2021, according to the "China Digital Economy White Paper (2022)". The size is 39.8 percent of the country's GDP in the same period. Additionally, in 2015, the national government established a pilot program called the National Big Data Comprehensive Pilot Zone (NBDCPZ), with Guizhou province serving as the first listed region. This indicates that traditional economic growth model of China will become difficult to sustain in the future (Wang H. et al., 2023), but the digital transformation across various industries in China has opened a new prospect for green economic growth and transformation of the traditional economic model (Hu et al., 2023). The digital economy, characterized by rapid development, broad reach, and profound effect, plays a crucial role in transforming the global economic environment, optimizing the structure of the global economy, and achieving economic globalization. It provides new momentum for the countries to achieve their "dual carbon" targets.

In the reproduction process of society, carbon emissions are principally produced because of human production activities (Gao et al., 2021; Sousa and Bogas, 2021). Based on this, how exactly the digital economy influence emissions? What are the potential pathways? The research considers multiple dimensions of the "production-side", and integrates the effects of scale, structure and technology into a theoretical framework to analyze the emission-reduction pathway for the digital economy, followed by empirical testing. Moreover, whether other forces' involvement will have an impact on the digital economy's ability to decrease emissions of carbon dioxide. For example, China has been committed to develop digitization and big data, launching the NBDCPZ in Guizhou province in 2015. Chen and Li (2023) and Wei and Zhang (2023) used panel data to verify the expected effort of the NBDCPZ in decreasing emissions of carbon dioxide and strengthening urban sustainable. Thereby, the research further investigates whether the NBDCPZ affects the digital economy's effect on decreasing carbon dioxide emissions. It has grand practical and theoretical sense for our country to achieve its goals including transition to the low-carbon economy and "dual-carbon" as soon as possible, while also providing valuable insights to achieve the formation of low-carbon model by using of digital economy for other countries and economies.

2 Literature review

2.1 Digital economy and carbon emissions

Research of the association about the emissions of carbon dioxide and digital economy is abundant, existing studies contain various perspectives and findings. Scholars have presented two contrasting views on influence of the digital economy on emissions of carbon dioxide. A viewpoint suggests that the digital economy may promote an increase in carbon emissions. Some scholars argue that the development of the digital economy does not effectively curb carbon emissions as expected. They have found that the digital economy may exacerbate carbon dioxide emissions (Xue et al., 2022). These scholars believe that the digital economy is highly reliant on large-scale data storage and processing, which often requires extensive data centers. The operation of these data centers demands a large amount of electricity, particularly when renewable energy is not sufficiently utilized. In such cases, the electricity used tends to come from traditional fossil fuels, resulting in increased carbon emissions. More specifically, while digital technologies can reduce carbon emissions in certain areas, technological progress often leads to significant increases in resource consumption, ultimately driving an overall rise in carbon emissions.

Furthermore, the processes of storing, transmitting, processing, and analyzing data expand the demand for electricity (Sui and Rejeski, 2002). The growth of China's digital economy, for example, not only fails to decrease emissions but also has actually intensified emissions of carbon dioxide because of the rise in electricity consumption (Zhang et al., 2022). Meanwhile, the expansion of the digital economy has driven the production and upgrading of various electronic devices. The production and rapid upgrading of devices such as smartphones, computers, and servers not only lead to excessive resource consumption but also generate large amounts of electronic waste (Dong et al., 2023).

Digital economy enhances energy efficiency to aid in carbon reduction while supporting economic growth according to one perspective. This perspective is supported by Meng and Zhao (2022), who argue that improving energy efficiency leads to fewer emissions of carbon dioxide. Firstly, it was discovered that digital economy may successfully achieve its carbon benefits by decreasing regional carbon emission intensity. For instance, Liu (2024) assessed the digital growth level of Chinese cities, and their research confirms that the construction of digital cities effectively lowers carbon intensity. Secondly, improvements in total carbon emission performance also have a connection to the digital economy. Some researchers used total factor carbon productivity to assess carbon emission performance. They discovered that internet infrastructure significantly reduces emissions of carbon dioxide and enhances total factor carbon productivity (Kou and Xu, 2022). In addition, under the environment of e-commerce pilot policy, the influence of digital technologies on emissions of carbon dioxide and transmission mechanisms are investigated (Wang H. et al., 2023), finding that e-commerce policies have a beneficial impact. Additionally, constructing and improving digital infrastructure is one of the fundamental prerequisites for advancing the digital economy. The urban development model, which leverages smart mobile devices, virtualization platforms, and other digital infrastructure, provides a certain technological foundation for the low-carbon economic transition. For instance, the spread of internet infrastructure in the digital era contributes to supporting low-carbon transformation in resource-dependent regions (Pan et al., 2023).

Carbon dioxide emissions are primarily influenced through pathways such as technological advancements, energy utilization efficiency, and energy structure (Yi et al., 2022). Huang and Lin (2024) found that improving energy efficiency and promoting energy structure transformation are two essential mechanisms for carbon reduction in the digital economy. Zhao et al. (2022) also pointed out that the digital economy is able to minimize emissions of cities through optimizing the efficiency and structure of energy. Additionally, Xie et al. (2023) analyzed the effect pathway from one aspect of technical innovation, showing that the innovation of digital technologies enhances synergy and collaboration among innovation entities. They argued that the digital economy fosters an overall innovative environment through technological advancements, thus catalyzing technological innovation to achieve carbon reduction. From the standpoint of urbanization, Lu and Chen (2022) empirically tests the impact of digital economy and new-type urbanization on carbon emissions, and found the improvement of the new-type urbanization level curbs carbon emissions reduction.

2.2 National big data comprehensive pilot zone policy and carbon emissions

China has been dedicated to developing big data in order to advance the creation of new digital technologies and improve global competitiveness. A key step in this effort is the establishment of the NBDCPZ. The first phase began in 2015, when Guizhou was designated as the first region. And in 2016, other regions were added into the second batch, like Beijing-Tianjin-Hebei, Shanghai and Inner Mongolia. By leveraging its unique production factor, the NBDCPZ policy effectively unleashes the value of digital innovation and foundational resource, improving big data application and utilization, promoting disruptive changes and sustainability in production methods (Liu and Li, 2023). This process will significantly reduce carbon emissions in various regions. Wu et al. (2024) used provincial panel data and applied the Difference-in-Differences Model (DID) to assess the influence of the construction of the NBDCPZ on the agricultural carbon emission levels. They found that the establishment of the NBDCPZ effectively lowered the region's agricultural carbon emission levels, with industry upgrading and technical innovation playing a major role in the inhibitory effect. At the same time, the digital drive model of the policy pilot zone helps the transition of agricultural production model to low carbon, which may significantly lower the levels of agricultural carbon dioxide emissions (Li et al., 2023). Similarly, Liu et al. (2023) found that the launching of the NBDCPZ encourages urban sustainable development. Bu et al. (2023) also taken the NBDCPZ as a quasi-natural experiment, and concluded that new digital technology considerably lowers the level of carbon emissions.

2.3 Research gap

Although various scholars have examined the influence of the digital economy on the emissions of carbon dioxide, with extensive studies about its mechanisms, most prior research has been focusing on individual aspects such as energy consumption, energy structure, technical innovation, and urbanization. Few research has systematically integrated multiple dimensions of the production process into a unified framework to investigate how the digital economy impacts emissions, and the contribution of government intervention has often been overlooked. Therefore, this paper seeks to make the following contributions. First, this paper innovatively constructs a theoretical framework that encompasses several dimensions of the "production-side", including output scale, energy structure, and technological progress, examining whether the digital economy creates an effect of inhibiting the emissions of carbon dioxide and the specific pathways or mechanisms involved, both theoretically and empirically. Second, regarding the mechanism of the technological progress effect, previous research has primarily analyzed this effect from the single perspective of technical innovation or total factor productivity. However, the research investigates the dual effects of total factor productivity and energy cost efficiency brought by the digital economy, providing more comprehensive and deeper analysis of the mechanism of technological effects. Third, unlike existing literature, we also explore the moderating role of the NBDCPZ on the influence of the digital economy on emissions of carbon dioxide, rather than solely researching the direct role of the NBDCPZ in carbon dioxide emissions. It examines whether the NBDCPZ and the digital economy create synergistic or interactive effects on carbon reduction, offering insights into the relationship between mitigating environmental pollution and developing the digital economy.

