frontiers | Frontiers in Ecology and Evolution

TYPE Original Research
PUBLISHED 28 March 2023
DOI 10.3389/fevo.2023.1151017

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Can artificial intelligence achieve carbon neutrality? Evidence from a quasi-natural experiment

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SPECIALTY SECTION
This article was submitted to Urban Ecology, a section of the journal Frontiers in Ecology and Evolution

RECEIVED 25 January 2023
ACCEPTED 20 February 2023
PUBLISHED 28 March 2023

CITATION
Chen S, Zhang S, Zeng Q, Ao J, Chen X and Zhang S (2023) Can artificial intelligence achieve carbon neutrality? Evidence from a quasi-natural experiment. *Front. Ecol. Evol.* 11:1151017. doi: 10.3389/fevo.2023.1151017

Introduction: As the global climate crisis worsens, carbon neutrality has attracted the attention of various nations.

Methods: Based on panel data from 282 Chinese prefecture-level cities from 2008 to 2019, this research considers the execution of the artificial intelligence strategy as a quasi-natural experiment. It uses the difference-in-differences (DID) model to evaluate the effect of artificial intelligence construction on carbon emission reduction.

Results: The findings indicate that implementing the artificial intelligence strategy into practice can lower carbon emissions and advance carbon neutrality, and this conclusion still passes after various robustness tests. The mediating effects reveal that developing green technologies and upgrading the industrial structure are crucial mechanisms for achieving carbon neutrality. The implementation effect varies with time, geographical location, natural resource endowment, and city level.

Discussion: This article examines the influence of artificial intelligence on urban carbon neutrality at the city level, adding to the notion of urban carbon neutrality and providing research support for urban development transformation.

KEYWORDS

artificial intelligence, carbon neutrality, industrial structure upgrading, green technology innovation, difference-in-differences

1. Introduction

The global harm caused by the greenhouse effect has become the focus of attention of all countries in the 21st century. Therefore, the concept of carbon neutrality has been promoted in more and more countries (Millot and Maizi, 2021; Huovila et al., 2022). Similarly, to reverse the trend of environmental degradation, China has proposed reaching carbon dioxide peak levels by 2030 and carbon neutrality by 2060. In order to fulfill economic structure transformation and upgrade, the Chinese government proposed the "Broadband China" strategy in 2011. It approved three pilot cities in 2014, 2015, and 2016. China is trying to build the digital economy into a major engine of growth in the economy. The positive spillover effect brought about by advanced network infrastructure construction is not only conducive to improving green technology innovation capability (Zeng et al., 2019; Yu, 2022; Zhu T. et al., 2022), but also conducive to promoting the optimization of the overall economic structure (Zhang et al., 2021; Wang et al., 2022; Zhang, 2022).

According to the Environmental Kuznets Curve (EKC hypothesis), the initial growth of a country's economic development leads to the gradual deterioration of environmental quality, and environmental conditions are improved after the economic development reaches a specific value (Grossman and Krueger, 1991). So, does constructing network infrastructure beneficial for reaching carbon neutrality while promoting economic growth? It is a critical issue urgently discussed in this article. In essence, the impact of network infrastructure construction on carbon emissions belongs to the topic of infrastructure environmental effects. However, a large number of existing studies focus on transportation infrastructure (Churchill et al., 2021; Jia et al., 2021), energy infrastructure (Ling et al., 2021; Dong et al., 2022), and carbon emissions. New infrastructure such as 5G, AI, and IoT have caught the attention of academics due to the growing prominence of structural contradictions in traditional infrastructure. Improving network infrastructure construction in pilot cities has dramatically increased the speed of information dissemination and city informatization and modernization. This has a positive impact on urban green technology innovation level (Luo S. et al., 2022), industrial upgrading (Dong et al., 2022), and green total factor productivity of enterprises (Yu, 2022). On the Economic Effects of Network Infrastructure (Luo Q. et al., 2022; Zhou et al., 2022) and technological effects (Wang et al., 2022; Yang M. et al., 2022), a large number of empirical studies have been conducted. However, from the existing literature, only a few scholars have discussed the ecological performance of network infrastructure construction (Rao et al., 2022a,b). It also provides potential opportunities for the study of this article.

This study aims to explore the impact of network infrastructure construction on urban carbon neutrality with the demonstration policy of "Broadband China" as the entry point to make up for the shortcomings of existing studies on the ecological effects of network infrastructure. Ahmed and Le (2021) used the data from the six ASEAN countries from 1990 to 2018 and found that broadband development is conducive to reducing carbon emissions. At the same time, researchers also found this fact in North America, China, South Asia, and other countries and regions (Ahmed et al., 2021; Usman et al., 2021; Rao et al., 2022b). Further, from a spatial perspective, network infrastructure significantly promotes local carbon emission reduction efficiency and positively affects neighboring regions (Wu et al., 2021b). However, some academics have the opposing viewpoint. They believe the construction of early base stations, network equipment, and other network infrastructure will increase total energy consumption, thus increasing carbon dioxide emissions (Avom et al., 2020; Wei and Ullah, 2022). Khan et al. (2022) studied the data of BRICS countries from 1990 to 2019 and found that improving network infrastructure construction significantly increased carbon emissions. Therefore, the tangible impact of network infrastructure building on carbon emissions still lacks strong identification. It offers a chance for further investigation in this article. To that purpose, this article attempts to explore the impact of "Broadband China" strategy on achieving carbon neutrality and its influencing mechanism, and further studies the effect of this policy heterogeneous among different regions and different types of cities.

