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# The carbon emission reduction effect and mechanism analysis of digital economy: Evidence of prefecture-level cities in China

Zhihao Wang<sup>a</sup> and Ziyang Zhang <sup>a,b</sup>

<sup>a</sup>College of Management and Economics, Tianjin University, Tianjin, PR China; <sup>b</sup>Research Center for National Intellectual Property Strategy Implementation of Tianjin University, Tianjin University, Tianjin, PR China

## ABSTRACT

This study investigates the impact and mechanisms of carbon emission reduction associated with digital economy development, utilizing data from 265 prefecture-level cities in China during the period of 2003 to 2019. The comprehensive index of digital economy development at the prefecture level is evaluated using the entropy method, followed by empirical analysis employing the dual fixed effect model. The findings confirm a significant improvement in urban carbon emission reduction resulting from the digital economy. Mechanism analysis reveals that the digital economy enhances the carbon emission reduction effect in cities by promoting urban green innovation and reducing energy consumption intensity. Additionally, heterogeneity analysis demonstrates that the carbon reduction effect of digital economy development is influenced by factors such as city location, population size, and development type. By shedding light on the relationship between the digital economy and carbon emission reduction, this study offers valuable insights into the mechanisms through which the digital economy contributes to sustainable urban development.

## KEYWORDS

Digital economy; carbon emission level; energy consumption intensity; green innovation

## JEL CLASSIFICATION

C23; Q53; Q56; Q58

## I. Introduction

The global environmental problem, particularly carbon dioxide emission, has garnered significant attention due to its impact on the ecological crisis (Li et al. 2021). Excessive carbon dioxide emissions contribute to the rise in greenhouse gas concentration, resulting in global warming that severely hampers sustainable economic development. The IPCC report on climate change mitigation emphasizes the need for deep mitigation actions in all sectors, as global per capita carbon emissions reached their highest level between 2010 and 2019, albeit with a slowed growth rate, to limit global climate change to 1.5°C. As the largest developing country, China must balance economic growth with environmentally friendly development. Consequently, China has assumed a greater responsibility for controlling carbon dioxide emissions. It has committed to reaching a carbon peak by 2030 and striving for carbon neutrality by 2060. These goals mark China's transition towards green, innovative, and low-carbon development. It is

important to note that low-carbon development does not imply halting production; rather, it emphasizes environmentally conscious and creative development. However, compared to Western developed countries, China encounters various challenges in achieving its dual-carbon goals, including a large population and a slower transition (Xu 2023). In the pursuit of these goals, there is an increasing focus on the role of the digital economy in mitigating carbon emissions (Sovacool and Griffiths 2020).

The Future Earth international initiative, introduced by the Global Climate Action Summit (GCAS), recognizes the vital role of the digital economy in achieving carbon neutrality, especially considering the slow progress of the global economic low-carbon transition (Falk et al. 2018). This initiative advocates for the adoption of digital alternatives, transitioning from traditional to digital-driven economies, and reducing carbon emissions while maintaining production capacity. Many economies are actively aligning themselves with the

**CONTACT** Ziyang Zhang  zhangziyan@tju.edu.cn  Research Center for National Intellectual Property Strategy Implementation of Tianjin University, Tianjin University, Tianjin 300072, PR China

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pace of the digital economy (Zhou et al. 2021). According to the White Paper on China's Digital Economy Development (2022), China's digital economy accounted for 39.8% of the GDP, reaching RMB 45.5 trillion in 2021. It exhibited an impressive year-on-year nominal growth rate of 16.2%, surpassing the nominal GDP growth rate (Xinhua 2022). Recognizing the significance of digitalization, intelligence, and green integration, the Chinese government's 'Action Plan to Reach the Carbon Peak by 2030' prioritizes these aspects within the industrial sector for future endeavours. However, the question of whether developing a digital economy effectively reduces carbon emissions, as predicted by various think tanks, remains an open empirical question. Additionally, our understanding of the impacts of city location, population size, and development type on carbon emission reduction is still limited. As the Chinese government faces substantial pressure to reduce carbon emissions in pursuit of the 'double carbon' goal, these issues hold both theoretical and practical significance.

In summary, this study makes three distinct marginal contributions. Firstly, unlike previous research that mainly focuses on provincial-level analysis, we provide a fresh perspective by examining the digital economy at the meso-level of prefecture-level cities. We review the concept of the digital economy, consider the availability of relevant indicators, and construct comprehensive indicators to measure its development. This approach allows us to confirm the carbon emission reduction effect associated with the digital economy and address the research gap in meso-level digital economy studies. Secondly, through empirical investigation, we explore the quantitative relationship between the digital economy and carbon emissions. We analyse the transmission path of the carbon emission reduction effect, considering factors such as green innovation and energy consumption intensity. Additionally, we consider the heterogeneity arising from variations in resource endowment at the city level. This contribution enriches the existing literature on the impact of the digital economy on the environment and provides substantial empirical support for the carbon emission reduction effect facilitated by the digital economy. Thirdly, we provide practical strategies for

policymakers to effectively address the challenges associated with carbon emission reduction and accelerate the achievement of the 'double carbon' goal. Our recommendations include promoting the development of the digital economy, enhancing the level of green innovation and energy efficiency in cities, and fostering low-carbon sustainable development. These strategies offer feasible pathways for policymakers to mitigate carbon emissions and promote sustainable development.

The remain of this study is as follows: Section 2 is the literature review. Section 3 puts forward theoretical hypotheses. Section 4 provides research methods and data description. Section 5 analyzes the empirical results. Section 6 sets further conclusions and policy suggestions.

## II. Related works

### *The concept and effects of digital economy*

Given the 'double carbon' goal and the increasing concern for climate change and carbon emissions reduction, addressing the effective strategies to tackle these challenges has become a prominent issue in society. Consequently, scholars have conducted extensive research on the factors influencing carbon emissions. The emergence of the digital economy has provided a new avenue for achieving the 'double carbon' goal, and there is considerable interest in exploring its potential for reducing emissions (Ang 2007; Apergis and Payne 2009; Pirciog et al. 2023).

The concept of the digital economy was initially introduced by economist Don Tapscott to describe an economic system that extensively and efficiently utilizes information and communication technologies (Tapscott 2008). Subsequently, scholars have examined and explored the various aspects of the digital economy, including its definition, scope, measurement, and impact (Miao 2021). Initially, the concept of the digital economy was primarily associated with the digital technology industry. However, later research has shifted towards the direction of digital transformation (He, Du, and Tu 2023). Stavytskyy, Kharlamova, and Stoica (2019) argue that the digital economy involves transforming the economic and social structure of production organization through the digitization of production

factors, extending beyond the realm of information to encompass the development of industries and internet technologies (Kristoffersen et al. 2020; Riesener et al. 2019; Trevisan et al. 2021).

