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Original Research

The Green Effects of Digital Economy: Evidence from Carbon Emission Reduction in China

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Abstract

Using a city-level panel data set with 283 cities in China, this study applies a fixed effect model to estimate the effects of the digital economy on carbon emissions, along with the contribution of green technology innovation. It shows that the digital economy can not only directly decrease carbon emissions, but also reduce them through promoting green technology innovation. Moreover, the effects are heterogeneous among cities in different geographic locations and administrative levels, as well as policy shocks. In particular, the carbon reduction effect of the digital economy is greater for cities in the eastern coastal region, cities at higher administrative levels, and cities enjoying the Big Data Pilot Zone policy. The findings that the digital economy can help prompt green technology innovation and reduce carbon emissions have implications for developing countries with similar characteristics to China to promote sustainable development.

Keywords: carbon emission reduction, carbon neutrality, digital technology, sustainable development, technological progress

Introduction

The worldwide economy is confronting serious challenges, especially climate change, which might threaten biodiversity, environmental health, and human society [1]. According to statistics from the World Meteorological Organization, the average global temperature in 2021 was around 1.11±0.13ºC higher than the pre-industrial average of 1850-1900 [2]. Particularly, the increase in carbon emissions has been considered greatly contributing to global warming [3]. In the previous century, the global CO_2 levels have risen dramatically with rapid urbanization and industrialization. In the1900s, the amount of the world's CO_2 emissions was only about 1.96 billion tons, while it increased to 23.45 billion tons in 2000. Within the last two decades, the amount of CO_2 emissions has risen fiercely and reached 34.34 billion tons in 2019 [4].

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The developing countries contributed over 50% of the CO_2 emissions, particularly China, India, and Russia, accounting for 31.18%, 7.15%, and 4.96% of global CO_2 emissions, respectively.

At the moment, China contributes the majority of global carbon emissions. Since the 1990s, China has witnessed a rapid increase in CO_2 emissions from 2.17 billion tons, when they made up 10.54% of global emissions. In 2005, it increased to 5.82 billion tons, accounting for 21.25% more CO_2 emissions globally than the US [4]. Since then, China has overtaken the United States as the nation with the highest carbon emissions. In 2019, about one-third of global CO_2 emissions came from China, whose carbon emissions were 10.71 billion tons. It is, hence, urgent for China to take measures to decrease carbon emissions to prompt sustainable development. The reduction of carbon emissions has raised various public concerns in China. The policymakers have attempted to curb the increasing carbon emissions. To combat environmental issues and advance the green economy, the Chinese government proposed the goals of peak carbon by 2030 and carbon neutrality by 2060 in 2020. As a result, policies and actions to reduce carbon emissions have continuously been taken. The concept of sustainable development came up in the 1970s. Sustainable development is a mixed concept that combines development, needs, and future generations, and it contains a triple bottom line concept, that is, environmental sustainability, social sustainability, and economic sustainability [5]. Today's turbulent times require re-valuation and re-accession of sustainable development as a theoretical concept and an analytical framework [6].

Meanwhile, previous researchers have been striving to identify factors targeted at carbon emission reduction and to capture drivers including economic development, energy structure, foreign investment, international trade, technology innovations, and policies [7, 8]. It has been demonstrated that advancements in technology, such as information technology, help cut carbon emissions [9]. Interestingly, with the advancement of information and communications technologies, the digital economy is identified as having the potential to be one of the most important factors contributing to economic growth [10, 11]. China has officially started to stimulate the development of the digital economy since 2010. In February 2022, the Chinese government issued a document to start to launch eight national computing hub nodes and plan a cluster of ten national data centers. The statistics from China's Digital Economy Development Report 2022 released by CAICT show that China's digital economy has reached 45.5 trillion CNY in 2021, representing 39.8% of the country's GDP and a rise of 16.2% year over year. However, the expansion of the digital economy is incredibly differentiated, and CO_2 emissions are unevenly distributed among cities with similar economies and population scales. For instance, both Hangzhou and Wuhan are the most noticeable second-tier cities in China, with about 1600 billion CNY of GDP in 2020 [12]. Hangzhou city, as one of the most developed cities in terms of digital economy, ranked fourth in the top 100 cities for Digital Economy Development and only emitted 63.22 million tons of CO_2, while Wuhan city ranked tenth and emitted 87.12 million tons of CO_2 in 2016. A question arises; whether the variances of the digital economy explain the CO_2 emission differences?

It is generally perceived that the digital economy contributes to economic growth, technological progress, energy transition, and environmental improvement [13-15]. However, there is still limited knowledge on whether and how the digital economy decreases carbon emissions. Only a few pieces of literature have explored the relationship between the digital economy and CO_2 emissions. The results, however, are unclear and even conflicting. While some researchers suggest that the digital economy has negative impacts on carbon emissions [16, 17], others assume that it has either no significant effects or even positive impacts sometimes [18, 19].

The inconsistency of the existing findings may result from the endogeneity problems arising from heterogeneous methodologies applied. For example, most previous studies use provincial-level data [20, 21], with little city-level evidence, especially for developing countries with broad territories such as China. In particular, the differences in urbanization and industrialization levels are quite significant among different cities in the same province in China, which is a very critical factor impacting the digital economy and carbon emissions. Hence, more city-level evidence should be provided to reach a reasonable conclusion. The ambiguous and scant evidence on the mechanisms of the digital economy affecting CO_2 emissions in the existing literature may also be a contributing factor to the inconsistent results. To fill in the research gap, we use a city-level panel data set with 283 cities in China to examine the relationship between the digital economy and carbon emissions, along with the mediating role of green technology innovations. The reliability and validity of the estimation can be improved by introducing specific effect terms to capture individual heterogeneity in the city-level panel data model.

