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Impact of digital greening synergistic transformation on urban economic resilience in China: Evidence from quasi-natural experiments

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Digital greening synergistic transformation (DGST) has emerged as a crucial driver of high-quality economic development, notably enhancing urban economic resilience. This paper examines panel data from 280 Chinese cities (2008–2021) by performing quasi-natural experiments from the 'Broadband China' and 'Low-Carbon Cities' pilot initiatives and employing a multi-period difference-in-differences (DID) approach. The main findings are as follows. (1) DGST notably enhances urban economic resilience, showing stronger effects than standalone pilot projects. (2) DGST strengthens economic resilience by enhancing defence, adaptation and learning capacities through labour absorption, industrial structure optimisation and green technology innovation. (3) The effect of DGST on economic resilience is influenced by factors such as human capital, financial resources and infrastructure, with cities possessing greater resources deriving more substantial benefits. (4) Cities that implemented 'Low-Carbon Cities' prior to 'Broadband China' experienced more pronounced improvements in economic resilience. This paper underscores the synergy between digital and green policies in strengthening economic resilience and provides recommendations to advance DGST and strengthen urban economies.

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Introduction

Digitisation and greening represent two dominant trends in global economic and social development. The integration of these elements serves as a crucial driver for the sustainable growth of economies and societies worldwide. Recognising this, the Chinese government has prioritised the advancement of digitisation and greening, adopting the concept of 'leading greening with digitization and driving digitization with greening' as a central strategy for economic development and transformation.[1] Digitisation functions both as a tool and a pathway for green development, enabling and facilitating sustainable progress. At the same time, greening provides the framework and direction for digital advancement, offering practical applications for digital solutions and shaping the goals of digital progress (Zhou et al., (2021)). The interplay between digitisation and greening fosters mutual reinforcement, positioning them as critical drivers of high-quality urban economic development. In recent years, the Chinese government has implemented the 'Broadband China' and 'Low-Carbon Cities' pilot programmes in phases, aiming to advance the development and application of digital technologies while fostering green and low-carbon urban growth.[23] These initiatives provide robust policy support for digital and green transformation. The World Economic Forum's 'Global Risks Report 2023' emphasises the pivotal role of digital technologies in achieving green objectives, highlighting the necessity of collaboration between digital and green sectors to drive sustainable development.[4] Consequently, examining the synergistic effect of digital and green transformation, along with their impact, not only facilitates the coordinated development of these areas but also promotes high-quality urban economic growth, aligning with the goals of digital China and beautiful China.

Economic resilience refers to the capacity of an economic system to absorb external shocks, mitigate risks and restore performance. It is a critical competitive edge in a nation's economic progress (Martin and Sunley, 2015; Briguglio et al., 2014). Enhancing a city's economic resilience is essential for maintaining economic stability and achieving high-quality development. In recent years, global economic risks and uncertainties have escalated, with major economies facing challenges such as supply chain disruptions, geopolitical tensions, inflationary pressures and the prolonged impact of the COVID-19 pandemic (Ivanov and Dolgui, 2020; Gereffi, 2020). As one of the world's leading economies, China also confronts the added task of transitioning its development model and shifting its growth drivers. These challenges have intensified economic pressures, highlighting the urgent need for resilient and adaptive economic strategies. Consequently, addressing how to effectively manage external shocks, enhance urban economic resilience and ensure the safe and stable development of the economy and society has become a critical issue at this stage.

The existing literature primarily explores factors such as industrial structure (Tang et al., 2023; Ji and Zhang, 2024), human capital (Zhou and Qi, 2023; He and Wang, 2024) and infrastructure development (Li et al., 2023; Zhou et al., 2024). Additionally, studies have examined the positive impacts of Internet development (Shi et al., 2023), new productivity (Shi et al., 2024) and coordinated regional development (Feng et al., 2023 ; Xu and Zhang, 2024).

Recent research has begun exploring the relationship between digital and greening transformation and urban economic resilience. The academic consensus suggests that digital transformation enhances urban economic resilience through various factors, including digitalisation (Zhang, Xian (2024)), digital infrastructure development (Zhang et al., 2023), the popularisation of digital finance (Yang et al., 2024) and the implementation of policies such as 'Broadband China' and 'Smart City' initiatives (Guo et al., 2023; Qian et al., (2021); Zhu et al., 2019). Similarly, studies show that green development efforts, such as green finance (Wei, 2024), green innovation (Lv et al., 2023), energy consumption structure transformation (Wang et al., 2020) and 'Low-Carbon City' pilot projects (Liu, 2023; Deng et al., 2023), significantly enhance urban economic resilience. However, limited research has addressed the relationship between digital greening synergistic transformation (DGST) and urban economic resilience within a unified framework.

Existing research on DGST largely focuses on its environmental advantages. This transformation facilitates industrial structure adjustment and low-carbon technological innovation while enhancing urban digitalisation, market orientation and industrial innovation, all contributing to carbon emission reductions (Hou et al., 2023; Zhang and Fan, 2023). Furthermore, studies indicate that DGST strengthens urban industrial, supply and value chains (Li et al., 2023; Tao et al., 2023; Spieske and Birkel, 2021) and simultaneously improves urban export resilience (Zhang et al., 2023) and ecosystem resilience (Khurana et al., (2022)).

However, does DGST significantly impact urban economic resilience? While existing studies primarily focus on the individual effects of digitisation or greening on urban economic resilience, comprehensive analyses exploring the synergistic effects of both transformations remain limited. This paper fills this gap by examining how DGST influences urban economic resilience within the context of the 'Broadband China' and 'Low-Carbon Cities' pilot policies. It investigates whether these policies create synergistic effects, the underlying mechanisms and potential variations in their impact across different urban settings. By exploring these aspects, the paper seeks to theoretically uncover the internal dynamics of DGST in enhancing urban economic resilience and to promote practical progress in both economic and societal development.

Using panel data from 280 Chinese prefecture-level cities collected between 2008 and 2021, this paper examines the effects and mechanisms of DGST on urban economic resilience through a multi-period DID model. The contributions of this paper to the existing literature are as follows:

First, while there is considerable research on DGST and economic resilience, studies exploring their relationship remain limited. Most existing literature focuses on the impact of industrial structure upgrading and human capital on urban economic resilience, typically examining digital or green development from a single perspective. This paper, using a unified analytical framework, focuses on the dual-pilot projects of 'Broadband China' and 'Low-Carbon Cities' as key variables for DGST, investigating its synergistic effect on urban economic resilience and quantitatively evaluating the impact of the current pilot policies. This enhances the theoretical understanding of DGST and urban economic resilience.

