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Digital infrastructure construction drives green economic transformation: evidence from Chinese cities

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Existing studies mostly discussed the impact of transportation infrastructure on the economy and society. However, the environmental performance of digital infrastructure has been discussed less. This study explores the effect of digital infrastructure construction on green economic transformation based on theoretical analysis. Using the Broadband China policy as a quasi-natural experiment, the authors construct a staggered difference-in-difference (DID) model and empirically assess the effect of digital infrastructure on green economic development with panel data of Chinese 271 cities from 2003 to 2019. First, the main results indicate that digital infrastructure can enable green economic performance in Chinese cities. The results remain robust after considering the heterogeneous treatment effects, placebo test, and excluding the effect of other policies. Second, the heterogeneity results indicate that green economic performance in eastern and economically developed cities benefits more from digital infrastructure construction. Finally, by enhancing energy efficiency, fostering digital industrialization, and stimulating green technology innovation, the digital infrastructure indirectly contributes to the urban green economy development. This study put forward some constructive policy suggestions to promote green economic transformation from the digital infrastructure construction perspective.

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Introduction

Resource depletion and environmental degradation have gradually been regarded as significant constraints on sustainable economic growth. Environmental pollution also threatens human health (H. Zhang et al., 2022). China has become the world's largest consumer of fossil fuels and carbon dioxide emitter as a result of its rapid economic development, which has resulted in significant environmental degradation (Liang et al., 2021). The Chinese economy urgently needs green transformation to achieve economic growth while achieving resource conservation and environmental improvement (Musango et al., 2014). Green economic development is an economic development model that is oriented toward saving resources and protecting the environment. Green economic transformation is an effective path to high-quality economic growth and an inherent requirement to cope with climate change. Under the background of resource scarcity and environmental degradation, it is of great practical significance to promote green transition.

Green economic development needs to be put into practice. As the main center of population, industries, commercial activities, and resource consumption, cities should become the forerunners of economic green transformation (Long et al., 2021). With the increasing workforce specialization, the labor force has accelerated the transfer from traditional agricultural activities to industry and service sectors, pushing rapid urban population growth. Urban expansion can exert an agglomeration effect and promote technological progress, which may also bring about traffic congestion, environmental deterioration, energy wastage, and other "urban diseases". Cities emit approximately 70% of global carbon dioxide emissions (Shen et al., 2023), which have yet to shake off the economic growth model of high resource consumption, high emissions, and heavy expansion, urgently needing to transform the economic growth model. With the advancement of urbanization, the problem of resource consumption and environmental deterioration may be further aggravated. In tackling global climate change and protecting the environment, promoting urban green economic development has become a common challenge all countries face. According to the latest seventh census, China's urbanization rate is 63.9% (D. Wu et al., 2023). China, as a country with the most rapid urbanization process in the world, is facing a particularly severe situation. Therefore, exploring the green transformation path of the urban economy is not only of great theoretical value and practical meaning for China but also of great significance for other developing countries.

Effectively promoting the green transformation of cities is a difficult problem in reality, which requires joint efforts from all walks of life to explore novel development models. As modern society enters the digital era, digital technologies are developing vigorously, constantly integrating into all aspects of production and life (Wang et al., 2022). According to the China Academy of Information and Communications Technology (CAICT), the Chinese digital economy was the second largest in the world with $7.1 trillion in 2021. The digital economy, a novel model of economic development, has emerged as an important driver for economic growth over time (J. Zhang et al., 2022). Digital infrastructure is an important basis and guarantee for digital economy development. As modern society rapidly enters the digital era, digital infrastructure also experiences a period of swift growth. In the context of green economic transition, it has become a real problem that digital infrastructure is energy-intensive. Meanwhile, cities with the help of digital infrastructure can use digital technology to change their economic development mode, reduce resource waste, and protect the natural environment (Yang et al., 2022). With its unique inherent characteristics, digital infrastructure is expected to become a significant driving force empowering different industries to achieve green and low-carbon transition (Yang et al., 2021). Therefore, it is urgent to clarify the effect and influencing mechanisms of digital infrastructure construction on the urban economic development model. Digital economy and green developments are respectively the internal driving force and important goal of Chinese future economic growth. This paper aims to explore how digital infrastructure influences urban green transformation in China. The topic has both theoretical and practical importance in the digital age. Meanwhile, this paper can also offer useful insights and ideas for other emerging economies planning to push green economic development through digital infrastructure construction.

Specifically, this paper makes the following improvements to the existing literature. Firstly, from the research perspective, the previous research has discussed the effect of transport infrastructure on economic and social development. However, the essential attributes of digital infrastructure are distinct from those of transportation infrastructure, such as highways and high-speed rail, and their influencing mechanism on economic development will also be significantly different. From the perspective of digital infrastructure construction, this paper studies how digital infrastructure influences green economic development, which is helpful to complement the related studies on the nexus between infrastructure construction and green economy development. Secondly, most articles discussing new digital infrastructure are in the stage of qualitative research. In particular, the impact of building digital infrastructure on environmental performance is not empirically evaluated. Rigorous causal identification and empirical evidence are lacking. The non-radial directional distance function (NDDF) is applied to measure the cities' green economic development level in China. The authors use the staggered DID model to explore the influential mechanism of digital infrastructure construction on green development, which provides some new empirical evidence. Finally, from the digital infrastructure construction perspective, some constructive policy suggestions are proposed to promote the cities' green economic transformation.