Overall, developing network infrastructure can help cities become carbon neutral. Our research results can be used as a reference for policy implementation in developed and developing countries. In comparison to previous studies, this study's marginal contribution consists mostly of the following three points: First, the transmission mechanism of network infrastructure to urban carbon neutrality was studied from the two aspects of industrial structure upgrading and green technology innovation. It enriches the research field on the ecological effects of infrastructure. Second, in the empirical analysis, a relatively comprehensive measurement of carbon emissions is carried out from the city level. The difference-in-differences (DID) models is used to investigate the specific impact of network infrastructure on urban carbon neutrality. Third, we evaluated the heterogeneity of policy effects in different cities.

The remaining sections of this article are arranged as follows: section "2. Literature review and hypothesis development" review the literature and proposes the hypothesis. Section "3. Research design" contains the methodologies and data. Section "4. Results and discussion" analyzes the empirical results. Section "5. Further discussion" elaborates on the empirical results. Section "6. Conclusion," the corresponding conclusions and policy implications are offered based on the research results.

2. Literature review and hypothesis development

2.1. Direct impact of the "Broadband China" strategy on carbon emission

In order to accurately assess the specific impact of network infrastructure on carbon neutrality, this article discusses three perspectives: production, consumption, and regulation.

First, from the production perspective, network communication technology breaks the time-space constraints based on traditional means of production (Zou and Pan, 2022). Enterprises can exchange product information or professional and technical personnel through digital platforms (Henderson, 1997). Thus, technology diffusion and knowledge spillover are generated, and the production process is optimized to transform from the traditional extensive production mode to the intensive production mode (Gaglio et al., 2022). At the same time, the improvement of network infrastructure promotes the emergence of new business forms, such as the digital economy and virtual economy (Zhong et al., 2022), which helps enterprises to change from experience-driven to data-driven and identify the direction of green development (Hao et al., 2023). In addition, as network infrastructure continues to improve, digital finance will also flourish. The wide application of digital finance will help traditional credit departments identify enterprises' financing motives and potential risks (Berg et al., 2020). The available financial resources in the market are expanded, providing a new source of funds for enterprises to carry out emission reduction activities (Feng et al., 2022; Zhang, 2022).

Secondly, from the perspective of consumption, household consumption plays an important role in China's carbon emissions (Zhang et al., 2017). Yang C. et al. (2022) studied the correlation between the Internet and household consumption and believed that the Internet's development significantly improved household consumption. Household consumption influences carbon emissions through direct and indirect energy consumption (Liu et al., 2021). Xu and Zhong (2023) found that digitization has a significant moderating effect on household energy consumption in middle and high-income countries, which is valid in both free and non-free economies (Ma et al., 2021; Zhao and Chan, 2022). At the same time, the application of Internet technology can promote the Pareto optimal allocation of factors, thus causing innovation and reform of consumption patterns (Verhoef et al., 2021) and reducing energy consumption. In addition, the popularization of the Internet accelerates the dissemination of knowledge and information related to environmental protection, effectively forms the traction effect of the demand side on the supply side, realizes the accurate matching of supply and demand, and promotes green consumption (Bastida et al., 2019).

Finally, from the supervision perspective, digital technology enables the dynamic and informational level of environmental monitoring between departments. Effectively improve the decision-making efficiency of ecological governance of government departments to realize pollution prevention and control, which is conducive to sustainable urban development (Bakker and Ritts, 2018; Nost, 2022). On the other hand, the development of the Internet breaks information barriers, builds a green bridge connecting the government, enterprises, and the public, and accelerates the dissemination of environmental protection information (Yang et al., 2020). This is conducive to creating an ecologically friendly social atmosphere, cultivating people's awareness of low-carbon consumption, realizing the transparency of environmental information, enhancing citizens' willingness to participate in environmental co-governance, and accelerating the realization of urban carbon neutrality (Yang Y. et al., 2022). Based on the above, we postulate the following hypothesis:

> Hypothesis 1: The implementation of the "Broadband China" strategy has reduced urban carbon emission levels and promoted carbon neutrality.

2.2. Indirect impact of the "Broadband China" strategy on carbon emission

The strategy of "Broadband China" increases the application of information technology in the production process by improving the construction of network infrastructure and promotes the optimization and upgrading of industrial structure (Wu et al., 2021a; Liu et al., 2022; Hao et al., 2023). On the one hand, improving the construction level of network infrastructure drives the emergence of new industries, such as information-based Internet, big data, and artificial intelligence, to upgrade the industrial structure (Su et al., 2020; Zhu Z. et al., 2022). On the other hand, as a new production factor, data increases innovative factors' mobility with the characteristics of high efficiency, cleanliness, and easy replication (Hao et al., 2023). The continuous influx of innovation factors changes the structure of consumption demand. In order to meet the changing needs of consumers, traditional industries must drive innovation in their production areas through comprehensive digital empowerment, which promotes the transformation of industrial structure from labor-intensive to technology-intensive, and This effectively improves the efficiency of resource allocation (Ding et al., 2022a,b; Wang et al., 2022; Xue et al., 2022), which ultimately contributes to the reduction of energy consumption and pollutant emissions.

Implementing the "Broadband China" strategy is conducive to improving the green innovation capability of cities (Bertschek et al., 2013; Alam et al., 2022; Saleem et al., 2022). It is mainly visible in the two following aspects. First, the network infrastructure improvement breaks the time and space barriers and accelerates the cross-regional integration of innovative elements such as technology, talent, and capital (Dong et al., 2022). It is conducive to the generation of knowledge spillover effect, reducing the flow cost of green innovation elements, thus improving factor allocation efficiency and resource utilization and promoting green technology innovation (Iqbal et al., 2018). Second, in all facets of business production and operation, technologies like AI, IoT, and big data have been widely utilized. The network infrastructure improvement is conducive to establishing a green digital platform for traditional production enterprises (Zou and Pan, 2022). Thus, big data technology is used to obtain consumers' preference for green products, and assist enterprises in green R&D and production decisions (Benzidia et al., 2021; Zhu Z. et al., 2022). Based on the above discussion, we propose hypothesis 2 as follows:

> Hypothesis 2: "Broadband China" strategy promotes carbon neutrality through green technology innovation and industrial structure upgrading.