Second, while existing literature largely examines the effects of DGST on economic resilience from government and market perspectives, this paper explores the mechanisms in greater detail by analysing how the three dimensions of defence capacity, adaptability and learning ability in the economic system respond to uncertain shocks. Specifically, it investigates the roles of labour absorption, industrial structure optimisation and green technology innovation in enhancing economic resilience.

Finally, this paper explores the factor endowment conditions that support urban digital greening policy coordination. It assesses how variations in human capital, fiscal expenditure and infrastructure influence urban economic resilience. The findings highlight that successful digital greening coordination depends on significant factor endowments. By identifying the conditions under which DGST is most effective, this paper offers valuable insights for advancing digital greening initiatives and informing more targeted policy development.

Theoretical Analysis and Research Hypothesis

Economic resilience is an inherent trait of economic systems that face unforeseen shocks (Evenhuis, 2017). A resilient city can reallocate resources both internally and externally to withstand external disturbances (defensive capacity), adapt and adjust to manage disruptions (adaptive capacity) and continuously innovate to create new pathways for economic development (learning capacity).

Path analysis of DGST influencing urban economic resilience from a defensive capacity perspective. At the defensive capacity level, an urban economic system manages uncertainties by optimally utilising both internal and external resources, such as human, financial and material resources, with human resources being particularly vital. Labour in the urban economic system plays a key role in absorbing and mitigating the impact of uncertainty shocks (Martin et al., (2016)). Therefore, a city's ability to effectively allocate and absorb labour reflects the defensive strength of its economic system.

DGST enhances urban economic resilience through labour absorption in two main ways. First, digital transformation creates new labour and employment opportunities. The 'Broadband China' initiative has accelerated the deployment of Internet broadband, improving information sharing and connectivity. This connectivity helps match workers with job opportunities, reduces frictional unemployment and promotes more efficient labour allocation in the job market (Zhang and Sun, 2023). The expansion of broadband networks drives the growth of the digital economy and boosts sectors such as artificial intelligence and big data, increasing demand for skilled labour in areas like information transmission and software development. Additionally, the continuous development of new-generation information technologies is transforming traditional employment patterns, giving rise to new business models and creating emerging job opportunities (Atasoy, 2013). At the same time, network infrastructure supports public, information and financial services in cities (Li et al., 2023), fostering various employment channels, including innovation, entrepreneurship, flexible employment and inclusive employment, thereby injecting new vitality into the job market (Huang et al., 2023; Qiu and Qiao, 2021).

Conversely, green transformation positively influences labour employment in cities. The 'Low-Carbon Cities' initiative promotes clean industries, green infrastructure, waste recycling, ecological protection and urban greening, creating new job opportunities in research and development, production, manufacturing and maintenance, thus providing employment for relevant professionals. In line with green production and ecological sustainability principles, many green jobs have emerged, particularly in areas such as energy conservation, environmental protection, cleaner production and green services. As a result, there is an increasing demand for professionals skilled in these green sectors. Furthermore, environmental regulations can encourage companies to adopt greener, low-carbon practices, driving innovation that reduces production costs, lowers product prices and boosts product demand, which, in turn, increases the need for labour (Gray et al., 2014; Wang, Ge (2022)).

Overall, the impact of digital greening synergistic transformation on employment is complex. The coordinated development of digitalisation and greening will not only improve traditional forms of employment but also increase demand for 'digital+green' multi-skilled talent, foster the growth of emerging industries, create more job opportunities and improve the efficiency of labour resource allocation. The ongoing development of the employment market contributes to the creation of a more sustainable and dynamic economic system. This system can better organise and allocate internal human resources, strengthen defence capacity against external shocks and stabilise both employment and economic operations.

Based on this, the paper proposes the following research hypothesis:

Hypothesis 1: DGST promotes the absorption of employed labour to enhance urban economic resilience.

Path analysis of DGST influencing urban economic resilience from an adaptive capacity perspective. At the adaptive capacity level, the urban economic system shows its ability to organise and coordinate various resource factors, allowing it to adapt to environmental changes and respond quickly to external risks. The modernisation and transformation of the industrial structure are key indicators of a city's ability to reorganise and function in response to external disruptions, thus reflecting the adaptive capacity of the economic system.

DGST plays a crucial role in optimising the industrial structure to enhance urban economic resilience. On one hand, digital transformation significantly contributes to this optimisation. The 'Broadband China' initiative has notably developed network infrastructure, accelerated data dissemination and facilitated efficient information flow. This progress reduces information asymmetry and allows for more rational allocation of capital and labour. As a result, resource allocation efficiency improves, and the structure of resource distribution is optimised, supporting industrial upgrading (Shi et al., 2023). Moreover, increased digitisation fosters knowledge transmission and sharing, encouraging industries to adopt advanced information technologies. This leads to smarter and more flexible production and management methods, process optimisation and innovation in emerging industrial models. Additionally, the growing Internet industry has shifted production factors from labour-intensive to technology-intensive sectors (Hou et al., 2023), promoting the expansion of high-tech industries and driving the industrial structure towards greater technological sophistication, thus significantly contributing to industrial optimisation.

Conversely, green transformation plays a significant role in optimising the industrial structure. Under the 'Low-Carbon Cities' pilot policy, the government strengthens oversight of high-pollution and energy-intensive sectors by setting stricter environmental standards and encouraging businesses to reduce emissions through market mechanisms (Zhang et al., 2023; Li et al., 2023). This guidance helps shift the industrial structure towards cleaner practices. Additionally, governments are introducing tax incentives for green and low-carbon enterprises, as well as providing financial support and subsidies. These measures encourage businesses to invest in research and innovation in green and clean technologies. Such efforts support traditional industries in transitioning to low-carbon and clean practices, improving the overall environmental performance of the industry and promoting the growth of low-emission sectors. Furthermore, clean energy infrastructure, such as wind, water and solar power, provides renewable energy support to businesses, reducing dependence on traditional high-pollution energy sources and helping establish a green, low-carbon industrial chain. These developments are crucial in moving the industrial structure towards greater environmental sustainability.