In addition to examining the concept of the digital economy, the existing literature also focuses on the spillover benefits resulting from technological breakthroughs, industrial structure upgrading, entrepreneurship, and talent flow associated with its development (Barbieri, Marzucchi, and Rizzo 2020; Teece 2018; Wang and He 2022; Wang and Petrovna 2021).

### **The carbon reduction effect of digital economy**

The digital economy plays a crucial role in enhancing the energy structure, upgrading traditional industries, and improving production efficiency. As a result, the Chinese government is committed to integrating and applying digital technologies in traditional resources, energy, industry, and the environment to facilitate the achievement of the ‘double carbon’ goal (Wang et al. 2022). However, there is no consensus among scholars regarding the actual impact of the digital economy on reducing carbon emissions.

Some academics suggest that the digital economy plays a crucial role in driving low-carbon development and contributes significantly to carbon reduction efforts (Zhang et al. 2022). This perspective is based on the ‘structural dividend hypothesis’, which argues that optimizing the industrial structure enhances the productivity of production factors, resulting in positive impacts on economic and environmental sustainability (Timmer and Szirmai 2000). For example, Acemoglu et al. (2012) assert that the digital economy enables environmental change monitoring and facilitates the development of energy-saving technologies through digital advancements, thereby enhancing production and management efficiency while promoting sustainable economic development. However, it is important to note that some academics have expressed concerns regarding the potential increase in carbon emissions and environmental burdens associated with the development of the digital economy (Shvakov and Petrova 2020). They argue that while digital technologies can improve productivity and energy

efficiency, the growing use of machinery and equipment, coupled with increased electricity demands and capital investment due to heightened productivity, can also lead to higher carbon emissions (Asongu, Le Roux, and Biekpe 2018; Salahuddin and Alam 2015).

The impact of the digital economy on carbon emissions is a topic of great interest and ongoing debate in academia. However, there is currently no consensus on the relationship between the two, and the discussion on the pathways through which the digital economy affects carbon emissions remains fragmented. Furthermore, most studies that examine this impact focus on provincial-level data, lacking a more detailed analysis. Therefore, it is crucial to expedite the development of the digital economy and assess its impact on carbon emissions at the meso-level, specifically at the city level. This approach is vital for achieving the ‘double carbon’ goal and providing a scientific assessment of how the digital economy influences carbon emissions.

### **III. Hypothesis development**

We analyse how the digital economy can reduce carbon emissions from four perspectives. Firstly, from an industry perspective, the development of the digital economy represents the growth of the digital industry and industrial digitization. Digital industries, such as the Internet and information service sectors, are more intelligence-oriented and greener compared to conventional enterprises, resulting in lower carbon emissions. Moreover, the digital industry enjoys a strong economic foundation, enabling increased investment in research and green innovation, which in turn yield better ecological benefits (Costantini and Mazzanti 2012). Additionally, the digital industry can also promote emission reduction in other sectors. Through the transformation and upgrading of traditional industries, digital technology facilitates the green and digital development of enterprises, enhances value creation, and subsequently reduces carbon emissions (Jensen 2021, 2022).

Secondly, from a city perspective, digital development accelerates the urbanization process and drives the digital transformation of cities. Pirciog et al. (2023) argue that the integration of digital tools such as big data and artificial intelligence can

reshape urban operations. By optimizing urban management practices, energy efficiency can be improved, leading to reduced energy consumption and lower carbon emissions.

Thirdly, from an energy perspective, the digital economy directly incorporates digital and intelligent features into energy development, production, and utilization processes. This entails reforming and innovating energy use, as well as promoting research, development, and utilization of renewable energy sources. By reducing reliance on non-renewable energy such as coal and oil (Solarin and Bello 2021), the digital economy fundamentally decreases the utilization of high-carbon emission resources, thereby significantly enhancing urban carbon emission reduction efforts.

Lastly, from the standpoint of China's carbon trading market, the launch of the national carbon trading market pilot cities in 2011 has played a crucial role in carbon emission reduction (Li et al. 2018; Pirciog et al. 2023). The development of digital technology can further enhance the efficiency and flexibility of the carbon market, facilitating the trading of carbon emission rights. Energy-efficient companies benefit from selling their excess carbon permits to other firms. This incentivizes enterprises to focus on low-carbon behaviour, motivating high carbon-emitting companies to undertake energy-saving innovation activities aimed at reducing carbon emissions (Wang and He 2022).

Based on these observations, we propose the following hypothesis:

**Hypothesis 1:** The development of the digital economy significantly enhances the carbon emission reduction effect in cities.

The digital economy contributes to market efficiency in several ways. Firstly, the advancement of Internet technology allows digital enterprises to lower production costs, thereby enhancing their competitive advantage. Through the analysis of digital data, enterprises can gain insights into consumer preferences and habits, enabling them to innovate more efficiently and reduce costs related to production, research, and development.

Secondly, digitization improves the security of information transmission and provides users with greater access to information, leading to a more transparent social market environment. This transparency facilitates scientific and technological innovation activities within enterprises (Friedrichs and Inderwildi 2013).

Thirdly, the development of the digital economy, along with the Internet of Things, enables innovation activities to occur simultaneously across different locations, breaking the limitations of time and space (Pirciog et al. 2023).

Lastly, the rapid progress of urban green technology drives the utilization and growth of clean energy in cities, optimizing the overall energy structure and promoting energy-saving and emission-reduction practices among enterprises. The advancement of green technology also encourages the adoption of green industries and products, facilitates the transformation and upgrading of traditional industries, and effectively contributes to urban carbon emission reduction efforts. The integration and upgrading of green technology innovation chains and industrial chains transform the production mode of traditional industries and guide the development of the industrial chain towards sustainability. This promotes the optimization and upgrading of traditional industries, reduces the carbon emissions associated with these industries, and facilitates the achievement of carbon emission reduction goals.

Based on these observations, we propose the following hypothesis:

**Hypothesis 2:** Digital economy improves urban green innovation and indirectly promotes urban carbon emission reduction effect.

The development of the digital economy drives the growth of the Internet industry, enabling enterprises to leverage digital information in their production and operational processes. This adoption of digital technology brings about new sources of competitiveness and improves enterprises' levels of production, research and development, and innovation. Additionally, digitization optimizes energy utilization technology, thereby influencing energy utilization efficiency and energy consumption (Sohag et al. 2015).

