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The impact of digital infrastructure on carbon productivity Analysis based on provincial panel data

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Abstract

The digital economy has become a mainstream force in promoting the green and low-carbon transformation of industry. This paper, based on balanced panel data from 30 provinces in China from 2011 to 2021, constructs a two-way fixed effect model and a mediation effect model to explore the impact of digital infrastructure construction (DIC) on industrial carbon productivity (ICP). The research finds that DIC can significantly enhance ICP. This conclusion remains valid after variable substitution, Bootstrap tests, and addressing endogeneity issues. DIC influences ICP through industrial structure upgrading. The heterogeneity analysis shows that the impact of DIC on ICP is significant in both eastern and western regions, but not significant in the central region. This study provides empirical evidence and targeted suggestions for enhancing digital infrastructure construction and carbon productivity.

Keywords

Digital infrastructure construction; carbon productivity; industrial structure upgrading.

1. Introduction

Nowadays, the issue of global warming is severe, which is caused by carbon emissions. It is worth noting that the current situation of the industrial sector has a profound impact on the level of carbon emissions[1]. In China, relevant data shows that in 2022, industrial carbon emissions were 4.2 billion tons, accounting for 38.18% of the national total. To achieve the dual carbon goals as soon as possible, industrial development must shift to an efficient, low-carbon and environmentally friendly track, and this is inseparable from the assistance of the digital economy. Digital infrastructure construction (*DIC*), which is the cornerstone of the development of the digital economy, refers to a series of infrastructure used to support the development of the digital economy and society, including information and communication technology infrastructure, the Internet of Things, cloud computing, artificial intelligence, data centers, etc. It has become an important support for promoting economic development, improving the efficiency of social governance and enhancing people's well-being. By the end of 2023, the number of 5G base stations in China reached 3.377 million, and the proportion of 5G mobile phone users among mobile users was 46.6%, reaching 805 million; 636 million households have accessed fixed broadband; the total number of mobile network terminal connections reached 4.059 billion; the number of active IPv6 users has reached 776 million. The scale and level of China's overall digital infrastructure construction have significantly improved. Against the backdrop of the world economy having entered the low-carbon development stage in substance, incorporating carbon emissions into the efficiency of production factor allocation and exploring the low-carbon driving effect of digital infrastructure construction is a necessary and urgent research topic.

As a direct investment, the impact of digital infrastructure on environmental governance has attracted the attention of academics and industry. Digital infrastructure construction can improve the quality of human capital through the development of digital technology[2]

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Improving energy efficiency[3], facilitating energy system operation[4], improving total factor productivity[5], promoting regional innovation[6]. In terms of influencing factors of carbon emissions, different scholars have respectively discussed the carbon reduction effects of "broadband China" strategy[7], industrial structure upgrading[8], and industrial green transformation[9]. In the industrial sector, the energy trading system[10], the development of the digital economy[11], and the advancement of industrial intelligence[12] and the Internet[13] have all had a positive impact on industrial carbon productivity. At the same time, scholars also discussed that the development of digital economy mainly achieves carbon emission reduction by improving innovation efficiency[14] and optimizing and upgrading industrial structure[15,16]. Regarding digital infrastructure construction and carbon emissions, it is generally believed that the development of digital infrastructure construction reduces carbon intensity[17], but some scholars have found that there is a U-shaped nonlinear relationship between digital infrastructure construction and carbon emissions[18].

To sum up, most of the current literature focuses on digital infrastructure construction and carbon emissions, or digital economy and carbon productivity. There are few studies on the impact of carbon productivity in the industrial field, and there is still a large space for research. Based on the panel data of 30 provinces from 2011 to 2021, this paper explores the impact of digital infrastructure construction level on industrial carbon productivity, considers the mechanism of industrial structure in the influencing process, and analyzes regional heterogeneity.

2. Theoretical analysis and hypothesis

2.1. Direct effect

Digital infrastructure creates the conditions for carbon reduction. First, digital infrastructure can stimulate the vitality and potential of factors and facilitate the expansion of production scale[3]. Scale effect will promote the increase of economic aggregate and total carbon emission, but the growth rate of the latter will be smaller than that of the former, and digital infrastructure has a significant negative impact on carbon emission intensity[19]. Second, with advantages in data mining and processing, digital facilities can help governments manage carbon effectively. Through measurement technologies such as big data, cloud computing and remote sensing, effective monitoring of carbon emissions can be achieved to improve carbon emission management capabilities, and environmental protection feedback mechanisms can be established with the help of big data platforms to effectively integrate monitoring data and use data to support the formulation of carbon emission reduction policies. Third, the construction of digital infrastructure has affected social life and changed the way people live. The popularity of digital finance has benefited from the development of the Internet, which has improved the convenience of human life consumption[20]. People can purchase goods and services without leaving their homes, and they can also realize online office work, reducing travel demand and energy consumption in all aspects.

