frontiers | Frontiers in Environmental Science

ORIGINAL RESEARCH
published: 02 September 2022
doi: 10.3389/fenvs.2022.943177

Nonlinear Effect of Digital Economy on Carbon Emission Intensity—Based on Dynamic Panel Threshold Model

Runjie Wu[1], Xin Hua[1]*, Lin Peng[2], Yiyi Liao[2] and Yuan Yuan[3]

[1]College of Economics and Management, Tianjin University of Science and Technology, Tianjin, China, [2]Discipline of International Business, The University of Sydney, Sydney, NSW, Australia, [3]School of Science, Lanzhou University of Technology, Lanzhou, China

Under the background of carbon peak and carbon neutralization, it is vital to study the impact of digital economy on carbon emission reduction. Based on a provincial panel data from 2013 to 2019, this paper establishes a dynamic panel model, a dynamic spatial autoregressive model, and a dynamic threshold model to study the impact of digital economy on carbon emission intensity. Our findings show that digital economy has a significant inhibitory effect on carbon emission intensity. Results of regional heterogeneity show that the central region can transform the impact of digital economy on carbon emission reduction more efficiently. After adding the time lag term of carbon emission intensity, the impact coefficient of digital economy is still significant. Carbon emission intensity has obvious spatial effect, and the carbon emission of adjacent areas will significantly inhibit local carbon emission reduction activities. Under the threshold of innovation and environmental regulation, the emission reduction effect of digital economy is different. For regions with low technological level, digital economy is difficult to give full scope to its emission reduction advantages. At the same time, stricter environmental regulations can cooperate with digital economy to accelerate regional carbon emission reduction. Therefore, China should continue to improve the construction of digital infrastructure and promote the reform and innovation of enterprise digital technology in order to release the carbon emission reduction effect of digital economy.

Keywords: digital economy, carbon emission reduction, threshold model, dynamic panel model, spatial autoregressive model

Edited by:
Xuefeng Shao, University of Newcastle, Australia

Reviewed by:
Rong Zhou, University of Malaya, Malaysia
Bingqing Wang, City University of Macau, Macao SAR, China

****Correspondence:***
Xin Hua
huaxin@tust.edu.cn

Specialty section:
This article was submitted to Environmental Informatics and Remote Sensing, a section of the journal Frontiers in Environmental Science

Received: *13 May 2022*
Accepted: *20 May 2022*
Published: *02 September 2022*

Citation:
Wu R, Hua X, Peng L, Liao Y and Yuan Y (2022) Nonlinear Effect of Digital Economy on Carbon Emission Intensity—Based on Dynamic Panel Threshold Model. Front. Environ. Sci. 10:943177. doi: 10.3389/fenvs.2022.943177

1 INTRODUCTION AND LITERATURE REVIEW

The spread of COVID-19 has caused economic losses such as global supply chain interruption (Nikolopoulos et al., 2021) and the slowdown of the aviation industry and other transportation industries (Liu et al., 2022). At the same time, the substantial decrease of economic activity has reduced global carbon dioxide emissions. However, with the gradual economic recovery in various countries, carbon dioxide emissions from local production and living activities have shown a retaliatory growth trend (Wang et al., 2020). As the first economy to recover from COVID-19, China has continually faced environmental pollution problems (Yang et al., 2021). As the world's largest carbon emitter, China has not only acted responsibly as an advocate in addressing climate change but is also committed to finding a new path of carbon emission reduction. At the General Assembly of the United Nations in 2020, the Chinese government proposed the goal of achieving carbon peak in 2030 and carbon neutralization in 2060, demonstrating China's determined resolution to reduce carbon emission. In recent years, China has responded to climate change by upgrading carbon emission reduction technologies and adopting various carbon emission reduction measures. In 2021, the Chinese scientific research team released the global carbon flux data set based on China's first carbon satellite, marking that China has the ability to quantitatively monitor the global carbon budget. In July 2021, China's first carbon emission market officially began trading. In October of the same year, The State Council issued the Action Plan for Peaking Carbon Emissions by 2030, proposing that by 2030, carbon emission intensity would be reduced by over 65% compared with 2005. In November 2021, The People's Bank of China has set up carbon emission reduction support tools to help enterprises with large space for carbon emission reduction from a financial perspective. The high energy consumption oriented by resource consumption needs to be transformed (Irfan et al., 2021), and the problem of economic slowdown caused by COVID-19 needs to be solved urgently. Sustainable development and high-quality economic development are the inevitable choices to deal with the above problems (Yang et al., 2022).

Meanwhile, the digital economy has become the backbone of the new round of industrial reform in China. COVID-19 has accelerated the application of digital technology (Amankwah-Amoah et al., 2021). The combination of the digital revolution and technological innovation has paved the way for the fourth industrial revolution (Wang ang Wang, 2020). Meanwhile, digital platforms provide many employment opportunities, and those with advanced technological skills are accelerating the digitization process (Zaman and Sarker, 2021). In recent years, the digital economy has developed rapidly and the digitization process is steadily advancing in most emerging economies, especially in Asian countries. Digital government affairs such as electronic identity authentication have facilitated convenience in daily life and solved the problem of information asymmetry between the government and other enterprises (Yang et al., 2014; Liu et al., 2021). The gradual improvement of digital infrastructure has laid the foundation for the rise of e-commerce in various countries. Consumers are able to read detailed descriptions, view photos of goods, and even compare prices with intelligent software, which reduces not only the time and cost of shopping but also the information asymmetry between consumers and goods (Li et al., 2020). The digital economy has contributed to cross-border business development (Autio, 2017), business opportunities (Smith et al., 2017; Von Briel et al., 2018), an intelligent transportation network (Ablyazov and Asaul, 2021), and a shared economy (Sutherland and Jarrahi, 2018; Pouri and Hilty, 2021).

In addition, the digital economy also has the potential to prevent and control pollution. The application of digital technologies shortens the distance between upstream and downstream industries, realizes the optimal allocation of inventory, improves the efficiency of supply chain distribution, and reduces unnecessary losses in transportation (Watanabe et al., 2018). Furthermore, the digital economy can break the boundaries of time and space (Richardson, 2020), simplify steps of information flow, reduce unnecessary waste of resources, eventually improve carbon performance (Zhang et al., 2022), and help economically underdeveloped areas solve energy-related problems (Xu et al., 2022). Due to the continuous advancement of digital processes in the energy field, improved carbon efficiency will reduce the growth rate of digital emissions (Zhou et al., 2022). The improvement of digital production structures will make energy use safer and more efficient, improve green total factor productivity (Zhang et al., 2021), and realize the sustainable development of resources and environment (Hosan et al., 2022). Digital production can also reduce power generation (Wang J. et al., 2022), improve resource utilization (Shao et al., 2021) and green innovation output, and make positive contributions to the development of green and circular economies (Kristoffersen et al., 2020; Uçar, 2020; Kivimaa et al., 2021; Yue et al., 2021).