Overall, the synergistic transformation of digital and green development can better support traditional industries, provide a strong foundation for the growth of emerging industries, create new opportunities for the integration of digital and green sectors and encourage the diversification and transformation of industries. This leads to a more rationalised and advanced industrial structure. The ongoing optimisation of the industrial structure results in a more diversified urban economic framework. As the economic system becomes more capable of self-organisation and adjustment to absorb and mitigate external risks (Cui et al., 2023), it enhances the urban economy's adaptability to uncertain shocks, thereby improving its resilience.

Based on this, the paper proposes the following research hypothesis:

Hypothesis 2: DGST can optimise industrial structure, thereby enhancing urban economic resilience.

Path analysis of DGST influencing urban economic resilience from a learning capacity perspective. At the learning capacity level, urban economic systems utilise their resources and elements to engage in continuous learning and innovation, increasingly adopting emerging technologies to stimulate economic growth. In the context of promoting green and sustainable development, green technological innovation has become a key focus. This emphasis is essential for supporting the creation of new development strategies and pathways, thus driving high-quality economic and societal progress. As a result, expertise in green technological innovation is a more effective indicator of the learning capacity of economic systems.

DGST plays a vital role in promoting green technological innovation, thus strengthening economic resilience. Digital transformation acts as a driver for green technological innovation. The 'Broadband China' initiative has been pivotal in the widespread adoption of digital technologies, improving infrastructure and overcoming knowledge dissemination barriers across time and space, leading to technological spillovers (Xu et al., 2020). This broad adoption enhances the mobility and utilisation of innovation resources, thus increasing the level of green innovation (Li et al., 2021; Zhai et al., 2023). Moreover, advancements in network infrastructure contribute to urban informatisation, fostering the concentration of science and technology talent, which in turn elevates the city's human capital. This concentration supports the spread and spillover of innovative knowledge and technology within cities, providing the necessary talent for green innovation efforts (Li et al.,2023). Furthermore, the rise of Internet finance and digital inclusive finance has transformed traditional financial services, expanding their scope and improving efficiency. This transformation alleviates financing constraints for enterprises and offers vital support for funding green innovation research and development in cities (Xin et al., 2023).

Conversely, green transformation significantly promotes green innovation. The 'Low-Carbon Cities' initiative improves the energy structure, enhances energy efficiency, develops green and low-carbon industries and drives enterprises towards more sustainable practices. This policy framework encourages research and innovation in green and low-carbon technologies (Li et al., 2023). Environmental regulations impose restrictions that lead local governments to tighten oversight of high-pollution and energy-intensive industries. This increased monitoring, along with appropriate corrective and punitive actions, forces these enterprises to adopt technological changes and pursue green development strategies suited to their specific needs (Qi et al., 2021; Huo et al., 2022). Additionally, the 'Low-Carbon Cities' pilot areas offer various incentives, including tax benefits, financial subsidies, talent development programmes and funding opportunities to support innovative organisations (Li and Wang, 2023). These incentives not only motivate businesses to invest in green innovation but also encourage them to engage in such activities. Furthermore, the 'Low-Carbon Cities' pilot project fosters collaboration among different organisations and sectors, creating an environment conducive to low-carbon innovation and enhancing the overall level of green technological innovation.

Overall, the synergistic transformation of digital and green technologies has facilitated the integration and mutual enhancement of digital and green technologies, improving traditional technologies and advancing the research, development and application of green, low-carbon technologies. At the same time, by offering technical, human, capital and policy support for innovation activities, the feasibility and effectiveness of these activities are increased, promoting green technology innovation. Higher levels of innovation enhance the adaptability and flexibility of the economic system (Bristow and Healy, 2018). In response to external environmental changes, urban economies can leverage their learning and iterative updating abilities to develop new growth strategies and pathways, helping to mitigate the adverse effects of external shocks and boosting economic resilience.

Based on this, this paper proposes the following research hypothesis:

Hypothesis 3: DGST can drive green technological innovation and, thus, contribute to urban economic resilience.

Research Design

Empirical model. This paper uses the 'Broadband China' and 'Low-Carbon Cities' dual-pilot programmes as a quasi-natural experiment and applies a multi-period DID model to examine the impact of DGST, represented by these two pilots, on economic resilience. Given the varying implementation of these policies across different cities and years, the multi-period DID model is particularly suited for this analysis. Compared to traditional DID, multi-period DID better accounts for potential confounding treatment effects and contemporaneous trends, offering a more robust approach. The model is structured as follows:

$$UER_{i,t} = \alpha_0 + \alpha_1 DGST_{i,t} + \alpha_2 Digital_{i,t} + \alpha_3 Green_{i,t} + \alpha_4 Control_{i,t} + \mu_i + \delta_t + \varepsilon_{i,t}$$

The indices i and t represent the city and year, respectively. $UER_{i,t}$ is the dependent variable, indicating urban economic resilience. $DGST_{i,t}$ is the main explanatory variable, denoting whether the city has implemented the dual-pilot policy of 'Broadband China' and 'Low-Carbon Cities'. $Digital_{i,t}$ is associated with the 'Broadband China' pilot, while $Green_{i,t}$ is linked to the 'Low-Carbon Cities' pilot. $Control_{i,t}$ represents the control variables. μ_i accounts for city-fixed effects, δ_t captures time-fixed effects and $\varepsilon_{i,t}$ is the random error term.

Variable selection

Dependent variable. Following Martin et al., (2016), this paper divides the time into two phases: the resistance period (2008–2010) and the recovery period (2010–2021). Urban economic resilience is measured by the deviation between the actual economic output change and the expected economic output change.

The formula for each city's expected economic output change is:

$$\left(\Delta E_i^{t+k}\right)^e = \sum_r g_N^{t+k} E_{ir}^t$$

where $\left(\Delta E_i^{t+k}\right)^e$ represents the expected change in economic output for city i during the resistance or recovery period $[t, t+k]$; g_N^{t+k} is the national economic output change rate during the

Table 1 Descriptive statistics of main variables.

Variables	Mean	Standard deviation	Min	Max
UER	2.425	2.142	0.119	43.84
Fis	2.425	2.142	0.119	43.84
Edu	0.167	0.0540	0.00699	1.667
Con	15.44	1.114	5.472	19.01
Sav	16.17	1.027	13.04	19.92
Inter	0.672	3.833	−8.735	10.51
Pgdp	49,837	34,136	99	467,749

respective period; E_{ir}^{t} is the economic output of city i in year t; and t is the base year when the economy began shifting to either the recession or recovery phase.