The rest is organized as follows. Section "Policy context and theoretical foundation" is the policy background and theoretical foundation. Section "Method" explains the method and variables. The authors represent the empirical findings and discussions in the section "Results". Section "Conclusions and policy suggestions" is the conclusions and policy implications.

Policy context and theoretical foundation

Policy background. Specifically, information infrastructure and the digital transformation of physical infrastructure are the two primary components of digital infrastructure. As a national strategic infrastructure, the broadband network is the core component of digital infrastructure, which significantly supports the new round of technological innovation and industrial revolution. In August 2013, the State Council issued the "Broadband China Strategy and Implementation Plan", which laid out the goals and paths for broadband development in the next eight years. As the core information infrastructure, broadband pushes the rapid development of digital industries. After independent application by local governments and comprehensive evaluation by experts, 120 cities have been approved to carry out the Broadband China pilot cities in China (Tang et al., 2022). The pilot cities are designed to promote broadband infrastructure construction, expand the new generation of information technology industries, and realize the development of regional networking, information, and intelligence. After a three-year construction period, the pilot cities need to achieve the national leading level in terms of broadband network speed and Internet penetration rate. From the perspective of geographic location, the location of the 120 pilot cities is relatively random and does not show an obvious pattern. Existing research has regarded the pilot cities as a quasi-natural experiment to evaluate the economic and social effects of broadband networks (Hong et al., 2023; Tang et al., 2022; Wen et al., 2022). Thus, the pilot cities provide a good quasi-natural experiment, offering a good opportunity to assess the effect of digital infrastructure development.

Theoretical mechanism. Digital infrastructure is a crucial prerequisite and guarantee for developing digital technologies like artificial intelligence and the Internet of Things. It has gradually become an important infrastructure driving the high-quality growth of the economy. Digitalization can influence all walks of life, which has great potential to promote low-carbon industrial transformation, stimulate technology innovation, and guide low-carbon consumption.

Digital Infrastructure and energy consumption. There is a complex relationship between digital infrastructure and energy consumption. On the one hand, the 5G base stations, data centers, and other digital infrastructure consume a lot of electricity, far more than computers, mobile phones, and other electronic products. Because the digital infrastructure is not included in traditional energy-intensive industries, its high electric consumption is easily ignored. According to the CAICT, the annual energy consumption of Chinese data centers increased from 27.076 billion kWh in 2017 to 57.67 billion kWh in 2020. Beijing, the capital of China, consumed 106.69 billion kWh of electricity in 2017 and 114 billion kWh in 2020. In 2020, China's data centers consumed approximately half of Beijing's electricity consumption. On the other hand, digital infrastructure promotes the application of digital technologies in various industries. It has been found that using digital technologies and smart devices can help improve energy efficiency in agriculture and manufacturing (Horner et al., 2016).

Digital Infrastructure and industrial transformation. Digitalization is driving a new round of industrial transformation, penetrating the organizational forms of all kinds of industries (Wu et al., 2021). Specifically, the impact of digital infrastructure on industrial transformation can be seen in two aspects: industrial digitalization and digital industrialization. The penetration rate of digital technology into agriculture, industry, and services is increasing yearly, as the digitalization process keeps accelerating (Aaldering and Song, 2021). In terms of industrial digitalization, digital technology is combined with traditional manufacturing to push the transformation of machine manufacturing to automation and intelligent manufacturing. With the help of digital technology, enterprises can easily assess resource consumption and get better energy efficiency in the production process. In terms of digital industrialization, new business models such as online shopping, office, and medical care are thriving. The rapidly growing digital industry is generally less environmentally harmful (Lange et al., 2020). New business forms, such as smart transportation and smart logistics, can contribute to the realization of circular and low-carbon economies (Zhao et al., 2022). In a word, digital infrastructure not only facilitates the digital transformation of traditional industries but also accelerates the emergence of digital industries, which promotes the optimization of the overall industrial structure.

Digital Infrastructure and innovation. Urban green economic transformation needs the support of technological innovation, especially environmentally friendly technology (Huang et al., 2021; Lin and Ma, 2022). Digital infrastructure can break through geographical location restrictions, greatly improve the transmission scope and popularization of data and knowledge, and reduce the acquisition cost of data and knowledge (Tang et al., 2021). Knowledge spillover and sharing can significantly promote technological innovation (Czernich et al., 2011), including green technology innovation. With the development of digital platforms, information communication in daily life is becoming more and more convenient. Frequent communication between enterprises and technology demanders can reduce the uncertainty of green innovation activities. Therefore, digital infrastructure can alleviate the information asymmetry problem, which stimulates the innovation vitality of the whole society.

Digital Infrastructure and consumer behavior. Currently, it is significant to push the green economic transition from the production side. Additionally, it is essential to encourage consumers to lead green and low-carbon lifestyles and to raise public awareness of these issues, as doing so can support the green transformation of the economic consumption side (Z. Wu et al., 2023). The government uses digital platforms to issue vouchers, which can guide consumers to low-carbon consumption (Yang et al., 2022). In transportation, the emergence of digital platforms such as smart buses and Didi Chuxing can better reduce the travel rate of private cars, which can not only alleviate urban road traffic congestion but also reduces air pollutant (Zhao et al., 2022). Therefore, digital infrastructure has great potential to change consumer behavior in many areas, such as clothing, food, housing, and transportation. In short, the influencing channels are shown in Fig. 1.