Most of the existing literature separates the digital economy from carbon emissions; very few articles discuss the impact of the digital economy on carbon emissions. From the existing limited literature, some researchers focus on implicit carbon emissions and carbon emission performance (Wang P. et al., 2022; Zhang et al., 2022), or pay attention to the spatial effect and intermediary factors of digital economy on carbon emissions (Li and Wang, 2022). From the perspective of existing research, there is a long-term cointegration relationship between digital economy and carbon emissions (Ma et al., 2022). From the perspective of digital industry, its direct structural effect reduces the implied carbon emissions, but its indirect structural effect has the opposite effect (Wang J. et al., 2022). Firstly, based on the existing literature, the researcher will sort out the path of the impact of digital economy on carbon emissions in this paper. Secondly, the researcher will focus on carbon emission intensity, which is the target index of reaching carbon peak; the time-lag term of carbon emission intensity will be incorporated into the empirical model to establish a dynamic spatial panel model. Thirdly, the researcher will establish a threshold regression model to study whether the impact of the digital economy on carbon emission intensity will change under different levels of scientific and technological innovation and environmental regulation and to study the threshold effect of digital economy decomposition indicators, respectively.

2 THEORETICAL ANALYSIS AND RESEARCH HYPOTHESES

The impact mechanism of the digital economy on carbon emission reduction can be summarized in five ways. The first is the effect on industrial structure optimization. Digital inclusion can drive the digital transformation of traditional enterprises, and the continuous penetration of digital technology can eliminate information asymmetry among enterprises. The emergence of data, a new factor of production, can reduce the excessive dependence of enterprises on resources (Ren et al., 2021), optimize the allocation of resources, weaken the boundaries of economic activities (Eapen, 2012), and promote transformation of enterprises to green and low-energy consumption. The second is the effect on technological innovation (Weina et al., 2016). The application of digital technologies such as cloud computing reshapes enterprise production, management, and sale, and further allocates the use of resources, such as to plan pollution treatment strategies through digitization to build a new platform for safe, green, low-carbon resource utilization. The third way is the effect on resource utilization. Digital economy can improve total factor productivity (Diaz-Ramos et al., 2019; Pan et al., 2022), minimize loss of energy allocation, and gradually drive consumers to develop digital habits such as using a paperless office, attending online conferences, and reading e-books (Bai, 2021). Big data and other digital technologies can provide personalized service experiences and optimization schemes intelligently by collecting exclusive energy consumption habits of enterprises and individual users. The fourth is the effect on international competitiveness. Digital technology can solve problems in the process of exporting original products, such as complicated procedures and long customs clearance times, which improves the efficiency and success rate of commodity trading and reshapes the international industrial chain and regional trade model (Li et al., 2020). The fifth is the intelligent effect of supervision platforms. The establishment of carbon emission trading markets is inseparable from the application of digital technology, which has curbed the carbon emission violations of a small number of enterprises. Intelligent carbon emission supervision platforms realize the power of energy-saving planning in advance, real-time supervision in the process, and prevention management after the event. Enterprises can reduce the information asymmetry of pollution behavior in supervision by realizing accurate and efficient management of carbon emissions.

Hypothesis 1: The digital economy can reduce the intensity of regional carbon emissions.

Judging from the current development of China's digital economy, there has been unbalanced development in both the manufacturing industry and the intelligence industry. Most enterprises have stagnated in the "internet +" stage and have not stepped into the "artificial intelligence" field. Because carbon emission is the unexpected output from enterprises' economic activities, the production activities of enterprises located in different spaces are bound to be affected by the overall local technical level. Digital technology can help enterprises realize real-time tracking of supply chains (Centobelli et al., 2020), simplify production processes, and improve supply chain efficiency by using cloud technology and carry out dynamic monitoring and early warning of pollutant emission at the same time. Use of digital technology will fundamentally change the production and life efficiency of enterprises (Ranta et al., 2021). Some enterprises in high-tech areas will use digital technology more actively to maximize expected output and minimize carbon emissions. In addition, the popularity of digital facilities affects consumers' consumption behavior. Consumers in areas with adequate digital support facilities will have a variety of digital consumption choices. In the long run, digital consumption choices will have a positive impact on regional carbon emission reduction. Judging from the current development of China's digital economy, there is a trend of deep digitization in the eastern region and sluggish digitization in the western region. Therefore, the digital technologies that enterprises can master vary among different regions, which may lead to the heterogeneity of the impact of digital economy on carbon emission intensity.

Hypothesis 2: There may be regional heterogeneity in the impact of the digital economy on carbon emission intensity.

5G and other digital technologies have set off a huge wave of change in the intelligence, manufacturing, and service industries, with infinite scalability (Attaran, 2021). As a highly permeable and leading economic form, it can enable all links of enterprise production comprehensively and boost the transformation of energy structure (Lyu and Liu, 2021). Digital technology needs to cooperate with digital infrastructure and digital talent to make full use of its advantages. Therefore, in the early stages of the development of the digital economy, if digital support facilities in a region are not complete, the system construction will be outdated, the technical tools will not be fully mastered by firms, and the cumulative effect of the digital economy may be hidden. In addition, environmental regulations are an important factor that affect the green development of enterprises (Meng et al., 2020), like the renewable energy structure affect enterprises (Polzin et al., 2015). Appropriate environmental regulations can establish comparative advantages for green enterprises, whereas regulations that are too strict will be a heavy burden to enterprises. Low-carbon technology can play a role in emission reduction only when environmental regulation reaches a certain level. In areas with stricter environmental regulations, enterprises are more inclined to choose green processing technology to achieve emission reduction. Digital technology is favored by enterprises because of its low cost, high return and replicable characteristics.

Hypothesis 3: The threshold effect of scientific and technological innovation and environmental regulation may exist in the impact of the digital economy on carbon emission intensity.

3 VARIABLE SELECTION AND MODEL CONSTRUCTION

3.1 Variable Selection

Due to the lack of data in Tibet, Hong Kong, Macao and Taiwan, this paper uses the data of 30 provinces in China as research sample. The data comes from China energy statistical yearbook, China Statistical Yearbook, China Science and technology statistical yearbook and statistical yearbooks of provinces and cities.

Carbon emission intensity (TCO2) is the explained variable, which measures the amount of carbon dioxide consumed per unit of GDP. Eight kinds of main consumption energy are selected, we refer to IPCC to calculate carbon emission as follows:

$$CO_2 = \sum_{i=1}^{8} CO_{2,i} = \sum_{i=1}^{8} E_i \times NCV_i \times CEF_i \times COF_i \times \frac{44}{12} \quad (1)$$

The level of digital economy (DGC) is the core explanatory variable. Based on the measurement standard introduced by Li et al. (2021), this paper constructs the measurement of digital economy index, determines the weight of each index through entropy weight method, and calculates the digital economy index.

The threshold variables are scientific and technological innovation (IN) and environmental regulation (ER). Scientific and technological innovation (IN) is measured by the proportion of scientific and technological expenditure in local financial expenditure, while environmental regulation (ER) is measured by the ratio of industrial pollution investment to GDP.

In this paper, the control variables are: Industrial structure (ISU), which is measured by the ratio of the added value of the tertiary industry to the added value of the secondary industry. Economic development level (PGDP) is measured by the ratio of regional GDP to resident population at the end of the year. Foreign direct investment (FDI) is measured by the total investment of foreign-invested enterprises. Income of residents (INCOME) is measured by per capita disposable income of residents. Government expenditure (EXP) is measured by the ratio of regional general public service expenditure to public budget expenditure. Energy consumption is measured by total regional energy consumption. Green coverage rate (GREEN) is measured by the green coverage rate of built-up areas. In order to alleviate the influence of heteroscedasticity, control variables are all logarithmicized.