The formula for measuring resistance is as follows

$$\mathrm{resis_i} = \frac{\left(\Delta E_i^{\mathrm{Contraction}}\right) - \left(\Delta E_i^{\mathrm{Contraction}}\right)^{\mathrm{expected}}}{\left|\left(\Delta E_i^{\mathrm{Contraction}}\right)^{\mathrm{expected}}\right|}$$

The formula for measuring recovery is as follows:

$$\mathrm{rescov_i} = \frac{\left(\Delta E_i^{\mathrm{Recovery}}\right) - \left(\Delta E_i^{\mathrm{Recovery}}\right)^{\mathrm{expected}}}{\left|\left(\Delta E_i^{\mathrm{Recovery}}\right)^{\mathrm{expected}}\right|}$$

A positive resistance or recovery value indicates that the region's ability to withstand or recover from external shocks exceeds the national average, while a negative value indicates the region's capability is below the national average. The higher the resistance or recovery value, the stronger the urban economic resilience.

Core dependent variable. In this paper, DGST is represented by the dual-pilot policies of 'Broadband China' and 'Low-Carbon Cities', which illustrate the integration of digital and green efforts. DGST is given a value of 1 in the year and subsequent years when a city is designated as a pilot for both 'Broadband China' and 'Low-Carbon Cities'; otherwise, it is assigned a value of 0. Similarly, the control variables for 'Broadband China' and 'Low-Carbon Cities' are given a value of 1 in the year and the following year when the city is selected as a pilot and 0 for other years. In the sample, 107 cities were identified as pilots for 'Broadband China', 120 for 'Low-Carbon Cities' and 50 as dual-pilot cities.

Control variables. Based on studies, such as Jiang, Jiang (2024) and Zhou and Qi (2023), this paper includes the following control variables: (1) Fiscal Freedom (Fis), measured by the ratio of local general public budget expenses to revenues; (2) Educational Level (Edu), defined as the ratio of education spending to the total public budget; (3) Consumption Level of Residents (Con), expressed as the logarithm of total retail sales of consumer goods; (4) Savings Level of Residents (Sav), measured by the logarithm of household savings; (5) Internet Level (Inter), indicated by the proportion of individuals with broadband Internet access per 100 people ; and (6) Economic development level (Pgdp), expressed by per capita GDP.

Data sources and descriptive statistics. This paper selected 280 prefecture-level cities in China from 2008 to 2021 as the research sample, excluding cities with major administrative area changes or missing data. The missing data from some cities were addressed and integrated into panel data for analysis.

The data for the variables primarily came from sources such as the National Bureau of Statistics and the China Urban Statistical Yearbook. Additionally, the list of pilot cities for 'Broadband China' and 'Low-Carbon Cities' was sourced from the websites of the Ministry of Industry and Information Technology and the National Development and Reform Commission. Descriptive statistics for the main variables are provided in Table 1.

Table 2 Benchmark regression results.

Variables	(1) UER	(2) UER	(3) UER	(4) UER
DGST			0.0575**	0.0860**
			(0.0280)	(0.0369)
Digital	0.0191			−0.0144
	(0.0214)			(0.0258)
Green		−0.0103		−0.0366
		(0.0219)		(0.0246)
Fis	−0.00478	−0.00491	−0.00480	−0.00474
	(0.00432)	(0.00431)	(0.00431)	(0.00432)
Edu	0.0174	0.0222	0.0104	0.0179
	(0.138)	(0.138)	(0.138)	(0.138)
Con	0.283***	0.284***	0.282***	0.282***
	(0.0223)	(0.0223)	(0.0223)	(0.0223)
Sav	0.165***	0.159***	0.172***	0.169***
	(0.0343)	(0.0342)	(0.0344)	(0.0345)
Inter	0.0204**	0.0206**	0.0204**	0.0207**
	(0.00925)	(0.00925)	(0.00925)	(0.00925)
Pgdp	6.12e-06***	6.18e-06***	6.08e-06***	6.14e-06***
	(4.73e-07)	(4.74e-07)	(4.73e-07)	(4.75e-07)
Constant	−7.304***	−7.218***	−7.408***	−7.347***
	(0.623)	(0.622)	(0.624)	(0.626)
City fixed	Yes	Yes	Yes	Yes
Year fixed	Yes	Yes	Yes	Yes
Observations	3920	3920	3920	3920
R-squared	0.566	0.566	0.567	0.567

***, ** and * indicate significance at the 1%, 5% and 10% levels, respectively, with standard errors in parentheses.

Empirical Analysis

Benchmark regression results. Table 2 presents the benchmark regression results for the effect of DGST on urban economic resilience. Column (3) shows that, without considering the individual effects of the 'Broadband China' and 'Low-Carbon Cities' initiative, DGST significantly improves urban economic resilience at the 5% significance level, with a one-unit increase in DGST resulting in a 5.75% increase in resilience. In Column (4), after accounting for the single-pilot policies, DGST continues to have a significant positive effect on urban economic resilience, suggesting that the dual-pilot policies of 'Broadband China' and 'Low-Carbon Cities' effectively enhance urban economic resilience.

Parallel trend test. The benchmark regression using a multi-period DID model confirms that the dual-pilot policy significantly enhances economic resilience. However, it is crucial to verify that the experimental and control groups followed a similar trend prior to the intervention. In other words, the economic resilience of dual-pilot cities and non-dual-pilot cities should not differ significantly before the treatment. Following Beck et al. (2010), this paper creates dummy variables for 3 years before and 5 years after the implementation of the pilot policy and conducts the parallel trend test. The results are presented in Fig. 1.

