

Synergy of Digitalization and Greenization: How AI Pioneer Zones Drive Enterprises to Reduce Carbon Emissions and Improve Efficiency

Linping Zhou

School of Public Administration, Southwestern University of Finance and Economics, Chengdu, China

linpingzhou528@gmail.com

Abstract. Against the backdrop of the "dual carbon" goals and high-quality development, this paper examines whether the National Artificial Intelligence Innovation and Application Pioneer Zone can promote enterprises to reduce carbon emissions and improve efficiency. Based on the sample of China's A-share listed companies from 2011 to 2023, this paper treats the establishment of the pioneer zone as a quasi-natural experiment and adopts the multi-period difference-in-differences model for identification. The results show that the pioneer zone policy significantly improves enterprise carbon productivity, and the conclusion remains robust after tests such as parallel trend test, PSM-DID and exclusion of pandemic years. Mechanism analysis indicates that the pioneer zone mainly promotes enterprises to reduce carbon emissions and improve efficiency by boosting green technological innovation. The results illustrate that the AI pioneer zone is an important policy tool to promote the synergistic transformation of enterprises' digitalization and greenization.

Keywords: synergy of digitalization and greenization, artificial intelligence pioneer zone, carbon reduction and efficiency improvement, green innovation

1. Introduction

In the context of high-quality development and fostering new quality productive forces, promoting the coordinated advancement of digital transformation and green and low-carbon transformation has become an important issue in policy practice and enterprise decision-making. As an important policy carrier for promoting the deep integration of artificial intelligence and the real economy, the National Artificial Intelligence Innovation and Application Pioneer Zone reshapes the enterprise innovation ecology and resource allocation environment through digital infrastructure construction, improvement of technical standards, and financial and regulatory support, and provides new technical and institutional support for enterprises' green transformation. Meanwhile, with the continuous advancement of the "dual carbon" goals, how to guide enterprises to shift from high input and high emissions to carbon reduction and efficiency improvement with the institutional advantages of the AI pioneer zone has become a practical issue worthy of attention.

The existing literature mainly focuses on two aspects: first, the impact of artificial intelligence application on enterprise carbon emissions. Relevant studies believe that artificial intelligence can play a role in emission reduction by optimizing production processes, improving resource allocation efficiency and reducing energy dependence, but it may also have a non-linear impact due to the rebound effect and rising costs in the initial stage of transformation; second, the implementation effect of the AI pioneer zone policy. Existing studies have found that it can promote enterprise green innovation, alleviate information asymmetry, and optimize financing and factor allocation. However, few existing studies combine the effect of artificial intelligence application with the effect of pioneer zone policy to systematically investigate whether the pioneer zone policy can promote the synergistic improvement of enterprises' "carbon reduction" and "efficiency improvement".

Based on this, this paper treats the establishment of the National Artificial Intelligence Innovation and Application Pioneer Zone as a quasi-natural experiment and adopts the multi-period difference-in-differences model to examine its impact on enterprise carbon productivity. The marginal contributions of this paper are mainly reflected in two aspects: first, the carbon productivity index that takes into account both economic output and environmental costs is adopted to more accurately depict the synergistic level of enterprises' carbon reduction and efficiency improvement; second, from the dual perspectives of intellectualization and greenization, this paper further reveals the mechanism and micro boundary of the pioneer zone policy affecting enterprise carbon productivity.

2. Theoretical analysis and research hypotheses

In the context of the deep integration of digital economy and green transformation, the synergistic evolution of digitalization and greenization has become an important path for enterprises' high-quality development. The so-called "synergy of digitalization and greenization" refers to promoting enterprises to reduce carbon emission intensity while improving production efficiency by relying on the embedded application of digital technologies such as artificial intelligence in R&D, production and management [1]. As an important national policy arrangement to promote the deep integration of artificial intelligence and the real economy, the AI Innovation and Application Pioneer Zone constructs a high-density technological innovation and industrial application ecology by gathering key factors such as computing power, data, talents and application scenarios, thus forming an exogenous institutional and factor supply shock to enterprises. This policy not only lowers the threshold for enterprises to acquire and apply digital technologies, but also accelerates the penetration of artificial intelligence into all links of the industrial chain, providing practical conditions for enterprises to achieve "intelligent efficiency improvement" and "green carbon reduction". As a result, enterprises in the pioneer zone are more likely to reduce carbon emission intensity while improving operational efficiency, which is ultimately reflected in the improvement of carbon productivity. Based on this, this paper puts forward Hypothesis H1:

