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Can the Digital Economy Accelerate "Carbon Neutrality"?—An Empirical Analysis Based on Provincial Data in China

Dong Xue [1], Tongyang Liu [1], Xiaomin Li [1,*] and Xiaolei Zhao [2]

[1] School of Economics, Henan University, Kaifeng 475001, China; xuedong@henu.edu.cn (D.X.)
[2] School of Economics and Management, Beijing Jiaotong University, Beijing 100044, China
* Correspondence: 10080048@vip.henu.edu.cn

Abstract: The prosperous development of the digital economy can trigger a comprehensive green transformation from factors of production to productivity and production relationships, providing a new path for China to achieve its goals of "peak carbon emissions" and "carbon neutrality." This paper measures the development level of the digital economy in each region using panel data of 30 Chinese provinces (autonomous regions, municipality directly under the central government) from 2007–2019, and explores the effect of the digital economy on CO_2 emissions, its transmission mechanism, and its impact characteristics through theoretical and empirical analyses. The results indicate that: (1) the development of the digital economy can effectively reduce CO_2 emissions; (2) in addition to direct effects, the digital economy can indirectly suppress CO_2 emissions by lowering energy intensity, promoting economic agglomeration, and increasing the use of robots; (3) the suppression effect of the digital economy on CO_2 emissions has significant regional heterogeneity; the digital construction in east, north, central, northeast, and southwest China has shown a better CO_2 emissions reduction effect, while the development of the digital economy in south and southwest China has not yet exerted the suppression effect on CO_2 emissions. In the next development process, it should improve the efficiency of energy use, give full effect to the positive externalities of economic agglomeration, lower the threshold of robot use and expand the application scenarios, and make full use of the green development advantages of the digital economy.

Keywords: digitization development; low-carbon development; CO_2 reduction effect; intermediary effect; regional heterogeneity

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1. Introduction

Climate change poses a formidable global challenge, impacting the long-term sustainability of human society. The burning of fossil fuels, chiefly responsible for the release of carbon dioxide (CO_2), is identified as the primary driver of climate change. In 2021, the total global emissions of greenhouse gases reached an alarming 40.8 billion tons of CO_2 equivalent. Among the major contributors, China accounted for 11.9 billion tons of CO_2, representing 29.2% of global CO_2 emissions. The United States and the European Union followed, contributing 11.3% and 6.6% of global CO_2 emissions, respectively [1]. The outbreak of the COVID-19 pandemic has had a significant impact on global CO_2 emissions, with China experiencing an average growth rate of CO_2 emissions surpassing that of other major economies from 2020 to 2021. Moreover, China's emissions exhibited a stronger growth trend compared to pre-pandemic levels. Consequently, China's per capita CO_2 emissions have continued to rise, surpassing those of developed and emerging economies in 2021 (Figure 1). While China, in November 2021, issued a joint statement with the United States known as the "China-US Joint Glasgow Declaration on Enhancing Climate Action in the 2020s", reiterating its commitment to peak carbon emissions by 2030 and achieve carbon neutrality by 2060 [2], the reality remains that China's CO_2 emissions persist at high levels, presenting formidable challenges in attaining the carbon neutrality target.

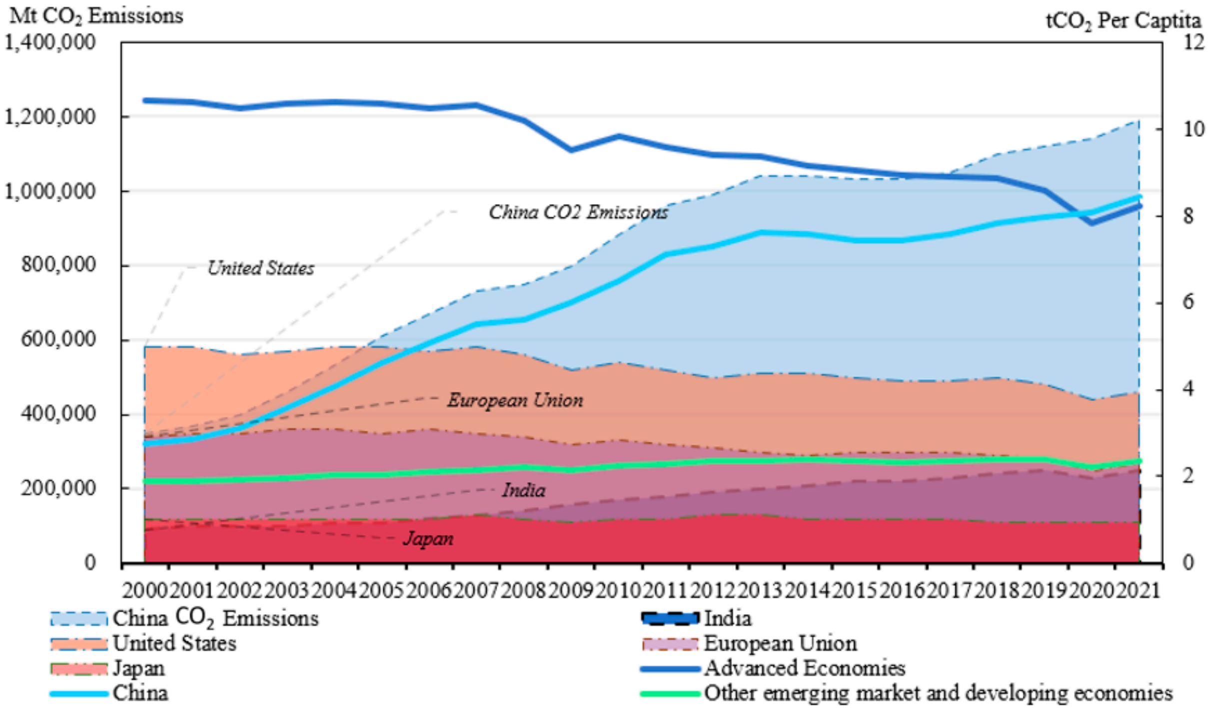

Figure 1. 2000–2021 CO_2 emissions from the world's major economies and CO_2 emissions per capita by region [1].

In fact, the "peak carbon emissions" strategy is an essential step towards the "carbon neutrality" strategy, which is the way to achieve a zero-carbon society. In China, as the largest emitter of CO_2 globally, the establishment of these goals holds significant importance in fulfilling the objectives set forth in the Paris Agreement. Recent research suggests that the energy revolution and digital revolution, driven by technological advancements and innovative management practices, play a pivotal role in facilitating industrial transformation and the achievement of peak carbon emissions and carbon neutrality [3]. In the era of global digitization, the rise of the digital economy not only presents new opportunities for China's low-carbon development [4], but also emerges as a promising avenue for realizing peak carbon emissions and carbon neutrality [5]. Particularly in the aftermath of the COVID-19 pandemic, digital transformation has driven recovery and growth across various regions and industries in China. Anchored on data elements, the digital economy can instigate comprehensive green transformations, spanning from factors of production to productivity and production relationships, thus empowering sustainable development [6]. According to data from the China Academy of Information and Communications Technology, China's digital economy expanded from CNY 22.6 trillion to CNY 45.5 trillion from 2016 to 2021, leaping to second position in the world and increasing from 30.3% to 39.8% of the domestic GDP [7].

The integration of digital technology with China's economy and society has gradually manifested efficiency and quality advantages. However, further research is needed to determine whether it has the potential to reduce China's CO_2 emissions and demonstrate green and low-carbon advantages. Based on this foundation, it is important to investigate the mechanisms and pathways through which the digital economy can contribute to carbon emission reduction. Moreover, the intertwining of China's digital divide and regional development imbalances raises the question of spatial heterogeneity in the digital economy's impact on carbon reduction. Exploring the issues will help clarify the relationship between China's digital economic development and carbon reduction, facilitating the timely achievement of carbon neutrality goals. Tapscott [8] first introduced the concept of the "digital economy" in his book "*The Digital Economy*" published in 1996. Subsequently, scholars have enriched the theory of the digital economy from different perspectives. Mesenbourg [9] defined the boundaries of the digital economy, identifying it as consisting of e-commerce infrastructure, e-commerce processes, and e-commerce itself. Negroponte et al. [10] emphasized information on technology's significant development prospects and application value. Kim et al. [11] defined the digital economy as a special economic form, with its essence being "the transaction of goods and services in an informative form." This definition captures the primary manifestation of the digital economy but is difficult to quantify. Knickrehm et al. [12] viewed the digital economy as the digital output resulting from digital input. While scholars have different understandings of the digital economy, it can essentially be seen as a collective term for a series of economic activities related to the digital economy [13].

Based on the "G20 Digital Economy Development and Cooperation Initiative" and existing research, this paper defines the digital economy as a new economic form that utilizes data elements as factors of production, relies on digital technology innovation as a core driving force, utilizes modern information networks as vital carriers, continuously enhances the digitization and intelligence levels of traditional industries, and accelerates the restructuring of economic development and government governance models. Based on this, this paper defines the digital economy, according to the "G20 Digital Economy Development and Cooperation Initiative" and existing research, as an emerging economic form that takes data elements as production factors, with digital technology innovation as its core driving force, and modern information networks as vital carriers. It aims to continuously improve the digitization and intelligence level of traditional industries, accelerating the restructuring of economic development and government governance models. Currently, research on carbon emissions mainly focuses on scenario simulation and prediction of future carbon emissions [14], optimization of carbon reduction processes [15], measurement of carbon emission levels, analysis of factors influencing carbon emissions, carbon taxation, and carbon emissions trading [16].