3.2 Model Establishment

Based on the STIRPAT model of population, economy and Technology (York et al., 2002), this paper establishes the basic model formula (2) to verify hypothesis 1, in which i and t represent specific cities and years, respectively. $tco2_{it}$ represent carbon emission intensity, DGC_{it} measure the level of digital economy, X_{it} expressed as control variables, μ_i and φ_t expressed as individual and time fixed effects respectively, and ε_{it} expressed as random disturbance terms.

$$tco2_{it} = \beta_0 + \beta_1 DGC_{it} + \Sigma\beta_c X_{it} + \mu_i + \varphi_t + \varepsilon_{it} \quad (2)$$

The first-order carbon emission intensity ($L.tco2_{it}$) is added as the explanatory variable, and establish the dynamic panel model formula (2) of the time lag term of carbon emission intensity:

$$tco2_{it} = \gamma_0 + \gamma_1 DGC_{it} + \gamma_2 L.\,tco2_{it} + \Sigma\gamma_c X_{it} + \mu_i + \varphi_t + \varepsilon_{it} \quad (3)$$

3.2.1 Dynamic Panel Space Measurement Model

Considering that carbon emissions may have spillover effect, this paper uses anti geographic matrix to construct spatial econometric model. Before model construction, Moran's I index, LM test and LR test shall be calculated. Firstly, the Moran's I index of carbon emission intensity of each year is calculated. From the results in **Supplementary Appendix Table S2**, it can be seen that the Moran's I value of each year from 2013 to 2019 is significantly positive, which represents the aggregation of regions with similar carbon emission intensity, but this impact shows a gradual decreasing trend. Secondly, the LM Test is conducted to determine the types of spatial econometric models. The *p*-value in LM SEM test and robust LM SEM test are all greater than 0.10, which means, it is considered that the spatial error term does not exist. And the *p*-value in LM SAR test and robust LM SAR test is less than 0.10. Therefore, it is considered that the spatial autoregressive (SAR) model should be established. After LR test, the results in rows 8-9 of **Supplementary Appendix Table S3** show that SDM model can be degraded into SEM or SAR model. Combined with LM test results, this paper believes that the SAR model is more robust. Lastly, combined with the results of Hausman test and LR test of fixed effect, this paper adopts the spatial autoregressive model of individual fixed effect (4):

$$tco2_{it} = \alpha_0 + \rho W tco2_{it} + \alpha_1 DGC_{it} + \alpha_2 L.tco2_{it} + \Sigma\alpha_c X_{it} + \mu_i + \varepsilon_{it} \quad (4)$$

ρ is the spatial coefficient, W is the spatial weight matrix, α_2 is the lag term coefficient of carbon emission intensity, and the interpretation of other variables is the same as that of the benchmark model (2).

3.2.2 Dynamic Panel Threshold Model

Before establishing the threshold model, we test whether there is a threshold effect on the impact of digital economy on carbon emissions first. Then, we set the threshold variable as scientific and technological innovation (IN) and environmental regulation (ER), and conduct self-sampling for 300 times. The results are shown in **Supplementary Appendix Table S4**. When scientific and technological innovation is used as the threshold variable, the digital economy index and decomposition index have significantly passed the first threshold test. At the same time, when environmental regulation is used as the threshold variable, the digital economy index and decomposition index also significantly pass the double threshold test. γ_1 and γ_2 are first threshold of innovation and first threshold of environmental regulation, while ζ_1 and ξ_1 are the lag coefficient of carbon emission intensity. Therefore, dynamic threshold models (10) 11) are established:

$$\begin{aligned} tco2_{it} &= \zeta_0 + \theta_1 DGC_{it}(IN < \gamma_1) + \theta_2 DGC_{it}(IN \geq \gamma_1) \\ &\quad + \zeta_1 L.tco2_{it} + \Sigma\zeta_c X_{it} + \varepsilon_{it} \end{aligned} \quad (5)$$

$$\begin{aligned} tco2_{it} &= \xi_0 + \lambda_1 DGC_{it}(ER < \gamma_2) + \lambda_2 DGC_{it}(ER \geq \gamma_2) \\ &\quad + \xi_1 L.tco2_{it}\Sigma\xi_c X_{it} + \varepsilon_{it} \end{aligned} \quad (6)$$

4 EMPIRICAL ANALYSIS

4.1 Distribution of Carbon Emission Intensity and Digital Economy Index in 2013 and 2019

Figures 1, **2** draw the distribution map of carbon emission intensity of provinces and cities in 2013 and 2019 through

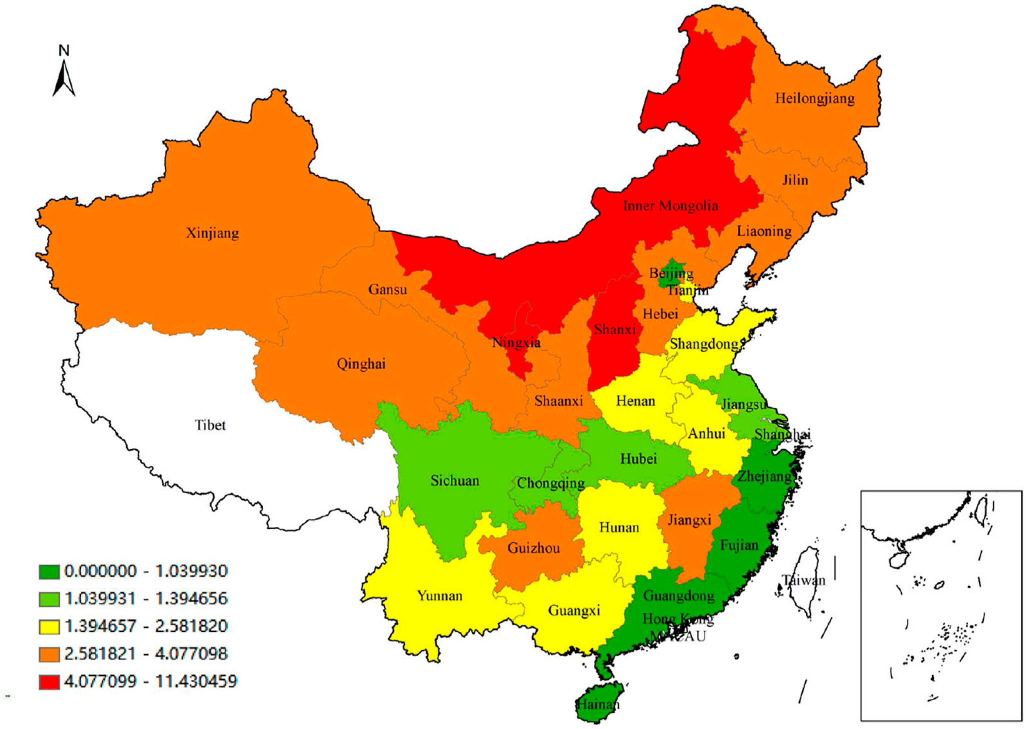

FIGURE 1 | Distribution map of carbon emission intensity in 2013.