Method

Econometric model

Staggered difference-in-differences model. The Broadband China policy is viewed as a quasi-natural experiment. Cities included in the Broadband China strategy pilot are regarded as the experimental group, whereas the other cities are treated as the control group. As the pilot cities are set up at different times, the authors

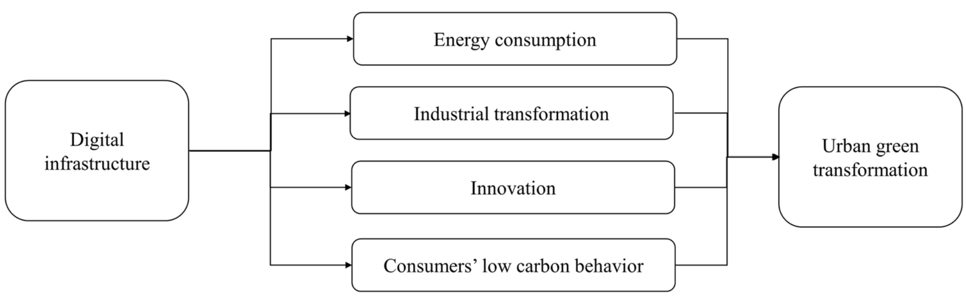

Fig. 1 Influencing channels of digital infrastructure on green transformation. The authors summarize four impact mechanisms.

construct the staggered difference-in-differences (DID) models to evaluate the effects of digital infrastructure on green economic development. Referring to existing studies (Lin and Huang, 2022), the model is established as follows:

$$Y_{it} = \alpha_0 + \alpha_1 \mathrm{DID}_{it} + \gamma X_{it} + \mu_i + \nu_t + \varepsilon_{it} \tag{1}$$

where the core independent variable DID_{it} indicates that city i is included in the list of pilot cities in year t. Y_{it} represents the green economic development level. The coefficient α_1 measures the net effect of Broadband China policy on urban green economic transformation. X_{it} denotes some important control variables. μ_i is the city-fixed effect, and ν_t indicates the time-fixed effect. ε_{it} is the error term.

Parallel trend test. The DID method's foundation should pass the parallel trend test, which means that the changing trend in treated and control groups was similar before the policy implementation. Additionally, the Broadband China policy may be affected by the intensity of policy implementation and other factors, resulting in a certain lag effect. Therefore, following the idea of the event research method (Lin and Huang, 2022), the following model is constructed to conduct a parallel trend test:

$$Y_{it} = \beta_0 + \sum_{j=-11}^{4} \beta_j D^j \mathrm{DID}_{it} + \gamma X_{it} + \mu_i + \nu_t + \varepsilon_{it} \tag{2}$$

where D^j is the dummy variable for year j. The authors take 2003 as the base period and set 16 dummy variables (D^{-11}–D^4). D^0 indicates the first year of policy implementation. β_j is the important coefficient, which indicates whether there are obvious differences in the green economy performance between the treated and control group in year j. If $j < 0$, β_j is not statistically different from 0, representing that there is no significant difference between the experimental and control group in green economy development before the policy implementation. It meets the parallel trend test.

Variable selections

Explained variable. The Chinese cities' green economic performance is the dependent variable, which is calculated by the non-radial directional distance function (NDDF). The NDDF can adjust the proportion of input, expected output, and unexpected output flexibly, which is widely used to measure green economic performance (Lin and Zhu, 2019; Li and Xu, 2018). Assuming N cities as the basic decision-making units (DMU) with T periods, each DMU puts in factors for production, which produces desired and undesirable output. The authors set up the following production technology:

$$P = \{(a, b; c) : a \text{ can produce } b \text{ and } c\} \tag{3}$$

Equation (3) represents the production function of desired and undesired outputs, which meet the fundamental axiom of production theory (Färe et al., 2005) and the following prerequisites.

$$\text{if } (a, b; c) \in P, \text{ and } 0 \le \theta \le 1, \text{ then} (a, \theta b; \theta c) \in P. \tag{4}$$

$$(a, b; c) \in P, \text{ if } c = 0, \text{ then } b = 0 \tag{5}$$

where a represents input factors including capital (a_1), labor (a_2), and energy (a_3). The real GDP is considered as the expected output (b). Following Lin and Zhu (2019), the authors take the discharge of industrial wastewater (c_1) and SO_2 emissions (c_2) as undesirable output owing to data limitations in Chinese cities. The global DEA model is applied to compare the green economic performance over different periods. The NDDF relaxes the restriction that desired and undesired output must change in the same proportion in the radial directional distance function (DDF) (Zhou et al., 2012). The authors set up the NDDF in Eq. (6).

$$\begin{aligned} &\overrightarrow{ND}(a_1, a_2, a_3, b, c_1, c_2; g) \\ &= \sup\{w^{\mathrm{T}}\beta : [(a_1, a_2, a_3, b, c_1, c_2) + g \cdot \mathrm{diag}(\beta)] \in P\} \end{aligned} \tag{6}$$