The rest of the research is as follows: Section 3 describes the theoretical framework and hypotheses. Section 4 details the method and data. Section 5 presents the empirical findings. Section 6 presents conclusions and policy recommendations.

3 Theoretical basis and research hypothesis

3.1 Digital economy and carbon emissions

Ren et al. (2021) argued that the digital economy compresses spatial and temporal distances because of the feature of its development, facilitating cross-spatial and temporal dissemination and sharing of information. This, in turn, lowers the cost of acquiring information and helps reduce emissions of carbon dioxide. Notably, comprising information enterprises, e-commerce companies, and internet firms, these digital industries have made an initial contribution to carbon reduction. Compared to the previous traditional manufacturing industry, the digital industry is greener and more focus on carbon reduction and ecological protection. For instance, in response to the "dual carbon" goals, several Chinese internet companies have publicly stated the carbon neutrality targets and their plans for action. Furthermore, e-commerce companies, particularly those in the internet retail sector, can generate substantial net ecological benefits, as online shopping typically results in a lower carbon footprint compared to brick-and-mortar retail, especially in contexts where car-dependent lifestyles prevail (Buldeo Rai et al., 2022). Such as electronic finance and e-books, the adoption of these digital e-commerce tools can raise awareness of carbon reduction among businesses and consumers. And by optimizing production, delivery, and consumption processes, these tools contribute to reducing emissions of carbon dioxide and minimizing waste of resources (Elheddad et al., 2021).

Moreover, the application of digital technologies, including data analysis, intelligent control, monitoring systems, and resource sharing, has been found to support eco-design innovations and the development of green products (Dubey et al., 2019), thereby enhancing carbon reduction efforts. Digital technologies have been shown to optimize production processes, save consumption of energies, mitigate climate change, and decrease air pollution, such as AI, big data and cloud computing (Li et al., 2020). The emergence of these technologies also expands the capabilities of big data platforms, enabling precise measurement, statistical analysis, evaluation, and supervision. This, in turn, provides technical support for market improvements, regulation, verification, and administrative oversight, helping to achieve more accurate carbon reduction targets (Yang et al., 2022). In conclusion, the digital economy can better help companies and countries optimize supply chain management, reduce energy consumption and ecological impacts, and increase transparency, controllability, and manageability in carbon reduction initiatives. Additionally, the digital industry can leverage its strengths to help other industries reduce their emissions of carbon. This will enhance the degree of industrial digitization, stimulate the rapid expansion of green and intelligent sectors, increase their added value, and lower related carbon dioxide emissions. Thereby, the research proposes:

Hypothesis 1: Digital economy contributes to lowering carbon emissions.

3.2 The impact mechanism of digital economy on carbon emissions

3.2.1 Scale effect

Digital optimization can help industries improve production efficiency, reduce resource waste, and lower carbon emissions per unit of output. This is achieved through technologies such as smart scheduling, data analysis, and Internet of Things device monitoring. For example, in manufacturing, digital technologies can optimize production processes, reduce energy consumption, and minimize raw material waste, thereby improving carbon emission efficiency (Geissdoerfer et al., 2016). This efficiency improvement results in a reduction in carbon emissions for the same level of output. However, they may also lead to an increase in total carbon emissions. For example, When production efficiency improves and energy use decreases, lower costs may lead to increased production, thus offsetting the energy-saving effects (Peng et al., 2023). The emergence and growth of the digital economy offer new potential for economic growth. Its inherent advantages in production specialization and labor division, promoting social welfare and growth of economic scale in participating countries or regions, lead to higher emissions of carbon and a series of related environmental issues (Narayan et al., 2016). Developing the digital economy demands a large amount of data centers and information technology equipment, which are associated with significant electricity consumption, especially in developing countries where urbanization started later but is growing rapidly. So, the intense electrical demand and the considerable energy consumption features of digital infrastructure have long been controversial. For example, Sun et al. (2024) points out that regional economic growth does not necessarily enhance carbon emission efficiency; on the contrary, it may accelerate energy consumption. The expansion of economic output is often accompanied by increased carbon emission pressure, ultimately leading to a rise in total carbon emissions. Digital technologies' promotion and commercialization have shortened the spatial and temporal distances among industries, reduced the cost of transactions and information acquisition, accelerated the knowledge spillover and the flow of factors of production among enterprises, regions, and countries, and supplemented the accumulation of new energy resource and technological innovation in enterprises (Maillat, 1998). All these factors have further expanded the regional scope and output scale of traditional production. Because of existing a bidirectional causal relationship, whenever economic growth increases or decreases, it will stimulate a corresponding increase or decrease in emissions (Mardani et al., 2019). Therefore, as a new and important potential of global economic growth, while promoting investment and economic expansion, the digital economy also increases the consumption and demands for energies to some extent, which results in an overall increasing in carbon emissions. Furthermore, according to some research, they suggested that digital technologies have improved productive efficiency, resulting in demand expansion and energy rebound effects, which contributed to a higher carbon emission level (Lange et al., 2020). Thereby, this research proposes:

Hypothesis 2a: Digital economy increases carbon emissions by scale expansion effect.

3.2.2 Structure effect

The new structural economics indicates that the energy structure at specific stages of development is a critical factor influencing the association between the emissions of carbon dioxide and the digital economy. The energy structure not only affects the consumption and demand for energy, but determines the quantities and types of air pollutants. Thus, it can be used as an essential indicator for directly assessing the efficiency and economic benefits of energy use. The process of optimizing and transforming energy structure is the process of realizing energy technology innovation and industrial economic structural upgrading. This upgrade not only promotes vertical growth within industries but also influences the development of adjacent industries through horizontal specialization. Ample evidence suggests that, the digital economy as a new "economic engine", will profoundly influence and shape energy systems, which in turn impact emissions of carbon dioxide (Xue et al., 2022; Huang and Lin, 2024). Theoretically, the digital economy has distinct advantages in fostering an innovation-driven, service-oriented, and resource-efficient society. It facilitates the transition of energy structures toward cleaner, low-carbon systems, thereby contributing to carbon emission reductions. Digitalization enhances the optimization of energy structure, which propels decarbonization of energy structure from the sides of demand and supply (Yang et al., 2022). From the side of supply, the digital transformation of energy systems upgrades production methods for various energies and supports the development of cleaner alternative energies (Lyu et al., 2023). The general use of digital technologies enhances the technical capabilities of renewable energies and increases the proportion of new energies in overall consumption. Additionally, digital transformation enables the digitization and intelligence of energy systems, advancing the exploitation and storage of renewable energies (Wang B. et al., 2023). On the demand side, the digital economy can not only facilitate the growth of new energy enterprises but promote a shift in domestic consumer behavior toward cleaner consumption patterns (Sun et al., 2023). Thereby, this paper proposes:

Hypothesis 2b: Digital economy lowers carbon emissions by structural upgrading effect.