H1: The National Artificial Intelligence Innovation and Application Pioneer Zone policy can significantly improve enterprise carbon productivity, thereby promoting enterprises to achieve carbon reduction and efficiency improvement.

Furthermore, green technological innovation may be an important transmission mechanism for the pioneer zone policy to affect enterprise carbon productivity. From the perspectives of resource-based theory and innovation economics, green innovation faces both environmental benefit externality and knowledge spillover externality, and relevant benefits are difficult to be internalized timely and fully, so enterprises often lack incentives for continuous investment [2]. The establishment of the AI pioneer zone provides new institutional and technical conditions for enterprises to break through this constraint. On the one hand, as a general-purpose technology,

artificial intelligence can reduce the trial-and-error cost, material consumption and uncertainty in the green R&D process with the help of data analysis, virtual simulation and algorithm optimization [3], thus improving the efficiency and quality of green innovation; on the other hand, the aggregation of technologies, talents and scenarios formed in the pioneer zone helps to promote the flow of tacit knowledge and the diffusion of green technologies, and enhances enterprises' ability to obtain energy-saving and emission-reduction schemes and low-carbon technical paths. The improvement of green technological innovation will further promote enterprises to reduce carbon emission intensity while maintaining or even improving output efficiency, which is ultimately reflected in the improvement of carbon productivity [4]. Based on this, this paper puts forward Hypothesis H2:

H2: The National Artificial Intelligence Innovation and Application Pioneer Zone policy improves enterprise carbon productivity by promoting green technological innovation.

3. Research design

3.1. Data sources

This paper uses China's listed companies from 2011 to 2023 as the research sample to evaluate the impact of the AI pioneer zone policy on enterprises' carbon reduction and efficiency improvement. Samples with ST, *ST special treatment and missing data are excluded, and 26,940 enterprise-year observations are obtained. The financial data of listed companies are from the China Stock Market & Accounting Research Database (CSMAR) and Chinese Research Data Services Platform (CNRDS).

3.2. Model construction

This paper regards the AI pioneer zone policy as a quasi-natural experiment, and uses the multi-period difference-in-differences model to evaluate the impact of the AI pioneer zone on enterprises' carbon reduction and efficiency improvement. The specific model is set as follows:

$$CR = \alpha + \beta_1 DID_{it} + \beta_2 control_{it} + \gamma_i + \mu_t + \varepsilon_{it} \quad (1)$$

Where CR represents the carbon productivity of enterprise i in year t , and DID_{it} is the core explanatory variable, which is obtained by the interaction between the treatment group dummy variable and the post-policy implementation dummy variable. γ_i and μ_t are the city fixed effect and year fixed effect respectively, and ε_{it} is the random error term. The coefficient β_1 reflects the impact of the AI pioneer zone policy on enterprises' carbon reduction and efficiency improvement. This paper adopts cluster-robust standard errors to alleviate the problems of heteroscedasticity and serial correlation.

3.3. Variable description

Explained variable. This paper uses carbon productivity (CR) to measure the level of enterprises' carbon reduction and efficiency improvement, defined as the ratio of enterprise's operating income in the current year to total carbon emissions. Compared with total carbon emissions or carbon emission intensity, carbon productivity can reflect both enterprise environmental performance and economic efficiency, so it is more in line with the research objective of this paper. Enterprise carbon emissions are estimated based on regional-industrial carbon emission factors, combined with enterprise industry category and registered address information.

Explanatory variable. The core explanatory variable of this paper is the National Artificial Intelligence Innovation and Application Pioneer Zone policy (AI). In view of the strong endogeneity of enterprise-level artificial intelligence application degree, this paper treats the establishment of the pioneer zone as an exogenous policy shock, and constructs the core explanatory variable of the multi-period difference-in-differences model accordingly.