A slack vector β indicates the percentage of input and output variables that can be changed. The directional vector g denotes the direction of change in input and output. w is the weight of input and output in calculating the green economic performance. diag represents the diagonal matrix. Following Lin and Zhu (2019), the authors assume that inputs, desired outputs, and undesired outputs are equally important and given equal weight. Since different inputs can be substituted with each other, the weights of capital and labor inputs are assumed to be 0 to eliminate the inefficiencies of these two inputs. Thus, the weight vector w is assumed to be $w = (0, 0, \frac{1}{3}, \frac{1}{3}, \frac{1}{6}, \frac{1}{6})^{\mathrm{T}}$. The directional vector g is consistent with the weight vector, which can be assumed as $g = (0, 0, -a_3, b, -c_1, -c_2)$. According to Li and Xu (2018), the green economic performance index (*GEPI*) of the city i in period t is defined in Eq. (7).

$$\begin{aligned} GEPI_{it} &= \frac{1}{2}\left(\frac{\frac{a_{3it} - \beta^*_{a_3,it} \times a_{3it}}{b_{it} + \beta^*_{b,it} \times b_{it}}}{\frac{a_{3it}}{b_{it}}}\right) + \frac{1}{2}\left(\frac{1}{2}\sum_{j=c_1,c_2} \frac{\frac{j_{it} - \beta^*_{j,it} \times j_{it}}{b_{it} + \beta^*_{b,it} \times b_{it}}}{\frac{j_{it}}{b_{it}}}\right) \\ &= \frac{\frac{1}{2}(1-\beta^*_{a_3,it}) + \frac{1}{4}(1-\beta^*_{c_1,it}) + \frac{1}{4}(1-\beta^*_{c_2,it})}{1+\beta^*_{b,it}} \end{aligned} \tag{7}$$

The optimal solution $\beta^* = (\beta^*_{a_1}, \beta^*_{a_2}, \beta^*_{a_3}, \beta^*_b, \beta^*_{c_1}, \beta^*_{c_2})^{\mathrm{T}}$ can be calculated from production technology. The authors calculate cities' capital stock following Zhang et al. (2004). The cities' employment numbers are used to measure a_2 input (Cheng et al., 2019). a_3 is measured by electric consumption due to the Chinese cities' data availability. Real GDP is used as the indicator of b. Industrial wastewater and SO_2 emissions are taken as the proxy of c_1 and c_2. The authors convert the data at 2003 constant prices.

Core explanatory variable. The authors assign values according to the list of Broadband China pilot cities. If city i is taken as a Broadband China pilot city in year t, DID_{it} is assigned a value of 1. Otherwise, the value is 0. After eliminating cities with severe data missing, the treatment group includes 100 pilot cities.

Control variables. Green economic transition is influenced by many factors. To alleviate the endogeneity problem caused by missing variables, some important control factors are added to the econometric model. First, economically developed cities can invest more funds in green technologies and industries to improve the environment. Per capita GDP (PGDP) measures the economic development level (Chen et al., 2021). Second, government fiscal expenditure has been proven to be an important factor affecting China's urban green economy development (Lin and Zhu, 2019). Excessive government intervention may result in the inefficiency of resource utilization and hinder the improvement of green economy performance. Government fiscal expenditure (GFE) is gauged using the ratio of public finance expenditure to GDP. Third, proper environmental regulations by local governments can spur enterprises to accelerate environmentally friendly technological innovation and use more renewable energy (Lin and Jia, 2020; Song et al., 2021). However, strict environmental regulations may greatly promote the cost of enterprises' pollution control and hinder green technology innovation, which inhibits green development (Lanoie et al., 2008). The authors use the comprehensive utilization rate of industrial solid waste to gauge environmental regulation (ER). Fourth, urban economic growth may have a path-dependence

Table 1 The descriptive statistics.

Abbreviation	Definition	Mean	Std. dev	Min	Max	*N*
GEPI	Green economic development	0.2014	0.1419	0.0287	1.0000	4607
DID	Core explanatory variable	0.0877	0.2829	0.0000	1.0000	4607
PGDP	Per capita GDP	9.9990	0.7625	7.5449	11.9783	4607
GFE	Government fiscal expenditure	0.1637	0.0845	0.0313	0.7044	4607
ER	Environmental regulation	0.7862	0.2287	0.0024	1.0000	4607
FAI	Investment in fixed asset	0.6747	0.3040	0.0830	2.4119	4607
FDI	Foreign direct investment	0.0201	0.0225	0.0000	0.3758	4607
EI	Energy intensity	0.0730	0.0667	0.0049	0.7811	4607
DI	Digital industrialization	0.0121	0.0086	0.0005	0.1086	4607
GREEN	Green technology innovation	0.0495	0.1788	0.0000	3.4670	4607