3.2.3 Technological effect

Through digital services and technologies, the digital economy has transformed service processes across various industrial sectors and driven innovations in production technologies, improving productivity and energy efficiency in many industries, thus contributing to a low-carbon transition (Sun et al., 2024). Compared with the traditional economy, the digital economy alters the traditional model's constraints on economies of scale, introduces new assumptions for conventional production factors like labor and capital, and incorporates digital elements to lower the excessive consumption of traditional energies. So the green total factor productivity (Deng et al., 2022) and low-carbon total factor productivity (Li and Liao, 2022) have been significantly enhanced by the digital economy. A series of innovative and digital technologies have been created due to the digital economy. The diffusion of these digital technologies and their deep integration across industrial sectors have minimized transaction costs to the greatest extent. Additionally, big data analysis and digital platforms improve the interaction and understanding between customers and producers, alleviating supply-demand mismatches and excessive resource consumption. It is well known that the development model of the traditional economic has the characteristics of excessive consumption of energies and environmental degradation. While promoting economic growth, it also causes environmental issues such as high energy depletion and air pollution. In the digital economy, however, data elements can partially replace traditional labor and capital factors, promoting technical innovation, lowering energy consumption and improving total productivity, so as to mitigate negative impacts on the climate and environment (Li et al., 2021). According to the majority of recent studies. The, the digital economy fosters social innovation. And the spatiotemporal nature of digital technologies enhance the application and diffusion of technological innovations in various sectors, enhancing energy efficiency and driving carbon reduction. For example, the role of digital economy in lowering emissions of carbon dioxide is faced with significant innovative capability threshold and energy endowment threshold. The rise in energy consumption and advancement in non-eco-friendly technologies mostly affect local emissions of carbon in the short term, whereas advancement of green technologies is as the predominant factors in the long term (Li and Wang, 2022). Moreover, Xie et al. (2023) analyzed the effect pathway from one aspect of total factor productivity, showing that the innovation of digital technologies enhances synergy and collaboration among innovation entities, so as to accomplish carbon reduction. In this research, in order to better analyze the technological effects mechanism, the technological progress effects are divided into two aspects: technical innovation (total factor productivity) and energy efficiency (Total factor energy efficiency). Therefore, the study proposes:

Hypothesis 2c: Digital economy reduces carbon emissions by technological progress effects.

3.3 The moderating role of national big data comprehensive pilot zone policy

The Chinese government included Guizhou province in the first batch of NBDCPZ in 2015, making it the first region in the country to build such a zone. And in 2016, China started to add other regions into the second batch of the construction list, such as Inner Mongolia, Shanghai and Beijing-Tianjin-Hebei, forming a total of eight zones. By leveraging its unique production factor features, the NBDCPZ policy perfectly unleashes the value of digital innovation and foundational resources, improving big data applications and utilization, promoting disruptive changes and sustainability in production methods

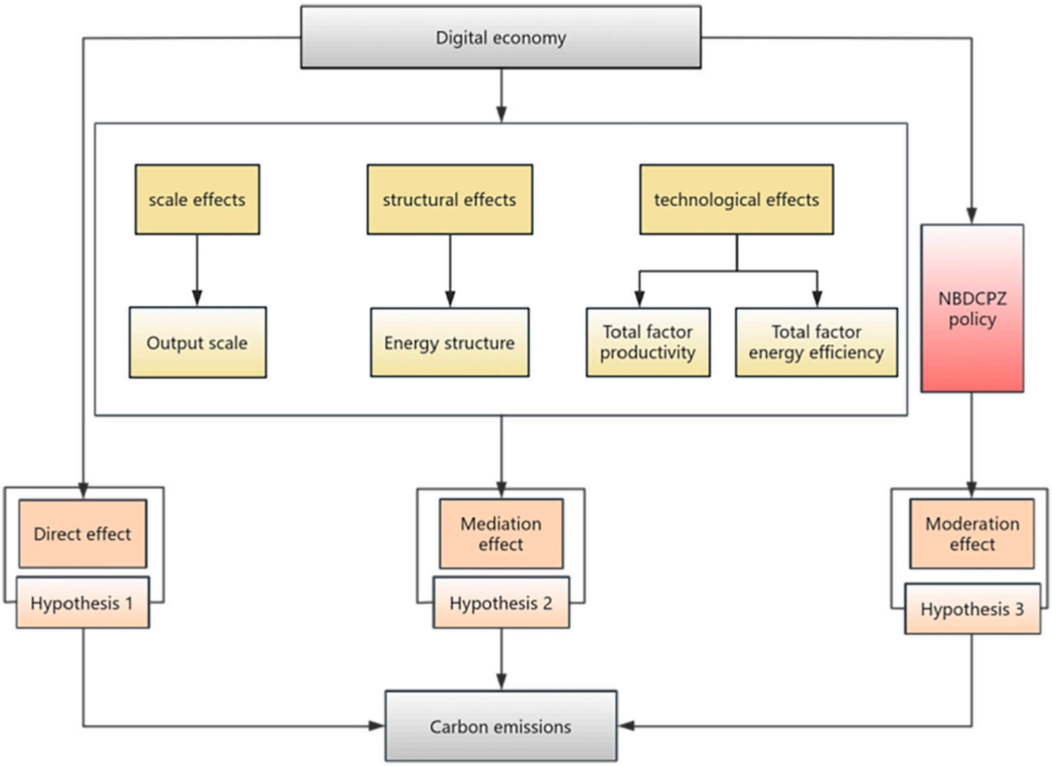

FIGURE 1
The mechanism of the digital economy on carbon emission reduction.

(Liu and Li, 2023). This process will significantly reduce carbon emissions in various regions. Specifically, with government empowerment, big data development receives more support, and its innovative applications in the pilot regions will further improve the transparency of emissions data and carbon reduction efficiency across different regions. For example, with the combination of resources for big data in these pilot areas, those relevant regulatory agencies may depend on the digital platforms and data infrastructure for collecting dynamic data statistics, so as to enhance the transparency and openness of the carbon regulating process, reduce the excessive consumption of resources in productive process, and curb speculative activities including illegal emissions and excessive carbon emissions (Lan et al., 2023). Based on big data analysis of the effectiveness of different emission reduction measures, the government can identify efficient policy options, adjust carbon taxes, carbon trading markets, and subsidy policies, in order to maximize emission reduction effects while minimizing economic losses (Wang et al., 2023). Additionally, the unique digital economy model formed by the digital production factors in the pilot regions can help agricultural production to achieve a low-carbon transformation, and significantly lower agricultural carbon emissions (Li et al., 2023). Finally, the deeper utilization of the digital technologies in the pilot regions of the NBDCPZ policy can enhance governance efficiency by rapidly collecting, organizing, and analyzing data, resulting in lower carbon emissions. For instance, the government can mine extensive business information by digital big data platforms, which contribute to formulate feasible economic policies, lower the cost of information searches, and promote emission reductions (Gomber et al., 2017). Additionally, new digital carbon emission measurement technologies can help the government manage carbon emissions by data collection, accurate analysis and real-time monitoring of emission levels. Therefore, this research proposes:

Hypothesis 3: The NBDCPZ policy positively augments the digital economy's contribution to carbon reduction.

To present the theoretical framework and transmission mechanism of this study more clearly, Figure 1 illustrates the relationships and interactive paths between the variables.

4 Method and data

4.1 Methods

4.1.1 Benchmark model

To explore the direct effect of the digital economy on emissions of carbon dioxide, setting the benchmark model as follows:

$$\boldsymbol{CE_{it}} = \boldsymbol{\beta_0} + \boldsymbol{\beta_1 DE_{it}} + \boldsymbol{\beta_2 control_{it}} + \boldsymbol{\eta_i} + \boldsymbol{\gamma_t} + \boldsymbol{\varepsilon_{it}} \quad (1)$$

In the Formula 1, i denotes the province, t denotes the year. CE_{it} is the carbon emissions; DE_{it} denotes development of digital economy. $control_{it}$ denotes all control variables. η_i and γ_t respectively denotes regional fixed effects and time fixed effects. ε_{it} denotes the error term.

TABLE 1 Comprehensive indicator system of digital economy development level.

Primary indicators	Secondary indicators	Unit	Attribute
Digital infrastructure	Number of domain names	10,000	Positive
	Number of IPV4 addresses	10,000	Positive
	Number of broadbands subscribers port of Internet	10,000 ports	Positive
	Mobile phone penetration rate	100 people	Positive
	Long-distance optical cable length per unit area	kilometre/square kilometer	Positive
Digital industry development	Number of enterprises in the electronic information industry	unit	Positive
	The number of websites per 100 enterprises	unit	Positive
	Proportion of enterprises engaged in e-commerce transaction activities	%	Positive
	E-commerce transaction volume	100 million yuan	Positive
	Software business revenue	100 million yuan	Positive
Digital Financial Inclusion Index	Coverage breadth index	—	Positive
	The depth index was used	—	Positive
	Digitization degree	—	Positive

4.1.2 Mediation effect model

In order to study the potential pathway through which the digital economy affects carbon emissions from the production side perspective, the study constructs the mediation effect model as follows:

$$SC_{it} = \beta_0 + \beta_1 DE_{it} + \beta_2 control_{it} + \eta_i + \gamma_t + \varepsilon_{it} \tag{2}$$

$$ES_{it} = \beta_0 + \beta_1 DE_{it} + \beta_2 control_{it} + \eta_i + \gamma_t + \varepsilon_{it} \tag{3}$$

$$TFP_{it} = \beta_0 + \beta_1 DE_{it} + \beta_2 control_{it} + \eta_i + \gamma_t + \varepsilon_{it} \tag{4}$$

$$TFEE_{it} = \beta_0 + \beta_1 DE_{it} + \beta_2 control_{it} + \eta_i + \gamma_t + \varepsilon_{it} \tag{5}$$

In the Formula 2-5, SC_{it}, ES_{it}, TFP_{it}, and $TFEE_{it}$ are all production-side mediating variables. SC_{it} represents scale effect, ES_{it} represents structural effect, and TFP_{it} and $TFEE_{it}$ represent technological effects.