The objectives of our study are two-fold. The first is to construct an evaluation index to measure the digital economy and calculate the amount of carbon emissions, applying feasible econometric models to explore the impacts of the digital economy on carbon emissions, along with the mediating role of green technology adoption. The second is to investigate the heterogeneous effects among cities in different geographic locations and administrative levels, as well as policy shock. Our analysis reveals that the digital economy prompts green technology innovation, thus decreasing carbon emissions. Specifically, the impacts of the digital economy on carbon emissions are stronger in the eastern coastal region than those in other regions, cities with higher administrative levels than those with lower ones, and cities in the Big Data Pilot Zone than those that are not in the zone. To our knowledge, this is among the first to investigate the impacts of the digital economy on carbon emission reduction through green technological innovation and provide city-level evidence from China, which helps shed light on the issue. This study also has important implications and provides substantial guidance for developing nations to achieve the target of carbon neutrality.

Literature Review and Research Hypotheses

Digital Economy and Carbon Emissions

As carbon emissions are considered one of the leading causes of global warming, resulting in various problems, a vast body of literature has investigated the factors affecting CO_2 emissions, such as economic development, industrial structure, urbanization, technological innovation, and energy structure [22-25].

Recently, the digital economy has aroused overwhelming attention because of its contributions to national strength. A vast body of literature has been focused on the economic, social, ecological, and environmental impacts of the digital economy [16, 26, 27]. Although a few studies have attempted to investigate how the digital economy may affect CO_2 emissions, the influence remains unclear. For instance, several pieces of literature suggest that the digital economy can help decrease carbon emissions because the digital economy stimulates innovations, upgrades industrial structure, prompts technological progress, and increases energy use, which affects carbon emissions [18, 22, 28]. It is noteworthy that the digital economy emerges with the popularization of ICTs, which exerts significant impacts on green technological progress [29]. In other words, the digital economy has positive impacts on green technological progress, which is essential for carbon emission reduction. The conceptual framework is shown in Fig. 1. Specifically, the effects are likely to be heterogeneous among cities with heterogeneous geographic, administrative, and policy characteristics.

Digital Economy and Green Technology Innovation

Green technology innovation is a type of technological innovation that can improve the ecological environment by lowering energy consumption [30]. It is generally believed that there are mainly three sources for technology innovation: indigenous innovation, innovation imitation, and technology import. The digital economy can help reduce the R&D costs of indigenous innovation, decrease the information searching costs of innovation imitation, and provide easier access to indigenous innovations for enterprises, which contributes to technology innovations.

The digital economy, which has nurtured new economic forms and inevitably transformed the production and management modes, is driven by data as opposed to the traditional economy [31]. A significant feature of the digital economy is 'green', which is specifically reflected in low resource consumption, transaction costs, and environmental pollution [30]. These inherited advantages and characteristics of the digital economy can guide green technological innovations and improve high-quality green development [32].

Green Technology Innovation and Carbon Emissions

Various literature aiming to examine the impacts of green technological progress on climate change adaptation shows that green technologies, including

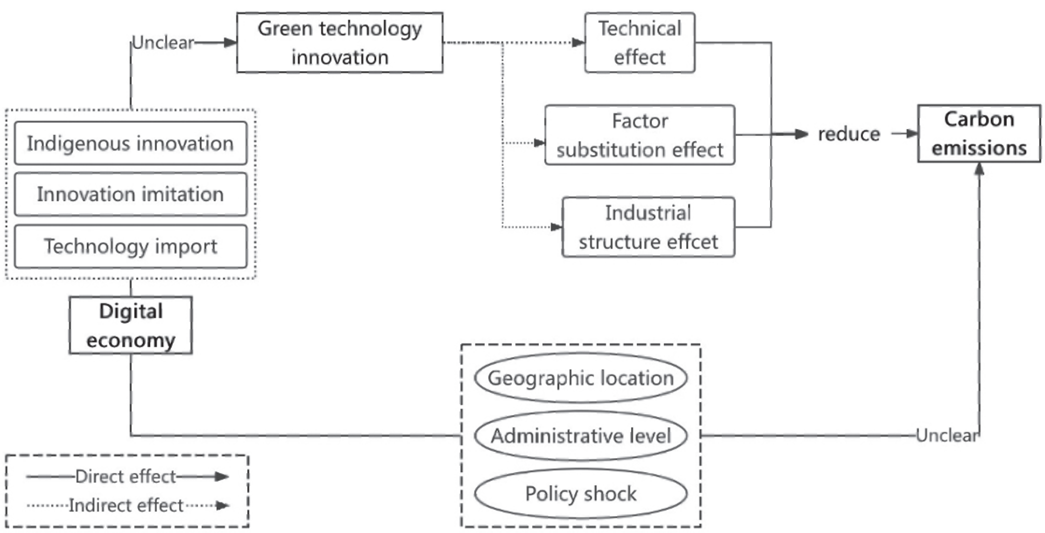

Fig. 1. Conceptual framework.

renewable energy technology, low-carbon technology, and climate-related technology, contribute to CO_2 reduction [33-35]. Green technology innovations mainly affect carbon emissions via three paths:

Technical Effect

Green technological progress contributes to the energy technology revolution. In particular, coal was substituted by biomass in the first industrial revolution. Oil and gas were the primary energy sources during the second industrial revolution, whereas electricity was the primary energy source during the third. In other words, the upgrading of energy utilization technologies helps to improve the energy mix and increase the efficiency of energy utilization, thus reducing carbon emissions [36].

Factor Substitution Effect

Technological progress is affected by the size of market demand, which in turn determines factor prices. Market size and factor price will increase the marginal output of a given input factor so that the proportion factor decreases, that is, the factor substitution effect. It is the so-called factor-biased technological progress. According to the existing findings, whether factor-biased technological progress can promote low-carbon development depends on the direction of technological innovation as well as the roles of energy and other factors [37]. In our case, technological progress is moving towards the direction of green inventions, which will help decrease CO_2 emissions. Some firms are becoming leaders in green technology innovation in certain areas, and others tend to follow in order to gain the same competitive advantages. This expands the scale of market demand for green production factors. As a result, green technology will diffuse, which maximizes the externality of technological innovations and helps reduce carbon emissions [37].