Although the existing research has carried out some beneficial exploration and research on network infrastructure and urban carbon neutrality, there are still the following areas for improvement. First, there needs to be more research on the specific impact of network infrastructure and carbon neutrality in the existing literature, and the conclusions are not uniform. It transmission mechanism which affect carbon neutrality is also scarce. Second, most of the current literature on network infrastructure analyzes the economic welfare brought by promoting network infrastructure construction from the perspective of improving economic efficiency and alleviating market distortions. However, there is little literature exploring its influence on the social domain of environmental pollution. This article's research conclusion extends the beneficial effects of network infrastructure further than the field of economic welfare to the field of social welfare, constituting an essential addition to the current literature.

3. Research design

3.1. Methodology

This article will further adopt the "Broadband China" strategy as an exogenous impact. The multi-phase DID method will evaluate whether network infrastructure can promote urban carbon neutrality more stably.

$$\mathbf{CO2}_{it} = a_0 + a_1 did_{it} + a_2 Z_{it} + \mu_i + \delta_t + \varepsilon_{it} \qquad (1)$$

In Eq. 1, $CO2_{it}$ is the carbon emission of $city_i$ in period t. did_{it} is exogenous policy influence. If city i implements the "Broadband

China" strategy in year t, the value is 1; otherwise, the value is 0. Refer to existing literature (Wu et al., 2021a; Dong et al., 2022; Wang et al., 2022), the main control variables are those listed below. Population density (*pnd*) is expressed as the ratio of the total population to the urban area at the end of the year. Foreign direct investment (*fdi*) is measured by the ratio of FDI to the GDP of the city where it is located. The degree of financial development (*fin*) is measured as the ratio of loans from financial institutions to GDP. Regarding energy efficiency (*energy*), we used GDP/million tons of standard coal to measure this indicator. We measured the urbanization rate (*urban*) as the ratio of the nonagricultural population to the year-end resident population. The degree of perfection of transportation facilities (*trans*), expressed as road miles/total area of the region, is the indicator. At the same time, to avoid the individual heterogeneity of intragroup regression, in the model μ_i represents city fixed effect, δ_t represents time fixed effect, and ε_{it} represents the random error term. If a_1 0, then the "Broadband China" strategy is reducing carbon emission.

3.2. Sample selection

3.2.1. Dependent variable

Many studies have shown a positive correlation between night light brightness and carbon dioxide emissions (Wang and Ye, 2017; Zhang et al., 2017). Drawing on the practice of existing literature (Zhu et al., 2019), this article constructs a panel data model to estimate urban carbon emissions based on night light data. Specifically, the steps for estimating urban carbon emissions are as follows. Firstly, according to the existing research (Elvidge et al., 2009, 2017), the original night light data was corrected, and the Chinese night light data set (2008–2019) was constructed and synthesized. Secondly, according to the method of carbon emission accounting for energy consumption in the IPCC report (Yeqing et al., 2014), carbon emissions of 30 provinces and cities in inland China (except Tibet) from 2008 to 2019 were calculated. Then, the relationship equation between the total value of night light and provincial carbon emissions was constructed, and the estimated coefficient between them was estimated. Finally, the total value of night light at the city level was combined with the estimated correlation coefficients to obtain the carbon emissions of 282 cities from 2008 to 2019.

$$CO2_{energy} = \sum_{i=1}^{i} \sum_{j=1}^{j} E_{ij} \cdot \varepsilon_j \cdot f_j \cdot 44/12 \tag{2}$$

In Eq. 2, *CO2energy* is the direct carbon emissions from energy consumption; i is industry type; j is different types of energy; E_{ij} is the consumption of different types of energy in different sectors; ε_j is the standard coal conversion coefficient of different energy sources; f_j is the carbon emission coefficient of different energy sources; 44/12 is the conversion coefficient of carbon to carbon dioxide.

$$CO2_{energy_{it}} = \alpha \cdot nlight_{it} + \mu_i + \nu_t + \varepsilon_{it} \tag{3}$$

In Eq. 3, $CO2energy_{it}$ is provincial carbon emissions based on government statistics, $nlight_{it}$ is night light brightness of the province. The rest is consistent with the baseline regression model. The estimated value of the coefficient can be obtained by Eq. 3. Further, a top-down estimation method is used to construct a city-level carbon emission measurement model as shown in Eq. 4. $CO2_{kt}$ is the carbon emission at the city level.

$$\begin{aligned} CO2_{kt} &= CO2_{energy_{it}} \cdot [(\alpha \cdot nlight_{kt} + \mu_i + \nu_t + \varepsilon_{it}) \\ &\quad + (\alpha \cdot nlight_{it} + \mu_i + \nu_t + \varepsilon_{it}) \end{aligned} \tag{4}$$

3.2.2. Mechanism variables

Industrial structure rationalization (is1) represents the degree of effective utilization of resources and the ability of structural transformation among various industries, and can also be used to measure the degree of coordination between the input and output structure of elements. In this article, use the reciprocal of Theil index to measure is1, and its calculation formula is as follows:

$$is\,1 = \frac{1}{TL} = \frac{1}{\sum_{i=1}^{3} (\frac{Y_i}{Y}) ln(\frac{Y_i}{L_i} / \frac{Y}{L})} \tag{5}$$

In Eq. 5, TL denotes Thiel index, Y denotes output, L denotes employment, i denotes industry, and n denotes the number of industrial sectors. The smaller *is1* value means the higher the level of industrial structure rationalization.