4.1.3 Moderating effect model

In order to study the moderating role of the National Comprehensive Big Data Pilot Zone policy in the process of digital economy affecting carbon emissions, the study construct the moderating effect model as follows:

$$CE_{it} = \beta_0 + \beta_1 DE_{it} + \beta_2 DID_{it} + \beta_3 DID_{it} \times DE_{it} + \beta_4 control_{it} + \eta_i + \gamma_t + \varepsilon_{it} \tag{6}$$

In the Formula 6: DID_{it} represents the dummy variable for the NBDCPZ policy.

4.2 Variables and data

4.2.1 Explained variable

Carbon Emissions (CE): Data on carbon dioxide emissions come from the Carbon Emission Accounts and Datasets (CEADs) database. Much study has been conducted on measuring emissions of carbon dioxide, and most studies use the IPCC emission factors when calculating emissions of carbon dioxide. However, the emission factors based on field measurements in the CEADs database can more accurately represent China's carbon emissions (Guan et al., 2021).

4.2.2 Explanatory variable

Unlike the traditional economic model, the digital economy's primary production factor is data. The digital economy takes new information networks for the primary carriers, with the comprehensive application of information and communication technologies serving as the key propelling force, forming a more efficient, unified, and rational new economic model. With reference to existing research (Zhang et al., 2022; Chen et al., 2023), the study comprehensively builds a digital economy indicator system. Following principles of scientific rigor, hierarchy, and data availability, a series of variables are selected (Table 1).

To determine the comprehensive index of digital economy development level, it is necessary not only to establish specific indicators that are available but also to assign weights to the relevant indicators. Generally, existing weighting methods include subjective and objective weighting methods. Regarding subjective weighting methods, the weights are assigned based on the relative importance of indicators through subjective judgment, such as Principal Component Analysis (PCA), Delphi method, and AHP method. On the other hand, objective weighting methods assign weights based on the raw information of the indicators, such as cluster analysis, standard deviation method, entropy method, and range method. Subjective weighting methods may be influenced by personal biases, leading to imbalanced weighting of indicators and thus failing to reflect the comprehensive index well. Therefore, considering the above, to avoid inaccuracies in index measurement caused by subjective weighting, the entropy method, an objective weighting method, is adopted to assign weights to the indicators. To ensure the time-series comparability of the relevant indicators, first, dimensionless processing is applied to indicators with different properties and units. In order to avoid the uneven distribution caused by large differences in indicator values, the data is standardized.

Since there are no negative indicators in this study, only the standardization formula for positive indicators is provided, as shown in Equation 7.

$$x_{ij} = \frac{x_{ij} - min\{x_j\}}{max\{x_j\} - min\{x_j\}} max\{x_j\} min\{x_j\} \tag{7}$$

Here, j represents indicator and i represents province. $max\{x_j\}$ and $min\{x_j\}$ respectively denote the maximum and minimum values of the indicator, and x_{ij} denotes the dimensionless result.

After normalizing the indicators, the study calculates the objective weight for each indicator according to the entropy method. Then the share of indicator j in province i can be expressed as, as shown in Equation 8:

$$\varphi_{ij} = \frac{X_{ij}}{\sum_{i=1}^{n} X_{ij}} \tag{8}$$

Next calculating the information entropy of each sub-indicator, expressed as, as shown in Equation 9:

$$e_j = -\frac{1}{ln\, m}\sum_{i=1}^{m} \varphi_{ij} \times ln\ \varphi_{ij}, 0 \le e_j \le 1 \tag{9}$$

Information entropy redundancy degree is calculated as, as shown in Equation 10:

$$d_j = 1 - e_j \tag{10}$$

For each indicator, the weight assigned is calculated and expressed as, as shown in Equation 11:

$$\omega_j = \frac{d_j}{\sum_{j=1}^{m} d_j} \quad (1 \le j \le m) \tag{11}$$

Based on the calculated index weight ω_j and the standardized index x_{ij}, the following can be used to derive the composite index of the digital economy (DE_i) as shown in Equation 12:

$$DE_i = \sum_{j=1}^{m} \omega_j \times x_{ij} \tag{12}$$

4.2.3 Mediating variables

①Output scale (*SC*), represented by each province's GDP, the GDP index is chosen as the conversion index and adjusted to the base year of 2000. ②Energy structure (*ES*), denoted by the percentage of coal consumption account for the consumption of energies. ③Technological progress, reflected in this study by two factors: total factor productivity (*TFP*) and total factor energy efficiency (*TFEE*).

For the *TFP* and *TFEE* indicators, this study refers to existing literature and to calculates *TFP* and *EN* by slack-based global DEA model (Chang et al., 2023). Specifically, the DEA model can be described by Equations 13–17, assuming constant returns to scale (CRS):

$$TFP = \mu^* = min\, \pi - \frac{1}{I}\sum_{i=1}^{I} \frac{S_i^x}{x_{i0}} \tag{13}$$

$$s.t.\ \pi + \frac{1}{s_1}\sum_{e=1}^{s_1} \frac{S_e^y}{y_{e0}} = 1; X\Lambda + S^x \le x_0 \pi \tag{14}$$

$$Y\Lambda - S^y \ge y_0; \pi, S^x, S^y, \Lambda \ge 0; I, s_1 = 1, \ldots, N; \tag{15}$$

$$\pi = \frac{1}{1 + \frac{1}{s_1}\sum_{c=1}^{s_1} \frac{s_e^y}{y_{e0}}} \tag{16}$$

$$S^x = \pi s^x, S^y = \pi s^y, \Lambda = \pi \zeta \tag{17}$$

where $\mu*$ denotes *TFP*, S_e^y and S_i^x respectively denote the slack vectors of output e and input i. y_{e0} and x_{i0} respectively represent the value of output and input. Y and X represent matrix vectors of output and input, respectively; ζ represent the intensity vector for the convex set of output and input of production function set.

In order to measure *TFP*, similar to many scholars (Chen and Golley, 2014), capital stock and labor are used as inputs, while GDP is chosen as the output. When measuring *TFEE*, energy input is additionally included as an input, and the unexpected output is additionally included. The specific variables are as follows:

1) Input variable: Capital input. Similar to other references (Zhu et al., 2018), this paper applies the perpetual inventory method to evaluate capital stock due to the lack of official data. The calculation method is shown in Equation 18:

$$K_{it} = K_{it-1}\ (1 - r_{it}) + I_{it}/P_{it} \tag{18}$$

As shown in the above formula, *r, I, K, P* respectively denote the fixed depreciation rate, fixed investment, capital stock, and price index. Setting 2001 as the base year K_0, and the growth rate method is used for the calculation. Labor input is calculated by using each province's employed population. Additionally, data about energy input is calculated from each province's energy balance tables.

2) Output variables: The GDP of 30 provinces is selected as the expected output, and each province's GDP index is taken as the conversion index, adjusted to the base year of 2000. Industrial SO_2 emissions, industrial wastewater, and emissions of industrial smoke and dust are taken as unexpected output variables.

