Sustainable development and climate governance in the age of digital intelligence – Original Research Article

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Digital economy and green transformation of regional industries: New insights from sustainability

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Abstract

Studying the impact of the digital economy on carbon emissions in the distribution industry is of great significance for realizing sustainable development goals and coping with climate change. This study finds that increasing the level of digital economy development can reduce the carbon emission intensity of the circulation industry through fixed-effects modeling. Moreover, the effect is different in different geographic regions, and the improvement of the digital economy development level in the east and central regions can significantly reduce the carbon emission intensity of the distribution industry. The digital economy can simultaneously reduce the carbon emission intensity of the circulation industry by reducing the degree of labor factor mismatch in the circulation industry and improving the regional green innovation capacity. Therefore, in order to promote the green development of the distribution industry, it is also necessary to make efforts to improve the construction of network infrastructure, accelerate the process of research and development and cultivation of green technology, and break down the barriers of cross-regional mobility of talents.

Keywords

Digital economy, circulation industry, carbon emission intensity, green transformation, green technological innovation

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Introduction

The escalation of carbon emissions, recognized as a critical driver of global warming, has engendered a proliferation of natural calamities, diminished crop production, and disturbed the delicate equilibrium of the ecological environment. Consequently, it poses a grave menace to the enduring viability of human civilization's sustainable advancement.[1,2] As the most rapidly developing nation, China is facing the double pressure and challenge of carbon emission reduction and low-carbon industry competition.[3,4] Amid the mounting pressure of international discourse and national policy, domestic progress in energy conservation and emission reduction has propelled the industrial and agricultural sectors to the forefront. Nonetheless, the service industry has been notably sluggish in its transition towards a greener paradigm.[5,6] In the 40 years after reform and opening up, the output value of China's service industry has been rising yearly. Furthermore, the service industry, with a specific emphasis on the circulation industry, has assumed a pivotal role in bolstering the high-caliber advancement of the national economy.[7] How to adapt to the current national environmental protection policy guidelines, achieve the goal of "carbon peaking and carbon neutrality," and then promote the transformation of the low-carbon economy has become one of the critical elements of China's economic structure and innovative development.[8,9] Figure 1 shows the carbon dioxide emissions of major developing countries, from which it can be seen that China's carbon dioxide emissions are growing in a more pronounced trend.

Some scholars have studied invisible carbon emissions in Chinese industries, comparing 28 industry sectors and finding differences in carbon emissions between different industries.[10] Some scholars have also analyzed the carbon emissions of industrial enterprises by investigating their energy consumption status and usage and made suggestions on how to improve energy efficiency.[11] There are fewer studies on carbon emissions from the distribution industry. The circulation industry, particularly the logistics industry, assumes a prominent position as a dominant sector in fostering the development of the

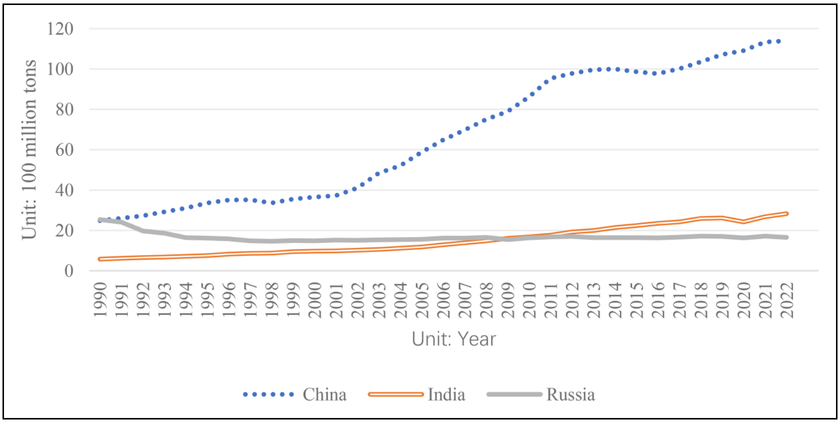

Figure 1. Carbon dioxide emissions from major developing countries.

national economy. Its significance lies in its instrumental role in harmonizing production processes, optimizing investment channels, and stimulating consumption. Additionally, the low-carbon green growth of the economy now includes an essential role.[12–14] But from the perspective of the growth of the circulation industry, the circulation industry's development stage is relatively low, and the realization of intensive development has a relatively large lag impact, with an evident irrational energy consumption structure.[15,16] These development characteristics may lead to a development impasse characterized by high input requirements, excessive resource consumption, and sub-optimal output levels, thus posing a challenge to sustainable economic growth at the local level. Moreover, the circulation industry's overall carbon emissions pattern will gradually show diversified and complex characteristics. Thus, boosting the low-carbon growth of the circulation industry is both a response to the national development goal in the new period and a key to promoting the green transformation of the region.[17]

Moreover, the advancement of novel digital technologies, which is characterized by digital information technology, has gradually become a significant impetus for the environmentally friendly development of the circulation industry.[18] The rapid advancement of the digital economy has the potential to play a significant part in the order service and production management practices of the circulation industry.[19,20] Therefore, realizing how to maintain the rapid growth of the circulation industry while considering the environmental benefits and fully exploiting the circulation industry is of great theoretical and practical significance. More importantly, still, the question of how to integrate the digital economy and the growth of carbon emission reduction in the circulation industry to accomplish the long-term and sustainable development of the circulation industry is an urgent problem that has to be addressed. Existing research on the digital economy driving carbon emissions in enterprises has found that the digital economy significantly improves the efficiency of enterprises through its efficient and convenient characteristics.[21] Based on advanced technologies such as big data, cloud computing, and the Internet of Things (IoT), the digital economy has enabled the optimization of various aspects of enterprises, thereby reducing unnecessary energy consumption and carbon emissions.[22] While the digital economy promotes business development, it also brings some new carbon emission problems. For example, with the prosperity of e-commerce platforms, the volume of online shopping has increased dramatically, which has led to a large amount of packaging materials being used and discarded, which in turn has increased carbon emissions. In addition, the rapid development of the digital economy has also brought about the large-scale construction of data centers, cloud computing, and other infrastructures, which also generate certain carbon emissions during their operation.[23] Therefore, how to promote the development of the digital economy while reducing its negative impact on corporate carbon emissions is a problem that needs to be thought about and solved.

The existing research has not paid enough attention to the distribution industry; in this regard, this paper deeply studies the interaction between the digital economy and the distribution industry, explores the effective ways to reduce carbon emissions, and contributes to the realization of sustainable development. In this study, a panel fixed-effects model and a mediated-effect model are constructed to conduct the study, and the carbon emissions of Carbon Emission Accounts and Datasets (CEADs) database are used to measure the carbon emission intensity of the distribution industry. The digital economy development level is constructed from four dimensions, namely, digital infrastructure, digital industrialization, industrial digitization, and digital environment, to analyze the impact of the level of digital economy development on the carbon emissions of the circulation industry. In the mediating effect model, a model containing three factors of circulation capital mismatch, circulation labor mismatch, and green technology innovation is established. This study helps to promote the green and sustainable development of the circulation industry. The rest of this study is organized as follows: the second part is the theoretical analysis and literature review, the third part is the research hypotheses, the fourth part is the empirical design, the fifth part is the analysis of the empirical results, and the sixth part is the research conclusions, policy recommendations, limitations of the article, and future prospects.