Industrial Structure Effect

To obtain the technical effect, the industrial agglomeration emerges. The knowledge spillover of green technological innovations can break the production boundaries among firms and industries by establishing a common technical base, which transforms the industrial structure and economic growth. The industrial structure would change with the changes in differences in the technological progress rate and diffusion effect [37]. When the dominant industry changes to low-carbon sectors, such as electronics and information industries, the changes in industrial structure would contribute to carbon emission reduction. Thus, green technological innovations can help decrease carbon emissions.

Based on the above analysis and observations, it has been clearly indicated that green technology innovation reduces carbon emissions. It is, however, still unclear whether the digital economy decreases carbon emissions and whether the digital economy promotes green technology innovations. Hence, we propose the following theoretical hypotheses and try to empirically examine them.

H_1: The digital economy has a significantly negative impact on carbon emissions;

H_2: The digital economy can help promote green technology innovation;

H_3: The effects of the digital economy on carbon emissions are heterogeneous among cities regarding geographic location, administrative level, and policy shocks.

Material and Methods

Source of Data

In this study, we aim to provide city-level evidence from China for the impacts of the digital economy on carbon emissions and the influence mechanism. The data is mostly obtained from the Carbon Emission Accounts & Database, China Urban Statistical Yearbook from 2011 to 2016, the prefecture-level cities' annual statistical report, and the Wind Database, which provides information about the digital economy, carbon emissions, economy, population, society, income, and expenditures.

To construct the indicator for the digital economy, this paper uses the Peking University Digital Financial Inclusion Index of China (PKU_DFIIC), which is jointly compiled by the Institute of Digital Finance Peking University and the Ant Financial Services Group.

The patent data is obtained from the Chinese Invention Patent Database. We identify the green patent by using the International Patent Classification (IPC) system code to merge the Chinese invention patent database. We obtain the city-level green patent data set after the identification.

As our research is focused on the relationship between the digital economy, green technology innovation, and carbon emissions, these data have to be matched to the city-level data. The final data set is an unbalanced panel data set covering 283 cities in China from 2011 to 2016. We chose the period as the timeline of our study considering that the digital economy has witnessed explosive growth since 2011 and the total scale of China's digital economy increased by 4.12 times, with a compound annual growth rate of 17.06% from 2011 to 2020. Meanwhile, the city-level data on green technology patents is only available for 2016 and before. Although the digital economy has developed rapidly in recent years, our study can still contribute to examining the relationship between the digital economy, green technology innovation, and carbon emissions by using city-level data, which provides evidence and references for developing nations to explore their carbon reduction approaches to realize the targets of carbon peaking and carbon neutrality.

Model Selection

To quantify the effects of the digital economy on CO_2 emissions, we start by applying a panel data regression model. The model for CO_2 emissions can be set as:

$$Y_{it} = \beta_0 + \beta_1 D_{it} + \beta_2 X_{it} + \gamma_i + \delta_t + \varepsilon_{it} \quad (1)$$

Where, Y_{it} is a continuous variable, indicating CO_2 emissions of city i at year t; D_{it} represents the digital economy index of city i at the same period; X_{it} is a vector of control variables that affect CO_2 emissions of the city; β_1, β_2 are parameters to be estimated; γ_i is an unobserved city-specific effect, δ_t is a time dummy; ε_{it} is the residual.

To address the potential endogeneity problem arising from omitted variables, the fixed effect (FE) model is applied. Equation (1) can be rewritten as:

$$\Delta Y_{it} = \beta_0 + \beta_1 \Delta D_{it} + \beta_2 \Delta X_{it} + \mu_{it} \quad (2)$$

Where $\Delta Y_{it} = Y_{it} - \bar{Y}_t$, $\Delta X_{it} = X_{it} - \bar{X}_t$, $\Delta\mu_{it} = \mu_{it} - \bar{\mu}_t$ and $\Delta D_{it} = D_{it} - \bar{D}_t$; μ_{it} is a random error term; the variable with the bar on the head denotes its average of the variable over time. Here, we apply the FE model to capture the time and individual fixed effect. The time FE can solve the problem of omitting variables that do not change with the individual but change over time. It is used to capture the digital economy as well as macroeconomic changes. In the meantime, the individual FE is used to capture differences between individuals that do not change over time, which helps address the issue of missing variables. Compared to the pooling OLS method, which contains the cross-sectional difference information, that is, the difference between individuals, and thus is more appropriate for cross-sectional analysis, the FE model is more suitable for panel data analysis.

Using Equations (1) - (2), we can measure the aggregate effects of the digital economy on CO_2 emissions of the city. However, it will not show how the digital economy impacts CO_2 emissions. Based on the conceptual framework, we assume that the impact of the digital economy on CO_2 emissions is mediated by green technology innovation. That is, the digital economy can promote green technology innovation. Hence, we set up the following model to further examine the mechanism:

$$G_{it} = \varphi_0 + \varphi_1 D_{it} + \varphi_2 X_{it} + \gamma_i + \delta_t + \xi_{it} \quad (3)$$

Where G_{it} is the green technology innovation of city i at year t, namely, the mediating variable; $\varphi 1$, $\varphi 2$ are parameters to be estimated; ξ_{it} is a random error term.

To address the potential endogeneity issue, the FE model is applied and set as:

$$\Delta G_{it} = \delta_0 + \delta_1 \Delta G_{it} + \delta_2 \Delta X_{it} + \upsilon_{it} \quad (4)$$

Where $\Delta G_{it} = G_{it} - \bar{G}_t$, and $\Delta v_{it} = v_{it} - \bar{v}_t$; v_{it} is a random error term.

Variable and Descriptive Statistics

Independent Variable: Carbon Emissions

Our independent variable is CO_2 emissions. The data on city-level CO_2 emissions is available in the Carbon Emission Accounts & Database. The carbon emission data is calculated as the total use of coal, natural gas, and liquefied petroleum gas.