ArcGIS 10.7, and **Figures 3**, **4** draw the distribution map of digital economy index of provinces and cities in 2013 and 2019, respectively. Horizontally, the carbon emission intensity of Qinghai, Guizhou, Henan and other places has decreased significantly, while Guangdong, Zhejiang, Fujian and other places have always maintained a low level of carbon emission intensity, but the carbon emission intensity of Inner Mongolia and Shanxi is still high. However, from the original data, the carbon emission intensity of these two places has decreased. It can be said that the overall carbon emission intensity across China has a significant downward trend. At the same time, **Figure 1** and **Figure 2** have a certain difference in carbon emission intensity between the north and the south, which may be due to the fact that the north still adopts the heating method of burning coal, and the fossil energy consumed has caused higher carbon emissions. In terms of digital economy index, Beijing has always been in the first echelon of digital economy development. Sichuan, Guangdong, Zhejiang and other places have strong digital economy strength, and the digital economy level of other provinces and cities has been improved. This is inseparable from the Chinese government's attention to the development of digital economy, the great breakthrough of digital technology and the improvement of digital infrastructure in recent years. From the perspective of regional heterogeneity, the level of digital economy shows an upward trend from the West to the East. The development of digital economy in the western region is generally deficient, the development of digital economy in the central region is average, and the level of digital economy in the eastern region is ahead the other regions.

From the vertical perspective, the carbon emission intensity of Beijing, Zhejiang, Guangdong, Jiangsu and other places with high digital economy level in 2013 is low, and that of Xinjiang, Qinghai, Heilongjiang, Gansu and other areas with poor digital economy development is high. In 2019, the carbon emission intensity of Sichuan, Jiangsu, Tianjin, Henan and other places with rapid development of digital economy decreased significantly, and the further development of digital economy in Qinghai, Liaoning, Shaanxi and other places also reduced the carbon emission intensity.

4.2 Benchmark Regression

Model (1) in **Supplementary Appendix Table S5** is the benchmark regression result. From a national perspective, the digital economy significantly inhibits the carbon emission intensity. Specifically, for every unit of digital economy development, the carbon emission intensity decreases by 27.15 units. This conclusion verifies *hypothesis 1*. Digital economy has penetrated into various regions at a lower cost. The application of digital technology can improve the production efficiency and resource utilization of enterprises. The rational allocation of resources can help regional carbon emission reduction by coordinating and balancing the energy structure. In terms of control variables, under the 1% confidence level the upgrading of industrial structure and energy consumption have increased the carbon emission intensity. The flow of industrial structure towards rationalization and upgrading can adjust the energy structure, but the carbon emission released in its

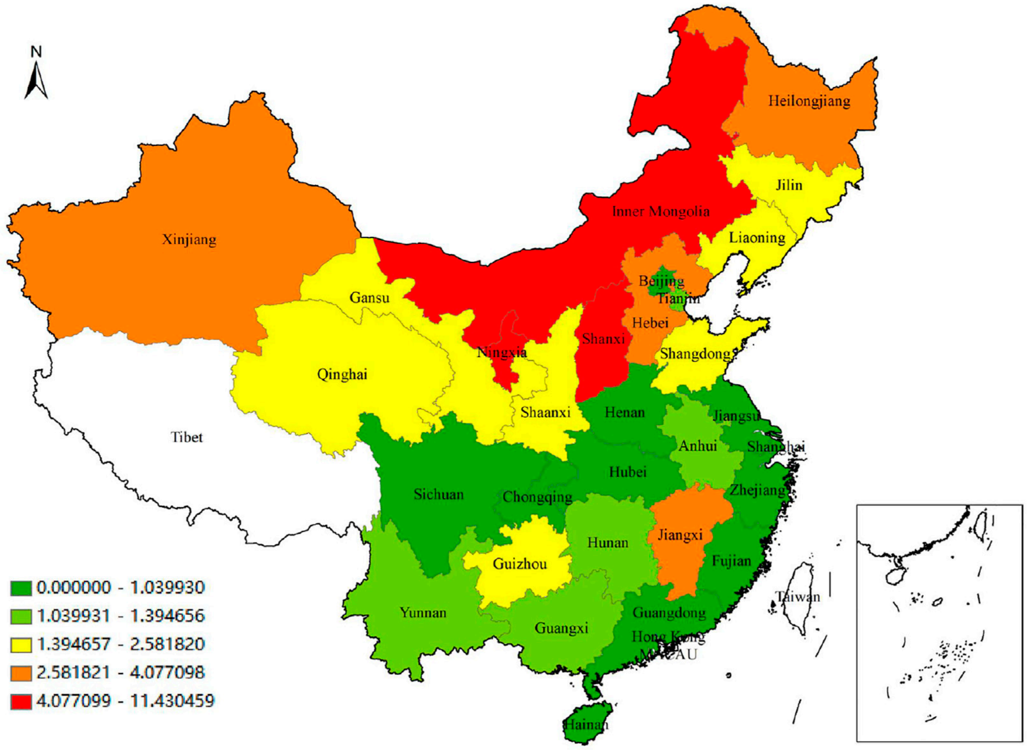

FIGURE 2 | Distribution map of carbon emission intensity in 2019.

transformation and upgrading is more than that of emission reduction. Therefore, to a certain extent, the upgrading of industrial structure interferes with carbon emission reduction. In addition, China is still in the stage of massive consumption of fossil energy, with fossil energy consumption exceeding 80%. The problem of carbon emission caused by the combustion of non-renewable energy has not been completely solved, which has restricted the realization of peaking carbon dioxide emissions and achieving carbon neutrality. At the same time, the level of economic development, residents' income and governmental investment have significantly reduced the intensity of carbon emissions. In areas with high level of economic development and residents' income, residents will have a strong desire to pursue green life and put the concept of green life into action and generally adopt an environmentally friendly lifestyle, which is more conducive to regional carbon emission reduction. Government investment provides a strong backing for the completion and application of infrastructure such as digitization. At the same time, regional governments put forward targeted carbon emission reduction suggestions, encourage and support more enterprises and residents to join the team of carbon emission reduction, accelerate the transformation of enterprises to the direction of low energy consumption and high efficiency, and provide conditions for carbon emission reduction.

Models (2)–(4) in **Supplementary Appendix Table S5** are the heterogeneity test of the impact of digital economy. The impact coefficient of digital economy on carbon emission reduction in the eastern region is −11.1239, while the absolute value of the impact coefficient of digital economy in the central region is the largest. Compared with the eastern region benefiting from digital economy for a long time, the development of digital economy in the central region is in the stage of rapid development. The application of digital technology, an emerging technology, provides cleaner and greener production technology for the industrially developed the central region and helps enterprises optimize production, operation, and sales processes. Therefore, compared with other regions, this influence coefficient is the largest. The impact coefficient of the western region failed to pass the significance test. Although the development of digital economy in the western region has improved to a certain extent from **Figure 3** and **Figure 4**, the level of digital economy in the western region is still poor from the original data. At the same time, the market development level is limited, and the emission reduction effect of digital empowerment cannot be maximized, which may cause the situation that the emission reduction effect is offset by the resources consumed by the application of digital technology. Therefore, the role of digital economy in emission reduction in the western region is not significant.