Hypothesis H1: digital infrastructure construction can promote the improvement of carbon productivity.

2.2. Indirect effect

The improvement of digital infrastructure can promote the optimization and upgrading of industrial structure. First, the construction of digital infrastructure has laid the foundation for promoting the development of various digital technologies, while promoting the free flow of production factors such as manpower, capital and energy in the market, helping enterprises to accurately and timely grasp the supply and demand of products in the market, and timely adjust the scale of production. With the help of digital technology, enterprises optimize the efficiency

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of resource allocation, continuously improve production efficiency, reduce transaction costs and risks, and finally realize the optimization and upgrading of industrial structure[21]. Second, the deep integration and development of digital technology with key carbon emission fields such as energy, power, industry, transportation, and buildings has effectively promoted the digital transformation of traditional high-energy industries and realized the optimization and upgrading of industrial structure. Third, digital infrastructure construction has spawned a series of low-energy and low-pollution emerging industries based on information and data, reducing the proportion of traditional high-energy industries. The optimization of industrial structure improves the allocation efficiency of various factor resources among various industries, the relationship between supply and demand structure is constantly clarified and improved, the production efficiency is significantly improved, and finally the carbon productivity is improved.

Hypothesis H2: digital infrastructure construction has an indirect impact on carbon productivity through upgrading industrial structure.

3. Methodology

3.1. Benchmark model

By referring to the practices of existing scholars and taking some influencing factors into consideration, this paper builds a bi-directional fixed effect model, as shown below:

$$ICP_{it}=\alpha_0+\beta_1 DIC_{it}+\beta_2 Controls_{it}+\varphi_i+\mu_t+\varepsilon_{it} \tag{1}$$

Where ICP refers to industrial carbon productivity; DIC is the level of regional digital infrastructure construction; Controls indicates all control variables; i stands for individual, that is, industrial enterprises in different regions; t represents the time, that is, the sample period from 2011 to 2021; α_0 represents the constant term; β represents the influence coefficient of each variable; φ_i represents the fixed effect of individual province (city); μ_t represents the fixed effect of the year, and ε_{it} is the random disturbance term.

3.2. Intermediate effect model

Based on the baseline regression model, the transmission mechanism of digital infrastructure construction affecting carbon productivity is deeply analyzed, and the impact of industrial structure upgrading on the mechanism is discussed.

$$M=\beta X+\varepsilon 1 \tag{2}$$

$$Y=\alpha X+\varepsilon 2 \tag{3}$$

$$Y=\alpha' X+\gamma M+\varepsilon 3 \tag{4}$$

Here, M stands for industrial structure, X stands for the level of digital infrastructure construction, and Y stands for industrial carbon productivity. The total effect of X on Y is $\alpha\gamma+\alpha'$.

3.3. Variables

3.3.1. Explained variable

Industrial carbon productivity (ICP) measures the amount of industrial output produced per unit of carbon. The scale of industrial carbon emissions in each province adopts the calculation method published by $IPCC$ (2006). The physical consumption of coal, coke, fuel oil, diesel, natural gas, gasoline, kerosene and crude oil in each province is converted into standard coal consumption, and then multiplied by the carbon emission factors of each energy to calculate. Then, according to the definition of carbon productivity, the carbon productivity of each province is calculated.

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3.3.2. Explanatory variable

With reference to the practice of Wang et al. (2021)[23], this study extracts eight indicators to build a level evaluation system for digital infrastructure construction(*DIC*). These dimensions include Internet penetration, number of mobile phone base stations, cable line length, Internet broadband access ports, number of domain names, number of websites, Internet broadband access users and mobile phone penetration. Then the level of digital infrastructure construction in each province is calculated by entropy method.

3.3.3. Intermediate variable

This paper studies the intermediary effect of industrial structure upgrading (*Ind*), referring to the practice of most scholars, and taking into account the availability of data, so use the ratio of the output value of the tertiary industry and the secondary industry to express.