4.2.4 Moderating variable

This paper uses the national big data comprehensive pilot zone policy variable (DID) as the moderating variable. The sample period for this study is from 2012 to 2022. In 2015, the Chinese government included Guizhou Province in the first batch of National Big Data Comprehensive Pilot Zones, making it the first region in the country to implement such a pilot project. In 2016, the government added Beijing-Tianjin-Hebei, the Pearl River Delta, Shanghai, Henan, Chongqing, Shenyang, and Inner Mongolia to the second batch of pilot zones. Noteworthily, to truly reflect the policy impact, we set the implementation time of the national big data integrated pilot area in the pilot program to 2016. Therefore, this paper sets 2016 as the point of policy impact (Zhang and Ran, 2023). In detail, DID equal one after enacting the National Big Data Comprehensive Pilot Zone policy in the corresponding province, and zero otherwise.

TABLE 2 Definition of each variable.

Variables	Variable name	Scalar notation	Definition
Explained variable	Carbon emission	*CE*	China Carbon Emission Database Accounting
Explanatory variable	Digital economy development level	*DE*	Composite index of digital economy calculated by the entropy method
Mediating variables	Output scale	*SC*	Real GDP by Province
	Energy structure	*ES*	Percentage of coal consumption account for the consumption of energies
	Technological progress	*TFP*	Total factor productivity
		TFEE	Total factor energy efficiency
Manipulating variable	National big data comprehensive pilot zone policy	*DID*	The current year and subsequent years of the pilot provinces are set to 1, and the rest are set to 0
Control variables	Industrialization level	*IN*	Percentage of industrial added value accounts for each province's GDP
	Research and development investment	*RD*	Percentage of RD investment accounts for each province's GDP
	Openness level	*OP*	Percentage of actual foreign direct investment accounts for each province's GDP
	Labor level	*LD*	Natural logarithm of the employed quantity in each area
	The level of urbanization	*UR*	Percentage of urban population accounts for the each province's population

TABLE 3 Descriptive statistics of main variables.

Variables	Observations	Mean	Standard deviation	Min	Max
CE	330	10.3042	0.5527	8.7657	10.5301
DE	330	0.1531	0.1179	0.0241	0.1142
SC	330	1.2869	0.8259	0.5423	0.9968
ES	330	0.3691	0.1494	0.0042	0.3764
TFP	330	0.5881	0.2656	0.1187	0.5951
TFEE	330	0.4389	0.1647	0.2350	0.3980
DID	330	0.1242	0.3304	0.0000	0.0000
IN	330	0.3165	0.0793	0.1008	0.3198
RD	330	0.0169	0.0112	0.0022	0.0143
OP	330	0.2430	0.2713	0.0003	0.1332
LD	330	7.6005	0.7675	5.5452	7.6582
UR	330	0.6005	0.1088	0.3630	0.5910

4.2.5 Control variables

With reference for previous research (Wang and Li, 2021; Du et al., 2023), the following control variables are chosen for the investigation. Industrialization level (*IN*), calculated by the percentage of industrial added value accounts for each province's GDP. Openness level (*OP*), calculated as the percentage of actual FDI accounts for each province's GDP. Research and development investment (*RD*), calculated as the percentage of RD investment accounts for each province's GDP. Labor level (*LD*), measured by the natural logarithm of the employed quantity in each area. Urbanization level (*UR*), denoted by the percentage of urban population accounts for each province's population.

4.2.6 Data sources

The sample data of the research comprises panel data from 30 Chinese provinces for the period 2012–2022. Because of existing potential reasons such as data availability, Hong Kong, Taiwan, Macau, and Tibet have been excluded from this examination. The variables data mainly comes from the CEADs database, the "China Statistical Yearbook," the "China Industrial Statistical Yearbook," the "China Energy Statistical Yearbook," and provincial statistical yearbooks from various years. The definitions and descriptive statistics for these variables are respectively shown in Tables 2, 3. Descriptive statistics for the variables can be found in Table 3. As can be seen, the average value of DE is 0.1531, with a maximum value of 0.7120 and a minimum value of 0.0241. This indicates that the development level of digital economy is relatively low in most provinces, suggesting significant room for growth. The average value of CE is 10.3042, with a maximum value of 11.0705 and a minimum value of 8.7657, indicating the carbon emissions in each province are relatively high. The maximum value of SC is 4.9335, the minimum value is 0.5423, and the mean value is 0.8259. This implies that there are still certain differences in the economic development levels among the provinces in China.

5 Results and analysis

5.1 Benchmark regression results

To control time and individual differences, the investigation uses the two-way fixed-effects model. Table 5 demonstrates the results without and with control variables. As shown in the table, we can observe that the coefficient of the digital economy is notably negative at the 1% level. This finding supports Hypothesis 1 of this paper, which states that the digital economy exerts a suppressing influence on emissions. This implies that the digital economy, as a new economic engine, plays an important role in effectively mitigating the contradiction between economic development and carbon emission reduction. Because aggressively encouraging the growth of the digital economy across regions can provide better data analysis and information sharing and enhance the availability and accuracy of environmental monitoring data to optimize supply chain management and address deficiencies in environmental governance. Moreover, by leveraging digital technology, digital services, and digital platforms as the main elements or forms, the development space in various fields can be further restructured and expanded, thereby better alleviating the pressure of carbon emissions across regions at its source. The regression results also indicate that the industrial development level lowers carbon emissions, primarily because industrial advancement is often accompanied by greater investment in and usage of renewable energy sources (e.g., nuclear energy and solar). These sources produce little to no carbon emissions compared to traditional fossil fuels, such as oil and coal. Conversely, the level of openness to foreign trade tends to increase carbon emissions, likely because trade liberalization stimulates the growth of international trade, which also raises demand for logistics and transportation, especially in international shipping and aviation—both of which rely heavily on high-carbon-emitting fuels. The transportation sector constitutes a considerable portion of emissions of carbon dioxide, so the expansion of international trade also leads to more emissions of carbon dioxide.

5.2 Robustness tests and endogeneity analyses

Although the article uses the two-way fixed-effects model and controlled for variables affecting carbon emissions as much as possible to minimize measurement errors, endogeneity bias may still occur because of existing omitted variables and reverse causality in the model estimation. For example, regions with high carbon emissions tend to have weaker foundations for digital economic development due to the dominance of heavy industries, indicating the presence of an endogeneity problem with mutual causality. Therefore, to ensure the reliability of the estimate results, the study further conducts robustness tests and endogeneity analyses.

TABLE 4 Results of robust test.

Variables	(1)	(2)	(3)
	CE	*CE*	*CE*
DE		−0.7038*	−0.0869***
		(0.3588)	(0.0326)
DE2	−0.1050**		
	(0.0531)		
IN	−0.1805	−0.1590	−0.0727*
	(0.1939)	(0.2207)	(0.0390)
RD	−0.2175	−1.7717	−0.0549
	(2.1426)	(4.2996)	(0.3554)
LD	0.1099	0.0565	−1.2923**
	(0.1116)	(0.1403)	(0.5842)
OP	0.0050	0.0243	0.0429
	(0.1001)	(0.1333)	(0.0320)
UR	−0.0425	−0.2717	−0.0451
	(0.2924)	(0.4715)	(0.0558)
Constant	9.5590***	10.1452***	17.0502***
	(0.8666)	(1.0680)	(0.0373)
Observations	330	286	2,793
Adjusted R-squared	0.9697	0.9679	0.9884
Controls	YES	YES	YES
Pro FE	YES	YES	YES
Year FE	YES	YES	YES

Note: standard errors are in parentheses, ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

5.2.1 Robustness tests

1) Replacing the explanatory variable. The digital economy mentioned earlier was estimated by the entropy weight method. To test the robustness of the estimate results, this research further re-estimates the digital economic development levels of various provinces by employing principal component analysis, referred to as DE2, and continues to examine the model. In column 1) of Table 4, the estimate findings have been revealed. It is clear that the influence of the digital economy on emissions of carbon dioxide remains significantly negative, showing a significant suppressive impact for emissions of carbon. It corresponds with the previous estimate results.
2) Part of the sample was removed. Additionally, this research considers the significant discrepancies in degrees of digital economic development across regions, particularly noting that the economic scale of the four municipalities—Chongqing,

TABLE 5 Results of endogeneity analysis (Instrumental variable method).