Industrial structure upgrading (is2) represents the transformation and upgrading process from low-level to high-level industries. The measurement of *is2* is based on the method of Lyu et al. (2023). By calculating the ratio of the output value of the primary, secondary, and tertiary industries to GDP as a component of a spatial vector, thus forming a set of three-dimensional vectors X_0 $(x_{1,0}, x_{2,0}, x_{3,0})$. Then measure the angle θ_1, θ_2, and θ_3 between X_0 and the vectors X_1 $(1, 0, 0)$, X_2 $(0, 1, 0)$, and X_3 $(0, 0, 1)$ arranged from low to high in the industry, respectively. The specific formula is shown in Eqs 6, 7.

$$\theta_j = arcos\left(\frac{\sum_{i=1}^{3} (x_{ij}, x_{i0})}{\sum_{i=1}^{3} \left(x_{ij}^2\right)^{1/2} \sum_{i=1}^{3} \left(x_{i0}^2\right)^{1/2}}\right) \tag{6}$$

$$\mathrm{is2} = \sum_{K=1}^{3} \sum_{j=1}^{K} \theta_j \tag{7}$$

The level of green innovation is calculated using the WIPO's "International Patent Green Classification List" issued in 2010. By matching it with the classification number of patent data of the CNIPA, green patent data at the enterprise level can be obtained. On this basis, it is matched to the city level according to the enterprise location's longitude and latitude, and the city's green patent data is obtained. As the proxy variable of green innovation, it is denoted as gri. In the empirical testing process, the variable was taken as the natural logarithm after adding 1 to it; the larger the value is, the higher the level of green innovation in the city (Bloom et al., 2016).

3.3. Data sources and descriptive statistics

China's prefecture-level cities from 2008 to 2019 are used as research samples in this article, and descriptive statistics for each index are provided in Table 1 below. The relevant data used in this article are from the CSMAR, the EPS, and the Wind database. In order to prevent the impact of dimension and outlier on the accuracy of regression, logarithmic processing was carried out for related variables, and 1% tail was reduced for all variable values at both ends. Meanwhile, the Spearman test showed no serious multicollinearity problems between the main variables, so they could be added to the regression equation together. On this basis, this article carries on a series of subsequent analyses and discussions.

4. Results and discussion

4.1. Baseline model

Table 2 presents the estimated results of the impact of the implementation of the "broadband China" strategy on urban CO2. The regression results of adding control variables in columns (1) to (7) show that the coefficients of the "broadband China" strategy are significantly negative at the 1% level, which indicates that the implementation of the "broadband China" strategy will reduce urban CO2 emissions, and hypothesis 1 is confirmed.

4.2. Parallel trend test

In this article, we refer to the existing studies (Yang et al., 2021; Li et al., 2022) to conduct the parallel trend test. Firstly, generate a series of time dummy variables and city dummy variables. Secondly, construct interaction terms for the time dummy variable and the city dummy variable, and examined the trend changes in the 5 years. Figure 1 reports the results of the analysis. From the results, all regressions before 2013 are insignificant, indicating that the parallel trend hypothesis is supported by the fact that the trends of the treatment and control groups were consistent prior to the pilot year.

4.3. Robustness results

4.3.1. Different variables

4.3.1.1. Replacing the dependent variable

In this article, a continuous dynamic distribution method based on a stochastic kernel density function is used to analyze the carbon emission intensity of Chinese cities, and add the carbon emissions from electricity, gas, and LPG, transportation and thermal energy consumption together to obtain the total carbon emissions of each city, which is denoted as CO22. The results in columns (1) of Table 3 shows that the "Broadband China" strategy can still significantly reduce carbon emissions and promote carbon neutrality under the change of carbon emission measurement, which further enhances the credibility of the conclusions.

4.3.1.2. Replacing fixed effect

Furthermore, due to historical and geographical factors, the effect between different regions may have a systematic trend over time. To this end, this article adds the interactive fixed effect of province and time. For this reason, we add $Pro \times Year$ in Eq. 1. The result in Table 3 column (2) shows that the "Broadband China" strategy still significantly reduce carbon emissions after accounting for different fixed effects.

4.3.2. Propensity score matching-difference in difference

To reduce the problem of sample selection bias under the "Broadband China" pilot policy (Heckman, 1979), this article further employs the propensity score matching-difference in difference (PSM-DID) model to assess the net effect of the policy. The particular procedures are as follows: First, the kernel matching method was used to match the samples of the experimental and control groups, and the matching results are represented in Figure 2. Second, this article performs PSM-DID regression on the matched samples based on satisfying the balance test, and the estimation results are represents in columns (4) and (5) of Table 3. The estimation results show that the estimated coefficient of the "Broadband China" strategy is still significantly negative after using PSM-DID, which indicates that the policy effect to reduce CO_2 emissions still exists.

4.3.3. Placebo test

4.3.3.1. Change the point of policy interventions

To remove the possible effect of time-varying random factors on the "Broadband China" strategy's implementation results, this article employs the counterfactual methodology of changing the time point of policy interventions to test. In order to do so, we advance the real intervention years of the "Broadband China" strategy by 1, 2, and 3 years, respectively, and obtain the new estimation results as shown in columns (5) to (7) of Table 3, it seems that the estimated coefficients of the "Broadband China" demonstration cities with advance policy implementation time are no longer significant.