The use of digital technology has a transformative impact on energy utilization technology and production processes, leading to significant reductions in energy consumption and energy intensity during production (Herring and Roy 2007). The presence of a digital economy network facilitates positive spillover effects on energy-oriented enterprises, driving research and development efforts and the upgrading of energy utilization technology (Barbieri, Marzucchi, and Rizzo 2020).

Furthermore, the integration of Internet technology and energy-saving technology enables intelligent transformations, directly reducing total energy consumption in the production process and improving energy utilization efficiency, which contributes to the reduction of urban carbon emissions (Murtishaw and Schipper 2001).

Based on these observations, we propose the following hypothesis:

**Hypothesis 3:** Digital economy can promote the urban carbon emission reduction effect by reducing energy consumption intensity.

## IV. Research design

### Empirical models

Considering various factors affecting the development of the digital economy and carbon emission reduction, we choose the dual fixed effect model as follow:

$$CE_{it} = \beta_0 + \beta_1 DE_{it} + \beta_j X_{it} + \mu_i + \nu_t + \varepsilon_{it} \quad (1)$$

Where  $i$  and  $t$  represent city and year, respectively,  $CE_{it}$  represents the annual carbon emission level of each city, and  $DE_{it}$  represents the comprehensive index of each city's digital economy development level.  $X_{it}$  represents the control variable, encompassing factors such as urban scientific and technological development, urban construction, and industrial structure.  $\mu_i$  and  $\nu_t$  represent individual urban effect and time-fixed effect, respectively, and  $\varepsilon_{it}$  represents the random error term.

### Variable design and data collection

For this study, we have selected a sample of 265 prefecture-level cities. The sample covers the period from 2003 to 2019. To ensure the reliability of our data, we have excluded cities in Tibet, Hong Kong, Macao, and Taiwan due to limited data availability. Our primary data sources include official databases such as the China City Statistical Yearbook, China Economic Net, Chinese Research Data Services Platform (CNRDS), and China Stock Market & Accounting Research Database (CSMAR). To ensure comparability, we have applied logarithmic transformation to all non-ratio variables. In cases where data is missing, we have utilized interpolation techniques to supplement the missing values and obtain a more comprehensive sample. Finally, after preprocessing the data and making minor adjustments, we have conducted regression analysis to examine the relationships.

### Dependent variable

The dependent variable in this study is the carbon dioxide emission level of each city. Various scholars have proposed different calculation methods for estimating carbon emission levels. In our research, we have adopted the calculation method proposed by Hiete, Berner, and Richter (2001). This method considers that all forms of energy consumption can ultimately be converted into standard coal consumption. Therefore, we use Equation (2) to transform the energy consumption of each city into standard coal consumption and then calculate the total carbon dioxide emission for each city.

$$CO_2 = \sum_{i=1}^3 E_i \cdot LCV_i \cdot CEF_i \cdot COF_i \cdot Q_i \quad (2)$$

Where  $i$  respectively represents electricity (10,000 kw-h), gas (10,000 cubic metres), and liquefied petroleum gas (tons).  $E$  represents the energy consumption level.  $LCV$  represents the average low calorific value of energy.  $CEF$  represents carbon emission coefficient.  $COF$  represents carbon oxidation factor. The value of  $Q$ =carbon dioxide molecular weight/carbon molecular weight is 3.67.

### ***Independent variable***

In 2016, China put forward a proposition during the G20 Summit, highlighting the digital economy as an economic activity driven using information technology. Building upon this, the China Academy of Information and Communications Technology (CAICT) further refined the concept in 2021, identifying four key aspects of the digital economy: data valorization, digital industrialization, digital governance, and industrial digitization. Considering this official definition and the broad scope of the digital economy, we classify its developmental stage into three tiers and establish a set of nine indicators to assess its progress.

***Digital infrastructure.*** Infrastructure construction plays a vital role in facilitating the rapid development of the digital economy. In our study, we consider several indicators to measure digital infrastructure. These indicators include the number of Internet broadband access users, the total number of telecom services per capita, the number of mobile phone users at the end of the year, and the proportion of people employed in related industries. These indicators collectively provide insights into the state of digital infrastructure and its capacity to support the digital economy.

***Digital talents.*** High-quality talents are essential for driving the development of the digital economy, as it relies on the expertise and skills of individuals with a strong understanding of digital technology. In our study, we use two indicators to measure digital talents. Firstly, we consider the proportion of education expenditure to the general public budget expenditure. This indicator reflects the investment made by the government in education, which plays a crucial role in nurturing and cultivating digital talents. Secondly, we examine the number of students enrolled in regular universities. This indicator provides insights into the supply of potential talents in the digital field and their readiness to contribute to the digital economy.

***Value of the digital industry.*** The digital industry plays a significant role in the integration and development of the primary, secondary, and tertiary industries, marking the advanced stage of

industrial development propelled by the digital economy. In order to measure the value of the digital industry, we consider the proportion of the added value of the primary, secondary, and tertiary industries in GDP. This indicator captures the contribution of the digital industry to the overall economic output and provides insights into the extent of its integration with the broader economy.

### ***Control variables***

This study incorporates various city characteristics to examine their impact on both carbon emissions and the development of the digital economy. The included city characteristics are as follows:

***Scientific and technological capability.*** This is measured by the logarithm of the government's per capita scientific and technical fiscal expenditure. It reflects the investment in research and development and the level of technological advancement.

***Level of economic development.*** This is measured by per capita GDP, which indicates the overall economic prosperity and productivity within the city.

***Level of financial development.*** The logarithm of each financial institution's per capita loan balance is used as a measure of financial development. It represents the availability of financial resources and the level of financial intermediation.

***Population density.*** This is measured by the number of people per unit area, providing insight into the population concentration and density within the city.

***Coal consumption level.*** Given the significant impact of coal use on urban carbon emissions and the digital economy, total coal consumption is used as a measure. It represents the extent of coal usage within the city.

***Industrial structure.*** The proportion of the added value of the secondary and tertiary industries in GDP is used to assess the industrial structure and the contribution of different sectors to the city's economy.