The exploration of the relationship between the digital economy and carbon emissions is in its early stages, with an increasing number of research topics emerging. On one hand, there is a focus on the digital economy itself and its impact on the economy and society. This includes measuring the level of digital economic development, strategic upgrading of business operations due to the digital economy [17], and the role of the digital economy in regional development. On the other hand, there is a focus on examining the relationship between the digital economy and carbon emissions. This involves investigating the potential for carbon reduction through digital technologies and digital industries [18], exploring the relationship between the digital economy and carbon emission performance, analyzing the connection between the digital economy and high-quality industrial development, and examining the regulatory role of innovation factors in the digital economy and carbon reduction [19].

In general, existing literature has mostly approached the relationship between the digital economy and carbon emissions from singular perspectives such as ICT, digital industries, digital innovation, and digital finance, etc. However, there is no definitive conclusion regarding the relationship between the digital economy and carbon emissions. In addition, few studies have combined the digital economy and carbon neutrality strategy, investigated the relationship between the digital economy and carbon emission reduction, found the transmission mechanism of the digital economy on carbon emission reduction, and verified whether it exhibits spatial heterogeneity. Therefore, to fill the research gap in the field of the digital economy and carbon neutrality, this paper attempts to construct a systematic analytical framework to comprehensively explore the role of the digital economy in the "carbon neutrality" strategy. The study utilizes panel data from 30 Chinese provinces (autonomous regions, municipalities directly under the central government) from 2007 to 2019. Building upon the research of Zhao et al. [20], an evaluation system for digital economy indicators is established to assess the level of digital economic development in each region. Through quantitative analysis, the study investigates the direct impact of the digital economy on carbon emissions, as well as the indirect effects of changing energy intensity, accelerating economic agglomeration, and enhancing the use of robots. Then, the study will further investigate the regional heterogeneity of this effect from the perspective of spatial distribution, and comprehensively test the carbon reduction effect of digital economy.

The marginal contributions of this paper are the following four aspects: First, this paper examines the effect of digital economy development on carbon emissions from the perspective of empirical analysis using 13 years of data from 30 Chinese provinces, which enriches and expands most of the current theoretical analysis studies on the relationship between digital development and carbon emissions. Secondly, the digital economy index is constructed and measured from three dimensions: digital infrastructure, digital transactions, and digital application degree, while a theoretical analysis framework for the effect of the digital economy on carbon emissions is constructed, discussing the direct and indirect impact mechanisms of digital economy development on carbon emissions. Thirdly, based on the intermediary effect, we evaluated the paths of the effect of digital economy development on carbon emissions and argued the mechanism of improving the digital economy on influencing carbon emission levels from three aspects: energy intensity, economic agglomeration, and robot use. Bearing in mind that regional digital economy development in China is unbalanced and there are differences in economic and social development patterns, the geographical distribution characteristics of the impact of digital economy development on regional carbon emissions are examined through heterogeneity analysis. Fourth, the number of fixed telephones per 10,000 people and the Internet penetration rate is used as entry points to construct instrumental variables to better control the endogeneity between the digital economy and carbon emissions, so as to better provide empirical references for China to use the digital economy to accelerate the achievement of the "carbon neutrality" goal.

The remaining sections of this paper are organized as follows. In Section 2, we will review and summarize the relevant literature in this field. Section 3 will illustrate the theoretical mechanisms, construct a systematic analytical framework, and propose corresponding research hypotheses. Section 4 will introduce the data, variables, and methods related to empirical analysis. Section 5 will discuss, analyze, and further justify the empirical results. Section 6 will provide further discussion, and the Section 7 will conclude and propose policy recommendations for the paper.

2. Literature Review

With the frequent occurrence of global extreme climate events, carbon emissions have become an important issue worthy of academic attention. Existing views suggest that urbanization construction [21], economic growth [22], industrial agglomeration, energy demand, and R&D innovation [23] are the main causes of carbon emissions. After clarifying the sources of carbon emissions, we are faced with the challenge of how to solve the problem of reducing carbon emissions. For the agricultural sector, Du et al. [24] argue that agricultural carbon reduction policies can significantly reduce carbon emissions from agricultural production by reducing financial support. For the industrial sector, Li and Xu [25] argue that industries with high-energy consumption and low carbon emissions should adopt a progressive carbon reduction improvement path, industries with low-energy consumption and high carbon emissions should adopt a single breakthrough carbon reduction path; and industries with high-energy consumption and high carbon emissions should adopt a leapfrog carbon reduction path. For the service sector, Hou et al. [26] concluded that 13–19% of carbon flows in China are caused by the service sector's demand for other sectors, so reducing carbon emissions from the service sector should focus on optimizing the energy use structure of the upstream production sector and increasing the proportion of clean energy usage. In addition, Wang et al. [27] found the contribution of renewable energy to carbon reduction using causality tests and scenario analysis methods, respectively.

In addition, the inhibitory effect of carbon quota and carbon emissions trading system on total carbon emissions cannot be ignored, Shi et al. [28] argued that the difference in carbon quota allocations resulted in different emission reduction effects, among which the historical method had the strongest effect. The carbon quota price and number of enterprises participating in the carbon trading market were the key factors affecting carbon emission reduction. Zhang et al. [29], on the other hand, argued that although carbon emissions trading can substantially reduce carbon emission levels and intensity, it will inhibit the innovation of green technologies in the short term. Zhang et al. [30] and Dong et al. [31] verified that carbon emissions trading can realize the Porter's effect, furthermore, Zhang et al. [30] also showed that carbon emissions trading can improve the efficiency of regional green development and realize regional carbon equality at the same time, achieving the effect of killing two birds with one stone.

The arrival of the digital economy has further expanded the realization path of carbon emission reduction, and some scholars have begun to explore the impact of digital technology as an emerging productivity on carbon emissions, and their main views can be divided into the following three aspects: The first view is that the digital economy can effectively reduce carbon emissions, and some research findings show that the development of ICT (Information and Communications Technology) and ICT industries can restrain carbon emissions through technical innovation and linkages, industrial transformation, and upgrading channels [32]. Jayaprakash and Radhakrishna [33] investigated the impact of ICT on national sustainable development in 80 countries, Ulucak et al. [34] examined the relationship between ICT and carbon emissions in the BRICS countries with the conclusion that ICT significantly reduced carbon emissions. Maleeki and Moriset [35] used a fixed effects panel model and quantile regression model to confirm that European countries with better ICT infrastructure have lower carbon emission levels by constructing a carbon emission analysis framework. The results show that digital technology can effectively reduce carbon emissions' intensity.

However, the second view is that the digital economy does not significantly reduce carbon emissions, and some studies have found that ICT cannot have a suppressive effect on carbon emissions because the embodied carbon emissions from ICT construction are much higher than the direct carbon emissions, thus creating a "rebound effect" [36,37]. Furthermore, the development of the digital economy relies on ICT and the Internet, which increases electricity and energy consumption leading to a certain degree of carbon emissions [38]. Salahuddin and Alam [39] studied the relationship between ICT and electricity consumption in the Organization for Economic Cooperation and Development (OECD) which showed that the use of ICT stimulates an increase in electricity consumption. The study by Longo and York [40] further verified the positive relationship shown by ICT penetration and energy consumption, they concluded that ICT is not effective in improving the environment, and even deteriorates it.

The third view is that the impact of the digital economy on carbon emissions is uncertain, Higón et al. [41] and Faisal et al. [42] summarizes the "inverted U-shaped" relationship between ICT and carbon emissions using unbalanced panel data for 142 countries and robust least squares estimation, respectively. Among them, Higón et al. [41] argue that ICT in developing countries brings a higher threshold of carbon emissions than in developed countries but developing countries do not enjoy the same environmental bonus as ICT in developed countries.

In summary, existing studies have explored the digital economy and carbon emission reduction in depth, but the relationship between the two has not yet reached a definite conclusion. The reason for the controversy may be that CO_2 is an environmental variable that can move across time and space, which may not necessarily conform to the assumption of "independent homogeneous distribution" in traditional econometric models. Secondly, many scholars only focus on the direct impact of digital technology and the digital industry on carbon emissions but lack the examination of their indirect impact and the interpretation of theoretical mechanisms, while the discussion of the role of mediating variables is also lacking. Finally, existing literature fails to further verify whether the digital economy has regional heterogeneous characteristics on carbon emission reduction by considering the fact that the development of the digital economy is unbalanced in China. Therefore, based on the shortcomings of existing studies, this paper firstly constructs and measures the digital economy index by using the entropy value method in three dimensions: digital infrastructure, digital transactions, and digital application degree. Then, we take carbon emission level, digital economy, energy intensity, economic agglomeration, and robot use into the theoretical analysis framework, specifically examining the direct influence, indirect influence, and regional heterogeneity influence mechanisms of digital economy development on carbon emissions, with a series of robustness tests, as well as using the good correlation, exogeneity of fixed telephone number per 10,000 people, and Internet penetration rate as instrumental variables to eliminate endogenous interference, corroborate the suppressive effect of the digital economy on carbon emissions, and clarify the path of the effect of digital economy development on carbon emission reduction. It provides a strong basis for further testing the theoretical hypotheses and making targeted policy recommendations.

3. Theoretical Analysis and Research Hypotheses

The emergence of the digital economy makes the data factor a brand-new factor of production, which will be incorporated into the factors of the production system, while Metcalfe's law and Moore's law give advantages such as high permeability, positive externality, high added value, and marginal cost diminishing to the digital economy, so it will not only provide a more efficient operation, but a more powerful development pattern, a greener production method, and a more modernized governance model. It will also accelerate the formation of a green and low-carbon energy system, promote green transformation of production and lifestyle, as well as achieve sustainable economic and social development.