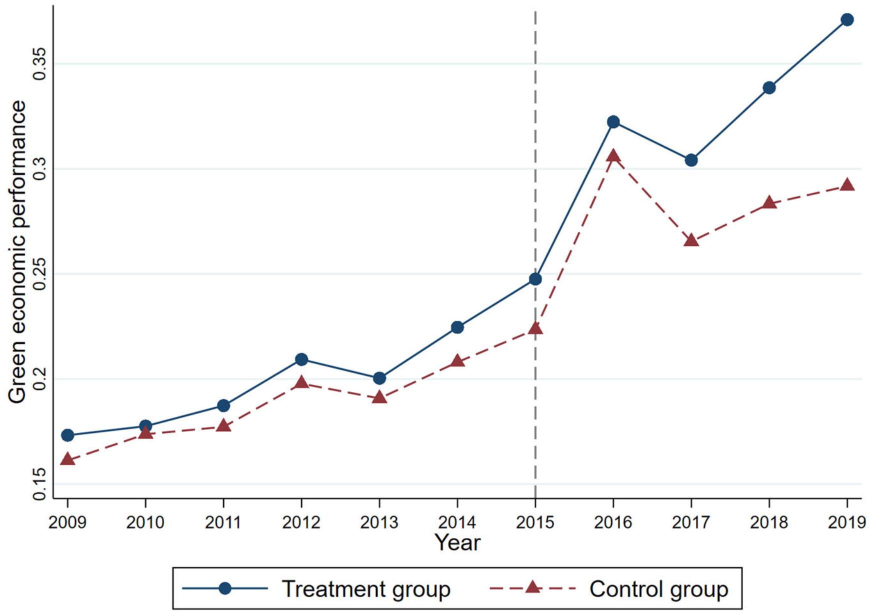

Fig. 2 The green economic performance of the treatment group and control group over the years. The annual averages are used to plot time trends.

effect if it depends too much on fixed assets and real estate investment, which is not good for local green economy development. The cities' fixed-asset investment (FAI) is evaluated using the fixed-asset investment to GDP ratio. Fifth, foreign direct investment (FDI) can bring capital and technology spillover to host countries, which promotes local green development (Wang et al., 2020). However, some scholars hold that FDI may transfer high-pollution and high-emission industries to the host country, causing damage to the local ecological environment (Zhang and Xiong et al., 2018). FDI is gauged by the proportion of foreign direct investment to GDP.

Data and statistical description. Many Chinese cities' data was missing before 2003. After removing the samples with missing data, the research samples are 271 prefecture-level cities from 2003 to 2019 in China. The original data is collected from the China City Statistical Yearbook and CEIC database. The data and descriptive statistics are represented in Table 1.

Results

Time trend graph of treated and control group. The year 2015 is the starting time point of the Broadband China policy. As can be seen from Fig. 2, the green economic performance of pilot cities (treatment group) showed a relatively consistent change trend compared with that of non-pilot cities (control group) before 2015. After 2015, the gap between the treated and control groups began to widen gradually. To some extent, it indicates that the DID model based on the Broadband China policy satisfies the assumption of parallel trends. However, whether there is a causal nexus between Broadband China policy and green economic development needs further detailed empirical research.

Parallel trend test. Furthermore, this paper draws on Eq. (2) to conduct a parallel trend test. Figure 3 represents the estimated results. If $j < 0$, the 95% confidence interval of β_j includes 0, which denotes that there is no appreciable performance difference in the green economy between the treated and the control group before the implementation of the policy. Thus, it is reasonable to use the staggered DID model to assess how digital infrastructure construction has affected urban green economy development. The effect on urban green economy development has a certain lag (see Fig. 3), and the policy effect increases yearly. The main reason is that digital infrastructure requires a long construction cycle.

Benchmark model result. The staggered DID model in Eq. (1) is applied to study the policy effect of Broadband China policy, which investigates the nexus between digital infrastructure construction and urban green economy transformation. The estimated coefficients of DID are significantly positive at the 1% level (see Table 2), meaning that digital infrastructure construction has pushed the green economy transition in Chinese cities. Dong et al. (2022) found that information infrastructure can improve

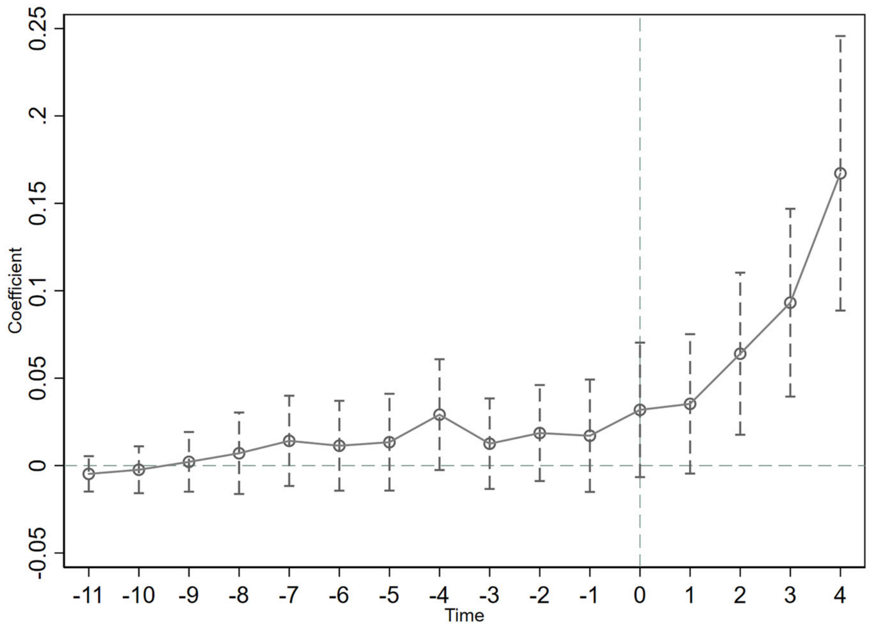

Fig. 3 Parallel trend test.