**Table 1.** Descriptive statistics of major variables.

Variables	Variable definition	Mean	Median	Std.	Obs.
<i>lnCE</i>	The relative value of total urban CO <sub>2</sub> emissions (megatons)	1.775	1.669	1.050	3642
<i>ACE</i>	Carbon dioxide emissions per unit of GDP (tons/10,000 yuan)	0.727	0.489	0.976	3642
<i>lnPCE</i>	The relative value of urban carbon dioxide emissions per capita (ton/person)	0.430	0.378	1.070	3642
<i>DE</i>	The index of the digital economy calculates by the entropy value method	0.127	0.122	0.027	3642
<i>lnSE</i>	The relative value of per capita expenditure on science and technology (yuan/person)	3.910	3.969	1.507	3642
<i>AGDP_1</i>	Per capita GDP (million Yuan)	0.044	0.033	0.111	3642
<i>PD</i>	Population density	463.200	408.500	321.100	3642
<i>lnALB</i>	Per capita balance of loans from financial institutions (yuan/person)	10.110	10.050	1.077	3642
<i>lnCC</i>	The relative value of urban coal consumption (tons)	9.510	9.517	0.674	3642
<i>lnAUC</i>	The relative value of construction land per capita (square kilometers/10,000 people)	0.268	0.206	0.209	3642
<i>lnFDI</i>	Value of the amount of foreign capital employed (US \$10,000)	9.948	10.020	1.820	3642
<i>IS</i>	The proportion of the added value of secondary and tertiary industries in GDP	89.220	89.260	68.390	3642
<i>lngrva</i>	Number of urban green patents authorized (PCS)	272.300	33.000	1083.999	3611
<i>ECI</i>	Energy intensity, energy consumption per unit of GDP	0.727	0.489	0.976	3642
<i>Policy</i>	Dummy variables of pilot cities of 'Broadband China' policy	0.121	0.000	0.326	4051

**Urban construction level.** Considering the substantial carbon emissions associated with urban construction and development, the per capita construction land area is selected as a measurement index. It captures the extent of urban construction and expansion.

By considering these city characteristics, the study aims to comprehensively analyse their influence on carbon emissions and the development of the digital economy.

### Descriptive statistics

We have conducted descriptive statistics on the variables. Table 1 shows the main results.

## V. Empirical results and analyses

### Baseline regression results

During the regression analysis, selecting an appropriate econometric model is crucial to ensure unbiased and valid estimation of regression parameters. Therefore, this study employs mixed effect, individual fixed effect, and dual fixed effect models as the benchmark regressions. The regression results from these three models were compared and considered in conjunction with the actual context to determine the most suitable benchmark regression model. The empirical results are presented in Table 2.

**Table 2.** Baseline regression results.

Variables	(1) lnCE	(2) lnCE	(3) lnCE
<i>DE</i>	5.067** (1.86)	-0.916 (0.76)	-2.754*** (0.79)
<i>lnSE</i>	-0.046** (0.02)	0.055*** (0.02)	0.066** (0.02)
<i>AGDP_1</i>	3.643** (1.74)	0.315 (1.09)	-0.024 (1.10)
<i>PD</i>	0.000** (0.00)	0.000*** (0.00)	0.000* (0.00)
<i>lnALB</i>	0.404*** (0.06)	0.281*** (0.05)	0.095 (0.07)
<i>lnCC</i>	0.234*** (0.07)	0.341*** (0.07)	0.386*** (0.11)
<i>lnAUC</i>	0.138 (0.22)	0.299** (0.12)	0.106 (0.13)
<i>IS</i>	0.031*** (0.00)	0.024*** (0.00)	0.019*** (0.00)
<i>lnFDI</i>	0.040* (0.02)	0.024** (0.01)	0.005 (0.01)
Constant	-8.463*** (0.95)	-7.184*** (0.72)	-4.894*** (0.89)
Time fixed effects	No	No	Yes
Individual fixed effects	No	Yes	Yes
Observations	3642	3642	3642
R <sup>2</sup>	0.632	0.782	0.788

Robust standard errors in parentheses. Statistical tests are two-sided. \*\*\* $p < 0.01$ , \*\* $p < 0.05$ , \* $p < 0.1$ .

The results of the mixed effects regression model in Column (1) indicate a positive correlation between the development level of the digital economy and the level of carbon emissions, which is not consistent with the theoretical expectations and economic reality of this study. Therefore, the findings from the mixed effects regression model are not considered for further analysis.

In Column (2), the empirical results of the individual fixed effect model are presented. By incorporating the fixed effects of individual cities, the development of the digital economy shows a negative but insignificant impact on carbon emissions. This result can be attributed to two main factors: Firstly, China encompasses a vast territory with numerous cities, each having different resources, varying levels of urban development, significant disparities in digitalization, and noticeable individual differences. Secondly, as urbanization and digitization deepen in China, there is an apparent temporal trend in the development of the digital economy and carbon emission levels. Therefore, it is essential to control for both city-specific effects in the model. Based on the above analysis, it is concluded that the dual fixed effect model is the most appropriate benchmark regression model. This model can comprehensively and systematically capture the objective facts by considering both the individual city effects and the time-fixed effects.

Column (3) presents the empirical results of the dual fixed effect model, revealing a significant negative relationship between the digital economy and urban carbon emissions. This finding supports Hypothesis 1, which posits that the digital economy contributes to reducing carbon emissions in urban areas. The development of the digital economy enhances the level of digitization within cities, optimizes information transmission methods, improves energy utilization efficiency, and facilitates the green and low-carbon development of urban areas. Consequently, it leads to a decrease in carbon emissions, aligning with the goal of achieving the '30·60' double carbon goal. Among the control variables, there is a significant positive correlation between urban science and technology expenditure and carbon emission levels, with a significance level of 5%.

Science and technology expenditure primarily covers the costs of scientific research and the construction of research infrastructure, including the development and testing of new products such as trial production and intermediate testing. These activities consume energy and resources, resulting in an increase in carbon emissions. As a result, an increase in science and technology expenditure significantly diminishes the carbon emission reduction effect in cities. Both urban energy consumption and industrial structure exert a significant positive impact on carbon emissions. This indicates that higher levels of energy consumption and a larger share of the secondary and tertiary industries contribute to increased carbon emissions in urban areas. The industrial structure reflects the level of urban economic development and growth potential, influencing the trend of energy intensity. Although the tertiary industry possesses significant emission reduction potential and can effectively mitigate carbon emissions, it does not fully offset the carbon emissions resulting from energy consumption and industrial activities. Consequently, the industrial structure hampers the reduction of carbon emissions in urban areas. Overall, the findings demonstrate that the digital economy plays a crucial role in promoting the reduction of urban carbon emissions. However, certain factors, such as increased science and technology expenditure, higher levels of energy consumption, and the composition of the industrial structure, can counteract the effectiveness of carbon emission reduction efforts.