3.3.4. Control variables

This study further controls for other potential factors that may affect industrial carbon productivity. Specifically, these control variables include: economic development, government intervention, *FDI*, environmental regulation. Level of economic development (*GDP*), represented by the logarithm of gross regional product; Government intervention (*Gov*), represented by the logarithm of general public budget expenditure in each region; Environmental regulation (*Env*) is expressed by the ratio of investment in industrial pollution control to industrial added value. *FDI* is the proportion of foreign investment.

3.4. Data

The sample data were mainly derived from China Industrial Statistics Yearbook, China Statistical Yearbook, China Energy Statistical Yearbook, China Science and Technology Statistical Yearbook, China High-tech Industry Statistical Yearbook, provinces (municipalities) statistical yearbooks and National Bureau of Statistics, etc. In some years, the missing values of provinces were supplemented by linear interpolation method.

Table 1 below reports a descriptive analysis of industrial carbon productivity and its influencing factors, providing the underlying data for an in-depth analysis. The gap between mean and median carbon productivity is too large, and there are obvious regional differences. The level of *DIC* in most regions is significantly lower than the national average. In addition, the standard deviation of industrial structure is large, indicating that the development level of this factor is significantly different in different regions of industrial enterprises. The large standard deviation of *GDP*, government intervention and other variables indicates the differentiation of development in each region, which lays a foundation for the subsequent heterogeneity analysis.

Table 1: Descriptive statistics

Variable	Observ	Mean	St Err	Min	Middle	Max
ICP	330	0.46	0.961	.0330923	.2685048	11.06791
DIC	330	0.20	0.158	.0159925	.149084	.8035464
GDP	330	8.22	0.845	5.990872	8.19167	9.749893
Gov	330	8.41	0.593	6.559488	8.450163	9.811757
Ind	330	1.25	0.705	.518032	1.08265	5.29682
Env	330	0.00	0.004	.000085	.002277	.030988
FDI	330	0.02	0.015	.0001	.0166	.0796

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4. Empirical result

4.1. Baseline regression result

The P-value obtained by Hausman test is 0.0086 and the significance level is 5%, rejecting the null hypothesis, so the fixed effect model is chosen. Table 2 below reports the results of the fixed effects regression model with the addition of control variables. The results show that after controlling the effect of time and individual dimension, the influence coefficient of *DIC* level on *ICP* is positive. When no control variable is added, the correlation coefficient of the two is 1.827, and the significance level is 5%. After adding a series of relevant control variables, the correlation coefficient decreases, but the significance level is still 5%. It shows that the improvement of *DIC* is conducive to the improvement of *ICP*. With the continuous improvement and optimization of *DIC*, the production efficiency and environmental performance of industrial enterprises can be improved. Therefore, hypothesis H1 is verified. At the same time, the positive impact of *GDP* on industrial carbon productivity suggests that *DIC* will further promote industrial production efficiency. Environmental regulation represents the proportion of the completed investment in industrial pollution control to the industrial added value. The larger the proportion, the more funds for industrial pollution control, the less carbon emissions in industrial production links, and the higher carbon productivity. As can be seen in column (5), government intervention has a negative impact on carbon productivity, and government intervention is the proportion of local governments' general public budget expenditure in *GDP*. The possible cause of the negative impact is excessive government financial expenditure, resulting in sufficient budget for industrial enterprises to reduce carbon emission constraints through carbon markets and carbon emission rights, thus leading to the improvement of carbon productivity.

Table 2: Benchmark regression

	(1) ICP	(2) ICP	(3) ICP	(4) ICP	(5) ICP
DIC	1.827**	1.462**	1.874**	1.625**	1.763**
	(2.48)	(2.25)	(2.26)	(2.09)	(2.18)
GDP		2.506***	2.823**	3.047***	3.348***
		(2.72)	(2.57)	(2.63)	(2.65)
Gov			-0.689	-0.716	-1.278*
			(-1.12)	(-1.15)	(-1.67)
Env				19.422**	20.889**
				(2.16)	(2.22)
FDI					8.882**
					(2.22)
_cons	0.095	-20.428***	-17.329***	-18.949***	-16.904***
	(0.62)	(-2.68)	(-2.65)	(-2.76)	(-2.77)
N	330	330	330	330	330
R2	0.612	0.621	0.623	0.624	0.628
Adj. R2	0.56	0.57	0.57	0.57	0.57

t statistics in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.0$

4.2. Mechanism analysis

According to the results of mechanism analysis in Table 3, column (1) shows that the influence coefficient of *DIC* on *ICP* is positive at the significance level of 5%, indicating that *DIC* has a