Mechanism variable. This paper mainly examines the mediating role of green technological innovation (GPatent), and further conducts an extended analysis from two dimensions: government environmental protection attention (GZD) and resource allocation efficiency (TFP_LP). Among them, GPatent is measured by the logarithm of the number of enterprise green patent applications plus 1; GZD is measured by the logarithm of the frequency of environmental protection-related words in prefecture-level city government work reports plus 1; TFP_LP is characterized by enterprise total factor productivity calculated by the LP method.

Control variables. The control variables mainly include enterprise size, asset-liability ratio, operating income growth rate, independent director ratio, equity concentration, management shareholding ratio, financial development level and industrialization level. The descriptive statistical results of variables are shown in Table 1.

Table 1. Descriptive statistics

Variable	SD	N	p50	Mean	Min	Max
CR	0.857	26940	0.322	0.698	0.244	4.276
did	0.198	26940	0.000	0.041	0.000	1.000
Size	1.356	26940	22.090	22.330	19.910	26.390
Lev	0.206	26940	0.411	0.418	0.057	0.905
Growth	0.810	26940	0.110	0.303	-0.653	5.618
Indep	0.054	26940	0.364	0.377	0.001	0.600
Top1	0.148	26940	0.327	0.347	0.088	0.730
ind	0.132	26940	0.363	0.344	0.000	1.000
finance	1.646	26940	3.528	3.843	0.588	13.530
Mshare	0.200	26940	0.010	0.143	0.000	0.705

4. Empirical results and analysis

4.1. Parallel trend test

The results of the parallel trend test are shown in Figure. 1. A prerequisite for the use of the difference-in-differences model is to satisfy the parallel trend assumption. The consistency of policy identification is rooted in the "counterfactual" logic, that is, it is necessary to rule out the potential interference of pre-policy differences on the estimation results. By examining the dynamic trend before the policy shock (t-3 to t-1), this paper finds that the treatment group and the control group do not show significant differentiation in growth paths in the base period. The statistical insignificance of the pre-policy coefficients effectively eliminates the endogenous interference of unobservable factors on carbon emission efficiency, thus ensuring that the effect changes after policy implementation can be accurately anchored to the AI pioneer zone policy.