Table 2 Estimated results of the baseline regression.

	(1) GEPI	(2) GEPI	(3) GEPI	(4) GEPI
DID	0.1446***	0.0477***	0.0918***	0.0474***
	(0.0071)	(0.0171)	(0.0071)	(0.0162)
PGDP			0.0516***	0.0157
			(0.0028)	(0.0406)
GFE			0.3324***	−0.0292
			(0.0270)	(0.0748)
ER			0.0556***	−0.0147
			(0.0084)	(0.0172)
FAI			0.0103	0.0340*
			(0.0074)	(0.0198)
FDI			−0.3818***	−0.3809
			(0.0874)	(0.2502)
Constant	0.1887***	0.1367***	−0.4197***	0.0056
	(0.0021)	(0.0053)	(0.0277)	(0.3702)
Year FE	No	Yes	No	Yes
City FE	No	Yes	No	Yes
N	4607	4607	4607	4607
R^2	0.0830	0.3639	0.1971	0.3689

Robust standard error in parentheses.
***$p < 0.01$, *$p < 0.10$.

urban GHG emission performance in China. Digital infrastructure is an important foundation for digital technologies, leading the social transformation of the current era. Digital technology can change the economic development mode. The low-quality and high-quality green innovation can be promoted by information infrastructure (Tang et al., 2021). Overall, digital infrastructure, with its unique inherent characteristics, is expected to become a major driving force for the green and low-carbon economy transition.

Robust checks

Heterogeneous treatment effects. When the staggered DID model is utilized to identify policy effects, the estimated parameters of the two-way fixed effect model (TWFE) may have significant estimation bias because of the heterogeneous treatment effects (Baker et al., 2022). The estimated parameter β^{fe} of the TWFE can be considered as the expected value of the weighted sum of all treatment effects:

$$\beta^{fe} = E\left(\sum_{(g,t):D_{g,t}=1} W_{g,t}\Delta_{g,t}\right) \quad (8)$$

where $\Delta_{g,t}$ is the treatment effect size of the g pilot city in t year. $W_{g,t}$ is the corresponding weight of the treatment effect. Chaisemartin and D'Haultfœuille (2020) argue that $W_{g,t}$ may be negative. When the negative weight accounts for a relatively large proportion, the estimation results of β^{fe} may not be robust. The twowayfeweights command in Stata is used to test the estimations of Eq. (1). The results indicate that $\Delta_{g,t}$ and $W_{g,t}$ are all positive. The robust indicator of heterogeneous treatment effects is 0.3405, indicating that the heterogeneous treatment effects have no significant impact on the estimated parameter β^{fe} of TWFE. The estimated results are robust. The two-way fixed effect model can be used for parameter estimation.

Placebo test. Some non-observed factors may affect the policy effect of Broadband China policy. Following Lin and Huang (2022), the authors conducted the placebo test by randomly selecting the treatment group and the treatment time. Specifically, the authors randomly select 100 cities as the treated group and policy treatment time. Theoretically, if there is no interference from other random factors, the estimated coefficient of the spurious policy dummy variable should not be significantly different from 0. To ensure the robustness of the estimation result, 2000 random samples are taken. Figure 4 plots the kernel density plot and P-value distribution of the estimation coefficients in the placebo test. It can be found that the estimation coefficient is centrally distributed near 0, and its corresponding P value is greater than 0.1. The estimated real policy effect is significantly different from the estimated value obtained from the placebo test, which is an outlier. We can argue that the policy effects of digital infrastructure construction are not random factors.

Excluding the effect of other policies. China's economic and social reform is a complex and systematic project. In the same region, multiple policies are often implemented simultaneously.

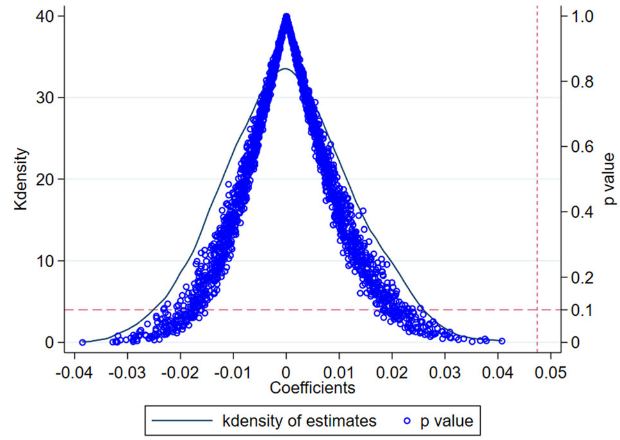

Fig. 4 Placebo test. The red vertical dashed line is the estimated real policy effect.

Table 3 Excluding the effect of other policies.

	(1) GEPI	(2) GEPI
DID	0.0321*	0.0362***
	(0.0173)	(0.0138)
PGDP	0.0673*	0.0753
	(0.0379)	(0.0638)
GFE	0.0239	0.0716
	(0.0805)	(0.0987)
ER	−0.0144	−0.0048
	(0.0179)	(0.0192)
FAI	0.0393*	0.0376*
	(0.0210)	(0.0193)
FDI	−0.4411	0.2490
	(0.2824)	(0.2956)
Constant	−0.4634	−0.6166
	(0.3435)	(0.6457)
Year FE	Yes	Yes
City FE	Yes	Yes
N	4046	2439
R^2	0.3475	0.3024

Robust standard error in parentheses.
***$p < 0.01$, *$p < 0.10$.