4.3 Dynamic Panel Model

The first-order lag term of carbon emission intensity ($L.tco2_{it}$) is added to the model (1) in **Supplementary Appendix Table S6**, and the lag term is significantly positive. The carbon emission

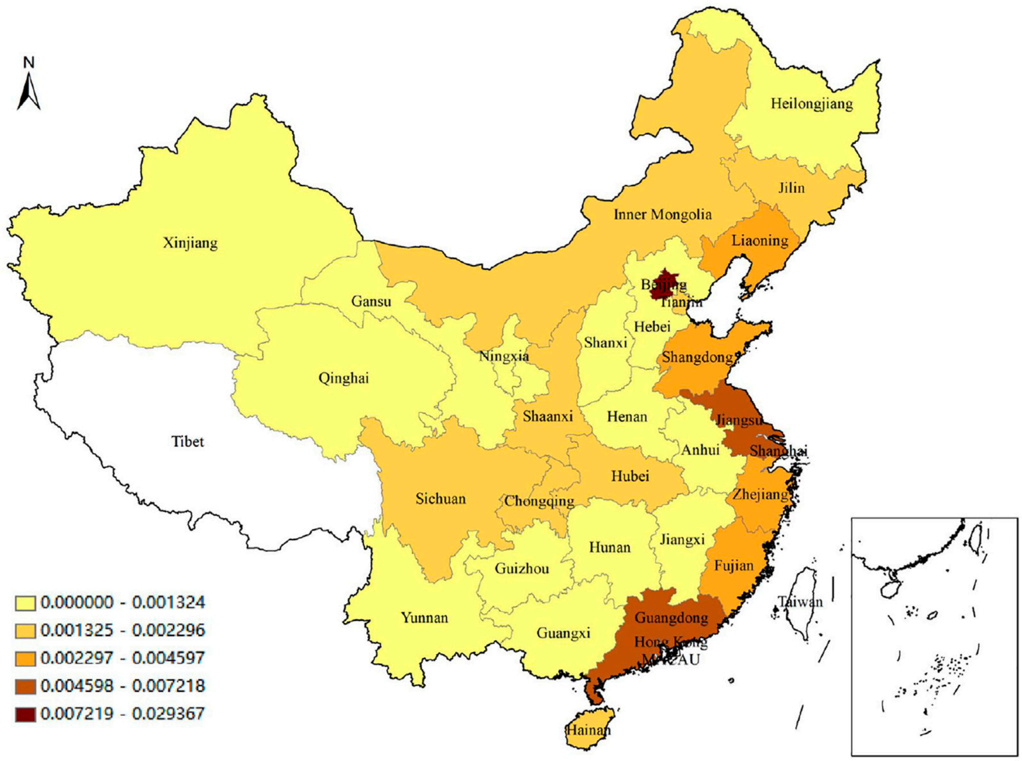

FIGURE 3 | Distribution map of digital economy index in 2013.

intensity has time lag, that means the carbon emission intensity will improve its own carbon emission in the next period. The core explanatory variable digital economy is significantly negative, which is consistent with the conclusions in **Supplementary Appendix Table S5**. In models (2)–(4) in **Supplementary Appendix Table S6**, the three decomposition indicators of the digital economy index are taken as explanatory variables, and they all significantly inhibit carbon emissions, indicating that the digital economy can contribute to carbon emission reduction through three directions: digital infrastructure, digital inclusive and digital transaction. In models (2)–(4), the lag term of carbon emission intensity is significant under 1% confidence, and the three decomposition indexes are significant under 5% confidence. In terms of the control variables, the transformation of industrial structure and energy consumption still improve the intensity of regional carbon emissions, and the improvement of economic development level and residents' income has a significant inhibitory effect on carbon emissions. On the impact of the level of digital infrastructure on carbon emission intensity, the government investment is significantly negative. The government's capital investment is conducive to the construction of digital platform and provides financial support for the improvement of digital infrastructure, which can help the digital economy display its advantages and is beneficial to carbon emission reduction. In the impact of digital trading level on carbon emission intensity, the increase of residents' income can significantly reduce carbon emissions.

4.4 Dynamic SAR Model

Supplementary Appendix Table S7 shows the results of spatial autoregressive model. The coefficient rho is significantly positive, indicating that the regions close to each other will affect the local carbon emission intensity, which is not conducive to the local carbon emission reduction. The coefficient of digital economy is −11.4161, and the time lag term is significantly positive. In terms of control variables, industrial structure and energy consumption are significantly positive, and economic level and residents' income are significantly negative, which is also consistent with the results of benchmark regression. Columns 3–5 of **Supplementary Appendix Table S7** decompose the spatial effects. From the results, digital economy, time lag term of carbon emission intensity, industrial structure, economic level, resident's income and energy consumption have significant direct and indirect effects on carbon emission intensity, and the direct effects are greater than the indirect effects.

4.5 Dynamic Panel Threshold Model

The threshold regression results of scientific and technological innovation as threshold variables are shown

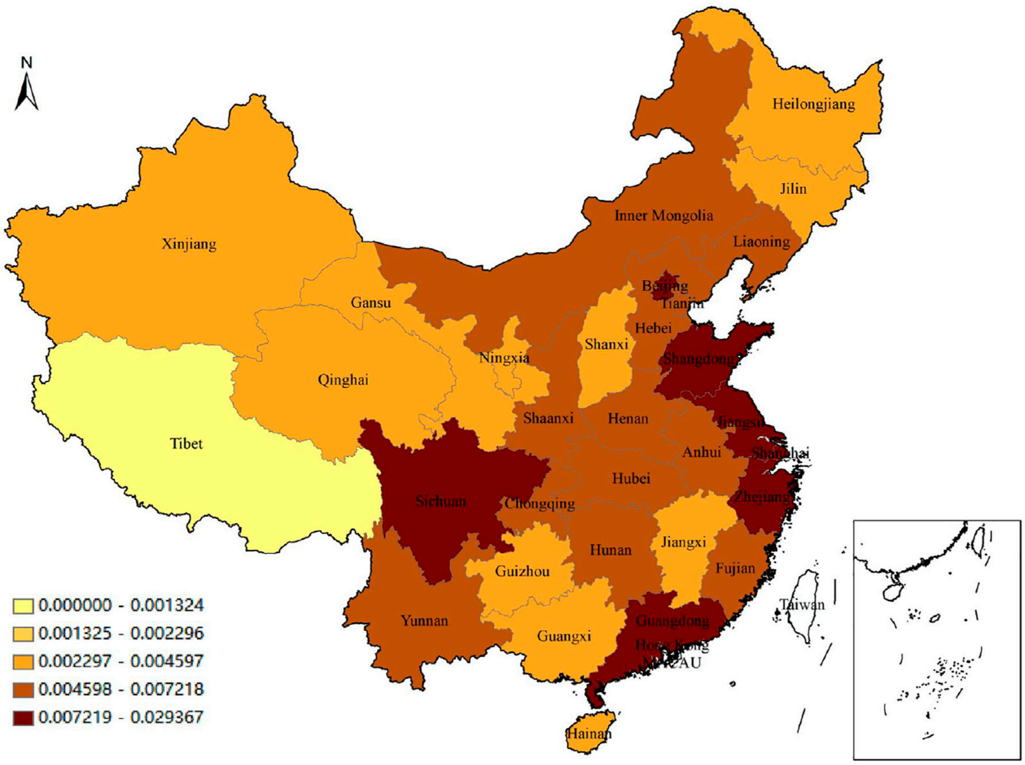

FIGURE 4 | Distribution map of digital economy index in 2019.

in **Supplementary Appendix Table S8** models (1)–(4). When scientific and technological innovation is lower than 0.0120, the digital economy index is not significant. While scientific and technological innovation is higher than 0.0120, the digital economy coefficient is −12.5949, indicating that for each unit of digital economy, the carbon emission intensity will be reduced by 12.5949 units. From the perspective of decomposition indicators, the digital infrastructure coefficient is significantly −28.1199 when the scientific and technological innovation is greater than 0.0120, and the digital transaction coefficient is significantly −20.5690 when the scientific and technological innovation is greater than 0.0120. The digital inclusive coefficient is not significant before and after threshold IN. From the specific value, the provinces with scientific and technological innovation less than 0.0120 are mainly distributed in western regions such as Qinghai and Gansu. The scientific and technological level is limited, which restricts the role of digital economy. It is urgent for these regions to actively introduce scientific and technological means from other regions to promote the matching of regional scientific and technological level with digital economy, so as to use digital advantages fully.