The innovation of this paper's research methodology is reflected in the following aspects: in terms of research design, the indicators selected for the construction of the indicator system are comprehensive. From the digital infrastructure construction, digital industrialization, industrial digitization, and digital environment to select indicators to build the level of digital economic development, usually scholars only use a single angle to measure the digital economy, but this paper chooses a wider range of perspectives and indicators, so as to measure the development of the digital economy in a more scientific way. The factors selected for consideration in the process of mechanism analysis are comprehensive. In this paper, in the study of the impact of digital economy development on carbon emissions in the distribution industry, the mechanism chosen to analyze the perspective is more comprehensive, respectively, from the circulation of capital mismatch, the circulation of labor mismatch, and the role of the mechanism of green technological innovation, the perspective is more comprehensive.

In terms of practical guidance, the study of the impact of the digital economy on the carbon emissions of the distribution industry has an important reference value for the development of developing countries. On the one hand, the digital economy provides developing countries with a new and effective way to reduce carbon emissions. With the wide application and popularization of digital technology, the level of digitization and intelligence in the circulation industry is increasing, which helps to reduce energy consumption and carbon emissions. Developing countries can draw on advanced digital technology and management experience to promote the digital transformation of the circulation industry, thereby reducing carbon emission intensity and realizing sustainable development. On the other hand, the digital economy has significant advantages in optimizing industrial structure and improving resource utilization efficiency. Promoting the digital transformation of the circulation industry can optimize resource allocation, improve labor productivity, reduce transaction costs, and further promote industrial upgrading and transformation. This can not only improve economic efficiency for developing countries but also reduce the negative impact on the environment and realize the coordinated development of the economy and environment. Finally, the study of the impact process of the digital economy on carbon emissions in the distribution industry can help developing countries formulate more scientific carbon emission reduction policies and measures. Through the in-depth study of the relationship between the digital economy and carbon emissions, we can more accurately grasp the rules and characteristics of carbon emissions in the circulation industry and provide a scientific basis for policy formulation. At the same time, it can also learn from the successful experience of developed countries, combined with the actual situation of their own countries, to formulate more effective carbon emission reduction policies and measures.

Theoretical analysis and literature review

The economic theory analysis of the digital economy on the carbon emission of the circulation industry mainly involves the following aspects: on the one hand, the influence of the digital economy on the carbon emission of the circulation industry has a scale effect, and the rapid development of the digital economy promotes the scale expansion of the circulation industry, which in turn increases the total amount of energy consumption and carbon emission.[24,25] However, with the continuous progress and deepening of the application of digital economy technology, the energy utilization efficiency of the circulation industry will be improved, and the intensity of carbon emissions may be gradually reduced.[26] On the other hand, the influence of the digital economy on carbon emission of circulation industry has a structural effect: the digital economy promotes the structural optimization and upgrading of the circulation industry and makes the circulation industry develop in the direction of more efficient and low carbon. For example, the development of e-commerce reduces the demand for traditional physical stores and lowers the energy consumption and emissions of physical stores; at the same time, new models such as the sharing economy also reduce carbon emissions by improving the efficiency of resource utilization. In addition, the impact of the digital economy on carbon allocation in the circulation industry also has a technical effect: the application of digital technology provides technical support for the reduction of carbon emissions in the circulation industry. Through big data, cloud computing, and other technical means, real-time monitoring and management of the circulation industry's energy consumption and carbon emissions can be realized, and then targeted emission reduction measures can be taken.

The exponential growth of the digital economy has become a focal point of scholarly inquiry, generating widespread discussions among experts. Coined by American economist Tapscott,[27] the term "digital economy" has since been refined and expanded upon by authoritative bodies such as the Organisation for Economic Co-operation and Development (OECD) and the US Department of Commerce, who have contributed to its conceptual framework and measurement methodologies. During the G20 Summit held in Hangzhou, China, the "G20 Digital Economy Development and Cooperation Initiative" was formally endorsed. This initiative adopts the term "digital economy" to encapsulate an economic ecosystem where digitalized information and knowledge constitute fundamental pillars of the production process. Additionally, modern information networks play a critical role as essential spaces for economic activities, while the digital economy assumes a central role as a key driver of production. The effective utilization of information and communication technology serves as a powerful impetus for enhancing overall efficiency and optimizing economic structures, emerging as a fundamental component across various economic sectors. The scale of the digital economy has reached an impressive 45.5 trillion yuan, contributing a substantial 39.8% to the nation's gross domestic product (GDP). A growing body of literature underscores the pivotal role played by the digital economy in fostering sustainable development ecosystems and effecting positive transformations in regional environments.[28]

Since the "dual-carbon" goal was put forward, how to reduce carbon emissions has become a hot topic of discussion in the academic community, and the digital economy is considered to be one of the effective means to promote energy saving and emission reduction. The literature that has been written on the relationship between the two can be categorized into the following three branches: first, numerous scholars in this field contend that the digital economy will aid us in achieving our carbon emission reduction objectives.[29] According to data gathered from cities in China, the vast majority of scholars in this field agreed that the digital economy plays a significant part in the reduction of carbon emissions.[30] It has accelerated the growth of e-commerce and Internet sectors, reduced emissions from polluting industries, streamlined the industrial structure of cities, improved environmental conditions, and provided an impetus for emission reduction.[31,32] Emerging industries in the digital economy context are characterized, which greatly reduce carbon emissions.[33] On the contrary, there are scholars who are of the opinion that the expansion of digital technology, which is the central pillar around which the digital economy is built, will result in other forms of energy, leading to an increase in carbon emissions.[34,35] In addition, some scholars believe that the impact of the digital economy on carbon emissions is not consistent.[35,36] Research conducted by scholars has demonstrated that the level of development in the digital economy exhibits regional heterogeneity concerning its influence on low-carbon development. Specifically, the digital economy notably suppresses carbon emissions in the eastern regions while promoting an increase in carbon emissions in the central regions. Certain research findings pertaining to carbon emissions reveal that the impact of the digital economy is more pronounced in the central and western regions compared to the eastern regions. Consequently, it can better facilitate regional carbon reduction efforts in these areas.[37]

In general, researchers have made substantial advancements in their knowledge of how the digital economy influences carbon emissions, which has provided crucial theoretical and empirical references for this research. However, some problems still need to be solved. First, instead of looking at sub-sectors, most scholars concentrated on how the digital economy affected total carbon emissions. In addition, the discussion on the impact of circulation industry is very limited. Second, the impact of the digital economy on reducing carbon emissions in the circulation industry is still unclear. Third, the mechanism of the digital economy in reducing carbon emissions in the circulation industry and the impact of the digital economy development level on carbon emissions in different regions still need to be investigated. The study analyzes both the link between the digital economy and carbon emissions in the circulation industry as well as the mechanism of the influence that the digital economy has on carbon emissions in the circulation industry. The data for this study comes from a panel that covers 30 provinces in China and spans the years 2011 to 2020. This study also analyzes the differences in the intensity of the effect of the digital economy on carbon emissions in the circulation industry in different regions.