Variables	(1)	(2)
	DE	*CE*
DE		−5.9477***
		(1.8139)
IV	0.0217***	
	(0.0028)	
IN	−0.2317***	−0.2317***
	(0.0344)	(0.0344)
RD	1.9330***	1.9330***
	(0.4161)	(0.4161)
LD	0.0339*	0.0339*
	(0.0205)	(0.0205)
OP	−0.1238***	−0.1238***
	(0.0178)	(0.0178)
UR	−0.0229	−0.0229
	(0.0558)	(0.0558)
Observations	330	330
R-squared		0.4389
Anderson canon Corr. LM	59.121 (0.0000)	
Cragg Donald Wald F	61.984 (16.38)	

Note: standard errors are in parentheses, ***p < 0.01, **p < 0.05, *p < 0.1.

TABLE 6 Results of endogeneity analysis (SYS-GMM).

Variables	(1)
	CE
DE	−2.2606*
	(1.2445)
IN	−7.0807***
	(1.6370)
RD	8.7595
	(10.6905)
LD	0.7503***
	(0.1411)
OP	0.0860
	(0.6266)
UR	2.7128*
	(1.5490)
Constant	5.5960***
	(1.1857)
Observations	330
Controls	YES
Pro FE	YES
Year FE	YES
AR (1)	0.051
AR (2)	0.540
Hansen test	0.769

Note: standard errors are in parentheses, ***p < 0.01, **p < 0.05, *p < 0.1.

Tianjin, Shanghai and Beijing—is significantly greater than other provinces. Therefore, the data of these four municipalities are removed in the paper, and continues to examine regression testing. In column 2), the regression results are presented. It is clear from the table that the digital economy's coefficient remains significantly negative, still showing a significant suppressive impact for emissions of carbon dioxide. It corresponds with the previous estimated results again.

3) Using city-level data samples, this paper considers the robustness of the regression results from a data perspective. In order to obtain more robust and reliable results, the regression is performed again using city-level data. The results are shown in column (3) of Table 4, where the coefficient of digital economy (DE) remains significantly negative at the 1% level, further confirming that the digital economy has a significant inhibiting effect on carbon emissions, consistent with the previous baseline regression results.

5.2.2 Endogeneity analyses

In order to tackle the potential endogeneity issue, the paper adopt the instrumental variable method. Regarding the instrumental variable, referring to the established literature (Chen et al., 2023), we select the historical data of post and telecommunications in 1984 as instrumental variables, denoted as IV. It uses two-stage least squares to test for endogeneity. The results are shown in Table 5. Results show that the effect of the digital economy on carbon emissions reduction is significant. Furthermore, the Anderson canon Corr. LM statistics significantly reject the null hypothesis that the equation is under-identified and the instrumental variable is irrelevant. The Cragg Donald Wald F statistic is 61.984, which is greater than the Stock-Yogo weak ID test critical values of 10% maximal IV size (16.38), so there are also no weak instrumental variables. Therefore, the instrumental variables selected in this paper are reasonable and effective.

Additionally, this paper adopted system-based generalized moment estimation (SYS-GMM) to test endogeneity. The analysis findings are presented in Table 6, and the digital economy still effectively lowers emissions of carbon dioxide. In summary, after robustness and endogeneity tests, the previous estimated results are further supported.

5.3 Heterogeneity analyses

5.3.1 Heterogeneity analysis based on regional administrative divisions

The research sample is divided into three regions: Western China, Central China, and Eastern China, to examine the regional heterogeneity of the effect. According to the results,

TABLE 7 Heterogeneity analysis based on regional administrative divisions.

Variables	(1)	(2)	(3)
	CE-E	*CE-C*	*CE-W*
DE	−5.8283***	−0.5404	−2.1290
	(1.6671)	(1.0972)	(1.2844)
IN	−0.2752	−0.2514	−0.7908
	(2.5166)	(0.3318)	(0.5120)
RD	4.1223	−1.7174	1.8437
	(10.8773)	(6.1101)	(8.8080)
LD	1.0698	−0.1703	1.2120
	(0.9141)	(0.1502)	(0.8551)
OP	2.3341***	0.9121**	0.3086
	(0.6124)	(0.4275)	(0.5177)
UR	−0.0541	−1.1103	−5.6836**
	(1.4327)	(1.1804)	(2.6570)
Constant	2.4913	12.4055***	4.5949
	(7.6133)	(1.1878)	(5.5219)
Observations	110	99	121
Adjusted R-squared	0.5292	0.9344	0.9629
Controls	YES	YES	YES
Pro FE	YES	YES	YES
Year FE	YES	YES	YES

Note: standard errors are in parentheses, ***p < 0.01, **p < 0.05, *p < 0.1.

TABLE 8 Heterogeneity analysis based on energy endowments.

Variables	Energy-A	Energy-S
	CE	*CE*
DE	−0.9721***	−0.1495
	(0.1901)	(0.2586)
IN	−0.7600	0.2029
	(0.6754)	(0.9989)
RD	−11.5157	19.2325*
	(13.3821)	(10.1187)
LD	0.2036	0.2688
	(0.4318)	(0.5688)
OP	1.8642***	1.6610***
	(0.3785)	(0.5715)
UR	−0.7673	0.8498
	(1.4431)	(1.1790)
Constant	9.1833***	6.9317*
	(3.4893)	(4.1764)
Observations	169	160
Adjusted R-squared	0.8406	0.7584
Controls	YES	YES
Pro FE	YES	YES
Year FE	YES	YES

Note: standard errors are in parentheses, ***p < 0.01, **p < 0.05, *p < 0.1.

which have been displayed in columns (1)–(3) of Table 7, the digital economy's coefficient is negative at the 1% significance level in Eastern China, it has better emission reduction outcomes in Eastern China. This result can be explained by several factors. First, the eastern region is economically advanced with a strong industrial structure and a high proportion of service and high-tech industries, leading in digital transformation. In contrast, the central and western regions are underdeveloped, with heavy industry and a high carbon emission base, limiting emission reduction effects. Second, the eastern region has advanced digital technologies like AI and big data, which improve carbon efficiency in industries. However, the central and western regions lack digital infrastructure and technical talent, hindering energy efficiency improvements. Third, the eastern region benefits from strong government support for green policies, while the central and western regions face weaker enforcement and limited resources, reducing policy effectiveness.

5.3.2 Heterogeneity analysis based on energy endowments

Additionally, a heterogeneity analysis based on energy endowment is conducted. Energy endowment is measured in this article by the total fixed-asset investment in the energy industry (Hu and Xiao, 2007). Then based on the average of the energy endowment across regions, areas are classified as either energy-abundant or energy-scarce. Table 8 presents the findings, indicating that in energy-abundant regions, the digital economy has a more apparent inhibitory effect on emissions of carbon dioxide. This finding aligns with most previous research (Sun and Wu, 2024; Yu et al., 2024), which suggests that the suppression effect is more significant in regions with relatively abundant energy. Compared to low-energy-consuming areas, high-energy-consuming regions experience relatively slower economic growth. The development of these regions relies on consumption of traditional resource and energy, which is comparatively inefficient. Along with the diffusion and application of digital technology, the growth of the digital economy will be able to help market participants in deeper understanding relationships in energy markets and pricing, thereby enhancing the effectiveness of allocating energy resources. Additionally, the use of new digital technologies can assist industries in enhancing energy efficiency, alleviating excessive energy consumption and ultimately lowering emissions of carbon dioxide.

5.3.3 Heterogeneity analysis based on the development level of the digital economy

The sample data is categorized according to the average level of digital economy development, dividing regions into those with high

TABLE 9 Heterogeneity analysis based on the development level of the digital economy.

Variables	DE-H	DE-L
	CE	*CE*
DE	−0.6876***	−0.1899
	(0.2592)	(0.1945)
IN	−1.3603	−0.9253**
	(1.3122)	(0.4291)
RD	6.4671	7.3558
	(9.0051)	(10.7218)
LD	−0.0934	0.8443**
	(0.5383)	(0.3772)
OP	2.4747***	0.5528
	(0.4494)	(0.5104)
UR	0.2104	−5.1736**
	(1.2800)	(2.1482)
Constant	10.7694**	6.7062***
	(4.5760)	(2.0841)
Observations	175	155
Adjusted R-squared	0.5134	0.9598
Controls	YES	YES
Pro FE	YES	YES
Year FE	YES	YES

Note: standard errors are in parentheses, ***p < 0.01, **p < 0.05, *p < 0.1.

