

Original Paper

The Mechanism of Digital Economy Development on Energy Intensity under the “Dual Carbon” Goals

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Abstract

Reducing energy intensity has become important in the context of the “dual carbon” goals. Panel data were collected from 30 provinces in China during the period of 2011-2020 to investigate how the digital economy affects energy intensity and the mechanisms underlies. The empirical findings indicate that digital economy development significantly lowers energy intensity. A series of robustness checks confirm that this result is not coincidental. Heterogeneity analysis shows that the energy-reduction effect is more pronounced in non-resource-based provinces and the western region, while varying degrees of heterogeneity are observed in resource-based provinces and the eastern and central regions. This paper elucidates the intrinsic mechanisms through which the digital economy enhances energy efficiency at the provincial level, providing empirical support and practical insights for promoting coordinated development of digitalization and greening under the “dual carbon” goals, as well as for formulating region-specific energy transition policies.

Keywords

Digital economy, Energy intensity, Technology market, “Dual Carbon” goal

1. Introduction

In recent years, global climate change has become severe, with energy-related carbon dioxide emissions reached 37.4 billion tons in 2023, of which China accounts for about 35% [1][2]. As the world’s largest emitter, China has set the “dual carbon” goals (2030 peak, 2060 neutrality). However, achieving these targets faces major challenges, including high carbon lock-in costs and technological constraints[1][2]. Traditional development models are inadequate for low-carbon transition. Breakthroughs urgently require digital-driven green transformation, enhanced ESG governance, and strengthened green finance [3][4].

As the core driver of the new round of technological revolution, the digital economy is profoundly

reshaping the energy economy landscape[5][6]. The deep integration of digital technologies such as big data and artificial intelligence throughout the entire energy production, transmission, and consumption chain has opened new avenues for achieving the dual carbon goals[1][2]. However, the impact of the digital economy on energy intensity is not simply linear. On one hand, digital technologies can significantly improve energy efficiency and reduce energy intensity by fostering green technological innovation and industrial structure upgrading[3][4]. On the other hand, the construction and operation of digital infrastructure itself consume substantial energy and may trigger a “rebound effect”[7]. Meanwhile, the scale of China's digital economy continues to expand, with its added value accounting for a steadily increasing share of the national economy[8]. Scholars have developed a multi-dimensional measurement system for assessing the level of digital economy development[8][9][10]. Existing literature primarily focuses on the direct effects of the digital economy on total factor productivity and manufacturing transformation[5][6]. However, systematic empirical studies focusing on how the digital economy influences energy intensity through green technological innovation remain insufficient[3]. Based on the above analysis, this study examines the mechanism by which the digital economy influences energy intensity within the context of China's dual-carbon goals, utilizing provincial panel data and a fixed-effects model. The research aims to provide theoretical support for the deep integration of digital technologies with the energy economy and the advancement of green transformation.

2. Methodology

2.1 Theoretical Framework and Hypotheses

2.1.1 Digital Economy Development and Energy Intensity

A key question under the “dual carbon” goals is whether digitalization affects energy intensity. Data and digital innovation are reshaping energy production, transmission, and consumption[1][2], which reminds us that technological progress is fundamental to efficiency gains. The applications such as big data, AI and intelligent systems had demonstrated such progress across the energy chain[3]. Prior studies confirmed that technological advancement was the main force lowering energy intensity, and digital-driven green transformation markedly boosts energy efficiency[3]. ESG governance further curbs energy use via better resource allocation[4]. Thus:

H1: Digital economy development reduces energy intensity.

2.1.2 The Intermediary Role of the Technology Market

Technology market bridges innovation with industrial application, which facilitating knowledge spillover, technology diffusion and resource allocation[11]. Digital economy development lowers information asymmetry and transaction costs while expanding transaction scope, thereby raising technology market efficiency[5][6]. Big data and digital platforms lower search costs and enhance transaction matching; at the same time, new digital innovations expand the range of tradable assets[7][9]. Growing technology markets then spread energy-saving technologies[12], channel

resources to green sectors, and accelerate commercialization of efficient solutions, thereby cutting energy intensity[3][4]. Prior evidence confirms that technological progress drives down energy intensity, with green innovation curbing energy use[3]. Thus:

H2a: Digital economy development boosts technology market growth.