### **Robustness tests**

#### **Replace digital economy indicators**

Considering that the measurement of the digital economy can vary from different perspectives, we have replaced the original explanatory variable with the digital financial inclusion index to assess the robustness of our findings. Column (4) of [Table 3](#) presents the empirical results based on this replacement. Remarkably, the estimated coefficient and significance of the digital economy's impact on urban carbon emissions remain consistent with the baseline results. This robustness check

**Table 3.** Robustness test results.

Variables	(1) lnCE	(2) ACE	(3) lnPCE	(4) lnCE
DE	-3.388** (1.68)	-2.970*** (1.03)	-3.139*** (0.74)	
Index				-0.006* (0.00)
Constant		-2.612* (1.46)	-5.376*** (0.77)	-8.760** (3.22)
Kleibergen-Paap rk LM statistic	9.309 ( 0.0023 )			
Kleibergen-Paap rk Wald F statistic	557.522 ( 29.277 )			
Control variables	Yes	Yes	Yes	Yes
Time fixed effects	Yes	Yes	Yes	Yes
Individual fixed effects	Yes	Yes	Yes	Yes
Observations	3464	3660	3642	2071
R <sup>2</sup>	0.778	0.465	0.771	0.371

Robust standard errors in parentheses. Statistical tests are two-sided. \*\*\* $p < 0.01$ , \*\* $p < 0.05$ , \* $p < 0.1$ .

**Table 4.** The effect of 'Broadband China' policy on carbon emission reduction.

Variables	(1) lnCE	(2) lnCE
Policy	-0.154*** (0.05)	-0.111*** (0.04)
Constant	0.915*** (0.04)	-5.433*** (0.98)
Control variables	No	Yes
Time fixed effects	Yes	Yes
Individual fixed effects	Yes	Yes
Observations	3992	3729
R <sup>2</sup>	0.761	0.788

Robust standard errors in parentheses. Statistical tests are two-sided. \*\*\* $p < 0.01$ , \*\* $p < 0.05$ , \* $p < 0.1$ .

confirms that the carbon emission reduction effect of the digital economy remains intact and reliable.

### Replace the carbon emission index

The population size of each city varies significantly, and as human beings are the primary contributors to carbon emissions, it has a substantial impact on overall carbon emissions. To account for this, per capita carbon emissions are considered as a crucial indicator for measuring carbon emissions, as it reflects fairness and efficiency in economic development. Additionally, GDP serves as a vital measure of economic development. It is important to acknowledge the carbon emissions resulting from economic growth. Furthermore, carbon emission intensity provides insights into the relationship between economic growth and carbon emissions. Therefore, in our analysis, we replace the explanatory variable with the above two indicators for a comprehensive assessment.

The regression results in column (2) of Table 3 indicate a negative impact of the digital economy

on carbon emission intensity. This means that as the digital economy develops, there is a decrease in the amount of carbon emissions produced per unit of economic output. Similarly, the regression results in column (3) of Table 3 demonstrate a negative impact of the digital economy on per capita carbon emissions. This implies that as the digital economy advances, there is a reduction in the amount of carbon emissions generated per individual. These consistent findings across different measures of carbon emissions indicate the robustness of the carbon emission reduction effect associated with the development of the digital economy.

### Instrumental variable method

On one hand, cities experiencing rapid development of the digital economy and possessing advanced digital technology can contribute to a certain reduction in carbon emissions. On the other hand, cities with higher carbon emission levels may face constraints in the development of the digital economy due to their industrial structure. As a result, a problem of reverse causality arises in this study.

To address this issue, the number of fixed telephones per 100 people in each city in 1984 was selected as an instrumental variable to address endogeneity concerns (Tao, Wang, and Zhu 2016). The progress of Internet technology serves as the foundation for the development of the digital economy, and traditional telecommunication infrastructure, such as fixed telephones, influences the development of Internet technology in terms of

technical advancements and usage patterns. Furthermore, traditional information tools like fixed-line phones have become less popular and have witnessed a decline in usage over time, resulting in minimal urban carbon emissions. Thus, this variable meets the requirements of being a suitable instrumental variable in terms of relevance and exclusivity.

To conduct regression analysis with only one year's data, which poses a challenge, we followed the data processing method proposed by Nunn and Qian (2014) by incorporating time panel data interaction terms. We constructed an interaction term using the number of national Internet users from the previous year in each city and the instrumental variables. This interaction term serves as the instrumental variable for the comprehensive index of the digital economy.

Column (1) in Table 3 presents the regression results using instrumental variables, demonstrating that the development of the digital economy continues to exhibit a significant negative impact on carbon emissions even after considering endogeneity. Thus, the selection of instrumental variables is deemed reasonable, and the carbon emission reduction effect of the digital economy remains robust.

### Exogenous policy impact

The development of the digital economy in cities is influenced by various factors, including the level of local economic development, energy consumption, and technological innovation capability. Similarly, these factors also impact a city's carbon emissions. As a result, concerns about biased estimation results and endogeneity arise due to the presence of reverse causality. In our study, we aim to address these concerns by evaluating the implementation effect of an exogenous policy directly linked to the digital economy.

One notable policy in this context is the 'Broadband China' policy, which was introduced by the Chinese State Council in 2013. This policy has demonstrated significant success in expanding network coverage and improving network speed, providing a crucial opportunity for the advancement of China's digital economy (Jia, Xie, and Wang 2023). For example, in Wuzhong, e-commerce services have been

successfully implemented in rural areas, facilitating the exchange of industrial products between rural and urban areas, and enabling the distribution of agricultural specialties to urban centres. The 'Broadband China' policy has effectively strengthened digital infrastructure and expedited the development of the country's digital economy. Consequently, the Chinese government identified over 120 cities for this policy during the three-year period from 2014 to 2016.

To investigate the causal mechanism between the digital economy and carbon emission reduction, we employ a multi-period Difference-in-Differences (DID) model following the approach proposed by Beck, Levine, and Levkov (2010). This model allows us to analyse the long-term effects of the digital economy on carbon emissions. The specific framework of the model is as follows:

$$CE_{it} = \beta_0 + \beta_1 Policy_{it} + \beta_j X_{it} + \mu_i + \nu_t + \varepsilon_{it} \quad (3)$$

Where  $Policy_{it}$  is the dummy variable of whether city  $i$  implements the 'Broadband China' policy in year  $t$ , if implemented, the value is 1; Otherwise, the value is 0. Other variables in Equation (3) have the same meaning as equation (1).