Before the implementation of the dual-pilot policy, the estimated coefficients for both the experimental and control groups are not significantly different. After the policy, the coefficients for economic resilience show a strong positive trend,

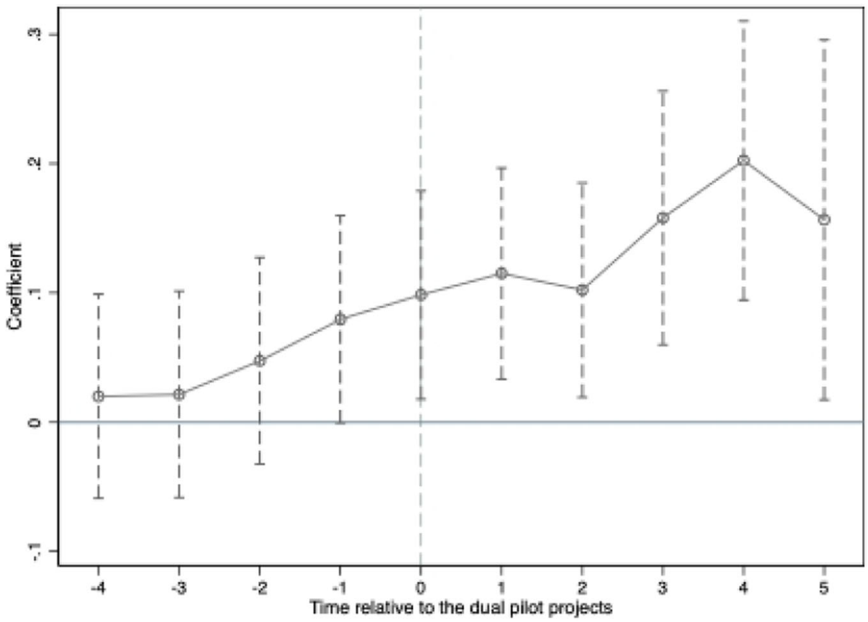

Fig. 1 Parallel trend test.

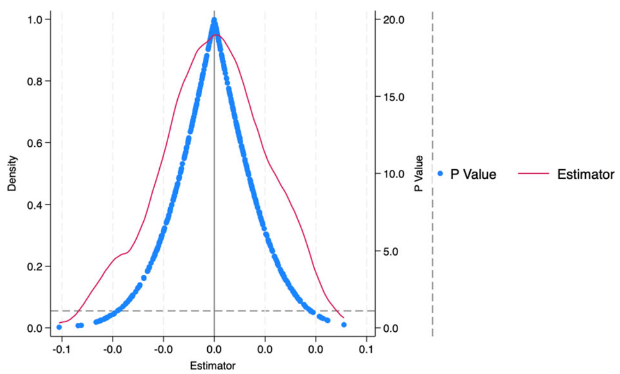

Fig. 2 Placebo test.

indicating that the dual-pilot policy effectively enhances urban economic resilience and passes the parallel trend test.

Placebo test. To reduce the potential impact of random and unobservable factors on the benchmark regression results, this paper employed a placebo test. The policy implementation time was kept constant, and the experimental group was randomly selected 500 times from the list of dual-pilot cities. The estimated coefficients and kernel density plots for each of the 500 random selections were calculated. The results, shown in Fig. 2, reveal that the estimated coefficients fall within the range of [−0.05, 0.05], are centred around 0 and follow an approximately normal distribution. This indicates that there is no significant difference in economic resilience levels between the experimental and control groups, consistent with the expectations of the placebo test.

Endogeneity analysis. To address potential endogeneity arising from reverse causality, this paper follows the approach of Liu M, Ma Q (2023) and uses each city's topographic relief as an instrumental variable for the core explanatory variable. Variations in terrain affect broadband access and network signals, with flatter areas providing natural advantages for digital infrastructure development. Additionally, topography influences population density and economic activities, which in turn impact the selection of low-carbon cities. As a result, topographic relief is related to the establishment of both 'Broadband China' and 'Low-Carbon Cities' pilots. Since topographic relief is an objective variable, it is unlikely to directly affect economic resilience, meeting the correlation and exogeneity assumptions for instrumental variables. Given that topographic relief is cross-sectional data, it is combined with the year variable to create an interaction term for panel data regression analysis. As shown in Table 3, the instrumental variables pass the relevant tests, confirming their validity. The regression coefficient for the core explanatory variable remains significantly positive, suggesting that the findings are not influenced by potential endogeneity and reinforcing the robustness of the conclusions.

Table 3 IV test results.

Variables	DGST	UER
IV	−0.00268***	
	(0.000741)	
DGST	0.393***	1.461**
	(0.00962)	(0.722)
Digital	0.304***	−0.554*
	(0.00987)	(0.285)
Green	−0.00268***	−0.452**
	(0.000741)	(0.220)
Controls	Yes	Yes
City fixed	Yes	Yes
Year fixed	Yes	Yes
Observations	3920	3920
R-squared	0.735	−0.228
Wald F test	13.100	

***, ** and * indicate significance at the 1%, 5% and 10% levels, respectively, with standard errors in parentheses.

Other robustness tests

Replacement of the explanatory variable. The baseline regression measures urban economic resilience by the deviation between actual and expected economic output. To assess the robustness of the regression, this paper follows Chao and Xue (2023) by using the deviation of actual economic output from the 2008 levels as

Table 4 Robustness results.

Variables	(1) Substitution of explanatory variables	(2) Control of temporal trends in provinces	(3) Removal of outliers	(4) Counterfactual approach	(5) Exclusion of other policy interference	(6) Change in sample time interval
DGST	0.151***	0.0877**	0.0773***	−0.00952	0.0866**	0.0832**
	(0.0367)	(0.0348)	(0.0290)	(0.0357)	(0.0369)	(0.0417)
Digital	−0.0465*	0.00464	−0.0147	0.0218	−0.0155	0.00905
	(0.0257)	(0.0231)	(0.0202)	(0.0234)	(0.0259)	(0.0289)
Green	0.0545**	−0.0435	−0.0278	−0.00807	−0.0362	−0.0374
	(0.0245)	(0.0294)	(0.0192)	(0.0239)	(0.0246)	(0.0266)
Controls	Yes	Yes	Yes	Yes	Yes	Yes
City fixed	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed	Yes	Yes	Yes	Yes	Yes	Yes
Province Fixed		Yes				
Province and year interaction fixed		Yes				
Observations	3920	3920	3920	3920	3920	3360
R-squared	0.887	0.741	0.640	0.566	0.567	0.528

***, ** and * represent significance at the 1%, 5% and 10% levels, respectively, with standard errors in parentheses.

an alternative explanatory variable. Following the impact of the 2008 global financial crisis, China's economy experienced fluctuations and declines in employment and output. The deviation of actual economic output from the 2008 levels can indicate cities' ability to withstand or recover from shocks. Greater economic resilience is reflected by higher values of this deviation. Column (1) of Table 4 presents the regression results using this alternative explanatory variable, with the outcomes confirming the previous findings, thereby validating the robustness of the benchmark regression results.