According to the research basis of the digital economy and carbon emission, this paper has constructed a theoretical analysis framework of the impact of the digital economy on carbon emission reduction which contains three aspects: direct impact, indirect impact, and spatial heterogeneity impact, as shown in Figure 2.

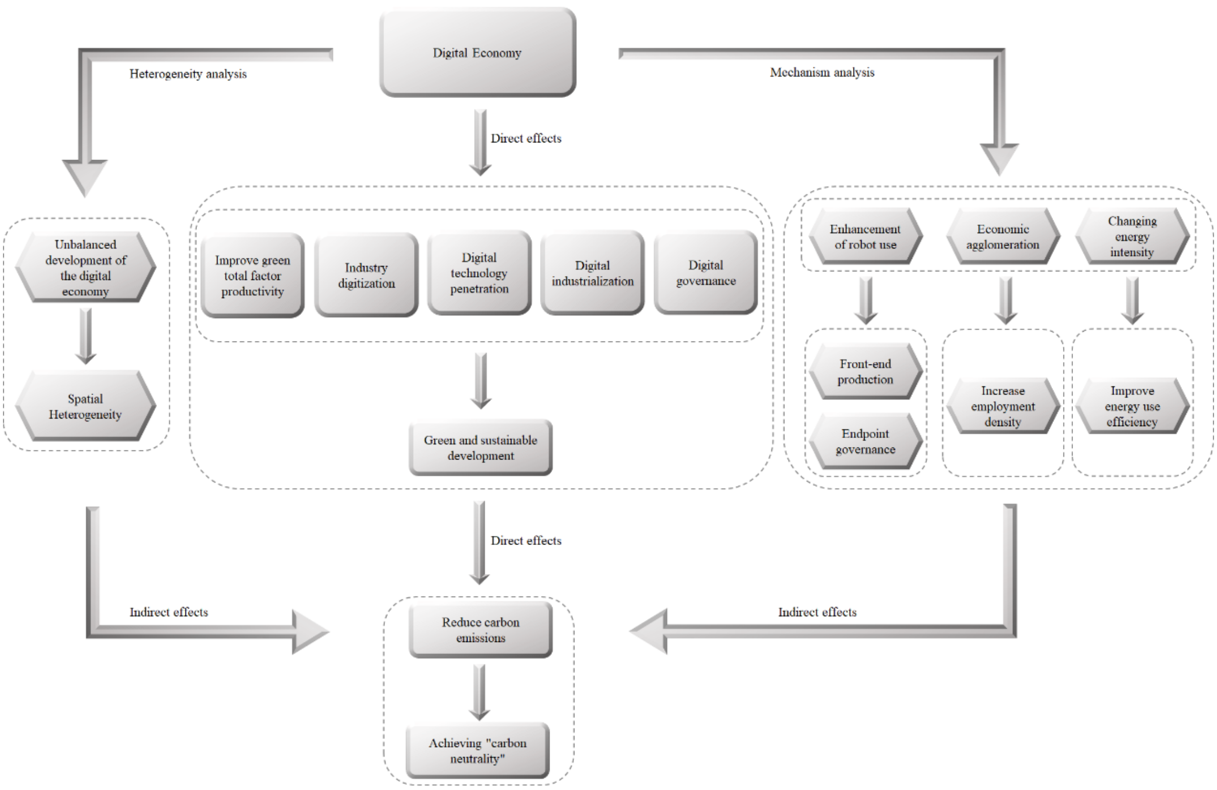

Figure 2. Mechanisms of the impact of the digital economy on carbon emissions.

3.1. The Direct Impact of the Digital Economy on Carbon Emissions

The digital economy refers to a series of economic activities that are carried out on platforms such as modern information networks and digital infrastructure. It relies on digital knowledge, information, and other data resources as key factors of production, and is also driven by the effective use and innovation of digital technologies such as ICT. The digital economy has the characteristics of high technology, high cleanness, and high growth development that can provide a new path for clean and low-carbon development [43].

Firstly, in terms of input factors, data elements are strategic resources in the era of the digital economy. They possess the information attributes of green development in the processes of collection, transmission, computation, analysis, and open sharing. Moreover, the supply mode of data elements can not only break through the supply constraints of traditional factors of production but also interact with physical entities to reduce element loss in enterprises, effectively improving the input–output efficiency of other factors of production [44]. This generates a multiplier effect, ultimately driving the rapid growth of green total factor productivity. From the perspective of technological innovation, Aghion and Howitt [45], based on Schumpeter's "creative destruction" model, found that technological innovation can improve environmental pollution, break the constraints of non-renewable resources, shift the economic equilibrium point outward, and achieve more economic output. In other words, technological innovation is the core driving force of green development. As a typical generic technology, digital technology itself carries green attributes and serves as a "technological reservoir" for green and low-carbon development. For example, technologies such as product database management (PDM), electronic data interchange (EDI), and multi-protocol label switching (MPLS) promote the development of sharing economy, second-hand economy, circular economy, and other green and low-carbon models. They form a closed loop of "production-consumption-recycling-regeneration", effectively reducing carbon emissions.

Secondly, industrial digitization and digital industrialization are two components of the digital economy. In the process of industrial digitization, industrial integration and innovation can generate new industries, models, and formats, facilitating the transformation and upgrading of traditional industries. Particularly within the ICT industry, cross-sector integration and convergence will break the boundaries of traditional industries, deepen the digitalization of various industries, and accelerate the comprehensive penetration of digital technology into all industries. It will enable the superposition and multiplier effect of the digital economy on green development [46]. With the emergence of digital service models such as "Internet Plus" the previous single offline operation mode has transformed into a diverse coexistence of online and "online-offline" modes, significantly reducing energy consumption and carbon emissions. In the process of digital industrialization, industrial linkages and substitutions can generate positive externalities for economic and social development, facilitating the transition of the economy and society towards a more green, low-carbon, efficient, and high-quality direction. As the scale of the ICT industry expands, on one hand, ICT products can partially or fully replace non-ICT products through technological substitution, promoting the ICT industry to substitute traditional industries partially or completely through this "creative destruction." On the other hand, it can attract a large amount of capital, enterprises, institutions, and other factors, driving the upgrading and transformation of existing industries. This leads to a shift in the national economic structure from labor-intensive and capital-intensive to technology-intensive, weakening the ability of energy-intensive industries to obtain factors of production, reducing energy consumption intensity across industries, improving energy consumption efficiency and clean energy utilization, and promoting energy conservation and environmental protection in traditional industries, which reduces the level of carbon emissions.

Lastly, the digital economy contributes to the government's efforts to accelerate the construction of a digital governance model. Based on digital technologies such as big data, cloud computing, bio-sensors, and remote sensing satellites, government departments can not only alleviate the problem of resource allocation imbalance caused by information asymmetry, but they can coordinate the efficient use of various resources and reduce resource waste. For example, the construction of a smart grid, can also comprehensively perceive various ecological environmental information, achieve precise data collection on emissions reductions down to individuals, enhance environmental pollution monitoring capabilities, supervise carbon emissions behavior of all entities in real-time, and promptly handle pollution emissions.

Therefore, based on the above theoretical analysis, the following hypotheses are proposed in this paper:

Hypothesis 1. *Digital economy can reduce CO_2 emissions.*

3.2. The Indirect Impact of the Digital Economy on Carbon Emissions

The impact of the digital economy on carbon emissions is not only reflected in its direct influence through the utilization of its factor advantages, efficiency advantages, and platform advantages but also in its indirect influence through changing energy intensity, accelerating economic agglomeration, and increasing the use of robots. From the perspective of enhancing energy efficiency, the continuous penetration of digital technology can significantly improve the flexibility and precision of production and manufacturing, optimize production processes, reduce waste, and establish a comprehensive energy monitoring system that covers the entire energy supply, which includes production, transportation, and consumption processes. This enables remote monitoring and intelligent control of energy production and consumption, greatly enhancing energy utilization efficiency [47]. On the other hand, the rapid iteration of digital technology is conducive to increasing the proportion of renewable energy and reducing the share of fossil fuels [48]. It also promotes innovation in energy technologies, significantly enhances the collaborative efficiency among energy-related sectors, and further accelerates breakthroughs in the energy technology through the effects of technological spillover. This effectively improves energy utilization efficiency and reduces carbon emissions.

From the perspective of promoting economic agglomeration, the impact of the digital economy on interregional resource allocation changes the concentration of economic activities, ultimately affecting regional environmental quality [4]. Attracted by the digital bonus, regions with a higher level of digital economic development are more likely to attract businesses and labor inflows [49]. Through a series of intelligent upgrades and transformations, rapid agglomeration of factors of production and enhanced production efficiency are achieved, laying the foundation for energy conservation and emissions reduction.

From the perspective of enhancing the application of robots, the development of the digital economy has promoted the use of industrial robots in production [50]. Although China's capital–labor substitution elasticity is less than 1 [51], the input of industrial robots can reduce labor inputs, thereby increasing the capital–labor substitution elasticity. Furthermore, the use of industrial robots is a capital-biased technological progress, which promotes continuous increases in R&D investment by companies. Driven by high R&D investment, it continuously promotes the large-scale application of industrial robots in production operations, ultimately forming a positive cycle that enhances industry-level technological capabilities and effectively mitigates environmental pollution. In terms of enterprise production and industrial integration, the use of industrial robots optimizes front-end production and end-of-pipe governance, achieves digital upgrades in traditional manufacturing, and ensures efficient resource allocation, thereby reducing pollution emissions by enterprises [52].