Table 4 Estimations of influencing mechanism.

	(1) EI	(2) DI	(3) GREEN
DID	−0.0205***	0.0039***	0.1282***
	(0.0068)	(0.0010)	(0.0305)
PGDP	0.0202	−0.0080***	−0.3297***
	(0.0135)	(0.0025)	(0.0853)
GFE	0.1071**	0.0007	−0.3873***
	(0.0543)	(0.0062)	(0.0794)
ER	−0.0040	−0.0001	−0.0078
	(0.0102)	(0.0008)	(0.0183)
FAI	−0.0308***	−0.0021**	−0.0378
	(0.0109)	(0.0010)	(0.0235)
FDI	0.0818	0.0212*	−0.1480
	(0.0959)	(0.0115)	(0.3272)
Constant	−0.1097	0.0825***	3.0645***
	(0.1263)	(0.0228)	(0.7720)
Year FE	Yes	Yes	Yes
City FE	Yes	Yes	Yes
N	4607	4607	4607
R^2	0.2229	0.1390	0.3104

Robust standard error in parentheses.
***$p < 0.01$, **$p < 0.05$, *$p < 0.10$.

Consequently, to accurately evaluate the net effect of digital infrastructure construction on green development, the effect from other policies should be excluded. For example, the impact of low-carbon city policies in promoting urban green economic growth has been verified (Yu and Zhang, 2021). To exclude the effect of other policies, the authors eliminate low-carbon cities from the research sample. Then, the estimated results can be seen in Table 3. Meanwhile, the authors shortened the policy time window to 2011–2019, which may eliminate the effects of other potential policies (see column (2) of Table 3). It can be seen from Table 3 that the estimations of DID are still significantly positive, indicating that digital infrastructure construction can encourage the urban green economy transition. The empirical findings are robust.

Analysis of influencing mechanism. Benchmark regression results find that digital infrastructure construction can significantly promote the urban green economy transformation. This section continues to explore the influencing channels. According to the content of the section "Theoretical mechanism", the authors argue that digital infrastructure can indirectly affect urban green development through the urban energy system, industrial structure optimization, and technology innovation. This section uses quantitative data to measure urban energy intensity, digital industrialization, and green technology innovation. The ratio of urban electricity consumption to GDP is used to calculate energy intensity (EI). The ratio of people employed in information transmission, computer services, and software to total urban employees is used to measure the degree of digital industrialization (DI). The authors gauge green technological innovation (GREEN) by counting the number of urban green patent applications.

As seen from Table 4, digital infrastructure construction can lower energy intensity, promote the development of digital industrialization and improve green innovation level. The main reasons are explained in the following aspects. First, enterprises with the help of digital technology can reduce resource waste in the production process, improving energy efficiency. Second, with the support of digital infrastructure, new forms such as e-commerce, smart logistics, and smart transportation are thriving. Compared with energy-intensive industries, digital industries are generally less harmful to the environment (Lange et al., 2020). Smart transportation and smart logistics have great potential to push green economy development (Zhao et al., 2022). Third, digital infrastructure accelerates the dissemination of data and information, alleviating information asymmetry in daily life. The exchange and sharing of knowledge significantly promote technological innovation (Tang et al., 2021). Green economic growth must be supported by environmentally friendly technologies (Wang et al., 2021).

Heterogeneous analysis. Different cities have obvious heterogeneity in geographical location, resource endowment, and other aspects, which may affect urban green economy development in China. Therefore, this section will explore the heterogeneity of digital infrastructure construction on the green economy transition from the following two aspects. Firstly, from the perspective of geographical location, Chinese cities show obvious spatial heterogeneity. The samples are divided into east, central, and west regions considering the cities' geographical location, and the

Table 5 Heterogeneous analysis.

	(1) East	(2) Central	(3) West	(4) Economically developed	(5) Economically undeveloped
DID	0.0688***	0.0603**	0.0001	0.0492**	0.0137
	(0.0257)	(0.0262)	(0.0280)	(0.0194)	(0.0287)
PGDP	−0.0997	0.1060**	0.1318*	−0.0170	0.1243**
	(0.0765)	(0.0467)	(0.0753)	(0.0538)	(0.0532)
GFE	−0.2439	0.1936	−0.0902	0.1858	0.0347
	(0.2051)	(0.1180)	(0.1093)	(0.1930)	(0.0717)
ER	−0.0112	−0.0136	−0.0098	−0.0174	−0.0109
	(0.0394)	(0.0258)	(0.0275)	(0.0311)	(0.0202)
FAI	0.0659	0.0440	0.0183	0.0027	0.0498*
	(0.0417)	(0.0280)	(0.0273)	(0.0289)	(0.0255)
FDI	−0.4203	0.1818	0.0290	−0.0539	−0.5899
	(0.3928)	(0.2903)	(0.6239)	(0.2271)	(0.5183)
Constant	1.1092	−0.8387*	−0.9976	0.2898	−0.9304**
	(0.7404)	(0.4261)	(0.6564)	(0.5217)	(0.4587)
Year FE	Yes	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes	Yes
N	1700	1700	1207	2295	2312
R^2	0.3827	0.4777	0.2983	0.4161	0.3376