Based on the regression results in Table 4, the carbon emission reduction effect of the 'Broadband China' policy remains significant regardless of the inclusion of control variables. This robust conclusion supports the notion that the digital economy promotes carbon emission reduction.

To assess the feasibility of the difference-in-differences (DID) model, this study conducted a parallel trend verification, the results of which are presented in Figure 1.

Figure 1 demonstrates that the 'Broadband China' policy satisfies the parallel trend test, indicating a consistent trend among the treated and control groups prior to policy implementation. Additionally, there is a time lag associated with the policy, where significant carbon reduction effects start to emerge in the third year following its implementation.

To assess the potential influence of unobservable random factors on the effects of the 'Broadband China' policy, a placebo test was conducted. The policy was implemented in different cities during the years 2013, 2014, and 2016, encompassing

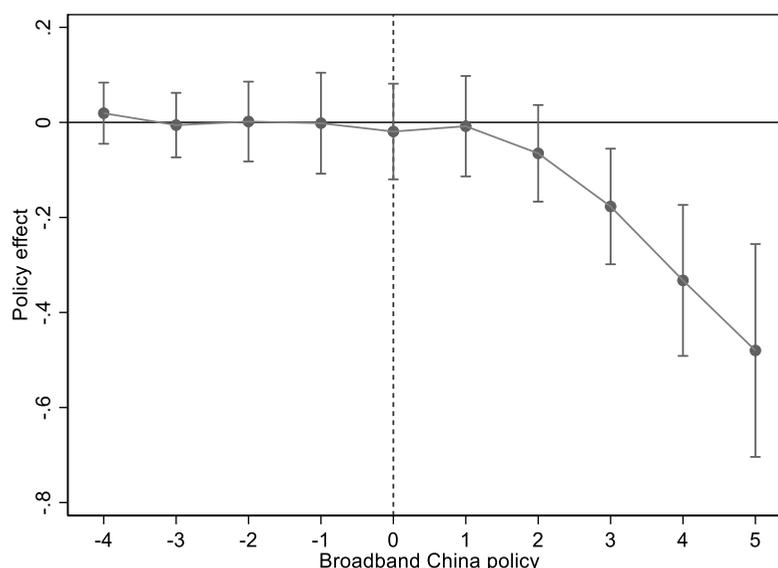


Figure 1. Parallel trend test chart.

a total of 34, 35, and 36 cities, respectively. In the placebo test, an equal number of cities were randomly selected, and a random year was assigned as the pseudo policy time-point. By using the DID model, the regression coefficient of the pseudo treatment variable was estimated. This process was repeated 500 times, and the distribution of coefficients and p-values from these iterations is illustrated in Figure 2.

The estimates of the pseudo treatment variable exhibited a nearly normal distribution, with an average close to zero. Most of the p-values exceeded 0.1, indicating no statistically significant relationship. However, the true estimate of  $-0.111$

deviated as an outlier in the left tail of the normal distribution. Fewer estimates yielded p-values below 0.05. These findings suggest that the observed carbon reduction effect can be attributed to the implementation of the 'Broadband China' policy, rather than being a result of random factors.

### *Mechanisms analyses*

The study constructs an intermediary mechanism model to explore the feasible path through which the development of the digital economy can influence the reduction of carbon emissions.

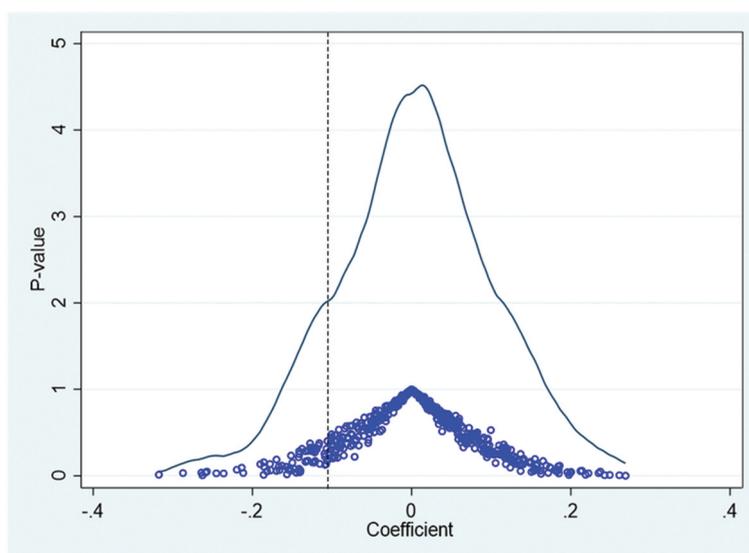


Figure 2. Placebo test results.

$$Y_{it} = \alpha_0 + \alpha_1 \cdot DE_{it} + \alpha_j X_{it} + \mu_i + \nu_t + \varepsilon_{it} \quad (4)$$

$$CE_{it} = \alpha_0 + \alpha_1 DE_{it} + \alpha_2 Y_{it} + \alpha_j X_{it} + \mu_i + \nu_t + \varepsilon_{it} \quad (5)$$

Where  $Y_{it}$  represents the intermediary variable urban green innovation (*Ingrva*) or energy consumption intensity (*ECI*). Other variables in Equation (4) and Equation (5) have the same meaning as Equation (1).

We selected the number of urban green patents as an indicator of urban green innovation and analysed the intermediary mechanism. The standard coal coefficient method was employed to calculate energy consumption for each type. The results are presented in Table 5.

Columns (1) and (2) in Table 5 present the regression results of the second step of the mediation analysis. It indicates that the digital economy has a significant positive impact on urban green innovation and a significant negative impact on energy consumption intensity. Column (3) focuses on the third step regression analysis, examining the intermediary role of urban green innovation and energy consumption intensity in the carbon emission reduction effect of digital economy development. The coefficient estimates for both urban green innovation and energy consumption intensity are significant, while the coefficient estimates for the digital economy are not substantial. This suggests that urban green innovation and energy consumption intensity serve as complete intermediary variables.

The results of the intermediary regression analysis demonstrate that the enhancement of urban green

innovation and the reduction of energy consumption intensity are viable pathways through which the digital economy can contribute to carbon emission reduction. The digital economy has played a significant role in improving the level of green innovation in cities, leading to positive externalities. By promoting urban green innovation, the digital economy accelerates the process of reducing carbon emissions in urban areas, supporting the validation of hypothesis 2. Furthermore, the development of the digital economy significantly decreases energy consumption intensity and enhances energy utilization efficiency, effectively contributing to urban carbon emission reduction, thereby confirming hypothesis 3.