4.3.3.2. Randomly generated experimental groups

To exclude the effect of other unobservable and unmeasurable city characteristics that change over time on the estimation results, this article confirms them by using a substitution test with randomly selected policy intervention groups. Figure 3 reports the results of the substitution test, the area enclosed by the solid black line is the kernel density curve of the estimated coefficients obtained from the randomly selected policy intervention group of the Broadband China strategy. Figure 3 shows that the distribution of the estimated coefficients after random sampling is around zero and follows a normal distribution, which further illustrates the robustness of the findings of this article.

5. Further discussion

5.1. Mechanism analysis

The above findings suggest that network infrastructure significantly reduces carbon emissions in the pilot cities, thereby contributing to regional carbon neutrality. So, what are the specific transmission mechanisms? In other words, which factors does the "Broadband China" strategy affect to lower carbon emission

TABLE 1 Descriptive statistics of variables.

Variables	Obs	Mean	SD	Min	Max
CO2	3,384	4.028	0.411	2.643	5.097
nlight	3,384	11.192	0.743	8.687	13.125
pnd	3,384	5.741	0.914	1.589	7.968
fin	3,384	0.917	0.580	0.075	9.595
fdi	3,384	0.003	0.003	0.000	0.030
trans	3,384	1.043	0.497	0.048	2.628
urban	3,384	0.325	0.208	0.019	2.432
energy	3,384	0.078	0.054	0.011	0.601
is1	3,384	1.670	1.085	−5.332	8.830
is2	3,384	6.516	0.346	5.517	7.836
grp	3,384	4.556	1.625	0.693	9.666

TABLE 2 Benchmark regression results.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
did	−0.014** (0.023)	−0.014** (0.023)	−0.013** (0.028)	−0.013** (0.029)	−0.014** (0.022)	−0.015** (0.012)	−0.019*** (0.001)
pnd		0.425*** (0.003)	0.445*** (0.002)	0.455*** (0.001)	0.478*** (0.001)	0.538*** (0.000)	0.361*** (0.009)
fdi			0.013*** (0.000)	0.013*** (0.000)	0.012*** (0.000)	0.012*** (0.000)	0.011*** (0.000)
fin				0.015* (0.051)	0.016** (0.033)	0.016** (0.031)	0.061*** (0.000)
trans					−0.033* (0.053)	−0.032* (0.064)	−0.020 (0.217)
urban						−0.049*** (0.000)	−0.040*** (0.000)
energy							−0.178*** (0.000)
_cons	4.031*** (0.000)	3.296*** (0.000)	3.343*** (0.000)	3.329*** (0.000)	3.283*** (0.000)	3.113*** (0.000)	2.948*** (0.000)
City FE	√	√	√	√	√	√	√
Time FE	√	√	√	√	√	√	√
N	3,384	3,384	3,384	3,384	3,384	3,384	3,384
Adj. R^2	0.956	0.956	0.956	0.956	0.956	0.957	0.960

Robust standard errors are reported in parentheses; *** $p < 0.01$, ** $p < 0.05$, and * $p < 0.1$, the same as the following tables.

levels? Following the examination of the theoretical mechanism in the preceding part, this article explores the concrete methods for reducing carbon emissions in the "Broadband China" strategy from two perspectives: industrial structure and green technology innovation. Specifically, this research further explores the influence mechanism of both by developing a model of mediation.

To overcome the statistical bias of the conventional stepwise regression method, in this article, after the regression analysis of *did* and carbon emission, only the regression analysis of did with the mediating variables is conducted. In contrast, use the theoretical literature to demonstrate the effect of mediating variables on carbon emission. The results are displayed in Table 4, where columns (1) and (2) represent the particular outcomes of industrial structure rationalization and industrial structure upgrading, respectively, and column (3) represents the specific result of the level of green innovation. Specifically, the execution of the "Broadband China" strategy may enhance industry structure rationalization and upgrading, and the promotion of industrial structure upgrading is strengthened. The critical reason for this phenomenon is that relying on the connectivity and sharing characteristics of network infrastructure, on the one hand, breaks the spatial and temporal restrictions of information flow, thus promoting the efficient linkage and reorganization of labor, capital, and resources in different regions, realizing the rational allocation of production elements and improving the energy use efficiency. On the other hand, comprehensive digitalization can empower traditional high-polluting industries, reduce energy intensity, reduce urban carbon emissions, and promote carbon neutrality.

Additionally, the impact of implementing the "Broadband China" policy on the level of green technology innovation in cities has been confirmed. Possible explanation is that the strengthening of network infrastructure accelerates the flow of green innovation factors, which increases the degree of green innovation in the pilot cities and encourages the green innovation in nearby cities through the radiation impact and demonstration effect of the flow of production factors. Simultaneously, the improvement of the green technology innovation capacity of cities not only improves the monitoring intensity of carbon emission in high-pollution industries but also helps the application of green production technology in high-pollution industries, which in turn reduces energy consumption, and promotes carbon neutrality. The above findings verify research hypothesis 2.