TABLE 10 Estimated results of mediation effects.

Variables	(1)	(2)	(3)	(4)
	SC	*ES*	*TFP*	*TFEE*
DE	0.8297**	−0.2853***	0.6176*	0.2376*
	(0.3227)	(0.1028)	(0.3374)	(0.1382)
IN	−1.1110***	0.1559**	0.4420**	0.4105***
	(0.2124)	(0.0677)	(0.2221)	(0.0910)
RD	−6.2397***	−1.4494*	2.8692	−0.6445
	(2.3303)	(0.7425)	(2.4367)	(0.9982)
LD	0.3785***	0.0831**	−0.0101	−0.2763***
	(0.1233)	(0.0393)	(0.1289)	(0.0528)
OP	−0.0201	−0.0777**	0.0769	0.0204
	(0.1135)	(0.0362)	(0.1187)	(0.0486)
UR	−1.3872***	−0.3111***	0.4738	−0.0439
	(0.3227)	(0.1028)	(0.3375)	(0.1382)
Constant	−0.4390	−0.0386	0.0791	2.4056***
	(0.9515)	(0.3032)	(0.9949)	(0.4076)
Observations	330	330	330	330
Adjusted R-squared	0.9819	0.9498	0.8249	0.9258
Controls	YES	YES	YES	YES
Pro FE	YES	YES	YES	YES
Year FE	YES	YES	YES	YES

Note: standard errors are in parentheses, ***p < 0.01, **p < 0.05, *p < 0.1.

and low level of development. Table 9 presents the findings of heterogeneity test, indicating that there is a more significant reduction in emissions in areas with higher level of digital economy. In contrast, there is no substantial reduction in emissions in regions with lower level of digital economy. Typically, digital economy development is linked to higher production efficiency and improved resource utilization. A more advanced digital economy allows businesses to optimize production processes through information technology, reducing resource waste, which in turn leads to higher output and less carbon emissions. Conversely, in regions with lower digital economic development, the use of digital equipment and infrastructure may raise energy demand. Due to less advanced technology, energy efficiency remains low, and traditional energy supply systems struggle to support low-carbon development, and the influence of reduction in emissions is not significant (Li et al., 2024).

5.4 Further discussion

5.4.1 Mediation effect analysis

On the basis of the previous section, we examine three mechanisms on the production-side: the scale, structural, and technological effects. The estimated results for production-side variables (output scale, energy structure, and technological progress) as explanatory variables are provided in columns (1)–(4) of Table 10. According to column (1), the digital economy's coefficient is positive at the 5% significance level, suggesting that it positively promotes the growth of output scale. The application of digital technology will be able to enhance the automation and accuracy of the production process, reducing production time and resource wastage, thereby increasing overall production efficiency. This increased efficiency leads to a larger scale of output. An increase in the scale of output is usually accompanied by an increase in production activities, which typically consume large amounts of energy. Even with improvements in production technology, if the scale of output grows rapidly, the absolute amount of energy consumed may still rise, leading to more emissions of carbon dioxide. In addition, growth in the scale of output may result in the generation of more waste, such as an increase in industrial waste and packaging materials. If waste is not managed properly (e.g., by incineration), this could further increase carbon emissions. Thereby as the economic scale expands, although the carbon footprint of individual products may decrease, increased overall production will raise energy input and consumption, leading to a rise in total carbon emissions levels (Wang and Chen, 2023; Zhu and Lan, 2023), confirming Hypothesis 2a of this paper.

As shown in column (2), the digital economy's coefficient is negative at the 1% significance level, showing that it can promote an upgrade in the energy consumption structure, lowering the percentage of coal consumption account for the consumption of energies. This is because digital technology makes energy management smarter and more efficient. One hand, with smart grids and energy management systems, the monitoring and deployment of power supply and consumption can be carried out in real time, thus optimizing energy use and reducing energy waste. On the other hand, this intelligence helps to integrate more renewable energies, more efficiently into the energy mix. It enhances the competitiveness of renewable energy sources and promotes their share in the energy mix. Furthermore, a large number of studies have shown that the transformation of the energy structure towards a clean and low-carbon direction can significantly improve carbon reduction efficiency, thereby effectively promoting environmental protection and sustainable development (Huang and Lin, 2024), confirming Hypothesis 2b.

According to columns (3) and (4), the digital economy's coefficient is significantly positive, suggesting that it can promote technological progress through increasing both total factor productivity and total factor energy efficiency. This is because digital technologies optimize all aspects of the production process, lower waste of time and resources, and increase productivity. For example, intelligent robots and automated production lines applied in the manufacturing industry can significantly improve productivity and product quality, thereby boosting TFP and TFEE. And the digital economy lowers the cost of information acquisition and dissemination, making it easier for businesses and individuals to access new knowledge and technology. This flow of information accelerates the rate of technology diffusion and innovation, driving productivity and technological progress upwards. Higher TFP means that the same or greater output can be achieved with fewer resources, thus reducing excessive consumption of resource and carbon emissions. Simultaneously, the utilization of digital technology boosts TFEE, making energy production more efficient per unit, thereby decreasing energy waste and carbon emissions. These economic mechanisms work together, making the digital economy a strong potential for driving reduction of carbon dioxide emissions (Li and Wang, 2022). Additionally, when considering patent data to measure technological progress for empirical analysis, the empirical results are consistent with the above conclusion, namely, that the digital economy can promote carbon reduction through technological progress, confirming Hypothesis 2c.

Meanwhile, the Table 11 ultimately displays the negative effect of the digital economy on carbon emissions, revealing that the digital economy finally lowers carbon emissions. The further analysis indicates that structural effect and technological effect are manifested as reducing carbon emissions in the mechanism test, while scale effect is manifested as promoting carbon emissions. The combined suppressive action of the structural and technological effects on carbon reduction outweighs the promoting action of the scale effect. The suppressive action ensures the digital economy plays its expected role in reducing emissions.

TABLE 11 Results of baseline regression.

Variables	(1)	(2)
	CE	*CE*
DE	−0.7376***	−0.5346***
	(0.0633)	(0.0767)
IN		−0.0964*
		(0.0505)
RD		0.8876
		(0.5538)
LD		0.0460
		(0.0293)
OP		0.1484***
		(0.0270)
UR		−0.0467
		(0.0767)
Constant	1.1355***	0.7627***
	(0.0097)	(0.2261)
Observations	330	330
Adjusted R-squared	0.7870	0.8216
Controls	NO	YES
Pro FE	YES	YES
Year FE	YES	YES

Note: standard errors are in parentheses, ***p < 0.01, **p < 0.05, *p < 0.1.

5.4.2 Moderating effect analysis

Based on Model (6), examining the role of the NBDCPZ policy in the process of the digital economy influences emissions of carbon dioxide, the Table 12 presents the estimation results. The coefficients of the digital economy, and its interaction term with the policy variable are both significantly negative, revealing that government support can further improve the digital economy's carbon-reduction impact. This is due to the fact that carbon emission measurement systems based on new digital technologies can rapidly develop with strong government support. These technologies enable data collection, accurate analysis and real-time monitoring of emissions data. By collecting and analyzing data on carbon emissions from various industries, the government can implement other policies that are more effective. This data-driven policy can enhance the government's efficiency in managing carbon emissions while avoiding negative impacts on economic growth, thereby achieving more effective carbon reduction (Shen and Wang, 2024). National big data policies not only provide technical support but may also incentivize businesses to adopt digital and low-carbon technologies through financial subsidies, tax incentives, and other measures. These policy incentives can accelerate the spread of green technologies, thereby boosting the emission reduction effects of the digital economy. Additionally, big data policies can help promote the establishment of smart cities and lower carbon emissions in cities

TABLE 12 Estimated results of moderating effects.