Dependent Variable of Interest: Digital Economy

Our dependent variable is the digital economy. In this study, following the existing studies [19, 38], we measure the digital economy from two dimensions, i.e., the development of the Internet and digital finance. Specifically, we use four sub-indicators, including the output of the Internet industry, employment of the Internet industry, Internet penetration rate, and mobile communication coverage, for the development of the Internet. These four sub-indicators of Internet development are measured as the number of Internet users per 100 people, the proportion of employees in the computer services and software industry in the urban sector, total telecom business per capita, and the number of mobile phone users per 100 people, respectively, in the China Urban Statistical Yearbook. We use the PKU_DFIIC, which is jointly compiled by the Institute of Digital Finance Peking University and the Ant Financial Services Group, to measure the development of digital finance. The digital economy index is then obtained by using principal component analysis and dimensional reduction.

Mediator: Green Technology Innovation

As one of our aims is to examine whether green technology innovation mediates the impacts of the digital economy on CO_2 emissions, we use the number of green technology patents granted as the proxy of green technology innovation.

Control Variable

Apart from the above-mentioned variables that we focus on, we also control for other factors affecting carbon emissions. Various studies show that economic development and population expansion contribute to carbon emissions [39]. With the improvement of material living standards, people's awareness and cognition regarding low-carbon lifestyles are likely to grow stronger as well, which contributes to carbon emission reduction. Hence, we control for economic development and population size. Also, we control foreign direct investment (FDI), industry structure, and government intervention, following the existing literature [7, 17, 29]. The variable and definition are shown in Table 1.

Table 1. Variable and definition.

Variable	Definition and Descriptions	Mean	Std. Dev	Min	Max
CO_2 emissions	The amount of CO_2 emissions of the city (million tons)	31.23	25.70	4.090	226.7
Digital economy	The digital economy index, measured from the dimensions of the development of the Internet of digital finance	0.596	0.0370	0.554	0.954
Green innovation	Green technology innovation, measured as the amount of green patents granted	65.50	177.6	0	2148
GDP	Economic development, measured as the real GDP per capita of the city (CNY, 2008 constant), in natural log	10.64	0.555	8.842	13.06
FDI	Foreign direct investment (FDI), measured as the ratio of the total amount of FDI to the GDP of the city	0.124	0.167	0	1.310
Industry structure	Measured as the percentage of the city's added value of the secondary industry to the city's GDP (%)	49.46	9.944	14.90	89.30
Population	Population size, measured as the amount of the people of the city (10,000), in natural log	5.916	0.670	3.401	8.129
Government intervention	The degree of the government intervention, measured as the ratio of the public finance expenditure of the city government to the GDP of the city	0.180	0.0770	0.0440	0.675

Results and Discussion

Results

The Impacts of the Digital Economy on Carbon Emissions: Baseline Regression

To examine the effects of the digital economy on carbon emissions, we first run OLS regressions on Equation (2), and the results are reported in Table 2. The column (1) reports the estimation results of carbon emissions without considering the control variables, column (2) presents the results without considering year FE, column (3) reports the results without considering city FE, and column (4) reports the estimation results considering control variables, city FE and year FE. It shows that the coefficient of the dependent variable is significant and negative in four models, suggesting that the digital economy can decrease CO_2 emissions as expected. The results reveal that cities with a more developed digital economy tend to be less pollutant than those with a less developed digital economy. The digital economy is greatly associated with information and communications technologies, which have reshaped the production mode and human lifestyles, which helps transform the conventional industry structure, thus decreasing carbon emissions.

In other factors affecting carbon emissions, the GDP variable has a significant and positive coefficient in models (2) and models (3), implying that economic development may have contributed to increasing carbon emissions. Although there are studies showing that people's living standards are improving with economic development, their awareness and cognition regarding low-carbon lifestyles are likely to grow stronger as well, which contributes to carbon emission reduction. The economic development brings more human activities associated with manufacturing, business, and services, which produce carbon emissions. Further, industry structure has a significantly positive effect on CO_2 emissions in models (2) and models (4), which also provides evidence that the development of the manufacturing industry will contribute to increasing carbon emissions [40]. Population has a significantly positive coefficient in the model (3), suggesting that more human activities mean more carbon emissions.

In particular, the FDI has a significantly positive coefficient, which means that FDI has increased carbon emissions. A possible explanation is that the foreign investments are mostly distributed in the manufacturing sectors. The developed countries tend to allocate the R&D bases domestically and allocate the manufacturing factories in developing countries with relatively cheap labor, such as China, India, Vietnam, etc., where they can gain comparative advantages. This phenomenon has been commonly seen since the open-up policies implemented in China, although the FDI has started shifting from China to Southeast Asian countries in recent years due to the disappearing advantages in labor costs. As our city-level panel data is from 2011 to 2016, the odds are FDI inflows are mostly in the secondary industry, which increases the carbon emissions in China. Interestingly, the relationship between the digital economy, FDI, and carbon emissions is rather complicated. A recent study shows that the impacts of FDI on carbon emissions are heterogeneous among the different regions. In particular, the existing studies showed that the bidirectional causality relationship between CO_2 emissions and FDI only exists in the Central region, while it doesn't exist in the Eastern region [41]. The relationship between FDI and carbon emissions could be highly correlated with the digital economy, which is considered to help stabilize FDI

Table 2. The impacts of the digital economy on carbon emissions: Baseline regression.

Variable	(1)	(2)	(3)	(4)
	CO_2	CO_2	CO_2	CO_2
Digital economy	-20.826***	-12.508***	-32.393**	-18.765***
	(3.893)	(4.218)	(14.818)	(4.031)
GDP		0.918***	37.658***	-0.257
		(0.285)	(1.351)	(0.419)
FDI		5.392***	8.140***	5.169***
		(1.387)	(2.910)	(1.315)
Industry structure		0.042***	-0.050	0.056***
		(0.015)	(0.049)	(0.019)
Population		0.739	26.209***	-0.369
		(1.312)	(0.678)	(1.239)
Government intervention		1.699	116.230***	1.853
		(1.950)	(7.836)	(1.901)
Constant	42.637***	21.502**	-524.696***	43.587***
	(2.316)	(8.375)	(15.641)	(8.863)
City FE	Yes	Yes	No	Yes
Year FE	Yes	No	Yes	Yes
N	1671	1580	1582	1580
R-squared	0.997	0.997	0.634	0.997

Note: Standard errors are in parenthesis, *** $p<0.01$, ** $p<0.05$.

inflows, and FDI can promote the digital transformation of enterprises in host countries.