The threshold regression results of environmental regulation as a threshold variable are shown in **Supplementary Appendix Table S8** models (5)–(8). When the environmental regulation is lower than 0.0115, the digital economy coefficient is significantly −12.2024. When the environmental regulation is higher than 0.0115, the digital economy is significantly −23.4579. The bias effect before and after the threshold value has increased. More stringent environmental regulation policies need to cooperate with green production methods to achieve the purpose of environmental protection, and the digital economy meets this requirement well. Under the relevant regulatory policies of the government, the digital economy leverages its own advantages and uses technologies such as Big Data and Blockchain to achieve high utilization of enterprise resources, save the cost of management and sales, escort the building of smart enterprises, and then contribute to regional carbon emission reduction. From the perspective of decomposition indicators, the partial effects of digital infrastructure and digital transactions before and after the threshold have increased and have always been significant. For digital inclusive level, the coefficient is significantly −5.3119 after crossing the environmental regulation threshold of 0.0115. After enterprises are burdened with more stringent environmental regulation policies, they either actively or passively choose digital technology and use digital platforms to realize business processes such as negotiation and transaction. Office workers are used to digital office imperceptibly, realizing a virtuous cycle of emission reduction. However, it is worth noting that the threshold value in model (8) is 0.0133, which is greater than the threshold value in models (5)–(7), indicating that digital transactions can play a full role only under higher-level environmental regulation measures.

5 DISCUSSION

5.1 Theoretical Significance

Starting from the background of the carbon peak and carbon neutralization goals, and based on the samples of 30 provincial panel data from 2013 to 2019, this paper focuses on exploring the theoretical mechanism of digital economy, a new way of carbon emission reduction. Overall, previous studies paid less attention to the relationship between digital economy and carbon emissions. Most of the existing literature focused on the current situation and impact of digital economy (Chen et al., 2022; Xue et al., 2022) and the driving factors of carbon emissions. In the past two years, a few pieces of literature have begun to study the carbon emission reduction effect of digital economy (Ma et al., 2022). However, it is worth noting that the existing research focuses on the intermediary effect and spatial effect. Based on existing literature, this paper not only measures the spatial effect of carbon emissions, but also focuses on the regional heterogeneity and threshold effect of the impact of digital economy on carbon emissions.

5.2 Practical Significance

First of all, China should continue to improve the construction of digital infrastructure and create a green production and living system. China should accelerate the construction of 5G base stations comprehensively, promote the carbon emission monitoring platform nationwide, and realize the "cloud prevention and control" of carbon emission through intelligent means such as UAV patrol. China should publicize the concept of green consumption by using digital platform, customize personalized green services by using VR and Big Data technology, improve customers' green service experience and build a green smart city. Secondly, enterprises should continue to promote the reform and innovation of digital technology and achieve breakthroughs in low-carbon technology and new energy technology. Enterprises should take the initiative to carry out digital technology reform. At present, enterprises have obtained the ability to use the Internet for production and marketing activities; however, very few enterprises can use artificial intelligence such as Machine Learning to realize product production and marketing analysis. Besides, enterprises should continue to explore carbon emission reduction technologies, formulate carbon sequestration measures according to local conditions through data analysis, and use 3S technology to find renewable energy that can replace fossil energy, so as to curb carbon emissions from the source of energy utilization. Thirdly, based on regional heterogeneity, the government reasonably formulates relevant policies and exerts to the government's regulatory role through a series of policy combinations (Rogge and Schleich, 2018). The government should use digital technology to accurately identify and actively help high pollution enterprises. In addition, the government can take the lead in introducing experts and scholars to carry out seminars and courses on digital emission reduction technology, so as to promote the implementation of digital technology in the production process of enterprises. The government should formulate targeted emission reduction targets and policies. While monitoring carbon emissions in real-time, the government should take the initiative to coordinate carbon emission transactions between enterprises that have excess emission and enterprises that fail to meet the quota, so as to achieve the overall carbon emission standard of enterprises.

5.3 Limitations and Future Research Directions

This study has some potential limitations. Firstly, this paper is based on China's provincial panel data and we acknowledge that there are some limitations in sample size. And this study may ignore the reduction effect of the digital economy carbon emission in prefecture-level cities and even county-level cities. Future research should pay more attention to the data of prefecture level cities and county-level cities.

Secondly, the progress of the digital economy in various countries is different. Therefore, it is difficult to generalize the carbon emission reduction effect of the digital economy. Thus, scholars should focus on survey data under different regions and aim to broaden regional coverage in the future research.

Lastly, there is no unified standard to measure the level of digital economy from the current literature. In future research, scholars can focus on formulating recognized measurement standards to accurately describe the development of digital economy.

6 CONCLUSION

Firstly, the overall carbon emission reduction across the country has continued to improve in recent years. There may be a north-south difference in carbon emission intensity due to the fact that the north still uses coal-burning heating. In terms of the digital economy, the digital economy level of all provinces in China has steadily improved by 2019, and the digital economy level from west to east in China has gradually increased. Secondly, the digital economy has a significant inhibitory effect on the carbon emission intensity. The improvement of residents' income, governmental investment, and economic development can reduce the regional carbon emission intensity. Given the regional heterogeneity, digital economy can play a more critical role in reducing carbon emission in the middle and eastern regions. Thirdly, after adding the time lag term of carbon emission intensity, the impact coefficient of the digital economy is still significant. At the same time, the decomposition items of the digital economy: digital infrastructure level, digital inclusive level, and digital transaction level are all conducive to carbon emission reduction. Fourthly, carbon emission intensity has an obvious spatial effect. Carbon emission in adjacent areas will significantly inhibit local carbon emission reduction activities, and the digital economy and control variables such as industrial structure mainly affect carbon emission through direct effect. Lastly, under the threshold of scientific and technological innovation and environmental regulation, the impact of digital economy on emission reduction is different. For regions with low levels of scientific and technological development, it is challenging for the digital economy to utilize its emission reduction advantages, and stricter environmental regulations can cooperate with the digital economy to reduce regional carbon emission.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

RW: Conceptualization, methodology, software, writing—original draft preparation; XH: Validation, formal analysis, investigation, resources, funding acquisition, supervision; LP: Data curation, writing—review and editing; visuali-zation. YL: Writing—original draft preparation, data collection; YY: Writing—review and editing, data curation. All authors have read and agreed to the published version of the manuscript.