Based on the above analysis, the following hypotheses are proposed in this paper:

Hypothesis 2a. *The digital economy can reduce CO_2 emissions by improving energy intensity.*

Hypothesis 2b. *The digital economy can reduce CO_2 emissions by promoting economic agglomeration.*

Hypothesis 2c. *The digital economy can reduce CO_2 emissions by increasing the proportion of robot use.*

3.3. Analysis of Spatial Heterogeneity

Compared to traditional economic models, digital platforms can effectively assist in the transmission of various information in the digital economy, significantly reducing spatial barriers and information asymmetry among market participants. This characteristic gives the digital economy strong temporal and spatial openness and inclusiveness. In particular, the emergence of the digital economy has not eliminated traditional offline operating models but has innovated upon them, realizing a dual-track combination of "online virtual-offline physical" mode. The decentralization of the digital economy lowers the barriers to entry for participants. Therefore, the impact of the digital economy on carbon emissions may differ from the impact of traditional regional economic development differentials on carbon emissions. However, existing research shows that the digital economy also exhibits strong regional dependency [53]. Under the influence of unbalanced regional economic development, the intensity of ICT investment is bound to vary. Liu and Wang [54] argued that although the growth rate of ICT investment in underdeveloped regions gradually surpasses that of developed regions, the level of ICT infrastructure in developed regions still exceeds that of underdeveloped regions. The resulting digital divide further leads to the imbalance in regional digital economic development, and under the Matthew Effect, the regional digital divide continues to widen. For China, Han et al. [43] found that the digital economy has been established earlier in southeastern coastal regions such as Fujian, Guangdong, and Zhejiang, while the development of the digital economy in central and western regions lags behind. There is an intertwined phenomenon of the digital divide and the gap in regional green development levels. It can be seen that the differential development of the digital economy has caused differences in the regional environment. Yi et al. [18] further confirmed this point in their research, as their results indicated that the digital economy has a negative impact on the environmental performance of eastern regions and exhibits a certain degree of linear inhibition in central and western regions. Therefore, the impact of the digital economy on carbon emissions may vary across regions.

Based on the above arguments, we propose the following hypotheses for the paper:

Hypothesis 3. *The impact of digital economy on CO_2 emissions will vary from region to region.*

4. Data and Models

4.1. Construction and Measurement of Digital Economy Evaluation System

Based on existing research and data availability, this paper constructs and measures the digital economy index from three dimensions: digital infrastructure, digital transactions, and digital application degree. Data from Tibet are excluded due to a serious lack of data. The specific indicators selected are shown in Table 1. The data of telecommunications service volume in the primary, secondary, and tertiary indicators are sourced from the "China Statistical Yearbook 2007–2019". The secondary indicators in the digital transactions dimension, namely "depth of digital financial usage", "breadth of digital financial coverage", and "degree of digitalization of digital finance", are sourced from the Digital Inclusive Finance Index of Peking University's Digital Finance Research Center.

Based on the above index data, this paper uses the entropy value method to calculate the weights of each index, then synthesizes the digital economy index of each region in China, and the specific calculation steps are as follows:

First, the indicators are standardized, and since the indicators in Table 1 are positive indicators, the standardization formula used is shown in Equation (1):

$$x_{ij}^{1} = \frac{x_{ij} - \min\{x_{ij}\}}{\max\{x_{ij}\} - \min\{x_{ij}\}} \tag{1}$$

where, x_{ij} in Equation (1) is the "j" indicator of each region "i" in Table 1, $j = 1, 2, 3 \cdots\cdots 10$.

Table 1. Digital economy indicator evaluation system.

	Primary Indicator	Secondary Indicator
	Digital infrastructure	Fiber optic cable density Internet port access density Internet penetration rate
Digital economy index evaluation system for provinces in China	Digital transaction	Telecommunications service volume Depth of digital financial usage Breadth of digital financial coverage
		Degree of digitalization of digital finance
	Digital application degree	Number of internet domain names Mobile phone penetration rate Innovation activity

The second step is to calculate the weights accounted for by each indicator in each region, and the calculation formula is shown in Equation (2):

$$P_{ij} = \frac{x_{ij}^1}{\sum_{i=1}^{30} x_{ij}^1} \quad (2)$$

The third step is to find the information entropy based on the calculation result of the second step, which is calculated as shown in Equation (3):

$$e_j = -\frac{1}{\ln(n)} \sum_{i=1}^{30} P_{ij} \times \ln(P_{ij}) \quad (3)$$

In the fourth step, the coefficient of variation of each index is calculated according to Equation (3), and the calculation formula is shown in Equation (4):

$$d_j = 1 - e_j \quad (4)$$

The fifth step is to normalize the coefficient of variation, as shown in Equation (5):

$$w_j = \frac{d_j}{\sum_{j=1}^{10} d_j} \quad (5)$$

In the sixth step, the comprehensive index of the digital economy in each region is calculated based on the weights, as shown in Equation (6):

$$Digital_i = \sum_{j=1}^{10} w_j \times x_{ij}^1 \quad (6)$$

The level of digital economic development and CO_2 emissions are the main variables in this paper, so it is necessary to analyze their spatial and temporal distribution characteristics. Figure 3 compares the level of digital economic development in China in 2007 and in 2019. From Figure 3, it can be observed that China's digital construction has made a qualitative leap over a span of 13 years. However, there are also significant differences in development and spatial heterogeneity. The regions with higher levels of digital economic development, except Beijing, are generally located in coastal areas, followed closely by the central, southwest, and northeast regions, while the northwest region lags in terms of the planning and layout of the digital economy. Figure 4 shows the spatial distribution of CO_2 emissions in China in 2007 and 2019. Similarly, CO_2 emissions in China exhibit distinct regional heterogeneity. Regions with higher carbon emissions are mainly concentrated in the northern region, while regions with lower carbon emissions are relatively concentrated in the southern, eastern, northwest, and southwest regions. In the following section, empirical analysis will be conducted to investigate whether the digital economy can reduce CO_2 emissions and whether the impact of the digital economy on CO_2 emissions exhibits spatial heterogeneity.

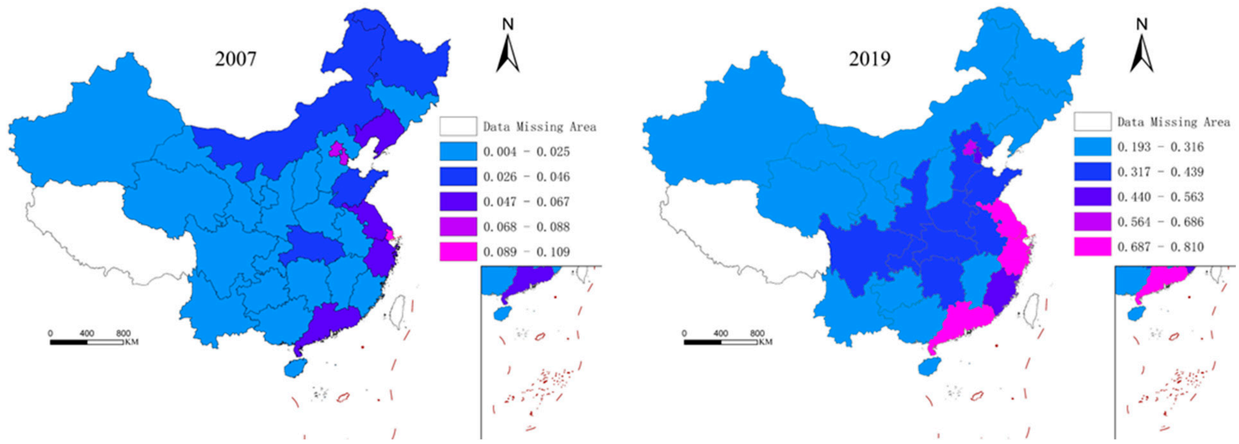

Figure 3. Spatial distribution of digital economy development levels in China (2007 and 2019, respectively).

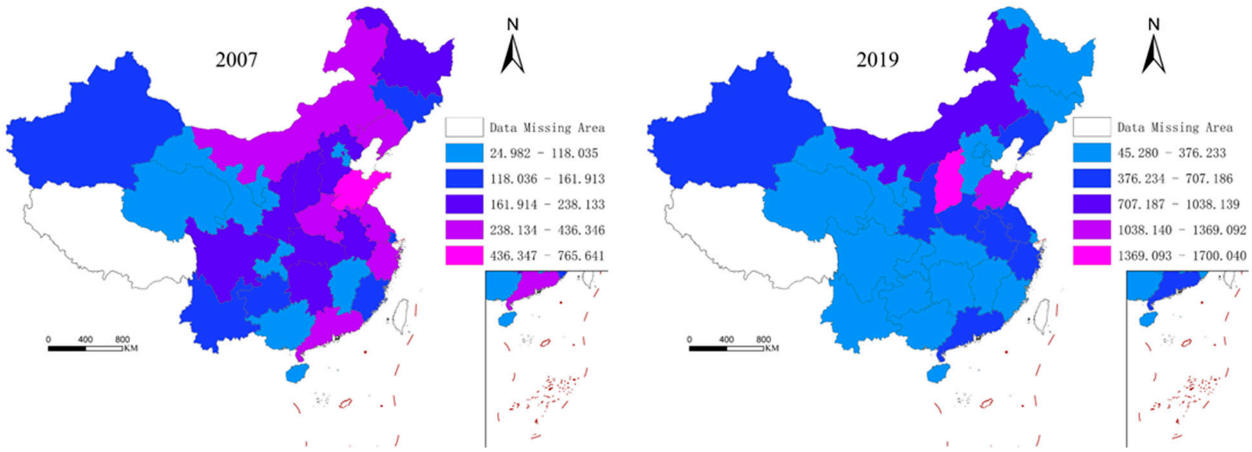

Figure 4. Spatial distribution of CO_2 emission in China (2007 and 2019, respectively).