Moreover, another interesting finding is that government intervention has a positive coefficient in the model (3), which implies that government activities may have targeted economic goals instead of environmental goals in the mid-2010s. This is plausible because China has been striving to achieve the goal of building a moderately prosperous society in all respects by 2020. It is likely that the government spent a large proportion of the financial investments to pursue economic growth and thus contribute to increasing CO_2.

The Mechanisms of Digital Economy Impacting Carbon Emissions

To examine how the digital economy impacts carbon emissions, we regress on Equation (2), and the estimation results are presented in Table 3. Column (1) reports the results without considering the control variables, while column (2) presents the results considering all control variables. The digital economy variable has positive and statistically significant coefficients, suggesting that the digital economy can increase green technology advancements. Our research results support the current findings [30]. As expected, the rapid growth of the digital economy encourages firms to conduct research and enables them to apply for more environmental patents. In turn, green technological advancements help to reduce carbon emissions.

In this study, we confirmed that the digital economy can help decrease carbon emissions, which contributes to the understanding of the emergence of new economic forms that would promote carbon emission reduction. The development of information technologies such as big data, 5G networks, and artificial intelligence is the most active field of industrial transformation and technological progress at present, providing a new path for the low-carbon development economy in China. Specifically, the development of the digital economy helps to decrease carbon emissions by prompting green technology innovations. The digital economy empowers enterprises in the industry to make low-carbon transformations. Firstly, digital technology enables the green development of high-carbon emission industries, such as electric power, manufacture, transportation, and construction; promotes the innovation of production processes and technical equipment; and reduces carbon emissions. Secondly,

Table 3. Mechanism analysis of the effects of digital economy on CO_2 emissions.

Variable	(1) Green innovation	(2) Green innovation
Digital economy	643.811***	673.480***
	(108.953)	(114.434)
GDP		34.660***
		(11.896)
FDI		52.332
		(37.338)
Industry structure		-0.815
		(0.550)
Population		29.245
		(35.161)
Government intervention		-92.368*
		(53.976)
Constant	-320.841***	-826.952***
	(64.822)	(251.593)
City FE	Yes	Yes
Year FE	Yes	Yes
N	1671	1580
R-squared	0.950	0.951

Note: Standard errors are in parenthesis, *** p<0.01, * p<0.1.

the digital economy enables firms to establish intelligent operation management systems to simulate the production process, thus reducing unnecessary carbon emissions. In addition, the digital economy has improved the efficiency of information interaction, alleviated the information asymmetry between consumers and manufacturers, reduced the time and transaction costs of manufacturers looking for customers, and reduced carbon emissions.

More importantly, the digital economy encourages residents to adopt low-carbon and healthy lifestyles. The digital economy has gradually changed the consumption concept and demand preference, adjusted the consumption structure, upgraded the consumption quality of residents, and eventually led to the transformation of residents' consumption behaviors and decisions. Meanwhile, the development and application of digital technology has further enhanced residents' green consumption, and green life awareness and increased the demand for green products. For instance, e-books, online shopping, and other low-carbon lifestyles have gradually become an important consumption mode in people's daily lives. It is predictable that the digital economy can reduce urban carbon emissions by improving the low-carbon transformation of enterprises and guiding residents to live a green life.

Table 4. Regional heterogeneity effects.

Variable	(1) CO_2	(2) CO_2	(3) CO_2
Eastern Region	-25.009***		
	(6.551)		
Borderland region		12.829	
		(11.147)	
Other inland region			-18.765***
			(4.031)
GDP	-0.209	3.060**	-0.257
	(0.664)	(1.439)	(0.419)
FDI	7.779***	3.417	5.169***
	(2.312)	(3.160)	(1.315)
Industry structure	0.147***	-0.058	0.056***
	(0.052)	(0.047)	(0.019)
Population	16.360***	-3.699	-0.369
	(6.262)	(4.449)	(1.239)
Government intervention	-2.348	5.246	1.853
	(5.594)	(3.845)	(1.901)
Constant	-52.589	12.479	42.792***
	(38.146)	(30.638)	(8.795)
City FE	Yes	YES	YES
Year FE	Yes	YES	YES
N	574	255	1581
R-squared	0.199	0.216	0.162

Note: Standard errors are in parenthesis, *** p<0.01, ** p<0.05.

Discussion

Heterogeneous Effects of the Digital Economy on Carbon Emissions

To further explore the heterogeneous effects of the digital economy on carbon emissions, we take into account regional heterogeneity, administrative heterogeneity, and policy heterogeneity. The results of the heterogeneous effects are presented in Table 4 and Table 5.

Regional Heterogeneity

We further divide our samples into three groups: cities in the eastern coastal region, borderland regions, and other inland regions, taking into account that regional variations in economic development and factor

Table 5. Administrative Heterogeneity and Policy Heterogeneity.

Variable	(1)	(2)
	CO_2	CO_2
Dig*admin	-76.126***	
	(7.291)	
Dig*policy		-49.699***
		(5.696)
GDP	-0.014	-0.114
	(0.407)	(0.411)
FDI	4.536***	4.057***
	(1.269)	(1.296)
Industry structure	0.041**	0.054***
	(0.019)	(0.019)
Population	0.111	0.304
	(1.200)	(1.215)
Government intervention	2.102	1.347
	(1.841)	(1.864)
Constant	37.398***	30.309***
	(8.198)	(8.275)
City FE	Yes	Yes
Year FE	Yes	Yes
N	1581	1581
R-squared	0.214	0.195

Note: Standard errors are in parenthesis, *** p<0.01, ** p<0.05.

endowment may have an impact on how the digital economy affects carbon emissions. To examine regional heterogeneity, we re-estimated the different regional samples according to Equation (2), where columns (1) through (3) show the regression results for the eastern coastal, borderland, and other inland samples, respectively. The results show that the coefficients of the digital economy variables in the regression results in columns (1) and (3) are significantly negative, and the absolute value of the regression coefficients is larger in the eastern coastal region. However, the coefficient in the regression result in column (2) is not significant. It can be seen that the carbon reduction effect of the digital economy in the eastern coastal area is the most significant, followed by other inland areas, but the development of the digital economy in the borderland area does not promote carbon reduction.