Robust standard error in parentheses.
***$p < 0.01$, **$p < 0.05$, *$p < 0.10$.

heterogeneity is analyzed by subgroup analysis (see columns (1)–(3) in Table 5). The findings indicate that digital infrastructure construction significantly pushes the green economic transformation in the central and eastern cities but has no obvious impact on western cities. Qiao et al. (2022) also argued that information infrastructure construction is only beneficial to improve air pollution in eastern cities, which is similar to the results of this paper. Secondly, the authors divide cities into economically developed and undeveloped cities on the basis of the average annual GDP. As shown in columns (4) and (5), digital infrastructure construction in economically developed cities significantly promotes green economic development. However, the effect is not obvious in economically undeveloped cities. The main reason for the above empirical results is that the digital infrastructure in eastern and economically developed cities has been established earlier and is more complete. Digital technology is actively used in eastern and economically developed cities to support the collaborative development of digitalization and greening in various industries. Zhao et al. (2022) found that the development level of smart transportation is highest in the eastern region of China. Smart transportation can significantly curb carbon dioxide emissions. Thus, the green economic development of the economically developed and eastern cities benefits more from digital infrastructure construction.

Conclusions and policy suggestions

Conclusions. Digital infrastructure as a digital base is an essential component of social development in the current era. However, the environmental performance of digital infrastructure has been discussed less. This study, using NDDF, calculates the cities' green economic performance with the research sample of Chinese 271 cities from 2003 to 2019. Taking the Broadband China policy as a quasi-natural experiment, this paper empirically estimates the effect and influencing mechanism of digital infrastructure construction on the green economic development of Chinese cities. The following conclusions are drawn.

(1) Digital infrastructure can enable green economic transformation in Chinese cities. The results remain robust after considering the heterogeneous treatment effects, placebo test, and excluding other policy effects. (2) The digital infrastructure is conducive to improving energy efficiency, promoting digital industrialization, and green technology innovation, indirectly promoting the urban green economy transformation. (3) The heterogeneity results indicate that green economic performance in eastern and economically developed cities benefits more from digital infrastructure construction.

Policy implications. From the perspective of political feasibility, the Chinese government has formulated numerous policies to vigorously promote the investment and construction of digital infrastructure, such as the Internet, data centers, and communication base stations, and attaches great importance to the Broadband China strategy. The digital economy has been seen as an emerging engine to drive high-quality economic development in the future. Therefore, promoting digital infrastructure has a strong political feasibility in China. From the perspective of economic feasibility, digital infrastructure construction is a long-term and systematic project. In the early construction phase, building digital infrastructure consumed a lot of resources and crowded out the investment in the green industry and green technology in local cities. Thus, the costs are greater than the benefits. When the digital infrastructure is completed, the penetration of digitalization in various industries gradually increases. Digital technology can help energy-intensive industries make the green transition. The law of Metcalfe indicates that a network's value is proportional to the square of the number of connected users. The marginal cost of serving one additional customer is almost zero once the digital infrastructure has been created. The digital dividend is gradually released. Therefore, the benefits outweigh the costs.

The policy recommendations are proposed. First, from the macro perspective, digital infrastructure is the basis for the high-quality growth of the digital economy. The national government should increase funding for and the scope of building digital infrastructure projects, like data centers and 5G base stations, as well as improve the breadth and depth of digital services. To further unleash the digital dividend, the penetration rate of digitalization in various industries needs to be further increased. Second, digital technologies have provided emerging drivers for green economic growth. From the micro perspective, enterprises should accelerate their digital transformation. In particular, energy-intensive industries promote energy efficiency with the help of digital technology, which facilitates the green transformation of industry. Finally, the electric consumption of digital infrastructure needs to be focused on. Digital infrastructure construction is a complex and systematic project. Before the project construction, reasonable layout and planning are necessary for advancement. On the one hand, large-scale data centers had better be built in areas with good wind power and photovoltaic resource endowment, which consume renewable energy nearby and control carbon dioxide emissions from the source. On the other hand, continuing in-depth research of energy conservation technology related to digital infrastructure is important, to get better energy efficiency of digital infrastructure. To sum up, the energy consumption structure and energy efficiency should be fully considered before digital infrastructure construction. Digital infrastructure becomes "green infrastructure" from the source.

This paper empirically evaluates how digital infrastructure construction affects green economy transformation in China, but there are still some limitations. First, the authors conduct an empirical study using data from 271 Chinese cities. The empirical evidence of micro-enterprises is also worth exploring. Second, this paper solely empirically discusses energy efficiency, industrial digitalization, and green technology innovation as influence channels due to the availability of data. Future studies may consider more potential channels, such as consumer behavior and environmental governance. Third, the Broadband China policy is taken as a quasi-natural experiment to measure digital infrastructure construction. Although the broadband network is an important digital infrastructure, digital infrastructure also includes digital centers, industrial Internet, and so on. More reasonable quantitative indicators can be used to measure digital infrastructure construction in the future.

Data availability

The datasets generated during the current study are available from the corresponding author on reasonable request.

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Boqiang Lin: Conceptualization, methodology, writing-original draft. Ruiyang Ma: Methodology, Software, Data collection, Writing-original draft.

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The authors declare no competing interests.

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