Research hypotheses analysis

Development of the digital economy and carbon emission of the circulation industry

The Internet, cloud computing, and big data are all examples of digital technologies that enable the opportunity for the fast expansion of the digital economy. This case can break the time and space limitations and barriers of people, improve the efficiency of goods transportation, and speed up the flow of production elements in order to decrease the amount of resources and energy that are wasted,[38,39] thereby reducing carbon emissions. On the one hand, the digital economy is widely used in commerce and transportation, which is conducive to shortening circulation channels, reducing circulation time, and improving circulation efficiency by reconstructing the relationship between people and goods, thereby reducing energy consumption in the circulation process. On the other hand, the continuous improvement of digital infrastructure construction guarantees circulation enterprises to optimize process management and improve operational efficiency. Corporations engaged in circulation industry that are undergoing digitization use less energy and materials. For instance, the establishment of digital platforms and digital warehouses in warehousing and logistics enterprises can enable self-control and optimization of commodity storage and circulation processes and enable the coordinated and orderly development of enterprise resources,[40,41] thereby reducing carbon emissions. Therefore, this study proposes the following hypotheses:

> Hypothesis 1: The development of the digital economy can reduce the carbon emissions of the circulation industry.

Mechanisms of the digital economy affecting carbon emissions in the circulation industry

Promoting green technology innovation. As an integral component of carbon emission reduction, green technology innovation is essential to the growth of renewable energy, the decrease in the use of coal, and the increase of energy use efficiency. Moreover, the digital economy can serve as a vital catalyst for green technological innovation, thereby promoting carbon emission reduction within the circulation industry. First, digital technologies facilitate accelerated technology research and development, nurturing processes for enterprises, universities, and research institutions. This, in turn, reduces the difficulty and enhances the efficiency of technological innovation, thus contributing to the elevation of green technological innovation levels.

As an important part of carbon emission reduction, green technology innovation is necessary to reduce coal consumption, increase energy utilization, and create sources of sustainable energy. Furthermore, the digital economy can serve as a crucial catalyst for green technological innovation, thereby facilitating carbon emission reduction within the circulation industry. First, digital technology makes it possible for businesses, academic institutions, and research centers to accelerate the process of technology research and development and cultivation. It also makes it easier and more effective, which contributes to an increase in the level of green technology innovation.[42]

Second, the digital economy relies on big data, blockchain, and other digital technologies to give rise to several new industries, which can attract high-quality human capital.[43,44] The wide penetration and use of digital technology will increase the demand for highly skilled and educated talents.[45] This event will help stimulate the increase of the talent pool and thus lay a good foundation of innovation factors for urban green technology development. This case can also help urban green technology innovation. Third, the fast growth of the digital economy has led to an increase in the popularity of digital financial transactions. In addition, financial institutions can accurately determine the business conditions of enterprises with the help of digital finance-related tools. For circulation enterprises with a high development potential and strong market influence, financial institutions can provide credit funds, thereby promoting the efficiency of capital allocation.[46] The easing of financing constraints provides financial security for circulation companies to carry out green technology innovation activities.

Green technology innovation has been increasingly used frequently in the production practices of circulation enterprises to promote cleaner production, improve energy efficiency, and reduce resource consumption. Specifically, green technology innovation will reduce carbon emissions in the circulation industry through different types of green technologies. Green technologies are generally classified as green production technologies, energy utilization technologies, and pollution control technologies.[47] Among them, green production technology may help raise the degree of green production in the circulation industry, which in turn can help control the growth in carbon emissions in the circulation industry.[48] The development of new technologies for using energy will result in an increase in the efficiency with which the circulation industry utilizes energy and a decrease in the amount of carbon emissions.[49] The progress of pollution control technology can reduce the scale of carbon emissions in the circulation industry through carbon sequestration and carbon capture technologies. Generally, the cost of decarbonization may be efficiently controlled by green technology innovation. Green technology innovation can also provide technical support for the development and large-scale application of carbon dioxide utilization, capture, and storage technologies. This innovation can also give rise to a "technology dividend" effect, which can help improve carbon emissions in the circulation industry.[50] In addition, the development of green technology innovation may enable businesses to improve end-of-pipe control of environmental pollutant emissions, ultimately lowering the carbon emissions of the circulation industry.

Strengthening the deep integration of innovation and green development is also of great significance for the development of enterprises and cities. Some scholars have found that environmental information disclosure can also improve the energy efficiency of the manufacturing industry and the impact of green credit on the green total factor productivity of enterprises. The research results also provide support for establishing green finance and formulating green development strategies for enterprises.[51–54]

> Hypothesis 2: The digital economy promotes carbon emission reduction in the circulation industry by promoting green technology innovation.

Improving the allocation of labor resources. The digital economy based on big data algorithms can accurately match supply and demand information, increase the number of flexible employment in the circulation industry, and break the spatial-regional limitation of labor factors to achieve the optimization of labor factor allocation. Specifically, the high permeability of digital technology can significantly enhance the employment absorption capacity in the development process of the circulation industry. The new industries, such as the platform economy and sharing economy spawned by the digital economy, have generated flexible employment models, such as freelance and part-time employment, widening employment channels, and realizing intensive and efficient allocation of labor resources. For example, the widespread application of 5G technology has broken the time and space barrier of labor resource employment. In addition, the flexibility of entrepreneurship and employment has been unprecedentedly improved.[55] Circulation businesses will be able to use less material as a result of the fair distribution of labor factors, which will help to lower the amount of industrial carbon emissions. Consequently, this research suggests the following:

> Hypothesis 3: The digital economy promotes carbon emission reduction in the circulation industry by enhancing the level of labor resource allocation.

Optimizing capital allocation. The use and advancement of digital technology in the financial market, as a key driver of the digital economy, encourage the growth of digital finance, the free flow and allocation of financial capital in the market, and the ability of market participants in the circulation industry to obtain more capital support.[56] In addition, as a representative form of the digital economy, the development of digital finance is conducive to equalizing entrepreneurial opportunities and provides a capital base and financing platform for developing circulation enterprises.[57] The enhanced financing capacity helps circulation enterprises to seek sustainable development to strengthen their market competitiveness, such as promoting the construction of green stores, implementing green supply chain management, and achieving high-quality development through innovative business models, which will play a positive role in reducing carbon emissions in the circulation industry.