FUNDING

This research is supported by Tianjin Philosophy and Social Science Planning Project (TJYJ20-010). The APC was funded by XH.

ACKNOWLEDGMENTS

XH acknowledges the financial support from Tianjin Philosophy and Social Science Planning Project (Project NO.TJYJ20-010) and Key Decision-Making Consulting Project of Tianjin Association for Science and Technology (Project No. TJSKXJCZX201904).

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2022.943177/full#supplementary-material

REFERENCES

Ablyazov, T., and Asaul, V. (2021). Development of the Arctic Transport Infrastructure in the Digital Economy. *Transp. Res. Procedia* 57, 1–8. doi:10.1016/j.trpro.2021.09.018

Amankwah-Amoah, J., Khan, Z., Wood, G., and Knight, G. (2021). Covid-19 and Digitalization: The Great Acceleration. *J. Bus. Res.* 136 (Nov 2021), 602–611. doi:10.1016/j.jbusres.2021.08.011

Attaran, M. (2021). The Impact of 5g on the Evolution of Intelligent Automation and Industry Digitization. *J. Ambient. Intell. Hum. Comput.* 1–17. doi:10.1007/s12652-020-02521-x

Autio, E. (2017). Strategic Entrepreneurial Internationalization: A Normative Framework. *Strat. Entrepreneursh. J.* 11, 211–227. doi:10.1002/sej.1261

Bai, H. (2021). Role of Digital Technology in Transforming Organizational Competencies Influencing Green Economy: Moderating Role of Product Knowledge HidingOriginal Research. *Front. Psychol.* 12, 792550. doi:10.3389/fpsyg.2021.792550

Centobelli, P., Cerchione, R., Chiaroni, D., Del Vecchio, P., and Urbinati, A. " (2020). Designing Business Models in Circular Economy: A Systematic Literature Review and Research Agenda." *Bus. Strat. Env.* 29(4) 1734–1749. doi:10.1002/bse.2466

Chen, X., Teng, L., and Chen, W. (2022). How Does Fintech Affect the Development of the Digital Economy? Evidence from China. *North Am. J. Econ. Finance* 61, 101697. doi:10.1016/j.najef.2022.101697

Diaz-Ramos, A., Eilbert, W., and Marquez, D. (2019). Euglycemic Diabetic Ketoacidosis Associated with Sodium-Glucose Cotransporter-2 Inhibitor Use: A Case Report and Review of the Literature. *Int. J. Emerg. Med.* 1227, 240. doi:10.1186/s12245-019-0240-0

Eapen, A. (2012). Social Structure and Technology Spillovers from Foreign to Domestic Firms. *J. Int. Bus. Stud.* 43 (3), 244–263. doi:10.1057/jibs.2012.210.1057/jibs.2012.2

Hosan, S., Karmaker, S. C., Rahman, M. M., Chapman, A. J., and Saha, B. B. (2022). Dynamic Links Among the Demographic Dividend, Digitalization, Energy Intensity and Sustainable Economic Growth: Empirical Evidence from Emerging Economies." *J. Clean. Prod.* 330. 129858. doi:10.1016/j.jclepro.2021.129858

Irfan, M., Zhao, Z.-Y., Rehman, A., Ozturk, I., and Li, H. (2021). Consumers' Intention-Based Influence Factors of Renewable Energy Adoption in Pakistan: a Structural Equation Modeling Approach. *Environ. Sci. Pollut. Res.* 28, 432–44545. doi:10.1007/s11356-020-10504-w

Kivimaa, P., Laakso, S., Lonkila, A., and Kaljonen, M. (2021). Moving beyond Disruptive Innovation: A Review of Disruption in Sustainability Transitions. *Environ. Innovation Soc. Transitions* 38 (2021), 110–126. doi:10.1016/j.eist.2020.12.001

Kristoffersen, E., Blomsma, F., Mikalef, P., and Li, J. (2020). The Smart Circular Economy: A Digital-Enabled Circular Strategies Framework for Manufacturing Companies. *J. Bus. Res.* 120, 241–261. doi:10.1016/j.jbusres.2020.07.044

Li, K., Kim, D. J., Lang, K. R., Kauffman, R. J., and Naldi, M. (2020). How Should We Understand the Digital Economy in Asia? Critical Assessment and Research Agenda." *Electron. Commer. Res. Appl.* 44, 101004. doi:10.1016/j.elerap.2020.101004

Li, Y., Yang, X., Ran, Q., Wu, H., Irfan, M., and Ahmad, M. (2021). Energy Structure, Digital Economy, and Carbon Emissions: Evidence from China. *Environ. Sci. Pollut. Res.* 28 (45), 64606–64629. doi:10.1007/s11356-021-15304-410.1007/s11356-021-15304-4

Li, Z., and Wang, J. (2022). The Dynamic Impact of Digital Economy on Carbon Emission Reduction: Evidence City-Level Empirical Data in China. *J. Clean. Prod.* 351, 131570. doi:10.1016/j.jclepro.2022.131570

Liu, J., Tian, J., Lyu, W., and Yu, Y. (2022). The Impact of Covid-19 on Reducing Carbon Emissions: From the Angle of International Student Mobility. *Appl. Energy* 317 119136. doi:10.1016/j.apenergy.2022.119136

Liu, W., Xu, Y., Fan, D., Li, Y., Shao, X.-F., and Zheng, J. (2021). Alleviating Corporate Environmental Pollution Threats toward Public Health and Safety: The Role of Smart City and Artificial Intelligence. *Saf. Sci.* 143 (11/01 2021), 105433. doi:10.1016/j.ssci.2021.105433

Lyu, W., and Liu, J. (2021). "Artificial Intelligence and Emerging Digital Technologies in the Energy Sector." *Appl. Energy* 303, 117615. doi:10.1016/j.apenergy.2021.117615

Ma, Q., Tariq, M., Mahmood, H., and Khan, Z. (2022). "The Nexus between Digital Economy and Carbon Dioxide Emissions in China: The Moderating Role of Investments in Research and Development, *Technol. Soc.* 68, 101910. doi:10.1016/j.techsoc.2022.101910

Meng, F., Xu, Y., and Zhao, G. (2020). Environmental Regulations, Green Innovation and Intelligent Upgrading of Manufacturing Enterprises: Evidence from China. *Sci. Rep.* 10, 114485. doi:10.1038/s41598-020-71423-x

Nikolopoulos, K., Punia, S., Schäfers, A., Tsinopoulos, C., and Vasilakis, C. (2021). Forecasting and Planning during a Pandemic: Covid-19 Growth Rates, Supply Chain Disruptions, and Governmental Decisions. *Eur. J. Operational Res.* 290 99–115. doi:10.1016/j.ejor.2020.08.001

Pan, W., Xie, T., Wang, Z., and Ma, L. (2022). "Digital Economy: An Innovation Driver for Total Factor Productivity." *J. Bus. Res.* 139. 303–311. doi:10.1016/j.jbusres.2021.09.061

Polzin, F., Migendt, M., Täube, F. A., and von Flotow, P. (2015). Public Policy Influence on Renewable Energy Investments-A Panel Data Study across OECD Countries." *Energy Policy* 80. 98–111. doi:10.1016/j.enpol.2015.01.026