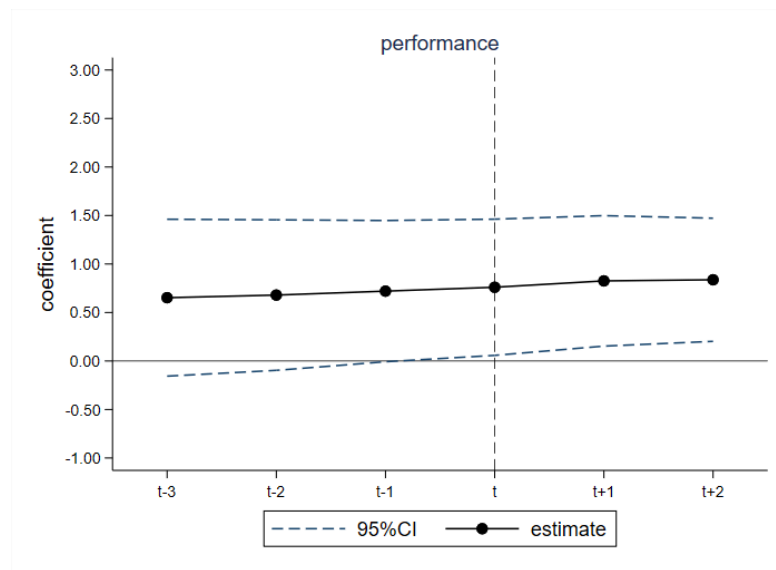


Figure 1. Parallel trends test results

4.2. Baseline regression

Column (1) of Table 2 reflects the baseline regression results without adding control variables, which are significantly positive. Column (2) of Table 2 shows that after adding control variables, the regression coefficient of the National Artificial Intelligence Innovation and Application Pioneer Zone policy (AI) is significantly positive at the 1% level, indicating that compared with regions without the National Artificial Intelligence Innovation and Application Pioneer Zone, the carbon efficiency level of manufacturing enterprises in the pioneer zone is significantly improved, that is, the pioneer zone policy enables enterprises in the pioneer zone to achieve green and low-carbon development. This policy dividend may stem from the following logic: the construction of the pioneer zone creates a high-concentration digital technology application environment, which on the one hand drives the intelligent transformation of enterprise production processes and significantly reduces the energy consumption intensity per unit output [5]; on the other hand, the technology aggregation effect brought by the policy and the improvement of government regulatory pressure force enterprises to accelerate green technological innovation and optimal allocation of resource factors, thus realizing the deep coordination of economic efficiency improvement and low-carbon transformation [6].

Table 2. Impact of artificial intelligence on carbon revenue

	-1	-2
	CR	CR
did	0.216***	0.082***
	-0.026	-0.018
Size		-0.026***
		-0.003
Lev		-0.01
		-0.021
Growth		-0.014***

Table 2. (continued)

		-0.005
Indep		-0.242***
		-0.064
Top1		0.220***
		-0.024
ind		1.089***
		-0.032
finance		0.001
		-0.003
Mshare		-0.092***
		-0.019
_cons	3.569***	3.817***
	-0.005	-0.076
Year	No	Yes
Industry	No	Yes
N	26940	26940
adj. R ²	0.003	0.584
F	69.295	196.095

Standard errors in parentheses

* p < 0.1, ** p < 0.05, *** p < 0.01

4.3. Robustness test

4.3.1. Test Based on PSM-DID Method

Since the establishment of the AI pilot zone is not randomly allocated but depends on the inherent foundation of cities, the baseline results may be affected by sample selection bias. Therefore, this paper adopts the method combining propensity score matching and difference-in-differences (PSM-DID). Based on covariates (such as enterprise size, debt ratio, growth, etc.), this paper matches the experimental group enterprises with the control group enterprises by the 1:4 nearest neighbor matching method. As shown in Column (1), although the sample size is reduced after matching, the coefficient of did is still significantly positive, indicating that the policy effect is not driven by the pre-policy differences between pilot cities and non-pilot cities.

4.3.2. Excluding the impact of pandemic years

The COVID-19 pandemic (mainly in 2020-2022), as a huge external shock, led to abnormal fluctuations in enterprise production and energy consumption, which may interfere with the estimation of carbon productivity. To eliminate this interference, this paper excludes the samples of pandemic years and re-estimates. As shown in Column (3), the coefficient of did is still significantly positive (0.095). This indicates that the driving effect of artificial intelligence on enterprises' carbon

reduction and efficiency improvement is a long-term structural improvement rather than a short-term anomaly caused by the pandemic.

Table 3. Robustness test

	PSM-DID	Excluding the Impact of Pandemic Years
	CR	CR
did	0.026**	0.095***
	-0.013	-0.032
Size	0.014**	-0.040***
	-0.006	-0.004
Lev	-0.123***	0.022
	-0.04	-0.028
Growth	-0.060***	0.017***
	-0.008	-0.006
Indep	-0.066	-0.310***
	-0.115	-0.085
Top1	0	0.311***
	-0.045	-0.032
ind	0.231***	1.402***
	-0.079	-0.041
finance	0.006	0.001
	-0.006	-0.003
Mshare	0.071**	-0.115***
	-0.034	-0.025
_cons	3.342***	3.989***
	-0.14	-0.102
Year	Yes	Yes
City		
Industry	Yes	Yes
N	2939	18564
adj. R2	0.734	0.558
F	11.137	204.381