> Hypothesis 4: The digital economy promotes carbon emission reduction in the circulation industry through optimal capital allocation.

Empirical design

Model building

Fixed-effects model. The following fixed-effects model is constructed for empirical analysis to measure the impact of the digital economy on the carbon emission intensity of the circulation industry:

$$Ce_{it} = \alpha_0 + \beta_1 + Digital_{it} + \beta_2 X_{it} + v_i + u_t + \varepsilon_{it}, \quad (1)$$

where i stands for the province, t stands for the year, Ce_{it} stands for the carbon emission intensity of the circulation industry, $Digital_{it}$ stands for the level of development of the digital economy, X_{it} stands for a set of control variables, ε_{it} stands for the random disturbance term, α_0 stands for the constant term, β_1 stands for the regression coefficients of the core explanatory variables, and β_2 stands for the regression coefficients of the control variables.

The rationale for choosing a panel fixed-effects model in this paper is as follows: first, the fixed-effects model assumes that individual-specific invariants have an impact on the observations, and these invariants may include an individual's gender, age, and education.[58,59] By introducing individual fixed-effects variables, the model is able to capture these influences and thus more accurately explain changes in observations. Second, panel data has numerous advantages that make the fixed-effects model an ideal choice. Panel data not only addresses the problem of omitted variables but also provides more information about the dynamic behavior of individuals. Since panel data contains both cross-sectional and time dimensions, it is not only capable of examining the time trend of effects for dynamic analysis but also has a larger sample capacity, thus improving the accuracy of estimation. In addition, the panel fixed-effects model is suitable for research scenarios where individual differences exist and do not change over time. When the research question involves comparisons between different individuals or units and there are stable and non-time-varying differences in the characteristics of these individuals or units, the fixed-effects model can provide more accurate and reliable estimation results. In this paper, in the study of the impact of the digital economy on carbon emissions in the distribution industry, it is consistent with the above research scenarios, so the research results obtained by utilizing the panel fixed-effects model are more reliable.

Intermediary effect model. A model containing circulation capital mismatch, circulation labor mismatch, and green technology innovation is further constructed for regression analysis. The objective is to test the mechanism of digital economy development affecting carbon emission intensity of the circulation industry, based on model (1). The specific model is shown below:

$$Abstauk_{it} = \alpha_0 + \beta_1 Digital_{it} + \beta_2 X_{it} + v_i + u_t + \varepsilon_{it} \tag{2}$$

$$Abstaul_{it} = \alpha_0 + \beta_1 Digital_{it} + \beta_2 X_{it} + v_i + u_t + \varepsilon_{it} \tag{3}$$

$$Gpat_{it} = \alpha_0 + \beta_1 Digital_{it} + \beta_2 X_{it} + v_i + u_t + \varepsilon_{it} \tag{4}$$

$$Ce_{it} = \alpha_0 + \beta_1 Digital_{it} + \beta_2 Gpat_{it} + \beta_3 X_{it} + v_i + u_t + \varepsilon_{it} \tag{5}$$

Models (2), (3), and (4) are designed to test whether the digital economy can affect circulating capital mismatch, circulating labor mismatch, and green technology innovation. Model (5) adds the mediating variables to the main regression, and if the regression coefficients of each mediating variable are significant, then there is a mediating effect.

The mediating effects model was chosen based on the following considerations[60]: first, to explore in depth the relationship between the development of the digital economy and carbon emissions in the distribution industry. Mediated effects modeling allows researchers to explore how the independent variable affects the dependent variable and to identify the mediating processes or mechanisms involved. By revealing the relationships within this "black box," it is possible to gain a deeper understanding of the complex linkages between variables and thus provide more comprehensive explanations and predictions. Second, it is to reveal the path of causality. The mediated effects model can reveal the path through which the independent variable affects the dependent variable through the mediating variable. This helps to understand the complexity and diversity of causal relationships and further validate and extend theoretical models.

Variable selection and data description

1. Explanatory variables: carbon emission intensity (*Ce*) of circulating industries. For the measurement of carbon emission, existing studies mainly used the carbon emission data of Carbon Emission Accounts and Datasets database to measure the carbon emission. However, this database only contains carbon emission data at the regional level and does not include those of each industry segment. No clear classification standard exists for the circulation industry in China's statistical yearbook. Hence, this study uses the "transportation, storage, and postal industry," "wholesale and retail industry," and "accommodation and catering industry" to represent the circulation industry according to the characteristics of the circulation industry. To calculate the carbon dioxide emissions in the circulation industry for each province in China using the baseline approach provided in the IPCC 2006 Guidelines for National Greenhouse Gas Inventories (Energy Sector), the following formula can be employed:

$$CO_2 = FC_i \times K_i \times NCV \times C_i \times O_i \times \frac{44}{12}. \tag{6}$$

where CO_2 represents the carbon dioxide emissions from the circulation industry in each province and FC_i represents the amount of fossil fuels, such as raw coal, gasoline, kerosene, diesel, fuel oil, liquefied petroleum gas, and natural gas consumed by the circulation industry. K_i represents the coal discount factor of various fuels. *NCV* stands for the net calorific value, which measures the amount of heat released per unit of standard coal burned. C_i represents the carbon content of fuel i and is able to measure the carbon content of fuel i per unit of net calorific value. O_i denotes the carbon oxidation rate of energy i. The rate at which carbon in fuels is oxidized to carbon in carbon dioxide may be measured during combustion. Finally, the rate is divided by the mass fraction of carbon in carbon dioxide 12/44 to obtain the carbon dioxide emissions from the circulation industry in each province.

Considering that the overall economic scale and industrial structure vary from region to region, the absolute CO_2 emissions cannot accurately reflect the regional CO_2 emission intensity. Therefore, this study uses the amount of CO_2 emitted per unit of value added by the circulation industry as a proxy variable for the carbon emission intensity of the circulation industry, which is calculated as shown in the following equation:

$$Ce = CO_2 / CI \tag{7}$$

where Ce denotes the carbon dioxide emission intensity of the circulation industry and CI denotes the value added of the circulation industry.

2. Explanatory variables: the level of digital economy development (Digital). The current academic community has not yet formed a unified standard for digital

economy measurement methods. Hence, this study draws on previous research to build an indicator system for the level of digital economy development at the provincial level from four dimensions[61,62]: digital infrastructure, digital industrialization, industrial digitization, and digital environment. Table 1 shows the specific indicators. The final digital economy development is measured using principal component analysis.

Table 1. Digital economy indicator system.