China is a vast country with large disparities in the quality of digital economic development between regions. The eastern seaboard has a relatively well-developed digital infrastructure and is ahead of other regions in terms of the level of development of the digital economy. The development of the digital economy in the central and western regions is relatively late, especially in the domestic border areas where the level of digital economy development is more limited. Influenced by the level of economic development, industrial structure, and relevant policies in different regions, the digital economy has a better effect on carbon emission reduction in the eastern coastal regions, while the effect in the inland regions is relatively weak. The industrial structure of border areas is relatively low-end, and the resources of local governments are devoted to the development of the local economy. It is not possible to utilize the technological effect and industrial structure effect brought by the digital economy. The carbon emission reduction pathway brought by the digital economy is limited.

Administrative Heterogeneity

The cities are entitled to allocate resources within a certain scope, according to their administrative level. Hence, we suspect that a higher administrative level can enlarge the negative impacts of the digital economy on carbon emissions. Considering the administrative heterogeneity, we categorize the cities into two groups: center cities (including National Center cities, province-level municipalities, sub-provincial cities, and provincial capital cities) and non-center cities. To examine the administrative heterogeneity, we introduce an interaction term of the digital economy and a dummy variable indicating whether the city is a National Center city and re-estimate the Equation (2). The results are shown in Column (1) of Table 5. The interaction term of the digital economy and National Center city dummy variable has a significantly negative coefficient, implying that the effect of the digital economy on carbon emissions is much higher among center cities than non-center cities. It implies that the administrative level of the city can enlarge the negative impacts of the digital economy on carbon emissions.

A higher administrative level of a city generally means a larger agglomeration effect. In particular, the agglomeration effect of talents and industries in the process of urbanization is a critical driver for the high-quality growth of China's economy. This study shows that the digital economy has relatively inhibitory effects on carbon emission intensity in National Center cities, which is relevant to the development of the urban digital economy. Specifically, National Center cities have higher administrative levels and are more likely to earn more resources. For instance, National Center cities can easily access funds, human capital, and infrastructure needed to develop a digital economy, and preferential policies are often more inclined toward these cities. Therefore, compared with other cities, National Center cities rely on more resources to achieve a better development environment, and the digital economy is also better developed.

It is quite interesting since China has widely been recognized for its powerful government-dominated institutions. One of the major advantages of China's administrative institution is that the government has sufficient manpower, material, and financial resources for making major decisions and promoting infrastructure development. The government mainly controls political, economic, and social resources. A higher administrative level means a stronger ability to control the resources, which makes carbon reduction targets easier to achieve.

Policy Heterogeneity

The digital economy is an emerging industry that is highly dependent on government policies. Similarly, the Chinese government issued the "Action Outline for Promoting the Development of Big Data" in 2015. The action outline proposed to summarize a set of reproducible experiences for big data industry development experiences and launch the 'Big Data Pilot Zone' in ten provinces in China. Moreover, the action outline deployed strategies to develop the digital economy industries from seven dimensions, i.e., data resource management and sharing, data center resource integration, data resource applications, data resource distribution, agglomeration of big data industries, international cooperation, and institutional innovation of big data. In this study, we categorize the cities into two groups: cities on the list of cities in the Big Data Pilot Zone, and those that are not in the zone. To examine the heterogeneity, we introduce an interaction term of the digital economy and a dummy variable indicating whether the city is in the Big Data Pilot Zone, and re-estimate Equation (2). The results are presented in column (2) of Table 5. The interaction term of the digital economy and the policy dummy has a significantly negative coefficient, suggesting that the digital economy has a stronger negative impact on carbon emissions among cities in the Big Data Pilot Zone than those that are not in the zone. The findings imply that government policies promoting the digital economy can contribute to reducing carbon emissions.

The cities in the Big Data Pilot Zone are mostly digital economy-developed cities and enjoy preferential policies. Generally, these cities are equipped with more favorable digital technologies, and infrastructure under government support and thus have a more efficient digital energy network than other cities. Compared with traditional resource-based cities, the cities in the Big Data Pilot Zone are usually better developed and have greater potential for carbon emission reduction. Nowadays the industrial layout and production mode are more rational, which optimizes the industry's energy and cost structure and achieves intelligent low-carbon development. Particularly, the application of digital technologies in source locking, prediction and early warning, supervision, and other scenarios of carbon emissions so as to exert significant effects on emission reduction. Therefore, the digital economy can release greater reduction effects on emissions for cities in the Big Data Pilot Zone.

Table 6. Results of robustness checks.

Variable	(1)	(2)	(3)
	CO_2	CO_2	CO_2
Digital economy			-16.627***
			(3.980)
Dig1	-8.111***		
	(1.848)		
LDig		-11.509***	
		(4.366)	
CET			-1.672***
			(0.253)
GDP	-0.344	-0.812*	-0.022
	(0.419)	(0.465)	(0.414)
FDI	5.433***	7.824***	4.296***
	(1.310)	(1.752)	(1.301)
Industry structure	0.061***	0.073***	0.068***
	(0.019)	(0.023)	(0.019)
Population	-0.542	0.340	0.031
	(1.241)	(1.257)	(1.220)
Government intervention	2.040	1.305	2.867
	(1.903)	(2.024)	(1.877)
Constant	34.331***	39.710***	36.083***
	(8.479)	(9.190)	(8.714)
City FE	Yes	YES	YES
Year FE	Yes	YES	YES
N	1581	1319	1581
R-squared	0.161	0.185	0.189

Note: Standard errors are in parenthesis, *** p<0.01, * p<0.1.