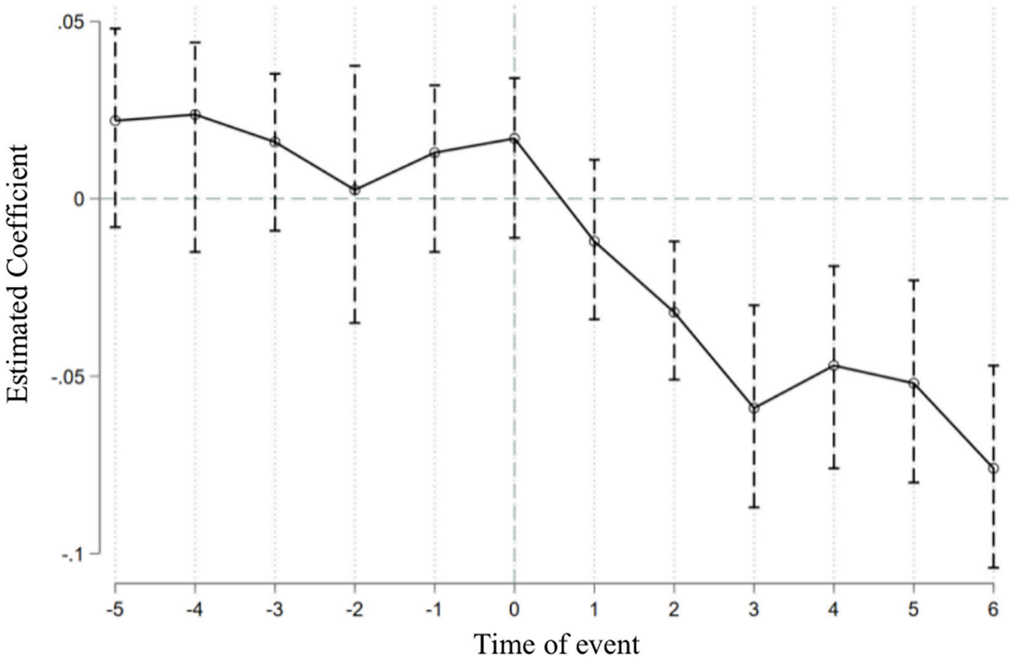

FIGURE 1
Results of a parallel trend test.

5.2. Heterogeneity analysis

Due to the different policy guidelines in different periods and the significant differences in geographic location, resource-based city type and city level among cities, the impact of the "Broadband China" pilot policy on urban carbon emissions may be different. This article further examines the heterogeneity from four aspects: time, geographic location, resource-based city type, and city level.

5.2.1. Heterogeneity analysis of time and geographical location

Although reducing carbon emissions is still the primary issue of carbon neutrality, the effect should not only be considered from the perspective of carbon emission reduction intensity but also from the perspective of carbon emission time and space. From the perspective of time, the "Broadband China" strategy was released in 2013, which enhanced the pulling effect of broadband on the economy. In 2016, the Chinese government further pointed out that it would "drive modernization with informationization and build a strong network country." For this reason, this article sets 2013 and 2016 as two-time points and divides the sample into three sub-samples to test: 2008–2013, 2014–2016, and 2017–2019.

From the geographical location perspective, cities in the eastern region which due have received support from pilot policies, for example, reform and opening up, rely on their advantageous transportation and location advantages and good network infrastructure construction conditions, have taken the lead in development. Compared with cities in the middle and western regions, their economic, human resources, scientific and educational resources, and other factors have advantages. In addition, due to climate differences, the northern regions may produce more carbon emissions due to winter heating than the southern regions. Therefore, this article divides the total sample into five subsamples, namely, the eastern, middle, western, and southern and northern regions, to examine the geographic location heterogeneity.

Table 5 columns (1) to (3) and (4) to (6) report the results based on time and geographical location heterogeneity analysis, respectively. According to estimation results based on a temporal heterogeneity analysis, the "Broadband China" strategy's implementation steadily strengthens its ability to reduce carbon emissions over time. The explanation might be that as Chinese network infrastructure and economic and technical level continue to develop, the execution of the "Broadband China" strategy has a stronger impact on enhancing green technology innovation capability and promoting the upgrading of industrial structure, hence boosting the carbon emission suppression effect.

The estimation results based on geographical location heterogeneity analysis show that the implementation of the "Broadband China" strategy significantly cuts carbon emissions in the eastern, southern, and northern regions. In contrast, the impact on carbon emissions is insignificant in the middle and western areas, and the carbon emissions reduction effect is greater in the north than in the south. On the one hand, it is more challenging for the middle and western areas to successfully play the driving role of network infrastructure construction due to the limits of economic size and resource endowment. On the other hand, as the traditional sectors such as coal and iron and steel account for a larger proportion in the northern regions of China, the environmental pollution is more severe than that in the southern regions, and there is more room for carbon emission reduction, so the technological innovation and achievement transformation capacity enhancement brought by the network infrastructure construction has a more significant impact in the northern regions.

TABLE 3 Robustness results.

	CO22	Pro x year FE	PSM-DID		Replacement of policy time		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
did	−0.022*** (0.002)	−0.037** (0.014)					
did-psm			−0.014** (0.023)	−0.019*** (0.001)			
*did*2013*					−0.010* (0.099)		
*did*2012*						0.003 (0.751)	
*did*2011*							0.008 (0.178)
pnd	0.123 (0.383)	0.112* (0.060)		0.361*** (0.009)	0.009*** (0.000)	0.009*** (0.000)	0.009*** (0.000)
fdi	0.007*** (0.001)	0.063** (0.035)		0.011*** (0.000)	0.592*** (0.000)	0.608*** (0.000)	0.606*** (0.000)
fin	0.083*** (0.000)	0.170*** (0.000)		0.061*** (0.000)	−0.002 (0.208)	−0.002 (0.221)	−0.002 (0.218)
trans	−0.025 (0.227)	−0.028 (0.131)		−0.020 (0.217)	−0.000 (0.973)	−0.000 (0.998)	−0.000 (0.995)
urban	−0.017* (0.082)	−0.0211 (0.446)		−0.040*** (0.000)	−0.310*** (0.000)	−0.310*** (0.000)	−0.310*** (0.000)
energy	−0.140*** (0.000)	−0.122*** (0.000)		−0.178*** (0.000)	0.793*** (0.000)	0.796*** (0.000)	0.796*** (0.000)
_cons	4.526*** (0.000)	4.037** (0.000)	4.031*** (0.000)	2.948*** (0.000)	2.839*** (0.000)	2.831*** (0.000)	2.831*** (0.000)
City FE	√	√	√	√	√	√	√
Time FE	√	√	√	√	√	√	√
Pro × year FE	×	√	×	×	×	×	×
N	3,384	3,384	3,384	3,384	3,384	3,384	3,384
Adj. R^2	0.977	0.825	0.956	0.960	0.960	0.959	0.959