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positive effect on the improvement of *ICP*. The correlation coefficient is α=1.763. Column (2) shows that the influence coefficient of *DIC* on industrial structure is negative β=-0.533, and the significance level is 5%. This is likely because the construction of digital infrastructure often takes a long time and has a lag effect on life and production activities, and the secondary industry in the current industrial structure has increased due to investment in infrastructure. Column (3) indicates that the effect of industrial structure upgrading on industrial carbon productivity is positive γ=1.830 and significant at 1% level. According to the theoretical analysis and mechanism model mentioned above, the results of mechanism test are contrary to the theory, and $\beta\gamma$ and α' are reversed, that is, indirect benefit and direct benefit are different numbers, and each coefficient is significant, and masking effect occurs [22]. In this study, digital infrastructure development may also have a rebound effect, leading to an increase in carbon emissions. In this case, the absolute value of $\beta\gamma/\alpha'$, i.e. 55.3%, is chosen to represent the effect size of the intermediary effect.

Table 3: Mediating effect

	(1)	(2)	(3)
	ICP	Ind	ICP
DIC	1.763**	-0.533**	2.738***
	(0.810)	(0.260)	(0.950)
GDP	3.348***	-0.902**	5.000***
	(1.264)	(0.351)	(1.441)
Gov	-1.278*	-0.049	-1.188*
	(0.767)	(0.172)	(0.717)
Env	20.889**	2.933	15.521*
	(9.422)	(3.792)	(9.099)
FDI	8.882**	-0.183	9.218**
	(4.009)	(1.164)	(3.613)
Ind			1.830***
			(0.535)
_cons	-16.904***	9.175***	-33.694***
	(6.099)	(3.066)	(9.749)
id	YES	YES	YES
year	YES	YES	YES
N	330.000	330.000	330.000
r2_a	0.570	0.950	0.659

4.3. Robustness test

Considering that digital infrastructure is a part of the development of digital economy, the closely related digital HP Financial Index (*DF*) is used to replace *DIC*, and then the fixed effects model regression is carried out. Table 4 shows the regression results for alternate explanatory variables. Column (1) of this table shows that after the replacement of explanatory variables, its impact on *ICP* is positive 0.019, with a significance level of 5%, which still indicates that the development of digital economy has a promoting effect on the improvement of *ICP*. At the same time, the intermediary effect is still significant; The *ICP* was replaced by the logarithm of industrial carbon emissions (*Lnc*) for fixed-effect model regression. The specific regression results are shown in column (2) of Table 4. The regression results show that after replacing the explained variables, the impact of *DIC* on industrial carbon emissions is negative, and the significance is 1%, indicating that *DIC* has a significant inhibition effect on industrial carbon

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emissions, which also verifies its promotion effect on industrial carbon productivity from the opposite side, and increases the stability of the model.

Table 4: Robustness test

	(1) ICP	(2) Lnc
DF	0.019**	
	(2.22)	
Ind	1.573***	-0.659***
	(3.18)	(-5.61)
GDP	4.153***	-1.061***
	(3.38)	(-2.86)
Gov	-0.936	0.143
	(-1.33)	(0.76)
Env	15.691*	-8.144**
	(1.75)	(-2.47)
FDI	8.941**	-0.240
	(2.53)	(-0.17)
DIC		-1.292***
		(-4.71)
_cons	-32.400***	18.663***
	(-3.32)	(6.29)
N	330	330
R2	0.711	0.972
Adj. R2	0.67	0.97

This paper adopted Bootstrap method to test the mechanism of action and obtained the test results in Table 5 through 500 samples. The test results show that in the path of the impact of *DIC* on *ICP* through the upgrading of green industrial structure, the confidence interval of its indirect impact does not contain 0, which is statistically significant. This is consistent with the results of the intermediary benefit analysis in the previous article.

Table 5: Bootstrap test

	Observed coefficient	Bootstrap std. err.	z	P>|z|	Normal-based [95% conf. interval]	
Direct	2.481471	.9624433	2.58	0.010	.5951167	4.367825
Indirect	1.294217	.2982693	4.34	0.000	.7096199	1.878814

In order to avoid the endogenous problems caused by various factors, it is necessary to test the endogenous problems in model estimation.

Table 6 shows the test results on the endogeneity of digital infrastructure construction variables. Using the one-stage lag of digital infrastructure construction (*L.DIC*) as an instrumental variable, the two-stage least square method (2SLS) is adopted to explore whether there is an endogeneity problem in digital transformation. The results of endogeneity test show that the *DIC* variable has endogeneity, and the selected instrumental variable, which lags the digital infrastructure construction (*L.DIC*) for a period, meets the weak correlation test and *CDF* value test required for the instrumental variable, indicating the effectiveness of the selection of instrumental variables.