Control of temporal trends in provinces. Cities with greater economic resilience are more conducive to DGST, which may introduce endogeneity due to reverse causality. To address this, the paper conducts regression analyses by controlling for province-fixed effects and the interaction effects of province and year. This helps mitigate the impact of macro-environmental changes resulting from the ongoing development of digitisation and greening. The results, shown in Column (2) of Table 4, indicate that the coefficients are all significantly positive, consistent with the previous regression findings, suggesting that potential endogenous bias does not affect the results of this paper.

Removal of outliers. To prevent extreme values from influencing the regression results, this paper applies a 5% bilateral tailing treatment to each variable. Column (3) of Table 4 shows that after the treatment, the coefficient remains significantly positive, indicating that the results are not affected by outliers.

Counterfactual approach. To further validate the robustness of the findings, this paper adopts a counterfactual approach based on Shi et al. (2018) and conducts a time placebo test. The dual-pilot policy's implementation time is assumed and its effect on urban economic resilience is tested. If the coefficient is not significant, the increase in economic resilience can be attributed to the dual-pilot policy rather than other factors. Column (4) of Table 4 shows that when the dual-pilot policy is assumed to start 4 years earlier, the regression coefficients are not significant, confirming that the results and conclusions are robust.

Exclusion of other policy interference. When examining the impact of DGST, represented by 'Broadband China' and 'Low-Carbon Cities', on urban economic resilience, other concurrent policies, such as the 'Smart Cities' pilot policy, may also affect the results. To address this, the 'Smart Cities' pilot policy is incorporated into the benchmark regression model, as shown in Column (5) of Table 4. The coefficient for DGST remains significantly positive, indicating that even after accounting for the influence of other policies, DGST continues to significantly promote urban economic resilience.

Change in sample time interval. To reduce the impact of the COVID-19 pandemic on the economy and the paper's findings, the data from 2020 to 2021 were excluded, and the estimation tests were re-run. The regression results in Column (6) of Table 4, after excluding this data, remain consistent with the benchmark regression results, indicating that the findings are robust.

Mechanism Analysis

This paper shows, through theoretical analysis, that DGST positively impacts urban economic resilience. This improvement is due to enhanced defensive, adaptive and learning capacities within the urban economic system. Specifically, the paper explores the pathways and mechanisms of DGST from three perspectives: employment absorption, industrial structure optimisation and green technology innovation. The results, based on Jiang's (2022) approach to mechanism analysis, are presented in Table 5.

Defensive capacity: absorbing employed labour. This paper first examines the effect of DGST on urban economic resilience through defensive capacity, focusing on the labour-absorbing pathway, measured by the logarithmic of the average number of employees on duty. As shown in Column (1) of Table 5, the coefficient for DGST's impact on labour absorption is significantly positive, indicating that DGST plays a key role in increasing the absorption of urban labour, thereby raising the employment rate.

The digital economy, a major driver of economic growth, significantly influences the labour market and employment opportunities. At the same time, the 'dual-carbon' goal highlights the need for a skilled workforce in the green sector, resulting in the creation of green jobs. DGST is also reshaping traditional employment patterns by providing more flexible job

Table 5 Mechanism test results.

Variables	(1) Absorption of employed labour	(2) Optimisation of industrial structure	(3) Green technology innovation
DGST	0.0692***	0.0597***	1.548***
	(0.0257)	(0.0147)	(0.137)
Digital	0.0490***	0.0236**	0.260***
	(0.0180)	(0.0103)	(0.0958)
Green	0.0316*	−0.00904	0.0754
	(0.0171)	(0.00979)	(0.0911)
Controls	Yes	Yes	Yes
City fixed	Yes	Yes	Yes
Year fixed	Yes	Yes	Yes
Observations	3920	3920	3920
R-squared	0.934	0.909	0.808

***, ** and * denote significance at the 1%, 5% and 10% levels, respectively, with standard errors in parentheses.

Table 6 Heterogeneity of human capital levels.

Variables	Low human capital UER	High human capital UER
DGST	0.0719	0.143***
	(0.0515)	(0.0540)
Digital	−0.0457	−0.0219
	(0.0375)	(0.0361)
Green	−0.0357	−0.0322
	(0.0352)	(0.0350)
Control variables	Yes	Yes
City fixed	Yes	Yes
Year fixed	Yes	Yes
Observations	1960	1960
R-squared	0.645	0.635

***, ** and * indicate significance at the 1%, 5% and 10% levels, respectively, with standard errors in parentheses

opportunities and broadening choices for workers. A strong labour force is essential for a region's resilience to economic shocks (Martin et al., (2016)). A higher employment rate strengthens the economic system's defensive capacity, stabilising employment and ensuring economic stability amid uncertainties.

Adaptive capacity: industrial structure optimisation. The paper then explores the effect of DGST on urban economic resilience through adaptive capacity, specifically focusing on industrial structure optimisation. Following the approach of Ma and Zhu (2022), industrial structure optimisation is measured by the ratio of the tertiary sector's to the primary and the secondary sector's production values. As shown in Column (2) of Table 5, the coefficient is significantly positive, suggesting that DGST plays a key role in optimising and diversifying the economic structure.

DGST effectively supports the growth of both digital and green industries, fostering their integration and mutual enhancement. It encourages the development of both traditional and strategic industries while accelerating the shift from high-pollution, energy-intensive sectors to high-tech, environmentally sustainable industries. This transformation creates new sectors, business models and operational strategies, contributing to the development of a high-end, intelligent and green industrial landscape.

The ongoing modernisation and optimisation of the industrial structure improve the rationalisation and progression of the economic structure. This process not only conserves resources and reduces environmental pollution but also enhances the efficiency of regional resource allocation. By creating new growth opportunities and supporting the economic system's adaptability to uncertainties, DGST significantly boosts urban economic resilience.

Learning capacity: green technology innovation. Lastly, the paper examines the effect of DGST on urban economic resilience through learning capacity, with a particular focus on green technology innovation. This analysis uses the number of patents for green inventions and utilities per 10000 people as key indicators. As shown in Column (3) of Table 5, the regression coefficient is significantly positive, underscoring DGST's crucial role in advancing green technology.