Pouri, M. J., and Hilty, L. M. (2021). The Digital Sharing Economy: A Confluence of Technical and Social Sharing. *Environ. Innovation Soc. Transitions* 38 (2021), 127–139. doi:10.1016/j.eist.2020.12.003

Ranta, V., Aarikka-Stenroos, L., Väisänen, J.-M., and Juha-Matti, V. (2021). Digital Technologies Catalyzing Business Model Innovation for Circular Economy-Multiple Case Study. *Resour. Conservation Recycl.* 164, 105155. doi:10.1016/j.resconrec.2020.105155

Ren, S., Hao, Y., Xu, L., Wu, H., and Ba, N. (2021). "Digitalization and Energy: How Does Internet Development Affect China's Energy Consumption?". *Energy Econ.* 98. 105220. doi:10.1016/j.eneco.2021.105220

Richardson, L. (2020). "Digital and Platform Economies," in *International Encyclopedia of Human Geography*. Editor A. Kobayashi. Second Edition (Oxford: Elsevier), 317–321. doi:10.1016/b978-0-08-102295-5.10533-5

Rogge, K. S., and Schleich, J. (2018). "Do Policy Mix Characteristics Matter for Low-Carbon Innovation? A Survey-Based Exploration of Renewable Power Generation Technologies in Germany." *Res. Policy* 47, 1639. doi:10.1016/j.respol.2018.05.011

Shao, X., Zhong, Y., Li, Y., and au, M. (2021). "Does Environmental and Renewable Energy R&D Help to Achieve Carbon Neutrality Target? A Case of the Us Economy." *J. Environ. Manag.* 296. 113229. doi:10.1016/j.jenvman.2021.113229

Smith, C., Smith, J. B., and Shaw, E. (2017). Embracing Digital Networks: Entrepreneurs' Social Capital Online. *J. Bus. Ventur.* 32 (1), 18–34. doi:10.1016/j.jbusvent.2016.10.003

Sutherland, W., and Jarrahi, M. H. (2018). The Sharing Economy and Digital Platforms: A Review and Research Agenda. *Int. J. Inf. Manag.* 43, 328–341. doi:10.1016/j.ijinfomgt.2018.07.004

Uçar, E., Dain, M.-A. L., and Joly, I. (2020). Digital Technologies in Circular Economy Transition: Evidence from Case Studies. *Procedia CIRP* 90, 133–136. doi:10.1016/j.procir.2020.01.058

Von Briel, F., Davidsson, P., and Recker, J. (2018). Digital Technologies as External Enablers of New Venture Creation in the IT Hardware Sector. *Entrepreneursh. Theory Pract.* 42 (01/01 2018), 47–69. doi:10.1177/1042258717732779

Wang, J., Dong, X., and Dong, K. (2022a). How Digital Industries Affect China's Carbon Emissions? Analysis of the Direct and Indirect Structural Effects. *Technol. Soc.* 68, 101911. doi:10.1016/j.techsoc.2022.101911

Wang, L., Luo, G.-l., Sari, A., and Shao, X.-F. (2020). What Nurtures Fourth Industrial Revolution? an Investigation of Economic and Social Determinants of Technological Innovation in Advanced Economies. *Technol. Forecast. Soc. Change* 161, 120305. doi:10.1016/j.techfore.2020.120305

Wang, P., Han, W., Kumail Abbas Rizvi, S., and Naqvi, B. (2022b). Is Digital Adoption the Way Forward to Curb Energy Poverty?". *Technol. Forecast. Soc. Change* 180 121722. doi:10.1016/j.techfore.2022.121722

Wang, Q., and Wang, S. (2020). "Preventing Carbon Emission Retaliatory Rebound Post-Covid-19 Requires Expanding Free Trade and Improving Energy Efficiency." *Sci. Total Environ.* 746 141158. doi:10.1016/j.scitotenv.2020.141158

Watanabe, C., Naveed, N., and Neittaanmäki, P. (2018). Digital Solutions Transform the Forest-Based Bioeconomy into a Digital Platform Industry - a Suggestion for a Disruptive Business Model in the Digital Economy. *Technol. Soc.* 54, 168–188. doi:10.1016/j.techsoc.2018.05.002

Weina, D., Gilli, M., Mazzanti, M., and Nicolli, F. (2016). Green Inventions and Greenhouse Gas Emission Dynamics: A Close Examination of Provincial Italian Data. *Environ. Econ. Policy Stud.* 18, 247–26363. doi:10.1007/s10018-015-0126-110.1007/s10018-015-0126-1

Xu, Q., Zhong, M., and Li, X. (2022). How Does Digitalization Affect Energy? International Evidence. *Energy Econ.* 107, 105879. doi:10.1016/j.eneco.2022.105879

Xue, Y., Tang, C., Wu, H., Liu, J., and Hao, Y. (2022). The Emerging Driving Force of Energy Consumption in China: Does Digital Economy Development Matter? *Energy Policy* 165 112997. doi:10.1016/j.enpol.2022.112997

Yang, C., Hao, Y., and Irfan, M. (2021). Energy Consumption Structural Adjustment and Carbon Neutrality in the Post-Covid-19 Era. *Struct. Change Econ. Dyn.* 59 442–453. doi:10.1016/j.strueco.2021.06.017

Yang, T.-M., Pardo, T., and Wu, Y.-J. (2014). "How Is Information Shared across the Boundaries of Government Agencies? an E-Government Case Study." *Gov. Inf. Q.* 31, 637–52. doi:10.1016/j.giq.2014.05.002

Yang, X., Guo, Y., Liu, Q., and Zhang, D. (2022). Dynamic Co-evolution Analysis of Low-Carbon Technology Innovation Compound System of New Energy Enterprise Based on the Perspective of Sustainable Development. *J. Clean. Prod.* 349, 131330. doi:10.1016/j.jclepro.2022.131330

York, R., Rosa, E. A., and Dietz., T. (2002). "Bridging Environmental Science with Environmental Policy: Plasticity of Population, Affluence, and Technology." *Soc. Sci. Q.* 83(1), 18, 34. doi:10.1111/1540-6237.00068

Yue, X.-G., Liao, Y., Zheng, S., Shao, X., and Gao, J. (2021). "The Role of Green Innovation and Tourism towards Carbon Neutrality in Thailand: Evidence from Bootstrap Adrl Approach." *J. Environ. Manag.* 292, 112778. doi:10.1016/j.jenvman.2021.112778

Zaman, K., and Sarker, T. (2021). Demographic Dividend, Digital Innovation, and Economic Growth: Bangladesh Experience. Available at: https://www.adb.org/publications/demographicdividend-digital-innovation-economic-growth-bangladesh

Zhang, S., Ma, X., and Cui, Q. (2021). Assessing the Impact of the Digital Economy on Green Total Factor Energy Efficiency in the Post-Covid-19 Era. *Front. Energy Res.* 9, 11–26. doi:10.3389/fenrg.2021.798922

Zhang, W., Liu, X., Wang, D., and Zhou, J. (2022). "Digital Economy and Carbon Emission Performance: Evidence at China's City Level." *Energy Policy* 165 112927. doi:10.1016/j.enpol.2022.112927

Zhou, X., Zhou, D., Zhao, Z., and Wang, Q. (2022). A Framework to Analyze Carbon Impacts of Digital Economy: The Case of China. *Sustain. Prod. Consum.* 31 (2022), 357. doi:10.1016/j.spc.2022.03.002

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