Level 1 indicators	Level 2 indicators	Indicator description
Digital infrastructure	Long-distance fiber optic cable line length	Length of long-distance fiber optic cable lines (billion kilometers)
	Internet broadband access port	Internet broadband access ports (million)
	Telephone penetration rate	Total number of telephones (including cell phones)/total population of the administrative area × 100 (departments)
	Internet penetration rate	Number of Internet users as a proportion of the resident population (%)
	Number of Internet domain names	Number of Internet domain names (million)
Digital industrialization	Number of digital economy companies	The number of electronic information manufacturing enterprises above the scale (a)
	Digital industry practitioners	Average year-end employees in the information transmission, software, and information technology service industry (persons)
	Digital industry revenue capacity	The main business income of the electronic information manufacturing industry above the scale (billion yuan)
	Software business revenue	Software business revenue (million yuan)
	Total telecommunications business	Total telecom business (billion yuan)
	Number of digital TV subscribers	Number of digital TV subscribers (million)
Industry digitization	E-commerce sales	E-commerce sales (billion yuan)
	Enterprise information level	Number of computers used by enterprises per 100 people (units)
	Corporate website coverage	Number of websites per 100 enterprises (pcs)
	Digital inclusive finance index	Peking University Digital Inclusive Finance Index
	Number of courier services	Courier volume (million pieces)
Digital environment	Data valorization	Number of data trading centers (pcs)
	R&D investment intensity	Ratio of internal spending on R&D to GDP (%)
	Number of granted patent applications	The number of inventions, utility models, and appearance of three kinds of patents authorized (pieces)
	Years of schooling per capita	Average years of education (years)

3. Mediating variables: circulation resource mismatch. Based on previous studies,[63] this study measures the capital mismatch index τ_{Ki} and labor mismatch index τ_{Li} of the circulation industry in each region by the following method with the following equations:

$$\gamma_{K_i} = \frac{1}{1+\tau_{K_i}}\ ,\ \gamma_{L_i} = \frac{1}{1+\tau_{L_i}}, \tag{8}$$

where γ_{K_i} and γ_{L_i} represent the absolute distortion coefficients of capital and labor in the circulating industry, respectively, and are measured in practice by the relative distortion coefficients of the following:

$$\widehat{\gamma_{K_i}} = \frac{K_i}{K} / \frac{s_i\beta_{K_i}}{\beta_K},\ \widehat{\gamma_{L_i}} = \frac{L_i}{L} / \frac{s_i\beta_{L_i}}{\beta_L}, \tag{9}$$

where s_i denotes the share of the total output value of the circulation industry in region i in the total output value of the whole sample and β_{K_i} and β_{L_i} denote the capital-output elasticity and labor-output elasticity of the circulation industry in region i, respectively. $\beta_K = \sum_i^n s_i\beta_{K_i}$ and $\beta_L = \sum_i^n s_i\beta_{L_i}$ denote the output-weighted capital and labor contribution values, respectively. The Solow residual method is used in this study to measure the capital-output elasticity and labor-output elasticity of the circulation industry as follows:

$$Ln(Y_{it} / L_{it}) = LnA + \beta_{K_i}Ln(K_{it} / L_{it}) + \sigma_i + \varepsilon_t + \theta_{it}, \tag{10}$$

where Y_{it} denotes the value added of the circulation industry in region i in year t, L_{it} denotes the number of people employed in the circulation industry in region i in year t, and K_{it} denotes the capital stock of the circulation industry in region i in year t, measured using the perpetual inventory method with the following equation:

$$K_t = I_t / P_t + (1 - s_t)K_{t-1}, \tag{11}$$

where I_t denotes the fixed asset investment in the circulation industry in year t, P_t denotes the fixed asset investment price index, and σ_i denotes the depreciation rate and is adapted to be expressed by 9.6%.

The capital and labor mismatch indices of the circulation industry are finally calculated through the above steps. The capital and labor mismatch indices of the circulation industry are treated as absolute values, which are noted as (Abstauk) and (Abstaul), respectively, to easily analyze the regression results.

Green technology innovation (Gpat), measured using the number of green patent applications in each province, is taken as the logarithmic value.

4. Control variables. We select the following variables as control variables to avoid possible error effects of omitted variables: level of economic development (*pgdp*), measured by GDP per capita; industrial structure (*industry*), measured by the ratio

of value added in the tertiary industry to value added in the secondary industry; foreign direct investment (*fdi*), measured by the ratio of total actual utilized foreign investment to GDP; fiscal expenditure level (*expenditure*), measured by the ratio of government fiscal expenditure to GDP; and market level (*market*), measured by the "Marketization in China by Provinces" compiled by Wang Xiaolu et al. The level of fiscal expenditure is measured by the share of government fiscal expenditure in GDP; the level of the market is measured by the marketization index disclosed in the "Marketization Index Report of China by Provinces" compiled by Wang Xiaolu et al.; the level of financial development is measured by the share of the loan balance of financial institutions in GDP; finally, the level of education (*education*) is measured by the number of years of education per capita.

Data sources and descriptive statistics

Since the digital inclusive finance index has been published since 2011, the sample period chosen for this paper is 2011–2020, and the selected research subjects are 30 provinces, municipalities, and autonomous regions except for Hong Kong, Macao, Taiwan, and Tibet. The relevant data come from the China Statistical Yearbook, China Energy Statistical Yearbook, and provincial statistical bureaus[a,b].

These yearbooks and statistics provide a large amount of detailed data on various aspects of China's economy, society, and energy, providing valuable reference information for researchers, policymakers, and people from all walks of life. The China Statistical Yearbook is prepared by the China Bureau of Statistics (CBS) and is published annually. It contains statistics on China's national economy and social development for the previous year. This yearbook contains a large number of tables and charts covering various fields such as population, employment, GDP, prices, finance, finance, science and technology, education, culture, health, and sports, providing researchers with comprehensive data support. The China Energy Statistics Yearbook, on the other hand, is compiled by the China Energy Bureau and focuses on statistics in the energy sector. This yearbook contains data on China's energy production, consumption, import and export, and energy structure and is an important reference for analyzing the development trend of China's energy industry, the effects of policies, and the relationship between energy and the environment. In addition, provincial statistical bureaus are also an important channel for obtaining local data. Provincial statistical bureaus will compile and release statistics on the economic and social development of their provinces according to the unified requirements of the China Statistics Bureau. These data cover all aspects of local economic operation, industrial development, demographic changes, and social and livelihood data, which provide a decision-making basis and reference information for local governments, enterprises, and institutions.

In summary, by reviewing the China Statistical Yearbook, China Energy Statistical Yearbook, and the data released by provincial statistical bureaus, we can obtain rich and comprehensive data resources, which can provide powerful support for research and analysis in various fields. Table 2 demonstrates the results of the descriptive statistics.