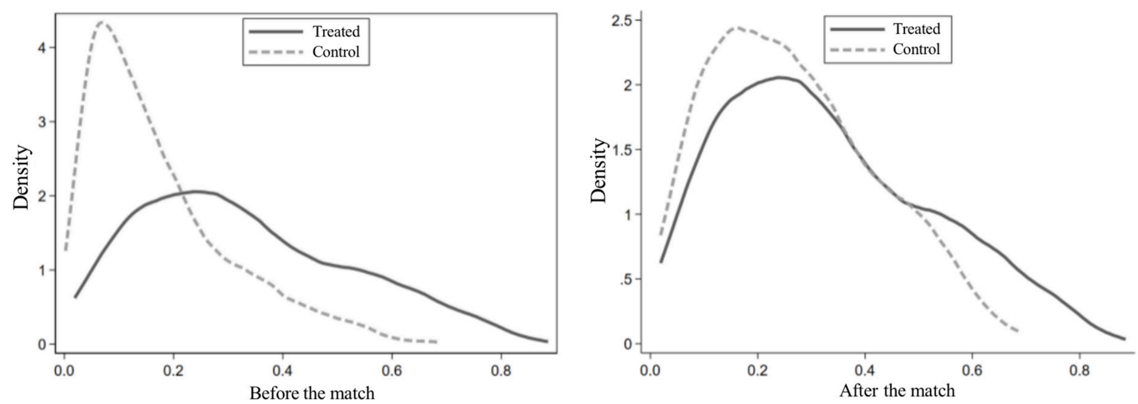

FIGURE 2
Density function of the probability distribution of propensity score values.

5.2.2. Heterogeneity analysis of city types and level

This article divides the samples into resource-based cities and non-resource-based cities for further discussion. Columns (1) and (2) in Table 6 show that the "Broadband China" strategy significantly lowers the carbon emissions level in non-resource-based cities. The primary explanation could be that non-resource cities have more diverse industrial structures than resource cities, which makes the network infrastructure construction more likely to promote advancements in green technology, improved resource allocation efficiency, and modernized industrial structures. In contrast, resource-based cities have more homogenous industrial structures, a weaker overall basis for innovation, and inefficient resource utilization. Therefore, it is difficult for the "Broadband China" strategy's execution to produce significant carbon emission reduction policy effects on resource-based cities.

In addition, the execution of the "Broadband China" strategy has a heterogeneous effect on CO_2 emissions because of the vast disparities in technical development, industrial structure, and energy consumption amongst cities at various levels. Therefore, the sample cities in this article were split into central and peripheral cities for research, and the results are displayed in columns (3) and (4) of Table 6. The results demonstrate that the "Broadband China"

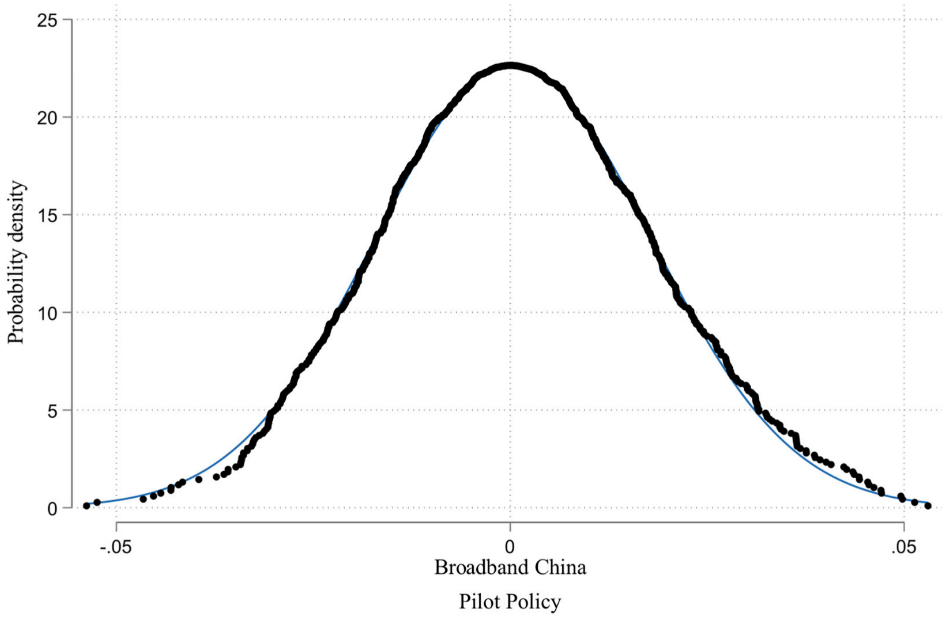

FIGURE 3
Placebo test.

TABLE 4 Mechanism exploration.