## Heterogeneity analyses

### Regional heterogeneity

Due to the existence of the ‘digital divide’ across different regions of China, there are notable disparities in digital infrastructure development and internet penetration among various areas (Jiang and Murmann 2022). To account for this regional variation, we categorized the cities into three groups: eastern, central, and western regions, and performed regression analysis. The empirical results are presented in Table 6.

In eastern China, the digital economy has a significant negative impact on carbon emissions. However, for the central region, there is no observed carbon emission reduction effect, while the western region shows some potential for reducing carbon emissions, although this finding lacks statistical significance.

**Table 5.** Results of mediating effect test.

Variables	(1) <i>Ingrva</i>	(2) <i>ECI</i>	(3) <i>lnCE</i>
<i>DE</i>	2.195*** (0.38)	-5.254* (2.82)	-0.816 (0.65)
<i>Ingrva</i>			-0.382*** (0.10)
<i>ECI</i>			0.211*** (0.06)
Constant	1.434 (0.98)	-1.694 (1.68)	-3.985*** (0.80)
Control variables	Yes	Yes	Yes
Time fixed effects	Yes	Yes	Yes
Individual fixed effects	Yes	Yes	Yes
Observations	3617	3660	3611
R <sup>2</sup>	0.425	0.319	0.836

Robust standard errors in parentheses. Statistical tests are two-sided. \*\*\*  $p < 0.01$ , \*\*  $p < 0.05$ , \*  $p < 0.1$ .

**Table 6.** Results of regional heterogeneity analysis.

Variables	(1) Eastern region	(2) Central region	(3) Western region
	lnCE	lnCE	lnCE
DE	-4.429*** (0.87)	0.675 (0.90)	-0.139 (1.43)
Constant	-6.270*** (1.49)	-6.184*** (1.39)	-2.017** (0.80)
Control variables	Yes	Yes	Yes
Time fixed effects	Yes	Yes	Yes
Individual fixed effects	Yes	Yes	Yes
Observations	1491	1333	818
R2	0.848	0.801	0.738

Robust standard errors in parentheses. Statistical tests are two-sided. \*\*\* $p < 0.01$ , \*\* $p < 0.05$ , \* $p < 0.1$ .

**Table 7.** Average of some indicators in each region.

Mean	Eastern region	Central region	Western region	The whole nation
Internet infrastructure	0.0352	0.0221	0.0248	0.0279
Added value of the secondary industry (%)	48.740	48.674	48.329	48.612
Value added of tertiary industry (%)	44.303	37.824	38.063	40.428

Based on the information in Table 7, we can make the following conclusions. On one hand, the level of internet development varies across regions. The eastern region, characterized by its large population and prosperous economy, has experienced rapid growth in internet infrastructure. This has facilitated resource and knowledge sharing, leading to more efficient resource allocation and higher energy use efficiency. Consequently, the digital economy significantly promotes carbon emission reduction in the eastern region. In contrast, the central region has witnessed slower internet development, and the establishment of internet infrastructure contributes to the rapid growth of energy consumption without a significant reduction in carbon emissions. As a result, the carbon emission reduction effect of the digital economy in the central region is insignificant. In the western region, which has a vast area and lower population density, digital infrastructure construction is relatively imperfect, and internet development is less advanced. Hence, the digital economy in western China has yet to demonstrate a notable ability to reduce carbon emissions.

On the other hand, the proposal of the 'double carbon' goal has instilled the concept of green development in people's minds. Promoting enterprise transformation and upgrading, pursuing high-quality economic development, and embracing green practices have become the dominant themes of contemporary social development. The eastern region, undergoing a critical period of transitioning

from a factor-driven to an innovation-driven economy (Tao, Wang, and Zhu 2016), experiences significantly higher value-added in the tertiary industry compared to other regions. The positive externalities resulting from the digital economy's development play a crucial role in promoting carbon emission reduction. In central China, which serves as a prominent manufacturing hub with a high proportion of heavy industries and limited development in the export-oriented sector, achieving short-term decoupling from carbon emissions proves challenging (Du, Li, and Yan 2019). The transformation and upgrading of regional heavy industries driven by the digital economy require considerable time and gradual progress. Consequently, the carbon emission reduction effect of the digital economy in central China is insignificant. As for the western region, which is currently undergoing industrialization, the digital economy can facilitate the initiation and development of green and clean industries. However, during the early stages, the 'rebound' effect of digital economy development on carbon emissions is more pronounced. Additionally, due to limitations in knowledge, technology, and industrial structure, the western region faces difficulties in swiftly promoting the transformation and upgrading of regional industries. Therefore, the carbon emission reduction effect of the digital economy in western China is insignificant.

### Population heterogeneity

According to results, humans are the primary energy consumers, and carbon emissions from residential activities rank second only to those from the industrial sector (Picano, Mangia, and D'Andrea 2023; Pirciog et al. 2023). In this study, we grouped the samples based on population size, and the results are presented in Table 8.

As observed in Table 8, the carbon emission levels associated with the digital economy are significant for big cities and super-mega cities at a significance level of 1%. Table 9 further reveals that the economic development level of these larger cities is significantly higher compared to other city types. The process of digitization is more advanced and impactful in these cities, playing a prominent role in reducing carbon emissions. Conversely, the impact on medium-sized cities is significantly positive at the 1% significance level, indicating that the development of the digital economy has improved the carbon emission levels in these cities. Medium-sized cities are often characterized by a dominance of heavy industries, such as manufacturing, with lower levels of economic development, a greater transfer of high-energy-consuming industries, and a lower degree of digitization. Moreover, the construction of internet infrastructure in these cities also requires a considerable amount of energy consumption, which contributes to increased urban carbon emissions and hinders the effectiveness of carbon emission reduction efforts. Consequently, the digital economy in medium-sized cities exhibits a significant negative correlation with the carbon emission reduction effect.

### Urban heterogeneity

The development characteristics of cities have a significant impact on the development of the digital economy and the level of urban carbon emissions. To account for these differences, we categorized cities into four types: old industrial cities, smart cities, service cities, and other cities (Guo, Wang, and Dong 2022). The results are presented in Table 10.

In old industrial cities, the carbon emission reduction effect of the digital economy is found to be insignificant. However, for smart cities and service cities, there is a negative and statistically significant coefficient between digital economy development and the urban carbon emission level, with a significance level of 5%. In other cities, the digital economy significantly and negatively impacts carbon emissions. Overall, the development of the digital economy promotes carbon reduction effects in all city types except for old industrial areas.