Variables	(1)
	CE
DE	−0.2667***
	(0.0684)
DID	0.0525***
	(0.0094)
*DID*DE*	−0.4312***
	(0.0423)
IN	−0.0521
	(0.0429)
RD	−1.2109**
	(0.4990)
LD	0.0201
	(0.0246)
OP	0.1222***
	(0.0226)
UR	−0.0261
	(0.0641)
Constant	0.9375***
	(0.1895)
Observations	330
Adjusted R-squared	0.8756
Controls	YES
Pro FE	YES
Year FE	YES

Note: standard errors are in parentheses, ***p < 0.01, **p < 0.05, *p < 0.1.

TABLE 13 Analysis of the regional heterogeneity.

	(1)	(2)	(3)
Variables	*CE-E*	*CE-C*	*CE-W*
DID	0.0257**	0.0144*	0.0037
	(0.0120)	(0.0078)	(0.0145)
IN	−0.2211***	−0.1411***	−0.3777***
	(0.0349)	(0.0307)	(0.1172)
RD	1.1505*	1.7043***	−0.8884
	(0.6904)	(0.5930)	(0.7452)
LD	−0.0766	0.0173	0.0152
	(0.0617)	(0.0154)	(0.0469)
OP	0.1145***	0.0290	0.1240***
	(0.0381)	(0.0429)	(0.0375)
UR	0.1785	0.3596***	−0.0146
	(0.1410)	(0.1172)	(0.0783)
Constant	0.5937	−0.2130*	0.2094
	(0.4269)	(0.1191)	(0.3803)
Observations	110	99	121
Adjusted R-squared	0.9393	0.9738	0.9655
Controls	YES	YES	YES
Pro FE	YES	YES	YES
Year FE	YES	YES	YES

Note: Standard errors in parentheses, ***p < 0.01, **p < 0.05, *p < 0.1.

through intelligent traffic management, energy-saving buildings and waste management. The construction of smart cities makes urban resources more reasonable and further reduces carbon emissions. In fact, the emission reduction effects of the digital economy are not singular. They often benefit from the interaction and synergy of multiple policies. Big data policies provide the data support and technical platform for the low-carbon transformation within the digital economy. Through big data analysis and optimization, businesses can more efficiently implement energy-saving and emission reduction measures, while governments can make more precise policy adjustments based on real-time data (Liu and Zhou, 2023).

Meanwhile, in order to compare the different effects of the policy across various pilot areas, the paper conducted a regional heterogeneity analysis of the NBDCPZ policy based on Formula 1. The results of the heterogeneity analysis are shown in the Table 13. The results in the table show that they are very similar to the findings on the regional heterogeneity of the digital economy. The impact of the national big data policy is more significant in the eastern and central regions, while its impact in the western region is small, or even insignificant. This is because, compared to the western region, the eastern and central regions generally have stronger implementation capabilities and resource support for policy implementation. For example, they invest more in policy promotion, technology research and development, and talent introduction, which allows big data policies to be implemented more smoothly and achieve results in these areas. In contrast, the western region may face issues such as insufficient policy enforcement and inadequate financial and technical support, resulting in weaker policy influence.

6 Research conclusions and policy implications

Digital economy development is crucial for supporting the attainment of China's "dual carbon" goals and accelerating low-carbon growth. It represents an essential pathway for fostering green, low-carbon economic progress. In the study, output scale, energy structure, and technological progress are all incorporated into the theoretical and empirical framework, analyzing the digital economy's effect pathway for carbon emissions from the perspective of production-side. Moreover, the study examines the moderating role of the NBDCPZ policy in the process of digital economy on emissions reduction.

The results reveal three key findings: 1) The digital economy demonstrates a substantial effect of lowering emissions of carbon dioxide, supported adequately by a series of robustness and endogeneity tests. Heterogeneity tests indicate that it is more effective in translating the digital economy's influence for carbon reduction in eastern region, and the reduction effort is more obvious in regions with abundant energy resources and higher digital economic development. 2) As presented by the mediation effect analysis, while digital economy increases emissions of carbon dioxide through the scale effect, it simultaneously reduces emissions of carbon dioxide via structure and technology effects, with the sum of latter two effects outweighing the former. 3) The moderating effect analysis indicates that the NBDCPZ policy enhances the digital economy's carbon-reduction impact, demonstrating that a governance model combining market mechanisms and government intervention can improve carbon emissions control efficiency.

The research offers the following policy insights based on the aforementioned conclusions. First, increasing investment in digital infrastructure to facilitate the spread and use of digital technologies, especially in energy-intensive and less developed regions. This can boost the digital economy's emissions reduction potential across different areas. In addition, governments and enterprises should increase research investment of green technologies, especially smart grid, renewable energy integration and low-power equipment, so as to make technological progress the driving force of achieving low-carbon economy, thus changing the production function in the long run, decoupling economic growth from resource consumption and achieving sustainable low-carbon development. Meanwhile, encouraging the digitization of supply chain management, especially in the transportation and logistics areas. Through logistics path optimization, storage management and other means, reduce unnecessary transportation, so as to reduce emissions of carbon dioxide. Based on regional characteristics, differentiated digital economy and emission reduction policies should be formulated. For example, the eastern region can focus on promoting technological innovation and green finance, while the central and western regions should prioritize addressing infrastructure construction and the widespread adoption of digital technologies.

Secondly, the utilization of the digital economy in industrial production ought to be strengthened to promote technological advancements and energy structure transitions, fostering green technology innovation and digital transformation across industries. This will reduce carbon emissions in both production and business operations. Specifically, it is the digital economy containing digital technology that can help transform the traditional industries featuring high emissions, low efficiency and high energy consumption. These technologies also facilitate the eliminating out outdated, energy-intensive production models, shifting the energy structure toward cleaner, low-carbon alternatives. Moreover, raising the traditional industries' digitalization level can optimize industrial processes and organizational structures, mitigating carbon emissions associated with output scale effects. Building an economic ecosystem and value chain that integrates digital technologies with low-carbon practices will further lower emissions of carbon dioxide by harnessing the advantages of digital platforms.

Thirdly, National Big Data Comprehensive Pilot Zone policy ought to be actively promoted, leveraging digital technologies to further innovate big data applications, enhance control over greenhouse gas emissions, and support the accomplishment of the dual carbon targets. Policymakers should capitalize on the opportunity presented by the pilot zone initiative, utilizing institutional advantages and tailoring policy implementation to the specific conditions, development foundations, and resource capacities of each region. A staggered and customized approach to advancing the NBDCPZ policy is essential. Additionally, strengthen policy synergies with big data zones: Expand and enhance the influence of big data zones to foster further collaboration between the government and private sectors. This can encourage the digital economy to integrate more effectively with carbon reduction strategies.

This study has the following limitations. First, the analysis is based on provincial-level data from 2012 to 2022. However, due to differences in data collection standards and scopes across provinces, there is some data heterogeneity, which may affect the reliability of the analysis results. Second, although this study constructs a comprehensive digital economy index based on existing literature, the rapid development of digital technologies has led to increasingly diverse ways of constructing digital economy indicators. Therefore, the existing indicators may not fully reflect the complexity of the digital economy. Third, this study primarily analyzes the impact mechanism of the digital economy on carbon dioxide emissions from the production perspective. However, since the impact of the digital economy on carbon emissions is complex and diverse, focusing solely on the production aspect has certain limitations.

To address the limitations mentioned above, this study proposes the following recommendations for future research. First, to further improve the research, future studies could consider collecting data at more granular levels, including city-level or enterprise-level data, to further examine the digital economy's carbon reduction effects at a more detailed scale. Second, as digital technologies continue to evolve, future research could optimize and expand the indicators of the digital economy to form a more comprehensive and accurate evaluation framework, leading to more reasonable conclusions. Third, future research could consider analyzing the impact mechanism of the digital economy on carbon emissions from a consumption perspective, further exploring the multidimensional impact of the digital economy on carbon emissions and helping to understand its potential and challenges on the consumption side.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

WX: Conceptualization, Funding acquisition, Investigation, Project administration, Resources, Supervision, Validation, Writing–original draft, Writing–review & editing. WW: Data curation, Formal Analysis, Investigation, Methodology, Software, Visualization, Writing–original draft.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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The author(s) declare that no Generative AI was used in the creation of this manuscript.

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Supplementary material

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