4.2. Variable Selection and Baseline Model Setting

The core independent variable in this study is the digital economy development index. The specific selection of indicators and the calculation methods have been explained in the previous section and will not be reiterated here. The dependent variable in this study is the CO_2 emissions in various regions of China, which are obtained from the CEADs (Carbon Emission Accounts & Datasets). The control variables in this paper are mainly controlled by the factors affecting carbon dioxide emissions, such as urbanization construction, economic and political system, talent construction, and cultural construction. Firstly, China's urbanization process is undoubtedly a key factor affecting CO_2 emissions; secondly, China's previous extensive development has caused some pollution to the environment, while the role of the political system on environmental pollution cannot be ignored [55], so the impact of economic development and political system on CO_2 emissions is also a controlling factor to be focused on in this paper; thirdly, China's import and export trade is also one of the important factors affecting environmental performance [56]; fourthly, existing studies show that culture construction [57] and talent construction [58,59] are closely related to carbon dioxide emissions, and it is also a key factor to be considered in this paper to control culture construction and talent construction by looking for proxies to be included in the model.

Based on the above analysis, the control variables selected in this paper specifically include: urbanization rate, industrial structure, per capita GDP, openness to foreign trade, human capital level, cultural atmosphere, and fiscal pressure. The urbanization rate represents the proportion of urban population to the total population in each region. The industrial structure indicates the ratio of the tertiary industry output to the total GDP of each region. The per capita GDP is adjusted using the GDP deflator to account for inflation. The variable of openness to foreign trade is represented by the total import value (in USD ten thousand) in each region. The human capital level is represented by the average years of education in each region. The cultural atmosphere is measured by the per capita number of books (volumes) in public libraries in each region. Fiscal pressure is calculated as the ratio of general budget expenditure to general budget revenue in each region. The definitions, data sources, and descriptive statistics of each variable are presented in Tables 2 and 3.

Table 2. Variable definition and data source.

Variable	Symbol	Definition	Source	UoM
Dependent variable	CO_2	China's CO_2 emissions by province in 2007–2019	Carbon Emission Accounts & Datasets	million tons
Independent variables	Digital	China's digital economy development level by provinces in 2007–2019, calculated according to the digital economy index system	<Yearbook of China Information Industry>; <Yearbook of China Communications>; <China Statistical Yearbook>; Digital Inclusive Finance Index of Institute of Digital Finance Peking University	
Intermediary variable	EI	The energy intensity of each province in China is represented by the ratio of the total energy use converted into the amount of standard coal used to the total local GDP for each region from 2007–2019	<China Energy Statistical Yearbook>	tons per yuan
	EA	The degree of economic agglomeration in China's provinces, is represented by the ratio of the number of employed people to the area of the administrative region in each region from 2007–2019	<China Population & Employment Statistical Yearbook>; <China Labour Statistical Yearbook>	People/square kilometer
	Robot	The number of robots installed in China by the province during 2007–2019	International Federation of Robotics (IFR)	
Control variables	City	China's urbanization rate by province in 2007–2019	<China Statistical Yearbook>	%
	Ind	The industrial structure of China's provinces is represented by the ratio of tertiary sector output to total GDP for each region from 2007–2019	<China Statistical Yearbook>	%
	pGDP	China's per capita GDP by province in 2007–2019	<China Statistical Yearbook>	RMB (yuan)
	Open	The degree of openness to foreign trade in each province of China is represented by the total import value from 2007–2019	<China Statistical Yearbook>	ten thousand US dollars
	HC	The level of human capital in each province of China is represented by the average years of education from 2007–2019. The calculation formula is as follows: Average years of education = (number of illiterate individuals × 1 + number of individuals with primary education × 6 + number of individuals with junior high school education × 9 + number of individuals with high school and technical school education × 12 + number of individuals with college and above education × 16)/total population aged 6 and above.	<China Statistical Yearbook>	years
	Cul	The cultural atmosphere of each province in China is represented by the per capita number of books held in public libraries from 2007–2019.	<China Library Yearbook>; <China Cultural Heritage and Tourism Statistical Yearbook>	volumes
	FiscPres	The fiscal pressure of each province in China is represented by the ratio of general budget expenditure to general budget revenue from 2007–2019	<China Statistical Yearbook>	%

Table 3. Descriptive statistics of variables.

Variable	Obs	Mean	Max	Min	Std. Dev.
CO_2	390	330.271	1700.044	24.983	274.122
$Digital$	390	0.214	0.809	0.004	0.155
EI	390	0.916	3.315	0.070	0.505
EA	390	79.761	1136.601	0.628	172.075
$Robot$	390	29,644.112	308,734	184.086	43,836.250
$City$	390	0.552	0.942	0.282	0.135
Ind	390	0.446	0.835	0.286	9.748
$pGDP$	390	44,172.79	164,563	6915	26,487.52
$Open$	390	5,457,700	45,500,000	15,914	9,317,580
HC	390	9.039	12.701	6.928	0.929
Cul	390	0.632	3.40	0.16	0.537
$FiscPres$	390	2.304	6.745	1.052	0.995

Based on the above data indicators, we established the following baseline regression model as shown in Equation (7):

$$\ln\left(CO_{2_{it}}\right) = \beta_0 + \begin{array}{l} \beta_1 Digital_{it} + \beta_2 City_{it} + \beta_3 Ind_{it} + \beta_4 pGDP_{it} + \beta_5 Open_{it} + \beta_6 HC_{it} + \beta_7 Cul_{it} \\ + \beta_8 \beta FiscPres_{it} + \partial_i + \gamma_t + \mu_{it}) \end{array} \quad (7)$$

The left side of the model (7) represents the logarithm of CO_2 emissions for each region. β_0 represents the intercept of the model. $Digital_{it}$ refers to the digital economy index, which is the core independent variable of this study, and β_1 represents the estimated coefficient of the core independent variable. Among the control variables, $City_{it}$ represents the urbanization rate, Ind_{it} represents the industrial structure, $pGDP_{it}$ represents per capita GDP, $Open_{it}$ represents openness to foreign trade, HC_{it} represents the level of human capital in each region, Cul_{it} represents the cultural atmosphere, and $FiscPres_{it}$ represents fiscal pressure. β_2–β_8 represent the estimated coefficients of the control variables. α_i represents individual fixed effects, γ_t represents time fixed effects, and μ_{it} represents the standard error, which follows a normal distribution with mean 0 and constant variance.

5. Empirical Results Discussion

5.1. Regression Results of the Baseline Model

Before conducting regression analysis, unit root tests are required for each variable, but since the data selected for this study are short panel data, according to Kao [60] and Chen [61], unit root tests are not conducted.

To determine whether the fixed-effects model established in model (7) is accurate, the Hausman test is conducted here to verify whether a fixed-effects model or a random effects model should be used. As shown in Table 4, the Hausman test results show that the Hausman value is 20.620 and significant at the 1% significance level. This indicates that there is a significant correlation between the independent variables (including core independent variables and control variables) and individual regions in model (7), which reflects that there are obvious regional characteristics of digital economy level, economic development level, economic growth pattern, and human capital level in each region, which is also consistent with the actual development characteristics of each region in China. For example, the eastern coastal region of China has a better level of economic development, a higher level of human capital, and is the frontier of China's opening up to the world, moreover, the application of digital technology is deeper than that of the central and western regions of China, so it is reasonable to use the fixed-effects model in this paper.

Table 4. Hausman test results.

Variables	FE	RE
Digital	−0.827 ***	−0.791 ***
	(0.189)	(0.188)
City	0.497	0.440
	(0.447)	(0.412)
Ind	−0.006 *	−0.007 **
	(0.003)	(0.003)
pGDP	−0.143 ***	−0.154 ***
	(0.051)	(0.051)
Open	−0.031	−0.009
	(0.028)	(0.027)
HC	−0.550	−0.450
	(0.452)	(0.449)
Cul	0.108	0.061
	(0.106)	(0.098)
FiscPres	−0.090 **	−0.123 ***
	(0.042)	(0.041)
cons	8.293 ***	8.050 ***
	(1.031)	(0.991)
Hausman	20.620 ***	
p-value	0.0082	

Note: ***, **, and * represent 1%, 5%, and 10% levels of statistical significance, respectively, and standard errors are in parentheses.

Estimation (1) in Table 5 represents a univariate regression of the digital economy index on CO_2 emissions. Estimations (2) to (8) progressively include control variables based on estimation (1). The estimated results of model (7) are presented in estimation (8). It can be observed that the impact of the digital economy on CO_2 emissions is significantly negative. The estimated coefficient is significantly negative at a significance level of 1%, indicating that the development of the digital economy can significantly reduce CO_2 emissions.

Table 5. Baseline model regression results of model (7).