Standard errors in parentheses

* p < 0.1, ** p < 0.05, *** p < 0.01

4.4. Mechanism test

The AI pioneer zone can lower the innovation threshold through "technology empowerment" and produce "agglomeration spillover effect" [7]. The results in Column (2) of Table 4 show that the regression coefficient of the AI pilot zone policy (did) on enterprise green patent applications (GPatent) is significantly positive (0.070, p<0.01). The data indicate that the pioneer zone indeed plays a role of "technology empowerment", replacing traditional energy-intensive trial-and-error

experiments with virtual modeling and digital screening, and reducing the sunk cost and uncertainty of green R&D; meanwhile, the high-concentration digital ecology in the pioneer zone accelerates the flow of tacit knowledge, enabling enterprises to rapidly improve green factor productivity through technology introduction and imitation innovation, thus achieving a win-win situation of carbon reduction and efficiency improvement through the "Porter effect". In view of this, Hypothesis H2 of this paper is verified.

Table 4. Tests of mediating effects

	(1)	(2)
	CR	GPatent
did	0.082***	0.070***
	-0.018	-0.026
Size	-0.026***	0.220***
	-0.003	-0.005
Lev	-0.01	0.006
	-0.021	-0.032
Growth	-0.014***	0.016**
	-0.005	-0.007
Indep	-0.242***	0.155
	-0.064	-0.096
Top1	0.220***	0.019
	-0.024	-0.036
ind	1.089***	-0.032
	-0.032	-0.057
finance	0.001	0.006
	-0.003	-0.004
Mshare	-0.092***	0.099***
	-0.019	-0.029
_cons	3.817***	-4.540***
	-0.076	-0.116
Year	Yes	Yes
Industry	Yes	Yes
N	26940	24068
adj. R2	0.584	0.206
F	196.095	289.714

Standard errors in parentheses

* p < 0.1, ** p < 0.05, *** p < 0.01

5. Conclusion

Against the backdrop of the "dual carbon" goals and high-quality development, promoting the coordinated advancement of enterprises' digital transformation and green and low-carbon

transformation has become an important path to achieve carbon reduction and efficiency improvement. Based on the sample of China's A-share listed companies from 2011 to 2023, this paper treats the establishment of the National Artificial Intelligence Innovation and Application Pioneer Zone as a quasi-natural experiment and tests it with the multi-period difference-in-differences model. The study finds that the AI pioneer zone policy can significantly improve enterprise carbon productivity, that is, effectively promote enterprises to achieve carbon reduction and efficiency improvement, and this conclusion is still valid after a series of robustness tests. Further mechanism analysis shows that the pioneer zone policy mainly plays a role through three paths: promoting green technological innovation, improving government environmental protection attention and alleviating resource misallocation.

The above results indicate that the AI pioneer zone is not only an important institutional arrangement to promote the diffusion of digital technologies, but also an important policy starting point to promote enterprise green transformation and improve resource allocation efficiency. In other words, the role of artificial intelligence policy is not limited to simply improving the level of enterprise intellectualization, but also can promote enterprises to achieve synergistic improvement between "carbon reduction" and "efficiency improvement" through innovation empowerment, governance strengthening and factor optimization. This conclusion provides enterprise-level empirical evidence for understanding how digital policies serve green development, and also provides a practical basis for promoting the integrated development of "artificial intelligence + green and low-carbon".

Based on this, this paper argues that future policy practice should focus on three aspects: first, continue to improve the construction of pioneer zones, strengthen the application of artificial intelligence in scenarios such as energy conservation and carbon reduction, green manufacturing and low-carbon governance, and enhance the supporting role of policies for enterprises' green transformation; second, further incentivize enterprise green technological innovation, and improve the accuracy and transparency of environmental governance with digital regulatory means to form a governance mechanism combining "technology empowerment - regulatory constraint"; third, increase the supply of key factors such as computing power, data, talents and platforms, lower the threshold for enterprises, especially small and medium-sized enterprises, to apply artificial intelligence, and promote the replication and diffusion of mature experience in pioneer zones to amplify the demonstration and driving effect of policies.

For follow-up research, future studies can further combine more direct enterprise artificial intelligence application data to investigate the long-term dynamic effect of the pioneer zone policy on enterprises' carbon reduction and efficiency improvement, and expand to non-listed enterprise samples to more comprehensively identify the micro mechanism and applicable boundary of the synergistic transformation of digitalization and greenization.

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