From Table 11, it can be inferred that old industrial cities have a relatively large scale of heavy chemical industries, resulting in high energy consumption. The digital economy's ability to improve the industrial structure of these cities is slow, and optimizing resource utilization efficiency poses significant challenges. As a result, the digital economy in old industrial cities does not play a significant role in carbon emission reduction. Additionally, the 'double carbon' goal presents even greater challenges for these cities (Friedrichs and Inderwildi 2013).

On the other hand, the promotion and application of digital information technology in smart city

**Table 8.** Results of population heterogeneity analysis.

Variables	(1) Medium sized cities lnCE	(2) Big cities lnCE	(3) Super-mega cities lnCE
DE	9.297*** (2.45)	-3.414*** (0.94)	-4.389*** (1.38)
Constant	-0.554 (2.95)	-4.531*** (1.48)	-5.705*** (1.22)
Control variables	Yes	Yes	Yes
Time fixed effects	Yes	Yes	Yes
Individual fixed effects	Yes	Yes	Yes
Observations	110	2144	1388
R <sup>2</sup>	0.851	0.747	0.857

Robust standard errors in parentheses. Statistical tests are two-sided. \*\*\* $p < 0.01$ , \*\* $p < 0.05$ , \* $p < 0.1$ .

**Table 9.** Mean results of some indexes in cities with different populations.

Mean	Medium-sized cities	Big cities	Super-mega cities	The whole nation
Economic development GDP (100 million yuan)	4001797	1.22*10 <sup>7</sup>	3.35*10 <sup>7</sup>	1.97*10 <sup>7</sup>
Added value of the secondary industry (%)	57.423	49.393	46.352	48.612
Value added of tertiary industry (%)	35.080	40.206	41.395	40.428

**Table 10.** Heterogeneity results of different types of cities.

Variables	(1) Old industrial cities	(2) Smart cities	(3) Service cities	(4) Other cities
	lnCE	lnCE	lnCE	lnCE
DE	-1.182	-3.106**	-9.935**	-4.940***
	-1.16	-1.31	-3.03	-1.11
Constant	-3.425*	-5.282***	1.363	-5.277***
	-1.73	-1.87	-3.01	-1.52
Control variables	Yes	Yes	Yes	Yes
Time fixed effects	Yes	Yes	Yes	Yes
Individual fixed effects	Yes	Yes	Yes	Yes
Observations	1259	898	161	1324
R <sup>2</sup>	0.791	0.834	0.913	0.791

Robust standard errors in parentheses. Statistical tests are two-sided. \*\*\* $p < 0.01$ , \*\* $p < 0.05$ , \* $p < 0.1$ .

**Table 11.** Mean results of some indexes in different types of cities.

Mean	Old industrial cities	Smart cities	Service cities	Other cities	The whole nation
Coal consumption (10,000 tons)	9.540	9.503	9.235	9.451	9.486
Added value of the secondary industry (%)	51.569	48.146	45.705	46.515	48.643
Value-added of tertiary industry (%)	39.187	43.088	46.153	39.108	40.428

construction create an economic environment with economies of scale and a long-tail effect, providing convenient public services for economic digitization (Jensen 2021, 2022). This accelerates the digital transformation of industries, explores new paths for industrial digitization, and transforms the operation and service modes of cities. Consequently, the carbon emission reduction effect brought about by the digital economy in smart cities is remarkable.

Service-oriented cities primarily focus on the tertiary industry, with minimal presence of high-energy industries. The digital economy exhibits higher efficiency in optimizing resource utilization, leading to a more significant carbon emission reduction effect in these cities.

## VI. Conclusions

Since the 1990s, the rapid development of electronic computer technology has given rise to a new mode of economic operation known as the digital economy. During this crucial period of economic reform and transition, our country is actively considering low-carbon development and the synchronized development of the green economy (Guo, Wang, and Dong 2022). In this study, we have established a unique index framework for measuring the digital economy and utilized the entropy method to calculate the comprehensive index of the digital economy at the prefecture-level city level in China. Using

the urban carbon emission level as the dependent variable, we have employed a dual fixed effect model to empirically examine the carbon emission reduction effect of digital economy development. Furthermore, we have verified that the level of urban green innovation and energy consumption intensity serve as two feasible pathways for achieving the carbon emission reduction effect of the digital economy. Finally, we have analysed the heterogeneity of the main effect from three perspectives: regional, population, and urban heterogeneity. The key findings of this study are as follows:

Firstly, the development of the digital economy can significantly promote the reduction of carbon emissions in cities. Even after conducting robustness tests, such as replacing dependent variables, changing digital economy measurement indicators, and conducting tests for endogeneity and policy impact, the carbon emission reduction effect of the digital economy remains statistically significant.

Secondly, the mechanism test reveals that the reduction in urban carbon emissions can be attributed to two factors. On one hand, the development of the digital economy improves the industrial structure, optimizes energy consumption, enhances resource allocation efficiency, and directly promotes the reduction of urban carbon emissions. On the other hand, the digital economy indirectly stimulates urban green innovation, enhances energy efficiency,

accelerates the development of green industries, such as clean new energy, and indirectly contributes to the reduction of urban carbon emissions.

Finally, the results of the heterogeneity test indicate that the carbon emission reduction effect of the digital economy is significant in the eastern region of China. This effect is particularly pronounced in large and super-mega cities. Among different types of cities, the development of the digital economy has a more substantial impact on carbon emission reduction in smart cities and service cities. However, the effect is insignificant in old industrial cities.

Based on these findings, we propose three policy recommendations. Firstly, the country should strengthen the application of digital technology in energy conservation and emission reduction. This entails prioritizing the application of digital technologies in areas such as the Internet and other advanced intelligent fields. Additionally, attention should be paid to the role of the digital economy as a catalyst and accelerator for driving the transformation and upgrading of traditional industries.

Secondly, emphasis should be placed on the role of digital technology in promoting green innovation. There should be active encouragement for the development of the digital economy, particularly in advancing the growth of clean energy and other environmentally friendly industries. Efforts should also be made to ensure the rationality and effectiveness of digital technology in energy allocation, thereby reducing overall energy consumption.

Thirdly, considering the different types of cities and their unique development characteristics, the country should adopt a tailored approach in developing the digital economy. Local conditions should be considered, and the development of the digital economy should be pursued in a manner that aligns with specific city contexts. Furthermore, the state should encourage enterprises to phase out outdated products, promote industrial upgrading, and achieve a win-win situation that combines green economic development with environmentally friendly practices.

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### ORCID

Ziyan Zhang  <http://orcid.org/0000-0002-3782-1414>

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