	Estimation (1) $\ln(CO_2)$	Estimation (2) $\ln(CO_2)$	Estimation (3) $\ln(CO_2)$	Estimation (4) $\ln(CO_2)$	Estimation (5) $\ln(CO_2)$	Estimation (6) $\ln(CO_2)$	Estimation (7) $\ln(CO_2)$	Estimation (8) $\ln(CO_2)$
Digital	−0.868 ***	−0.790 ***	−0.802 ***	−0.725 ***	−0.726 ***	−0.723 ***	−0.827 ***	−0.827 ***
	(0.149)	(0.180)	(0.180)	(0.179)	(0.179)	(0.179)	(0.189)	(0.189)
City		0.346	0.355	0.355	0.403	0.481	0.497	0.497
		(0.445)	(0.444)	(0.438)	(0.441)	(0.447)	(0.447)	(0.447)
Ind			−0.004	−0.008 **	−0.008 **	−0.008 **	−0.006 *	−0.006 *
			(0.003)	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)
pGDP				−0.155 ***	−0.147 ***	−0.134 ***	−0.143 ***	−0.143 ***
				(0.048)	(0.049)	(0.051)	(0.051)	(0.051)
Open					−0.028	−0.029	−0.031	−0.031
					(0.028)	(0.028)	(0.028)	(0.028)
HC						−0.464	−0.550	−0.550
						(0.447)	(0.452)	(0.452)
Cul							0.108	0.108
							(0.106)	(0.106)
FiscPres								−0.090 **
								(0.421)
cons	5.703 ***	5.496 ***	5.694 ***	7.482 ***	7.773 ***	8.624 ***	8.626 ***	9.007 ***
	(0.033)	(0.269)	(0.303)	(0.633)	(0.694)	(1.073)	(1.073)	(1.083)
R^2	0.969	0.969	0.970	0.970	0.971	0.971	0.971	0.971
Individual fixed effect	YES	YES	YES	YES	YES	YES	YES	YES
Time fixed effect	YES	YES	YES	YES	YES	YES	YES	YES
F	33.76 ***	17.16 ***	12.14 ***	11.92 ***	9.75 ***	8.30 ***	7.25 ***	6.99 ***
N	390	390	390	390	390	390	390	390

Note: ***, **, and * represent 1%, 5%, and 10% levels of statistical significance, respectively, and standard errors are in parentheses.

In general, the digital economy represented by data factors and digital technologies exhibits significant green attributes. Whether data factors are incorporated as emerging factors of production in the production process or digital technologies are comprehensively utilized for industrial digitalization, digital industrialization, smart governance, and other transformations, the development of the digital economy demonstrates a positive restraining effect on CO_2 emissions. Hypothesis 1 is verified. The regression results of the control variables show that, as the control variables are gradually included in the regression, there are no significant changes in the coefficients and significance of the core independent variable, which indicates good stability of the regression results.

The coefficients of urbanization rate, degree of openness to foreign trade, human capital, and regional cultural atmosphere are all insignificant. The reasons behind these results can be attributed to the following aspects: In terms of urbanization level, China's urbanization construction is driven by a large amount of infrastructure construction, accompanied by large-scale population movement to cities and a steep increase in electricity use, which brings a large number of carbon-intensive products, such as cement, iron and steel, coal, etc., driving the development of traditional "three high" (high pollution, high energy consumption, high emissions) industries, and generating a significant amount of CO_2 emissions [14]. In terms of openness to foreign trade, although it attracts the aggregation of global factors of production such as technological and capital elements, it may also create a pollution halo effect. Multinational firms may adopt a "beggar-thy-neighbor" mentality and transfer industrial chains that do not meet emission requirements to China, thus creating a pollution refuge effect [62,63]. Therefore, an increase in the level of openness to foreign trade may further enhance CO_2 emissions, offsetting the CO_2 reduction effect of the digital economy. In terms of human capital, the improvement of average years of education, which reflects the level of human capital, can effectively enhance innovation capabilities, and promote technological progress. However, new technologies often exhibit time-lag characteristics from development to application. Therefore, the carbon-reducing effect of current technological innovation may not be apparent, and it may not have a significant suppression effect on CO_2 emissions. In terms of cultural atmosphere, public cultural development helps shape diverse cultural values among the public, and different cultural values internalize different attitudes, perceptual behavior control, and expected guilt. Diverse cultural values have varying positive effects, negative effects, and mediating effects on low-carbon consumption behavior [64]. Therefore, the impact of the deepening cultural atmosphere on CO_2 emissions reduction is not unidirectional.

Finally, the industrial structure can be significantly negative at the 10% level and above in estimation (5) to estimation (8), except in estimation (4), which is not significant. This indicates that the increasing ratio of the tertiary industry can contribute to CO_2 emissions reduction to some extent. However, due to the current high level of embodied carbon emissions in the tertiary industry [36,37], the suppressive effect of optimizing industrial structure on CO_2 emissions reduction has not yet been fully highlighted. On the other hand, per capita GDP remains consistently significant and negative at the 1% level, demonstrating that the increase in per capita GDP can effectively restrain CO_2 emissions. As China gradually moves towards the new journey of building a modern socialist country in an all-round way, the process of common prosperity among the people will accelerate. The continuous increase in per capita GDP aligns to achieve "carbon neutrality". With the improvement of per capita GDP, consumers' preferences for goods will shift from focusing solely on price to considering both quality and environmental friendliness. To meet and satisfy the changing demands of consumers, producers will shift towards producing low-carbon and environmentally friendly high-quality goods, thereby reducing energy consumption and CO_2 emissions [65]. Furthermore, fiscal pressure is significant at the 5% level, indicating that an increase in general budget expenditure can reduce the level of CO_2 emissions. Zhou and Lin [66] suggest that government fiscal expenditure can drive investment, infrastructure, and industrial structural effects, channeling funds into areas related to low-carbon environmental protection and improving ecological performance.

5.2. Robustness Tests

5.2.1. Substitution of Independent Variables and Core Independent Variables

Considering that the selection errors of the core independent variables and the independent variables may lead to endogeneity, we use the relevant indicators for substitution in this paper to test the robustness of the baseline regression results. Estimation (9) in Table 6 shows the estimation results of replacing the independent variables, estimation (10) shows the estimation results of replacing the core dependent variables, and estimation (11) shows the estimation results of replacing both the core independent variables and the dependent variables.

Table 6. Robustness tests of the baseline regression results.

	Estimation (9) Substitution of Independent Variables	**Estimation (10) Substitution of Core Dependent Variables**	**Estimation (11) Substitution of Both Independent and Dependent Variables**
Digital	−1.276 ***	−0.063 **	−0.130 ***
	(0.255)	(0.025)	(0.034)
City	−0.838	1.025 **	−0.235
	(0.603)	(0.432)	(0.581)
Ind	0.008 *	−0.008 **	0.006
	(0.005)	(0.003)	(0.005)
pGDP	−0.343 ***	−0.169 ***	−0.383 ***
	(0.068)	(0.051)	(0.069)
Open	−0.074 **	−0.032	−0.074 *
	(0.038)	(0.028)	(0.038)
HC	−0.648	−0.482	−0.555
	(0.610)	(0.460)	(0.618)
Cul	0.227	0.039	0.160
	(0.143)	(0.107)	(0.144)
FiscPres	0.038	−0.082 *	0.044
	(0.057)	(0.043)	(0.058)
cons	2.191	8.812 ***	2.033
	(1.462)	(1.102)	(1.483)
R^2	0.946	0.970	0.944
Individual fixed effect	YES	YES	YES
Time fixed effect	YES	YES	YES
F	12.01 ***	5.20 ***	10.44 ***
N	390	390	390

Note: ***, **, and * represent 1%, 5%, and 10% levels of statistical significance, respectively, and standard errors are in parentheses.

In estimation (9) of Table 6, the independent variable, CO_2 emissions, is replaced with CO_2 emissions per unit of GDP. The regression results of estimation (9) indicate that the development of the digital economy significantly reduces CO_2 emissions per unit of GDP, which is consistent with the baseline regression results in Table 5. In estimation (10), the digital economy index is recalculated using principal component analysis, while the dependent variable remains as CO_2 emissions. The regression results show that the development of the digital economy significantly reduces CO_2 emissions. Estimation (11) builds upon estimations (9) and (10) by simultaneously replacing both the dependent variable and the core independent variable. The dependent variable is replaced with CO_2 emissions per unit of GDP, and the core independent variable is the digital economy index based on principal component analysis. The regression results reveal that the development of the digital economy significantly reduces CO_2 emissions per unit of GDP. Therefore, the development of the digital economy is beneficial to the achievement of carbon neutrality.

5.2.2. Endogenous Discussion

In the baseline regression, there may be some reverse causality and thus endogeneity between CO_2 emissions and the digital economy. In order to achieve the goal of carbon neutrality, strong environmental regulation by government agencies may promote the economy to shift to a low-energy and low-carbon development model, which may facilitate the development of the digital economy in the process of achieving lower CO_2 emissions. Thus, this paper uses the instrumental variables approach to correct possible endogeneity in the baseline regression, which uses the product of the number of fixed telephones per 10,000 people in each region in 1990 and the Internet penetration rate in each region from 2003 to 2015 after referring to the study by Zhao et al. [20]. The data on the number of fixed telephones per 10,000 people by region in 1990 were sourced from the "China Compendium of Statistics 1949–2008" and the Internet penetration rate data were sourced from the CNNIC (China Internet Network Information Center). The reason for choosing these instrumental variables is that the telecommunications infrastructure in each region serves as the fundamental carrier for the rapid development of the digital economy. The historical telecommunications infrastructure construction in each region is related to the subsequent application of various digital technologies. Moreover, the impact of past telecommunications infrastructure construction on current CO_2 emissions is relatively small, which is consistent with the instrumental variable influencing the independent variables by affecting the endogenous variables.

The reasons for choosing this instrumental variable are as follows: firstly, Huang et al. [67] argued that in the development history of China's Internet connection technology, the Internet came into the public vision basically since the public switched telephone network, followed by integrated services digital network, and asymmetric digital subscriber line access to the current fiber optic broadband connection technology. Therefore, the development of Internet technology should start from the popularization of fixed telephones, so that the regions with high historical fixed telephone penetration are also very likely to be the regions with high penetration of Internet networks. On the other hand, the digital economy is an emerging economic model with the Internet as the carrier, while the Internet is a continuation of the development based on traditional communication technologies, therefore, the number of fixed telephones in each region of China in 1990 chosen for this paper can reflect, to a certain extent, the level of construction of telecommunication infrastructure in each region, and the level of construction of telecommunication infrastructure in history is related to the degree of popularization and application of Internet technology in the future; Second, the telecommunication infrastructure development level in the past has had a minor impact on the current carbon emissions, which is consistent with the exogeneity hypothesis that instrumental variables affect the independent variables by influencing endogenous variables; Finally, since the fixed telephone user data in 1990 are cross-sectional data, they cannot be directly used for instrumental variable estimations of panel data.