	(1)	(2)	(3)
	is1	*is2*	*gri*
did	−0.080* (0.070)	−0.023*** (0.002)	0.484*** (0.000)
pnd	4.492*** (0.000)	0.288* (0.051)	0.010 (0.257)
fdi	0.005 (0.734)	0.008*** (0.001)	−3.197*** (0.001)
fin	0.115* (0.097)	0.069*** (0.000)	−0.011 (0.273)
trans	0.175 (0.184)	−0.002 (0.940)	0.003 (0.826)
urban	−0.058 (0.356)	0.010 (0.338)	−3.791*** (0.000)
energy	−0.406*** (0.000)	−0.033** (0.040)	−0.893 (0.265)
_cons	−7.258*** (0.000)	6.004*** (0.000)	3.201** (0.012)
City FE	√	√	√
Time FE	√	√	√
N	3,384	3,384	3,384
Adj. R^2	0.806	0.946	0.849

strategy significantly lowers the levels of carbon emissions in central and peripheral cities, and the estimated coefficients are −0.028 and −0.013, respectively, which to some extent indicates that the "Broadband China" strategy's implementation has a greater impact on the reduction of carbon emissions in central cities. The possible reason is that the central cities have a larger urban scale than the peripheral ones, and the cost of industrial digital transformation per unit falls as urban scale rises.

6. Conclusion

Accelerating carbon neutrality and achieving coordinated economic and ecological development is a significant issue that the Chinese government and the rest of the world all must address. This article is based on the digital economy era to explore the implementation path of carbon neutrality. Use the DID model, placebo test, and mediating effect model to multi-level test the effect of the "Broadband China" strategy in promoting carbon neutrality and its inner mechanism. The following are the primary conclusions: First, the "Broadband China" strategy significantly promotes carbon neutrality and reduces carbon emissions. This conclusion still holds through the robustness tests of Indicator substitution, Replacement fixed effect, PSM-DID, and Replacement of policy time. Secondly, the mechanism test shows that upgrading urban industrial structures and improving green innovation capacity are important channels for the "Broadband China" strategy to

TABLE 5 Heterogeneity analysis of time and geographical location.

	2008–2013	2014–2016	2017–2019	East	Middle	West	South	North
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
did	−0.028 (0.458)	−0.075*** (0.000)	−0.089*** (0.000)	−0.039*** (0.000)	−0.016 (0.134)	−0.009 (0.408)	−0.013** (0.038)	−0.025*** (0.000)
_cons	4.121*** (0.000)	3.572*** (0.000)	3.708*** (0.000)	3.631*** (0.000)	2.539*** (0.000)	3.262*** (0.000)	3.562*** (0.000)	3.099*** (0.000)
Control variables	√	√	√	√	√	√	√	√
City FE	√	√	√	√	√	√	√	√
Time FE	√	√	√	√	√	√	√	√
N	1,692	846	846	1,200	1,188	996	1,320	2,064
Adj. R^2	0.973	0.594	0.582	0.978	0.938	0.958	0.974	0.982

TABLE 6 Heterogeneity analysis of city types and levels.

	Resource-based city	Non-resource-based city	Central city	Peripheral city
	(1)	(2)	(3)	(5)
did	0.020 (0.260)	−0.026*** (0.000)	−0.028*** (0.000)	−0.013* (0.055)
_cons	5.113* (0.072)	3.253*** (0.000)	2.710*** (0.000)	5.821*** (0.003)
Control variables	√	√	√	√
City FE	√	√	√	√
Time FE	√	√	√	√
N	1,332	2,052	360	3,024
Adj. R^2	0.988	0.981	0.966	0.953

promote carbon neutrality. Third, the heterogeneity analysis demonstrates that the favorable impact of the "Broadband China" strategy on carbon emission reduction grows with time and is more pronounced in eastern, northern, non-resource-based, and central cities.

On the basis of the aforementioned research findings, this article provides the following policy recommendations:

The Chinese government should include more cities in the pilot project according to the development of each city, strengthen the positive spillover effect of network infrastructure construction, release the digital economy dividend, improve environmental pollution while increasing economic welfare, and create a situation where economic growth and ecological construction are beneficial to both parties.

The government should strengthen the penetration effect of broadband networks into traditional sectors, promote the optimum distribution of traditional industrial elements. On the other hand, increased government investment in science and technology innovation is required, especially to increase support for research institutions related to information, digitalization, and green ecology. At the same time, digital empowerment is an important grip to establish a green digital innovation platform to enhance further the driving effect of network infrastructure construction.

The central government should implement targeted urban strategies to take advantage of network infrastructure construction to boost green transformation and balanced regional development. For less developed regions, resource-based and peripheral cities, more preferential policies should be provided and introducing talents and technologies to speed the construction of local network infrastructure. For the developed eastern region and central city, you must create and improve the mechanism of the technology sharing, promote the balanced the balanced growth of China's urban digital economy.

7. Outlook and deficiencies

Despite the fact that this is a cutting-edge research study aimed at extending the beneficial influence of network infrastructure beyond the sphere of economic welfare to the field of social welfare, there are several limits and gaps that might be directions for future work. First, despite the fact that this article's results are backed up by rigorous analysis methods, further research is required to determine whether the "Broadband China" strategy can adequately address all aspects of network infrastructure and whether there are more suitable policies. Second, more study is required to establish that the findings of this work can be generalized given the disparate development levels of the world's nations. Third, the performance of network infrastructure in terms of carbon neutrality is only examined at the macro-city level in this study. It is a worth that future research into the matter at the micro-firm level.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: https://www.epsnet.com.cn/index.html#/Index.

Author contributions

SC proposed the research idea, collected the data, wrote the codes and original manuscript, and revised the manuscript. SyZ, QZ, JA, and SZ made the tables and figures, and helped to collect the data. All authors reviewed and approved the final version of this manuscript.

Funding

This research was funded by the National Social Science Fund of China (22BJL126), Humanities and Social Sciences Fund Project of the Ministry of Education of China (22YJC790016), Basal Research Fund of Zhejiang Sci-Tech University (No.22096201-Y), and National College Student Innovation and Entrepreneurship Training Program (202210338066X).

Conflict of interest

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

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