Empirical analysis and results

Baseline regression results

This study uses a fixed-effects model for regression analysis to test the impact of digital economy development on the carbon emission intensity of the circulation industry. Table 3 presents the specific calculation results. The attained regression coefficient of the digital economy has successfully met the significance test at the 1% level, displaying a negative sign. This outcome stands as compelling evidence, underscoring the substantial impact of digital economy development in significantly mitigating the carbon emission intensity within the circulation industry. Furthermore, in Column (2), after meticulous incorporation of all pertinent control variables, the regression results not only reaffirm the digital economy's influential role but also corroborate its statistically significant negative effect on the carbon emission intensity in the circulation industry. In the subsequent iteration, as depicted in Column (3), taking into account both control variables and individual fixed effects. The calculated regression coefficient of the digital economy, amounting to −0.157, holds substantive significance, illustrating that a one-unit increase in the level of digital economy development corresponds to a reduction of 0.157 units in the carbon emission intensity within the circulation industry.

Table 2. Descriptive statistical analysis of the variables of interest.

Variables	Observations	Averages	SD	Minimum value	Maximum value
Carbon dioxide emission intensity (*Ce*)	300	0.877	0.552	0.229	3.259
Digital economy development level (*Digital*)	300	0.797	0.731	0.005	3.858
Liquid capital mismatch (*Abstauk*)	300	0.45	0.386	0.002	1.982
Circulating labor mismatch (*Abstaul*)	300	0.379	0.339	0	1.369
Green technology innovation (*Gpat*)	300	7.454	1.4	2.565	10.382
Industry structure (*Industry*)	300	1.324	0.729	0.527	5.244
Foreign direct investment (*Fdi*)	300	0.516	1.902	0.047	32.696
Fiscal expenditure level (*Expenditure*)	300	0.264	0.114	0.12	0.758
Marketability level (*Market*)	300	6.588	1.875	2.33	10
Level of financial development (*Financial*)	300	0.044	0.021	0.02	0.158
Economic development level (*Pgdp*)	300	5.64	2.727	1.641	16.489
Education level (*Education*)	300	7.837	0.285	6.987	8.633

Table 3. Baseline regression analysis.

Variables	(1)	(2)	(3)
Digital	-0.331^{***} (0.035)	-0.203^{***} (0.046)	-0.157^{***} (0.055)
Industry		-0.400^{***} (0.080)	-0.610^{***} (0.095)
Fdi		0.000 (0.008)	0.006 (0.007)
Expenditure		1.462^{***} (0.529)	1.729^{**} (0.692)
Market		−0.033 (0.032)	0.008 (0.037)
Financial		−3.394 (2.166)	-7.451^{***} (2.473)
Pgdp		0.029 (0.018)	0.030 (0.019)
Education		−0.131 (0.169)	−0.107 (0.178)
Individual fixed effects	No	No	Yes
Year fixed effects	No	No	Yes
Constant term	0.877^{***} (0.093)	2.253^{*} (1.293)	2.172 (1.364)
N	300	300	300
R^2	0.334	0.213	0.386

Note: ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively; standard errors are in parentheses.

Robustness tests and endogeneity discussion

Robustness test. This study will employ five distinct methodologies in regression analysis to validate the robustness of the regression findings. Firstly, the explanatory variable of digital economy development (Digitalshangzhi) will be recalculated using the entropy method. The results are presented in Table 4, Column (1). Secondly, truncation is implemented to mitigate the influence of outliers on the regression outcomes. Table 4, Column (2), displays the findings. Thirdly, considering that municipalities are different from ordinary provincial administrative regions, in order to exclude the effect caused by this difference, the four largest municipalities are excluded, and the results are shown in Table 4 Column (3). Fourthly, an omitted variable test is conducted to address potential endogeneity issues arising from the comprehensive nature of the digital economy as an indicator in this study. Given the various factors affecting carbon emission intensity in the circulation industry, neglecting them and including them in the error term might lead to endogeneity concerns. As a solution, this study adopts the lagged explanatory variable as an additional control in the model, facilitating the application of difference generalized method of moments (GMM) and system GMM estimation. The results are shown in Table 4, Columns (4) and (5). Based on the findings from the robustness tests, the coefficient relationship between the digital economy and carbon emission intensity in the circulation industry remains significantly negative, consistent with the previous regression results.

Endogeneity test. The baseline regression results indicate a significant negative correlation between the development of the digital economy and the carbon emission intensity in the circulation industry, thereby implying that the former effectively reduces the latter. However, such analysis may overlook potential endogeneity concerns embedded within

Table 4. Robustness tests and treatment of endogeneity problems.

	(1) Substitution of explanatory variables	(2) Shrinkage processing	(3) Excluding municipalities	(4) Differential GMM	(5) System GMM	(6) Tool variables
Digitalshangzhi	−0.023*** (0.003)					
Digital		−0.355*** (0.076)	−0.114* (0.067)	−0.045*** (0.017)	−0.010** (0.004)	−1.260*** (0.260)
L.Ce				0.834*** (0.017)	0.905*** (0.016)	
Control variables	Yes	Yes	Yes	Yes	Yes	Yes
Individual fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
LM Statistical quantities						29.739 [0.000]
Cragg-Donald Wald F						32.430 {16.38}
AR (2)				0.392	0.405	
Hansen				1.000	1.000	
N	300	300	260	240	270	300

Note: ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively; values in parentheses are standard errors, values in square brackets are *P*-values, and values in curly brackets are critical values for the Stock-Yogo test at the 10% level. *AR*(2) and Hansen values are *P*-values for the test.

the model. Despite conscientiously controlling for relevant variables that influence carbon emission intensity in the circulation industry, the presence of unobservable omitted factors could potentially introduce endogeneity biases. In order to effectively handle this problem, it is necessary to pick relevant instrumental factors in order to strengthen the ability to draw a causal inference on the degree of growth of the digital economy. Following the methodology of prior studies,[64] we construct a novel instrumental variable by taking the cross-product term of the number of internet users and telephone lines for each province in the preceding year of 1984. Using a two-stage least squares (2SLS) regression analysis, this instrumental variable is used to determine the influence of the amount of digital economy growth on the intensity of carbon emissions in the circulation industry. The results, as shown in Table 4, Column (6), highlight the statistical significance of the inverse relationship between the growth of the digital economy and the intensity of carbon emissions in the industry of circulation, which was verified at the 1% level. This consistent alignment with the baseline regression outcomes reinforces the robust inhibitory effect of digital economy development on carbon emission intensity within the circulation industry, further corroborating the validity of our findings. Furthermore, the Kleibergen-Paaprk LM statistic attains a p-value of .000, denoting the absence of instrumental variables under identification issues. Additionally, the Cragg-Donald Wald F-statistic surpasses the critical value of the Stock-Yogo test at the 10% level, signifying the absence of weak instrumental variable problems. Consequently, our selection of the instrumental variable is well-justified and suitable for this study.