ISSN: 2710-0170

Table 6: Endogeneity test

	First	Second
	DIC	ICP
L.DIC	0.965***	1.314***
		（5.10）
Ind		0.922***
		（3.96）
GDP		0.304***
		（2.78）
Gov		-0.35**
		（-2.4）
Env		5.305
		（0.67）
FDI		-0.266
		（-0.1）
Constant		-0.531
		（-0.67）
N		300
R2		0.541
Cragg-Donald Wald F statistic		3933.06
Kleibergen-Paap rk Wald F Statistic		1553
Underidentification test		P=0.0000

5. Heterogeneity analysis

In this paper, the 30 provinces in the sample are divided into three categories, namely, the eastern part (11 provinces and cities), the central part (9 provinces and cities) and the western part (10 provinces and cities). Table 7 shows the results of regional heterogeneity analysis on the impact of digital infrastructure construction on industrial carbon emissions in eastern, central and western regions.

The results show that the influence coefficients of *DIC* on *ICP* in the three regions are all positive, and all have an impact through the intermediary mechanism of industrial structure upgrading. The benchmark regression results in the eastern region show that the influence coefficient of *DIC* on *ICP* in the eastern region is positive, and the significance level is 1%, indicating that digital infrastructure in the eastern region is conducive to the improvement of carbon productivity. The region has a high level of economic development, optimized industrial structure, rapid development of digital economy, and relatively perfect digital infrastructure construction. Secondly, the coefficient of *DIC* affecting *ICP* in the western region is also positive, and the significance level is 1%, and the effect of digital infrastructure to improve carbon productivity is also relatively obvious. This region has a unique geographical location and natural conditions, which is more suitable for the development of low-carbon energy economy and large-scale digital infrastructure construction. Finally, the influence coefficient of the central region is negative and not statistically significant, indicating that the level of digital infrastructure in this region needs to be further improved, and it has not yet enjoyed

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preferential treatment from the local digital infrastructure construction, and its huge potential remains to be tapped.

Table 7: Heterogeneity test

	(East) ICP	(Central) ICP	(West) ICP
DIC	1.933***	-0.043	1.284***
	(0.572)	(0.493)	(0.183)
Ind	1.139***	-0.071*	0.357***
	(0.278)	(0.043)	(0.101)
GDP	1.097**	-0.160*	-0.038
	(0.493)	(0.090)	(0.054)
Gov	-1.229*	0.537***	0.008
	(0.624)	(0.137)	(0.093)
Env	5.998	-37.906***	-12.121**
	(30.388)	(9.994)	(4.877)
FDI	0.674	-0.302	1.676
	(6.714)	(1.460)	(2.532)
_cons	-0.559	-2.751***	-0.048
	(1.439)	(0.883)	(0.379)
id	YES	YES	YES
year	YES	YES	YES
N	121.000	99.000	110.000
r2_a	0.543	0.446	0.443

6. Conclusion and suggestions

By focusing on the foundation of digital economy and the construction of digital infrastructure, taking into account the production efficiency and economic benefits of carbon, this paper conducts empirical research and analysis on the two, and considers the mechanism role of industrial structure upgrading, and specifically draws the following conclusions: First, the implementation and construction of digital infrastructure has a significant positive effect on carbon productivity, providing a good foundation for industrial enterprises to improve production efficiency and optimize resource allocation, and enhancing the economic value created by unit carbon emission. Second, upgrading industrial institutions is an important path for digital infrastructure construction to promote industrial carbon productivity. Third, digital infrastructure construction has heterogeneity in promoting industrial carbon productivity, and digital infrastructure construction in eastern and western regions significantly promotes industrial carbon productivity.

On the basis of the research conclusions, this paper puts forward the following suggestions: continuously improve and optimize the construction of digital infrastructure, and continuously increase the investment in the construction of industrial Internet, cloud computing, artificial intelligence, industrial big data center and other information infrastructure; Accelerate the establishment of a digital carbon management system in the industrial sector, establish a carbon emission data measurement, testing and analysis system by digital means, and improve the digital, networked and intelligent management capabilities of carbon emissions in the industrial sector; Develop in accordance with local conditions and promote coordinated development among regions. All localities can speed up and moderately advance the

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construction of digital infrastructure according to the needs of industrial development, while avoiding the excessive consumption of resources and other environmental problems caused by the excessive construction of digital infrastructure.

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