Therefore, this paper refers to Nunn and Qian's [68] method for this problem by introducing a time-varying variable to construct the panel instrumental variable. Then, we construct the instrumental variables of the digital economy for instrumental variable estimation with the interaction term of the number of fixed telephones per 10,000 people in each region by 1990 (associated with individual variation) and the Internet penetration rate in each region from 2003 to 2015 (associated with time variation). Both variables satisfied the exclusivity requirement of instrumental variables.

The regression results of the instrumental variables method are shown in Table 7. In the first-stage regression, the impact of instrumental variables on the digital economy is significantly positive at the 1% significance level, and the construction of telecommunication infrastructure in each region has a significant positive impact on the development of the digital economy in the future. In addition, the impact of the digital economy on CO_2 emissions remains significantly negative in the second-stage regression, which is consistent with the results of the baseline regression in Table 5 and proves again that the development of China's digital economy can contribute to carbon neutrality. Meanwhile, according to the results of Anderson canon.corr.LM statistic and Cragg-Donald Wald F statistic, the hypotheses of unidentifiable and weak instrumental variables of instrumental variables are significantly rejected, indicating that all instrumental variables are uncorrelated and exogenous, so the instrumental variables selected in this paper are reasonable and valid.

Table 7. Regression results of the instrumental variable.

	First-Stage Regression Digital	Second-Stage Regression $\ln(CO_2)$
Digital		−1.220 *** (0.465)
IV	0.452 *** (0.055)	
Control variables	YES	YES
Provincial fixed effect	YES	YES
Time fixed effect	YES	YES
Anderson canon.corr.LM statistic	65.303 ***	
Cragg-Donald Wald F statistic	68.381[16.38]	
F	5.40 ***	
N	390	

Note: *** represent 1% levels of statistical significance, respectively, and standard errors are in parentheses. Within "[]" is the critical value of the Stock–Yogo weak identification test at the 10% level.

5.3. Mechanism Analysis

The regression results of the digital economy index on the mechanism variables are shown in Table 8, and estimation (12) is the regression results of the digital economy index on energy intensity, where the ratio of the amount converted to standard coal used in each region to the total GDP is used, i.e., energy consumption per unit of GDP is used as a proxy variable for energy intensity, which is represented by EI in the empirical process, and the regression results show that the development of the digital economy significantly reduces energy intensity, meaning that the development of the digital economy can significantly improve energy efficiency and reduce CO_2 emissions. According to Yu and Zhu [69], we argue that under the impetus of the digital economy, both enterprises and users are motivated by information and technology. On one hand, enterprises are incentivized to promote the green transformation of the energy structure, and the integrated effects of the digital economy can enhance energy efficiency by reducing energy consumption in production, sales, and usage, thus suppressing CO_2 emissions. On the other hand, the application of digital technology promotes widespread awareness of green and environmental concepts, leading to an increased emphasis on energy conservation and environmental protection at the individual level, resulting in more people adopting low-carbon lifestyles.

Table 8. Mechanism variable regression.

	Estimation (12) Energy Consumption per Unit of GDP	Estimation (13) Economic Agglomeration	Estimation (14) The Number of Robots Installation
Digital	−1.053 ***	1.002 ***	0.408 ***
	(0.201)	(0.101)	(0.097)
City	−1.549 ***	0.158	1.340 ***
	(0.475)	(0.239)	(0.229)
Ind	0.011 ***	−0.004 **	−0.014 ***
	(0.004)	(0.002)	(0.002)
pGDP	−0.185 ***	0.061 **	0.170 ***
	(0.054)	(0.027)	(0.026)

Table 8. *Cont.*

	Estimation (12) Energy Consumption per Unit of GDP	Estimation (13) Economic Agglomeration	Estimation (14) The Number of Robots Installation
Open	−0.064 **	0.014	0.049 ***
	(0.030)	(0.015)	(0.014)
HC	−0.114	0.338	0.344
	(0.480)	(0.242)	(0.231)
Cul	0.249 **	−0.197 ***	−0.106 *
	(0.113)	(0.057)	(0.054)
FiscPres	0.020	−0.043 *	−0.109 ***
	(0.045)	(0.023)	(0.022)
cons	3.266 ***	1.776 ***	6.208 ***
	(1.151)	(0.580)	(0.554)
R^2	0.931	0.998	0.998
Individual fixed effect	YES	YES	YES
Time fixed effect	YES	YES	YES
F	10.14 ***	21.06 ***	39.43 ***
N	390	390	390

Note: ***, **, and * represent 1%, 5%, and 10% levels of statistical significance, respectively, and standard errors are in parentheses.

The independent variable of estimation (13) is economic agglomeration, and we use the ratio of the employed population to the administrative area as a proxy variable for economic agglomeration, denoted as EA in the empirical analysis. The regression results show that the coefficient of economic agglomeration is significantly positive at a 1% level of significance, indicating that the development of the digital economy can effectively suppress carbon dioxide emissions by promoting higher levels of economic agglomeration. The reason behind this is that the rapid development of the digital economy accelerates the inflow of labor force to large cities with higher levels of digital infrastructure. It can help to rationalize and specialize the local industrial structure and division of labor, and form the industrial agglomeration effects and positive externalities of economic agglomeration [4]. The effect on CO_2 emissions reduction can be indirectly achieved by changing the spatial distribution of economic resources.

The independent variable of the estimation (14) is the number of robots installed in each region, and we adopt the approach of Cheng and Duan [50], where the total number of robots is allocated to each prefecture-level city based on its GDP proportion to the national GDP, and it is represented as Robot in the empirical analysis. The regression results show a significantly positive coefficient for the number of robot installations, indicating that the use of robots has an intermediary effect on CO_2 emissions. This suggests that with the deepening of the digital economy, industrial change has gradually accelerated, which has both promoted the continuous optimization of production processes and led to a significant increase in the proportion of robots used in production. The use of industrial robots, on the one hand, improves the resource allocation efficiency of traditional manufacturing industries by fostering a profound integration with them, which ultimately propels productivity improvement and reduces enterprise CO_2 emissions. On the other hand, the large-scale use of robots can also further restrain CO_2 emission levels through two paths: front-end production and end-of-pipe governance [50].

6. Further Discussion

Heterogeneity Analysis

Because the digital economy development level is unbalanced in different regions of China, the digital divide phenomenon is more prominent, while the long-standing economic development level and economic growth pattern of China have a large difference among regions, so in this paper, we divided China into seven regions (This study divided China into central, south, southwest, northwest, east, north and northeast China for heterogeneity analysis. Central China includes: Hunan, Hubei, and Henan; South China includes: Hainan, Guangxi, and Guangdong; Southwest China includes: Guizhou, Yunnan, Sichuan, and Chongqing; Northwest China includes: Shaanxi, Gansu, Xinjiang, Ningxia, and Qinghai; East China includes: Fujian, Jiangxi, Zhejiang, Shanghai, Jiangsu, Anhui, and Shandong; North China includes: Hebei, Tianjin, Beijing, Shanxi, and Inner Mongolia; Northeast China includes: Liaoning, Jilin, and Heilongjiang.) of central, east, south, north, northeast, southwest, and northwest based on model (7), while the core independent variables have interacted with the dummy variables representing each region. The regression results are shown in Table 9.

Table 9. Heterogeneity regression results.

	$\ln(CO_2)$
Central China	−2.486 ***
	(0.313)
South China	−0.313
	(0.238)
Southwest China	−2.160 ***
	(0.316)
Northwest China	−0.036
	(0.347)
East China	−0.883 ***
	(0.174)
North China	−1.006 ***
	(0.210)
Northeast China	−3.054 ***
	(0.441)
Control variables	YES
Individual fixed effect	YES
Time fixed effect	YES
R^2	0.980
F	15.24
N	390

Note: *** represent 1% levels of statistical significance, respectively, and standard errors are in parentheses.

The regression results in Table 9 show that the development of the digital economy has a significantly negative impact on CO_2 emissions in all regions of China, with the impact of the digital economy on CO_2 emissions in central, southwest, east, north, and northeast China being significantly negative at the 1% significance level, while in south and northwest China the impact is negative but not significant. The development of the digital economy can significantly reduce CO_2 emissions in most regions of China, and the goal of the digital economy-empowered carbon neutrality has the potential to be achieved.

Further research has revealed that the digitalization construction in northwest China started late due to natural factors such as transportation, geography, and environment. During the early stages of development, a large amount of energy consumption is needed, such as electricity consumption brought by digital technology and production equipment, so the "emission-increasing" effect of the digital economy in its early stages outweighed the "emission-reducing" effect brought by digital technologies. Additionally, the region faced challenges in the application of digital technologies and the integration barriers of the digital economy, which resulted in higher marginal costs due to the early integration of digital technologies with various production sectors. On the other hand, the slow industrial transformation in the northwest region, with a higher proportion of resource-intensive industries, further weakens the CO_2 reduction potential of the digital economy.