DGST promotes the integration of digital and green technologies (Hou et al., 2023). Digital technology, with its inherent properties of sharing and spillover, helps overcome barriers to knowledge and information flow, facilitating the acquisition of green technology and expertise. The synergy between digital technology and green development not only supports each other but also attracts talent skilled in both fields. This synergy is essential for fostering further green technology innovations and providing substantial intellectual support.

Moreover, advancements in green technology innovation improve the efficiency of production factors in the economic development process, boosting cities' green production capabilities. At the same time, the development of green products contributes to a sustainable, low-carbon and recyclable framework, offering innovative solutions for sustainable economic growth. This process strengthens the economic system's ability to recover from shocks and enhances urban economic resilience.

Heterogeneity Analysis: How Do Urban Factor Endowments Influence Digital Greening Synergies?

Given the significant differences in factor endowments across cities, these variations impact the starting points and development paths of cities in their digital and green transformation efforts. As a result, there may be heterogeneity in how DGST contributes to urban economic resilience. As noted by Shi et al. (2018), the 'Broadband China' and 'Low-Carbon Cities' pilot policies are not implemented in isolation but are shaped by various factor endowments. The effect of DGST on economic resilience also depends on the availability of human, financial and material resources. This paper further explores how DGST's influence on economic resilience differs based on variations in human capital, financial investment and infrastructure development.

Human capital. A city's human capital, which reflects its level of education and skill quality, is a key factor in its ability to adopt and apply technology. Differences in human capital can result in variations in the availability of skilled workers and the capacity to adapt to and innovate in emerging technologies and industries. These differences significantly impact the effectiveness of digital–green transformation efforts. This paper uses the ratio of education spending to the total public budge as a proxy for human capital and divides the sample into two groups—cities with lower and higher human capital levels—based on the median value to conduct a heterogeneity analysis.

The regression results in Table 6 show that the impact of DGST on urban economic resilience varies depending on human capital levels. In cities with lower human capital, DGST does not have a significant effect on economic resilience. However, in cities with higher human capital, the transformation significantly enhances

Table 7 Heterogeneity in the level of fiscal expenditures.

Variables	Low level of fiscal expenditure	High level of fiscal expenditure
	UER	UER
DGST	0.0672	0.113**
	(0.0591)	(0.0497)
Digital	−0.0767**	0.0288
	(0.0369)	(0.0382)
Green	−0.0186	−0.0811**
	(0.0349)	(0.0365)
Controls	Yes	Yes
City fixed	Yes	Yes
Year fixed	Yes	Yes
Observations	1960	1960
R-squared	0.604	0.632

***, ** and * represent significance at the 1%, 5% and 10% levels, respectively, with standard errors in parentheses.

Table 8 Infrastructure level heterogeneity.

Variables	Low infrastructure	High infrastructure
	UER	UER
DGST	0.00979	0.0950***
	(0.0758)	(0.0326)
Digital	−0.0923*	0.0115
	(0.0480)	(0.0244)
Green	0.00698	−0.0831***
	(0.0415)	(0.0265)
Control variables	Yes	Yes
City fixed	Yes	Yes
Year fixed	Yes	Yes
Observations	1963	1957
R-squared	0.579	0.716

***, ** and * represent significance at the 1%, 5% and 10% levels, respectively, with standard errors in parentheses.

economic resilience. The success of the 'Broadband China' and 'Low-Carbon Cities' initiatives relies on a strong human resource foundation, including a skilled labour force with the knowledge and abilities to effectively apply digital and green technologies. Additionally, higher human capital levels are often linked to greater environmental awareness and public involvement, which encourage sustainable living and consumption habits, further enhancing urban economic resilience.

Fiscal expenditure. The economic strength and financial health of a city are key factors in supporting digital greening initiatives, which influence the level of digitisation and greening achieved. As a city's economic strength increases, it fosters the integration of digitisation and greening, a vital aspect of DGST. This paper uses the ratio of general public spending in municipal budgets to gross domestic product as a measure of a city's financial capacity and divides the sample into two groups based on the median value: cities with lower and higher levels of financial expenditure.

The results in Table 7 show that DGST has a minimal impact on economic resilience in cities with lower levels of financial expenditure. In contrast, cities with higher financial expenditure experience a significantly positive effect. Greater fiscal expenditure provides more funding for the 'Broadband China' and 'Low-Carbon Cities' initiatives, supporting the research, development and implementation of emerging technologies. Additionally, substantial financial resources allow governments to offer incentives like tax benefits and subsidies, encouraging more involvement from businesses and the public. Strong financial support also promotes broader economic development and infrastructure construction, creating a more favourable environment for overall economic growth in China.

Infrastructure construction. Infrastructure development is essential for enabling DGST. Proper infrastructure, such as 5G stations, broadband Internet, renewable energy facilities and efficient data processing systems, provides the necessary material and technical foundation for advancing both digitisation and greening. This paper uses the number of mobile phone subscribers as a proxy for infrastructure development, dividing the sample into two groups based on the median value of this indicator: cities with lower and higher levels of infrastructure development.

As shown in Table 8, DGST has a positive impact on urban economic resilience at all levels of infrastructure. However, the effect is notably stronger in cities with more advanced infrastructure. DGST relies heavily on infrastructure, especially in Information and Communications Technology and clean energy facilities. Well-developed infrastructure not only supports the 'Broadband China' and 'Low-Carbon Cities' policies but also acts as the foundation for the digital and green transformation of cities. This support is crucial for advancing the synergistic development of digital and green initiatives, significantly boosting urban economic resilience.

Further Analysis

Based on the previous analysis, this paper explores how DGST strengthens urban economic resilience by focusing on the defensive, adaptive and learning capacities of economic systems when facing uncertain shocks. The effect of DGST on economic resilience varies, mainly due to differences in resource endowments across cities. Additionally, the timing of adopting digital and green transformation adds complexity. Some cities may advance more quickly in digital transformation, while others may make faster progress in green transformation, potentially leading to different impacts on economic resilience. Therefore, this paper examines the effects of different sequences in implementing dual-pilot policies by analysing the economic resilience impacts of two sequences: first, becoming a 'Broadband China' pilot before a 'Low-Carbon Cities' pilot and second, the reverse order. This leads to an important question: which sequence—digital transformation first (Path 1) or green transformation first (Path 2)—more effectively enhances urban economic resilience?