Heterogeneity test

The impact of the development level of the digital economy on the carbon emission intensity of the circulation industry may differ from province to province, owing to their resource endowment. Moreover, the geographical location of each province is an important factor affecting their resource endowment. Hence, this study divides each province into three regions, namely, east, central, and west, based on the difference in their geographical locations. The goal is to determine how regional variability affects the digital economy's ability to reduce emissions. In addition, the differences in the provincial government's support for the digital economy influence the effect of the digital economy on the carbon emission intensity of the circulation industry. The Action Plan for Promoting Big Data Development issued by the State Council in August 2015 clearly puts forward the plan to vigorously promote the construction of comprehensive pilot zones for big data. This study examines the effect of policy support on the emission reduction of the digital economy based on whether each province becomes a comprehensive pilot zone for big data. This study also examines the influence of policy support in leveraging the emission reduction effects of the digital economy. Table 5 displays the outcomes. The regression analysis's findings are shown in Columns (1)–(3) according to the provinces' division into east, central, and west regions. In comparison, increasing the digital economy's degree of growth in the east and central regions may greatly lower the circulatory industry's carbon emission intensity. However, the regression coefficient of the western region is positive. The reasons may be that the

Table 5. Heterogeneity regression analysis.

	(1) Western	(2) Central	(3) Eastern	(4) Policy support
Digital	0.107* (0.054)	−1.284*** (0.266)	−0.0352*** (0.055)	−0.090 (0.055)
Bigdata × digital				−0.253*** (0.054)
Individual fixed effects	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes
Constant term	6.400*** (1.742)	−13.287*** (4.260)	5.182*** (1.107)	1.661 (1.305)
N	90	80	120	300
R^2	0.639	0.568	0.729	0.446

Note: ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively; standard errors are in parentheses.

development level of the digital economy in the western region is lower and the digital infrastructure is not sound. The digitalization process of the circulation industry is lagging behind. Therefore, considerable material resources need to be invested in the initial stage of digital economy development, which further aggravates the consumption of resources and pollution emissions. In this case, the western region's circulation industry cannot reduce its carbon emission intensity just by achieving a higher degree of digital economic growth. According to the heterogeneity of policy support regression findings, the cross-product term between the big data comprehensive pilot zone and the digital economy is statistically significantly negative. This finding suggests that the carbon emission intensity of the circulation industry may be reduced via the promotion of the inhibitory impact of the growth of the digital economy.

Test of influence mechanism

This study will conduct regression analysis on Models (8)–(11) to verify whether the theoretical mechanism is valid. Table 6 shows the specific results, in which the regression coefficients of the digital economy in Columns (1) and (2) are significantly negative at the 5% level. Moreover, the regression coefficients of the digital economy in Column (3) are significantly positive at the 1% level. Hence, the development of the digital economy can promote the improvement of green technology innovation. Thus, Hypotheses 2 and 3 are verified. The mediating effect of capital mismatch in the circulation industry is not significant probably because the circulation industry in China is labor-intensive. The capital mismatch in the circulation industry may be helped greatly by the rise of the digital economy. There won't be enough of an effect on the green growth of the circulation industry by fixing the capital mismatch. The reason for this is that the circulation industry's portion of capital production is much less than the manufacturing industry's part of capital output. The extent to which it will affect the circulation industry's carbon emission intensity is unknown at this time.

Table 6. Regression analysis of impact mechanism.

	(1) *Abstauk*	(2) *Abstaul*	(3) *Gpat*	(4) *Ce*
Digital	−0.027** (0.009)	−0.053** (0.024)	0.329*** (0.087)	−0.139** (0.057)
Abstauk				−0.066 (0.137)
Abstaul				0. (0.139)
Gpat				−0.100** (0.039)
Individual fixed effects	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes
Constant term	−0.208 (0.607)	−1.181* (0.601)	−0.890 (2.146)	1.783 (1.356)
N	300	300	300	300
R^2	0.321	0.126	0.745	0.409

Note: ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively; standard errors are in parentheses.

Conclusion

Research conclusion

This paper examines the effect and mechanism of the development of the digital economy on the carbon emission intensity of the circulation industry through theoretical and empirical analysis. The results of the study show that: first, the improvement of the level of digital economy development has a significant role in promoting carbon emission reduction in the circulation industry; in order to give full play to the potential of the digital economy in carbon emission reduction, it is necessary to further strengthen the research and development and application of digital technology and to promote the digital transformation and green development of the circulation industry.

Secondly, the impact of digital economic development on carbon emission reduction in the circulation industry is mainly realized through the improvement of labor allocation and the promotion of green technological innovation, and the indirect effect of capital allocation has not yet appeared. The impact of digital economic development on carbon emission reduction in the circulation industry is a complex and multidimensional process, in which improving labor allocation and promoting green technological innovation are two important ways to achieve. However, the point that the indirect effect of capital allocation has not yet appeared may need to be further explored. First, the development of the digital economy has a positive impact on carbon emission reduction in the distribution industry by improving labor allocation. The application of digital technology has enabled a more efficient allocation of labor resources, improving the flexibility and matching of the labor market. This helps to reduce the waste of labor resources, improve the overall work efficiency, and then reduce the carbon emissions of the circulation industry in the production and operation process. Secondly, the digital economy further promotes the process of carbon emission reduction in the circulation industry by promoting green technological innovation. Green technology innovation is an important means to reduce carbon emissions and realize sustainable development. The application of digital technology provides strong support for the research and development and application of green technology, and through data analysis and intelligent management, it can more accurately grasp the carbon emissions of the circulation industry and formulate more effective emission reduction strategies. As for the indirect role of capital allocation, although it has not yet appeared, it does not mean that it is not important or has no potential. Capital allocation plays an important role in carbon emission reduction in the distribution industry. With the development of the digital economy, the optimization and upgrading of capital allocation will be expected to indirectly promote carbon emission reduction in the circulation industry by improving investment efficiency and guiding the flow of capital to low-carbon and environmental protection projects. In addition, it is worth noting that the development of the digital economy also provides new opportunities and challenges for carbon emission reduction in the circulation industry. On the one hand, the application of digital technology provides a more efficient operation mode and broader market space for the circulation industry, which helps to promote the optimization and upgrading of industrial structure. On the other hand, the development of the digital economy also brings some new problems and challenges, such as data security and privacy protection, which need to be paid attention to and solved in the process of promoting carbon emission reduction. Therefore, in the process of promoting carbon emission reduction in the distribution industry, the advantages of the digital economy should be fully utilized, and the role of various factors should be considered comprehensively to achieve comprehensive, coordinated, and sustainable development.