As the pioneers of China's digital economy construction, east and north China had strong leading cities with robust digital economy development, such as Hangzhou, Shanghai, and Beijing. These cities not only stimulate the development of the digital economy in their surrounding areas, but the region's proactive layout of digital development and in-depth application of digital technology can help market participants effectively access information on various resource elements and improve resource allocation efficiency [18]. Moreover, the penetration of the digital economy into the primary, secondary, and tertiary industries can promote green and low-carbon operations of market entities, reducing CO_2 emissions in various aspects such as office work, production, and sales. It also encourages enterprises to lower energy intensity and improve energy efficiency, further reducing CO_2 emissions. In the central, northeast, and southwest regions, the digital economy started later compared to the east and north regions. However, these regions benefit from the spillover effects of digital technologies, which to some extent helps mitigate the risks of R&D investments and the negative impact of "emission-increasing" effects during the early stages of digital development. For the south region, its geographical advantage contributes to generally higher air quality. Except for Guangdong, CO_2 emissions in Guangxi and Hainan have remained at relatively low levels, indicating a better ecological environmental performance. Although Guangdong has made significant efforts and rapid progress in the digital economy, it is difficult for the region alone to manifest the CO_2 emissions reduction effects of the digital economy by itself compared to the whole region.

7. Conclusion and Policy Implications

The "peak carbon emissions" and "carbon neutrality" strategies are not only an internal requirement for China to accelerate the construction of a new development pattern, but also an important goal to achieve high-quality development. In the face of intensifying global climate change, China has taken the development of the digital economy as an important tool to achieve sustainable development, which has risen to an unprecedented level. The efficiency advantage of the digital economy has become the best way for the Chinese government to promote the green transformation of the economy and society.

Against this backdrop, firstly, this study utilizes panel data from 30 provinces (autonomous regions, municipality directly under the central government) in China from 2007–2019 and constructs an evaluation indicator system for the development of the digital economy, measuring the level of digital economy development in each region. Secondly, based on the current research of the digital economy and environmental sustainability, this paper puts forward the hypotheses that the digital economy development can reduce CO_2 emissions by improving energy efficiency, accelerating economic agglomeration, and increasing the proportion of robot use, and the impact of digital economy on CO_2 emissions has regional heterogeneity. Finally, through empirical analysis, it comprehensively examines the relationship between the digital economy and CO_2 emissions, as well as the intermediary effects, regional heterogeneity characteristics, and other internal mechanisms through empirical analysis in multiple dimensions, and the key is to construct instrumental variables by using the exogenous and exclusive characteristics of the number of fixed telephones per 10,000 people and the Internet penetration rate in each region, and the panel instrumental variables are constructed by introducing variables that have varied over time through an interactive approach, which better solves the endogeneity problem that may arise from the model, confirms the rationality of the model constructed, and more comprehensively verifies the hypotheses proposed in this paper.

The main findings are as follows: Firstly, the development of the digital economy has a significant suppression effect on CO_2 emissions and can contribute to the achievement of the "carbon neutrality" goal. This conclusion holds even after considering endogeneity, conducting a series of robustness tests, and using the number of fixed telephone and Internet penetration rate as instrumental variables in the regression. Secondly, the impact of the digital economy on CO_2 emissions also has an indirect mechanism, which can not only reduce CO_2 emissions by improving energy efficiency, changing the energy structure, and lowering energy intensity, but also reduce CO_2 emissions by accelerating economic agglomeration, creating a positive externality of economic agglomeration, or increasing the use of robots. Thirdly, the CO_2 emissions reduction effect of the digital economy exhibits regional heterogeneity. In the face of the digital divide and the fact that regional economic development is unbalanced, east and north China benefit from the early layout of the digital economy and have a significant suppression effect on CO_2 emissions, Additionally, the central, northeast, and southwest regions also reveal notable CO_2 reduction effects in the digital economy driven by the spillover effects of digital technology and radiation. On the other hand, the northwest and south regions were constrained by factors such as industrial structure, natural environment, and location, and have not yet shown substantial CO_2 emissions reduction effects in the development of the digital economy. Fourth, optimizing the industrial structure, increasing the proportion of tertiary industry, fostering common prosperity, raising the per capita income, enhancing fiscal expenditure, and lifting the proportion of general budget expenditure can all reduce CO_2 emission. In contrast, the suppression effect of urbanization, the degree of openness to foreign trade, human capital, and the regional cultural atmosphere on CO_2 emissions are not significant.

Based on the above conclusions, the policy implications of this paper are as follows:

First, in terms of the direct impact of the digital economy on CO_2 emissions, it is necessary for China to comprehensively promote digital construction, improve digital infrastructure, and enhance the quality and scale of digital resources supply. The government should take the lead in investing and operating new infrastructure, particularly focusing on the supply construction of new infrastructure such as gigabit fiber-optic networks, 5G base stations, and big data centers in underdeveloped areas. This will fully expand the CO_2 emissions reduction effects of the digital economy. On the other hand, it is necessary to enhance the innovation capacity of digital technology and leverage the empowering role of the digital economy in achieving green and low-carbon development of the economy and society. The government should implement more strictly regulated intellectual property protection policies, especially for technological R&D activities that combine the digital economy with low-carbon environment protection, and give policy support and financial subsidies to create a favorable innovation atmosphere. Enterprises should establish their own position as innovation leaders, actively explore the application scenarios of digital technologies in green technological innovation, accelerate the deep integration of the digital economy with the development of new energy, resource recycling, and energy extraction. Universities and research institutes should play a leading role in digital and green innovation, in order to accelerate the cultivation of talent that combines the digital economy with green and low-carbon integration.

Second, in terms of the indirect impact of the digital economy on CO_2 emissions, on one hand, it is necessary to optimize the energy utilization structure, improve energy efficiency, and lower energy intensity. It is also necessary to continue to promote the digital transformation of industries, especially to facilitate the digital transformation of traditional industries with digital empowerment at the core, embed data elements into all segments of industrial operation, and exert the green attributes of data elements. On the other hand, we should aim to accelerate industrial agglomeration and population agglomeration and increase the degree of economic agglomeration, break down regional circulation barriers, and comprehensively build a large national unified market. It is essential to exceed the low-level stage of economic agglomeration and its critical point for energy conservation and CO_2 emissions reduction as soon as possible while exerting its positive externalities for energy conservation and CO_2 emissions reduction. In addition, increasing the proportion of robot usage is another pathway to reduce CO_2 emissions. Encouragement should be given to industries to develop higher-end, intelligent, and green-oriented approaches. Increased investment in the R&D of robots is crucial to improve the level of the Chinese robot industry. Expanding the product line and usage scenarios of robots while lowering the threshold for their utilization should also be emphasized.

Third, from the perspective of the heterogeneous impact of regional digital economy development on CO_2 emission, it should be based on the objective law of emerging technology diffusion and accelerate the penetration to the underdeveloped areas of digital technology which are represented by northwest China. Developed regions such as east and north China, as the main battlegrounds for the digital industry and the driving force behind digital technology development, should explore the establishment of a coordinated development model for the regional digital economy. They should actively construct demonstration zones for the digital economy. Furthermore, it is important to promote differentiated development of the digital economy according to local conditions. The southwest and northwest regions should capitalize on their energy advantages and strategically develop the big data industry. Central and north China should take advantage of their geographical location and population scale, with a focus on promoting the development of the digital circulation industry and innovating digital consumption patterns. East and south China should make use of their advantages in talent, technology, industrial chains, and capital to deepen their involvement in high-precision areas of the digital economy and cultivate digital brands with global leadership positions. In addition, the government should increase investment and support for regions lagging in digital construction, guide regions who are leading digital economy development, and help regions lagging behind to pass the initial stage of digital construction as soon as possible, so as to mitigate the initial "emission-increasing" effect on CO_2 emissions and promote balanced regional digital economy development.

Fourth, it is necessary to continuously optimize the industrial structure and vigorously develop the tertiary industry, accelerate the promotion of green finance, green consumption, green services, and other modes, and propel the green transformation of the industries towards sustainability. Additionally, lowering energy consumption and CO_2 emissions in the primary and secondary sectors can effectively mitigate the embodied carbon emissions of the tertiary industry. Simultaneously, the government should not only continue to promote the common prosperity among the entire population, raise people's income, actively propagate the low-carbon and energy-saving lifestyle, and cultivate green and environmental friendly ideologies, but also increase the financial expenditure, allocate a higher proportion of the general budget to environmental pollution control, effectively guide social capital to participate in the investment on environmental pollution, and restrain CO_2 emissions.

8. Limitations and Future Improvement

Although this study has constructed a theoretical framework for analyzing the impact of the digital economy on CO_2 emissions and has empirically tested various relationships and mechanisms, there are still some limitations and room for improvement in this paper. Firstly, in terms of data usage, the construction of evaluation indicators for digital economy development was not comprehensive enough, which may lead to measurement errors. In future research, additional indicators such as digital governance capabilities, digital technologies, and digital innovation can be included to make the evaluation indicator system of digital economy development more objective and comprehensive. Secondly, in terms of data level, it can be further extended to city panel data to verify the relationship between the digital economy and CO_2 emission from a more micro perspective. Thirdly, in terms of time span, since the data of the core independent variable in this paper are obtained from the Institute of Digital Finance Peking University, but its digital finance index data are only updated up to 2020, this paper fails to further examine the impact of the digital economy on "carbon neutrality" in the context of the global impact suffered from COVID-19, and fails to discuss the impact of the COVID-19 on the results of this study. Then, in further research based on data availability, we will discuss in depth the relationship between the digital economy and carbon emissions under the shock of COVID-19 and in the post-epidemic era, and its impact on the results of this paper. Fourthly, in terms of empirical methods, we can use the Difference-in-Differences (DID) model to compare the real effect of the digital economy on carbon emissions between provinces in the National Pilot Zone for Digital Economy Innovation and Development and compare them with provinces outside of this zone.

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