The methodology is as follows: for testing Path 1, dual-pilot cities that initially become 'Broadband China' pilot cities are compared with non-dual-pilot cities. The former group is designated as the experimental group, while the latter serves as the control group. For testing Path 2, dual-pilot cities that first become 'Low-Carbon Cities' pilot cities are compared with non-dual-pilot cities. In this case, the 'Low-Carbon Cities' first movers form the experimental group, and non-dual-pilot cities serve as the control group. The regression results, presented in Table 9, show different outcomes for each path. Path 1 does not yield a statistically significant coefficient for the independent variable, while Path 2 shows a significant coefficient of 0.107. This suggests that cities that first become 'Low-Carbon Cities' pilots experience greater improvements in economic resilience compared to those that first become 'Broadband China' pilots. Therefore, Path 2 seems to be more effective in enhancing economic resilience than Path 1.

This result can be explained by the differing roles and priorities of green and digital transformation in urban development. The 'Low-Carbon Cities' pilot represents green transformation, which

Table 9 Impact of the sequence of digital greening synergistic transformation.

Variables	Path 1	Path 2
	UER	UER
DGST (digital before green)	0.0295	
	(0.0548)	
DGST (green before digital)		0.107***
		(0.0407)
Controls	Yes	Yes
City fixed	Yes	Yes
Year fixed	Yes	Yes
Observations	3679	3835
R-squared	0.555	0.566

***, ** and * represent significance at the 1%, 5% and 10% levels, respectively, with standard errors in parentheses.

is increasingly recognised as a crucial goal for future urban development. In contrast, digital transformation, as represented by the 'Broadband China' pilot, acts as a tool to achieve these developmental goals. For cities, prioritising their development objectives and then adopting corresponding measures is a more effective strategy for long-term sustainable growth. Therefore, initiating the 'Low-Carbon Cities' pilot policy first supports the green and low-carbon transformation of cities, addressing global climate change challenges, mitigating potential climate risks and providing a strong foundation for sustainable urban development. Subsequently, implementing the 'Broadband China' pilot policy enhances green development by promoting digital and green infrastructure, improving the efficiency and effectiveness of green industries, accelerating the development of green technologies, fostering emerging industries and innovations and generating more employment opportunities. This integrated approach better supports the high-quality development of the urban economy and strengthens its resilience.

Conclusions and Implications

Conclusions. In the face of growing global economic competition, the digital economy and green development have become key drivers of economic and social progress. The Chinese government has been actively promoting both digitisation and green transformation, and the integration of these two areas has started to yield positive results. The digital industry has made steady advancements towards green and low-carbon development, while the green transformation of industries increasingly benefits from innovations in the digital sector. This synergistic transformation is now seen as a critical factor in driving superior economic growth.

Despite these advancements, there remains a gap in understanding the impact of DGST on urban economic resilience. The 'Broadband China' and 'Low-Carbon Cities' pilot policies are at the forefront of digital and green transformation efforts. Exploring these policies, particularly their synergistic effects and mechanisms on urban economic resilience, is both theoretically and practically valuable.

This paper examines the effect and mechanisms of DGST on urban economic resilience through policy coordination. Using the 'Broadband China' and 'Low-Carbon Cities' dual-pilot projects as quasi-natural experiments, a multi-period DID model is developed. Based on panel data from 280 prefecture-level cities in China between 2008 and 2021, the empirical analysis shows that DGST significantly boosts urban economic resilience. This conclusion is robust, having passed several robustness and endogeneity tests. Compared to the individual 'Broadband China' and 'Low-Carbon Cities' pilot projects, the dual-pilot initiatives exhibit a stronger synergistic effect, more effectively enhancing urban economic resilience.

The findings indicate that the defensive capacity, adaptability and learning ability of the economic system are crucial factors through which DGST strengthens urban economic resilience. Specifically, labour absorption, industrial structure optimisation and green technology innovation are identified as key pathways. Furthermore, in cities with higher human capital, greater fiscal expenditure and stronger infrastructure, the impact of DGST on economic resilience is more significant. Additionally, cities that first become 'Low-Carbon Cities' pilots before transitioning to 'Broadband China' pilots experience a greater improvement in urban economic resilience compared to those that follow the reverse sequence.

Implications. The findings of this paper have important policy implications for supporting a coordinated transition to digital greening and improving urban economic resilience. First, it is crucial to encourage the deep integration of digitalisation and greening, facilitating their joint transformation. The government should expand the pilot programmes for the 'Broadband China' and 'Low-Carbon Cities' initiatives, ensuring their effective implementation. Focus should be placed not only on the outcomes of individual pilot policies but also on their synergistic effects. Strengthening the coordination between digital and green development policies will enhance urban economic resilience and foster sustainable societal development through the combined impact of these dual-pilot policies.

Additionally, exploring various pathways for the synergistic transformation of digital greening is essential for boosting urban economic resilience. This includes developing long-term mechanisms that improve labour employment, upgrade industrial structures and promote green technology innovation. Enhancing the labour market through effective talent training and recruitment systems is crucial. Encouraging talent mobility, ensuring the optimal allocation and use of human resources and improving the adaptability of the workforce to market demands will support high-quality employment. Furthermore, a strong industrial system should be built through well-designed industrial policies, focusing on specialisation and integration. This will foster the optimisation and upgrading of industrial and supply chains, advancing the rationalisation and modernisation of the industrial structure. Increased support for green innovation is also key. By strengthening the scientific research system, offering better incentives, promoting green research activities and investing more in research and development, green innovation can be significantly advanced.

Finally, it is crucial to develop targeted policies that align with the specific development characteristics of cities, offering sufficient external support for urban economic resilience. In terms of human capital, this includes strengthening talent training and recruitment, increasing education investment and developing a skilled workforce. These efforts will provide the necessary human resources to bolster urban economic resilience. Financially, there should be more capital investment in the 'Broadband China' and 'Low-Carbon Cities' pilot projects, alongside optimised tax policies and additional incentives to encourage public participation in the digital greening transition. Materially, greater investment in infrastructure development is needed to enhance the digital and intelligent capabilities of cities. Strengthening supporting infrastructure and leveraging resource advantages will provide the material foundation required for the coordinated transformation towards digital greening.

Data availability

The authors are committed to providing the raw data supporting their findings upon request.

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