Thirdly, the results of heterogeneity analysis show that the improvement of the level of digital economy development in the eastern and central regions can significantly promote the carbon emission reduction of the circulation industry, while the western region shows the opposite effect; the establishment of the comprehensive pilot zone of big data can give full play to the emission reduction effect of the digital economy and promote carbon emission reduction of the circulation industry. There are significant differences in the carbon emission reduction effect of digital economy development on the circulation industry in different regions. This difference may be due to the comprehensive influence of many factors, including, but not limited to, the level of economic development, industrial structure, technological innovation capacity, and policy support. For the central region, the improvement of the level of digital economy development may contribute to the carbon emission reduction of the distribution industry. This is because the development of the digital economy can promote digital transformation and intelligent upgrading of the distribution industry, improve the efficiency of distribution, and reduce energy consumption and carbon emissions. At the same time, the central region may have relatively good infrastructure and human resources, which can better support the development of the digital economy and thus promote the green transformation of the circulation industry. However, the western region may face a number of challenges in the development of the digital economy, causing it to show the opposite effect of the central region. These challenges may include a weak foundation for digital economy development, insufficient technological innovation capacity, and a shortage of talents. These factors may limit the development speed and depth of the digital economy in the Western region, which in turn affects its contribution to carbon emission reduction in the distribution industry. Both the central and western regions have the potential to promote carbon emission reduction in the circulation industry through the development of the digital economy. The key lies in strengthening policy guidance and support, promoting the in-depth integration of digital technology and the circulation industry, improving circulation efficiency and service quality, and realizing green and low-carbon development. In the process, it is necessary to comprehensively consider a variety of factors and inter-regional differences. By strengthening policy support and technological innovation, the coordinated development of the digital economy and the circulation industry can be realized and the development of a green low-carbon economy can be promoted.

Policy recommendations

Based on the above research conclusions, this paper gives the following policy recommendations: first, because the development of the digital economy has a significant role in promoting carbon emission reduction in the circulation industry, it is necessary to further improve the construction of network infrastructure, accelerate the development process of digital industrialization and industrial digitization, solidify the environment for the development of the digital economy, and guide the positive effects of the digital economy in terms of energy saving and emission reduction. First of all, improving network infrastructure construction is the foundation. A stable, efficient, and wide-coverage network system is a prerequisite for the rapid development of the digital economy. Only by ensuring the unimpeded flow of information can the digital economy play a greater role in various industries. Secondly, it is also crucial to accelerate the development process of digital industrialization and industrial digitization. This means not only developing new industries with digital technology at their core but also promoting the deep integration of traditional industries with digital technology and realizing the digital transformation of industries. In this way, industrial efficiency can be further enhanced and energy consumption reduced, thus realizing the goal of carbon emission reduction. In addition, consolidating the environment for the development of the digital economy can also not be ignored. This includes policy environment, rule of law environment, market environment, and many other aspects. The government should introduce more policy measures conducive to the development of the digital economy to provide enterprises with a better innovation environment and market space. Finally, it is crucial to guide the digital economy to play a positive effect in energy conservation and emission reduction. Through technological innovation and model innovation, more digital products and services with energy-saving and emission reduction functions can be developed, for example, the use of big data and artificial intelligence technology to optimize logistics paths and distribution methods to reduce energy consumption and emissions in the transportation process and the use of intelligent manufacturing and industrial Internet technology to improve the energy efficiency level of the production process.

Secondly, government should focus on the role played by green technology innovation in reducing carbon emissions in the circulation industry; accelerate the R&D and cultivation process of green technology; promote the in-depth integration of industry, academia, and research; and improve the efficiency of the green technology transformation of knowledge resources, which will in turn fully release the energy-saving and emission reduction effects of the digital economy. First of all, green technology innovation helps reduce carbon emissions in the circulation industry. Through the research and development and application of advanced green technology, energy consumption and pollution emissions can be effectively reduced, and resource utilization efficiency can be improved. For example, the application of the Internet of Things, big data, and artificial intelligence can realize the accurate monitoring and control of energy consumption, thus achieving the goal of energy saving and emission reduction. In addition, green technology innovation can also promote the greening and sustainable development of the circulation industry, laying a solid foundation for the long-term stable development of the industry. Secondly, it is crucial to accelerate the R&D and cultivation process of green technology. This requires the joint efforts of all parties, including the government, enterprises, and colleges and universities, to increase investment in and support for green technology innovation. The government can introduce relevant policies to encourage and guide enterprises to increase green technology research and development; enterprises can strengthen cooperation with universities and scientific research institutions to jointly carry out green technology innovation projects; universities and scientific research institutions can strengthen basic research to provide solid theoretical support for green technology innovation. Promoting the in-depth integration of industry, academia, and research is also the key to improving the efficiency of green technology transformation of knowledge resources. Through the establishment of an industry-university-research cooperation platform for green technology innovation, close cooperation among enterprises, universities, and research institutions can be promoted. This type of cooperation can help realize resource sharing and complementary advantages and accelerate the process of green technology research and development and application. At the same time, industry-university-research cooperation can also cultivate more talents with an innovative spirit and practical ability and provide a steady stream of talent support for green technology innovation.

Thirdly, breaking down barriers to cross-regional mobility of talents, building a more open, fair, and efficient labor market system, enhancing the allocation efficiency of the labor market with the digital economy, and guiding the flow of labor factors into efficient circulation areas to achieve efficient and economical allocation of resources. First, promote the reform of the household registration system to eliminate identity differences. Deepen the reform of the household registration system, gradually relax the conditions for settling down, and reduce the unfairness caused by the household registration system. Second, improve the social security system to reduce the risk of mobility. Establish a sound social security system covering both urban and rural areas, provide stable social security for workers, and reduce the risks associated with mobility. Third, strengthen the construction of information platforms to enhance market transparency. A unified national labor market information platform should be set up to release all kinds of labor supply and demand information in a timely manner, so as to improve the transparency of the labor market. In addition, the development of a digital economy should be promoted to enhance the allocation efficiency of the labor market. The digital economy, with its efficient and convenient features, provides a broader space for the labor market. By promoting the deep integration of digital technology and the labor market, the optimal allocation and efficient use of labor resources can be achieved. For example, through online recruitment platforms and telecommuting, it is possible to reduce the cost of job searching and recruitment and improve the matching efficiency of the labor market. Finally, labor factors are guided to flow into efficient circulation areas. Through policy guidance and the role of the market mechanism, labor is encouraged to move to areas with strong innovative capacity and development potential.

Authors' contributions

All authors contributed to the study's conception and design. Material preparation, data collection, and analysis were performed by Jiqiang Huang, Kengcheng Zheng, and Baoliu Liu. The first draft of the manuscript was written by Xiaoxing Wang, and all authors commented on previous versions of the manuscript.

Availability of data and materials

The datasets used and/or analyzed during the current study are available from the sources informed in the article or from the corresponding author on reasonable request.

Declaration of conflicting interests

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

Ethical approval

The study did not touch on ethical issues.

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Informed consent

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Notes

a. Website: https://www.stats.gov.cn/sj/ndsj/
b. Website: https://www.nea.gov.cn/zfxxgk/gzbg.htm

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