Robustness Checks

To provide robustness checks, we adopt three estimation strategies. The first is to address the potential endogeneity arising from measurement error by replacing the digital economy indicator measured using the principal component analysis with the indicator obtained using the questionable value method. The results are presented in Column (1) of Table 6. The coefficient of the replaced digital economy variable is significant and negative, meaning that the digital economy can decrease carbon emissions, as expected.

The second is to capture the lag effects of the digital economy on carbon emissions by re-estimating Equation (2) using a one-period lagged indicator of the digital economy. The results are shown in Column (2). The lagged digital economy indicator has a significantly negative coefficient, which indicates that our baseline regression results are quite robust.

The third is to eliminate the intervention of energy policies; that is, the effects of carbon emission reduction may come from environmental regulations. We introduce a dummy variable indicating whether the city engaged in carbon emission trading (CET) during the sample period. The digital economy has a significantly negative coefficient after the energy policy dummy variable is controlled, which means that the digital economy can decrease carbon emissions.

Conclusions

Since China proposed the targets of striving to peak CO_2 emissions by 2030 and striving for carbon neutrality by 2060 in 2020, the reduction of carbon emissions has raised a wide range of national concerns. The Chinese government has successively issued the "Opinions on Fully, Accurately, and Comprehensively Implementing the New Development Concepts to Achieve Carbon Peak Carbon Neutrality", the "Action Plan for Achieving Carbon Peak before 2030", and other documents, putting forward the requirements for decreasing carbon emissions with the help of digital economy and technology. For example, the opinions pointed out that low-carbon innovation and digital intelligent transformation in the industrial field are important paths to reduce carbon emissions, and the plan pointed out that smart transportation construction and intelligent energy development can systematically save energy and reduce carbon.

In fact, the integration and application innovation of digital technologies with resources, energy, industry, and environment make it possible for digital technology to promote the reduction of carbon emission intensity and achieve dual carbon targets. The "White Paper on Digital Carbon Neutrality", released by the China Academy of Information and Communications Technology, claimed that by 2030, digital technologies would enable the whole society to reduce carbon emissions by 12%~22%. Among them, the construction industry would be decreased by 23%~40%, the transportation industry would be decreased by 10%~33%, and the industry would be decreased by 13%~22%. In the meantime, the development of the digital economy, relying on its characteristics of high technology, high penetration, and high integration, has made important progress through the development mode of platform, intelligence, ecology, and sharing.

The aim of this study is to explore the relationship between the digital economy and carbon emission reduction, along with the mediating effect of green technology innovation. For that purpose, we construct a conceptual framework of the digital economy – green technology innovation – carbon emission reduction. Utilizing a city-level panel data set covering 283 cities in China, we apply a fixed effect model to explore the effects of the digital economy on carbon emissions and its influence mechanism. The results have clearly indicated that the digital economy has a significant and negative effect on the amount of carbon emissions. In other words, the digital economy can decrease carbon emissions and thus improve the environment. In particular, the digital economy facilitates the advancement of green technologies, thereby reducing emissions. Moreover, the carbon reduction effects of the digital economy are heterogeneous among cities in different geographic locations, cities at different administrative levels, and cities with different policy shocks.

Hence, it is suggested that the government prompt digital economic development, which enhances green technological progress and improves environmental quality. Sustainable development will require investment in the digital economy, especially with the popularization of ICTs, 5G networks, and other digital technologies. Therefore, policymakers should focus on the development and promotion of digital technologies. More importantly, this study suggests that the digital economy can effectively prompt green technological progress, resulting in carbon emission reduction. Policies should focus on green technology innovations. Also, the carbon reduction impacts of the digital economy vary by geographic location, administrative level, and policy shock, which suggests that a more developed economy, a higher administrative level, and favorable policy support can help improve the development of the digital economy, and thus, reduce carbon emissions. Our findings provide practical references and policy implications for other developing countries that are facing similar conditions to China.

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Conflict of Interest

The authors declare no conflict of interest.

References

1. YAIR Y. Lightning hazards to human societies in a changing climate. Environmental Research Letters, **13** (12), 123002, **2018**.
2. WMO. The State of the Global Climate 2021. WMO, Geneva, Switzerland, **2022**.

3. TOKARSKA K.B., GILLETT N.P. Cumulative carbon emissions budgets consistent with 1.5 degrees C global warming. Nature Climate Change, **8** (4), 296, **2018**.
4. WORLD BANK. Databank, World Development Indicators, **2022**.
5. KLARIN T. The concept of sustainable development: From its beginning to the contemporary issues. Zagreb International Review of Economics & Business, **21** (1), 67, **2018**.
6. MANIOUDIS M., MERAMVELIOTAKIS G. Broad strokes towards a grand theory in the analysis of sustainable development: a return to the classical political economy. New Political Economy, **27** (5), 866, **2022**.
7. DU K., LI P., YAN Z. Do green technology innovations contribute to carbon dioxide emission reduction? Empirical evidence from patent data. Technological Forecasting and Social Change, **146**, 297, **2019**.
8. ROMERO J.P., GRAMKOW C. Economic complexity and greenhouse gas emissions. World Development, **139**, 105317, **2021**.
9. CHEN X.D. TAN Y.T., LIN M.X., ZHANG G.Y., MA W.C., YANG S.W., PENG Y.L. How information technology investment affects green innovation in Chinese heavy polluting enterprises. Frontiers in Energy Research, **9**, 719052, **2021**.
10. JURAYEVICH M.B., BULTURBAYEVICH M.B. The impact of the digital economy on economic growth. International Journal on Integrated Education, **3** (6), 16, **2020**.
11. ZHANG J.Z., ZHAO W.Q., CHENG B.D., LI A.X., WANG Y.Z., YANG N., TIAN Y. The impact of digital economy on the economic growth and the development strategies in the post-COVID-19 era: Evidence from countries along the "Belt and Road". Frontiers in Public Health, **10**, 856142, **2022**.
12. NBSC. China Statistical Yearbook 2022, China Statistics Press, Beijing, China. **2022**.
13. LITVINENKO V.S. Digital economy as a factor in the technological development of the mineral sector. Natural Resources Research, **29** (3), 1521, **2020**.
14. REN S.M., LI L.Q., HAN Y.Q., HAO Y., WU H.T. The emerging driving force of inclusive green growth: Does digital economy agglomeration work? Business Strategy and the Environment, **31** (4), 1656, **2022**.
15. SHAHBAZ M., WANG J.D., DONG K.Y., ZHAO J. The impact of digital economy on energy transition across the globe: The mediating role of government governance. Renewable & Sustainable Energy Reviews, **166**, 112620, **2022**.
16. MA Q., TARIQ M., MAHMOOD H., KHAN Z. The nexus between digital economy and carbon dioxide emissions in China: The moderating role of investments in research and development. Technology in Society, **68**, 101910, **2022**.
17. ZHU Z.C., LIU B., YU Z.X., CAO J.H. Effects of the digital economy on carbon emissions: Evidence from China. International Journal of Environmental Research and Public Health, **19** (15), 9450, **2022**.
18. LI Z.G., WANG J. The dynamic impact of digital economy on carbon emission reduction: Evidence city-level empirical data in China. Journal of Cleaner Production, **351**, 131570, **2022**.
19. WU J.X., XU H., TANG K. Industrial agglomeration, CO_2 emissions and regional development programs: A decomposition analysis based on 286 Chinese cities. Energy, **225**, 120239, **2021**.
20. GE W.F., XU Y., LIU G.L., SHEN B., SU X.F., LIU L., YANG X.D., RAN Q.Y. Exploring the impact of the digital economy on carbon emission efficiency under factor misallocation constraints: New insights from China. Frontiers in Environmental Science, **10**, 953070, **2022**.
21. ZHONG K. M., FU H. Y., LI T. H. Can the digital economy facilitate carbon emissions decoupling? An empirical study based on provincial data in China. International Journal of Environmental Research and Public Health, **19** (11), 6800, **2022**.
22. CHENG Z., LI L., LIU J. Industrial structure, technical progress and carbon intensity in China's provinces. Renewable and Sustainable Energy Reviews, **81**, 2935, **2018**.
23. LI Y., YANG X., RAN Q., WU H., IRFAN M., AHAMD M. Energy structure, digital economy, and carbon emissions: evidence from China. Environmental Science and Pollution Research, **28**, 64606, **2021**.
24. WANG W.Z., LIU L.C., LIAO H., WEI Y.M. Impacts of urbanization on carbon emissions: An empirical analysis from OECD countries. Energy Policy, **151**, 112171, **2021**.
25. YANG J., HAO Y., FENG C. A race between economic growth and carbon emissions: What play important roles towards global low-carbon development? Energy Economics, **100**, 105327, **2021**.
26. CHE S., WANG J. Digital economy development and haze pollution: evidence from China. Environmental Science and Pollution Research, **29**, 73210, **2022**.
27. CUI L., HOU Y., LIU Y., ZHANG L. Text mining to explore the influencing factors of sharing economy driven digital platforms to promote social and economic development. Information Technology for Development, **27** (4), 779, **2021**.
28. ZHANG W., LIU X.M., WANG D., ZHOU J.P. Digital economy and carbon emission performance: Evidence at China's city level. Energy Policy, **165**, 112927, **2022**.
29. MA D., ZHU Q. Innovation in emerging economies: Research on the digital economy driving high-quality green development. Journal of Business Research, **145**, 801, **2022**.
30. HABIBA U.M.M.E., CAO X.B., AHSAN A. Do green technology innovations, financial development, and renewable energy use help to curb carbon emissions? Renewable Energy, **193**, 1082, **2022**.
31. CONG L.W., XIE D.X., ZHANG L.T. Knowledge accumulation, privacy, and growth in a data economy. Management Science, **67**, 6480, **2021**.
32. SAVCHENKO A.B., BORODINA T.L. Green and digital economy for sustainable development of urban areas. Regional Research of Russia, **10**, 583, **2020**.
33. SU H.N., MOANIBA I.M. Does innovation respond to climate change? Empirical evidence from patents and greenhouse gas emissions. Technological Forecasting and Social Change, **122**, 49, **2017**.
34. YAN Z.M., DU K.R., YANFG Z.M., DENG M. Convergence or divergence? Understanding the global development trend of low-carbon technologies. Energy Policy, **109**, 499, **2017**.
35. KUANG H., AKMAL Z., LI F. Measuring the effects of green technology innovations and renewable energy investment for reducing carbon emissions in China. Renewable Energy, **197**, 1, **2022**.
36. KANG Z.Y., LI K., QU J.Y. The path of technological progress for China's low-carbon development: Evidence from three urban agglomerations. Journal of Cleaner Production, **178**, 644, **2018**.

37. JIA P.R., LI K., SHAO S. Choice of technological change for China's low-carbon development: Evidence from three urban agglomerations. Journal of Environmental Management, **206**, 1308, **2018**.
38. ZHAO T., ZHANG Z., LIANG S. Digital economy, entrepreneurship, and high-quality economic development: Empirical evidence from urban China. Management World, **36** (10), 65, **2020** [In Chinese].
39. REHMAN A., MA H., OZTURK I., ULUCAK R. Sustainable development and pollution: The effects of CO_2 emission on population growth, food production, economic development, and energy consumption in Pakistan. Environmental Science and Pollution, **29** (12), 17319, **2022.**
40. JIN B., HAN Y. Influencing factors and decoupling analysis of carbon emissions in China's manufacturing industry. Environmental Science and Pollution Research, **28**, 64719, **2021**.
41. REN Y.S., APERGIS N., MA C.Q., BALTAS K., JIANG Y., LIU J.L. FDI, economic growth, and carbon emissions of the Chinese steel industry: new evidence from a 3SLS model. Environmental Science and Pollution Research, **28**, 52547, **2021**.