H2b: Technology market growth reduces energy intensity.

H2: Technology market mediates the digital economy's effect on energy intensity.

2.2 Data Sources

The data cover 30 provinces in China with the sample period running from 2011 to 2020, and excluding Hong Kong, Macao, Taiwan, and Xizang due to data deficiencies. Primary sources include the China Statistical Yearbook, the China Science, Technology Statistical Yearbook, CNRDS, CEADs and the Digital Inclusive Finance Index. Missing observations were handled via linear interpolation.

2.3 Variable Measurement

2.3.1 Dependent Variable: Energy Intensity

To measure energy intensity, one common approach relies on energy consumption per unit of GDP. The specific calculation is as follows:

$$EI_{i,t} = \frac{EC_{it}}{GDP_{it}} \quad (1)$$

2.3.2 Independent Variable: Digital Economy Development

Drawing on the research of Zhao[5] and Liu[9], we selected digital infrastructure, scale of the digital industry and level of digital application adoption for measurement and constructed a comprehensive index.

2.3.3 Mediating Variable: Technology Market Development

Based on the study by Wang (2021) [13], Technology market development is captured by a simple ratio. Calculation follows the formula presented below:

$$TECH_{i,t} = \frac{Trade_{it}}{GDP_{it}} \times 100\% \quad (2)$$

2.3.4 Control Variables

To accurately estimate the impact of the digital economy on energy intensity, the following control variables were selected: industrial structure, energy structure, environmental regulation intensity, population size, green technological innovation, and green total factor productivity.

2.4 Model Specification

2.4.1 Benchmark Regression Model

To examine the direct impact of digital economic development on energy intensity, a two-way fixed-effects model was constructed:

$$EI_{i,t} = \alpha_0 + \alpha_1 Digital_{it} + \alpha_2 X_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (3)$$

2.4.2 Mediation Effect Model

Drawing on the mediation testing method proposed by Wen(2004), a recursive equation system was

constructed.:

$$EI_{i,t} = \alpha_0 + \alpha_1 Digital_{it} + \alpha_2 X_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (3)$$

(4)

$$EI_{i,t} = \gamma_0 + \gamma_1 Digital_{it} + \gamma_2 TECH_{i,t} + \gamma_3 X_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (5)$$

2.4.3 Heterogeneity Analysis Model

Group regression analysis was employed to examine regional heterogeneity and resource heterogeneity:

$$EI_{i,t} = \alpha_0 + \alpha_1 Digital_{it} + \alpha_2 X_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (3)$$

3. Data

3.1 Descriptive Statistics

Prior to conducting in-depth data analysis, descriptive statistics were first performed on the primary variables, as shown in Table 1. The table clearly displays the statistical characteristics of each variable.

Table 1. Descriptive Statistics

VARIABLES	N	mean	sd	min	max
TS	334	0.479	0.0544	0.340	0.600
Digital	334	0.200	0.106	0.0585	0.494
Pop	334	3.025	2.203	0.0797	8.289
ES	334	0.0368	0.0241	0.00453	0.0937
Tech	320	0.0131	0.0157	0.000304	0.0798
ER	334	0.00285	0.00261	0.000159	0.0148
EI	334	0.718	0.367	0.296	1.733
ln_GTI	334	2.191	0.152	1.724	2.471
ln_GTFP	334	0.0263	0.0665	-0.163	0.223

3.2 Baseline Regression Results

A two-way fixed-effects model is applied here to assess how the digital economy influences energy intensity. In Column (1) of Table 2, where only province and year fixed effects are controlled, the estimated coefficient for the digital economy (Digital) comes out as -0.836 ($p < 0.01$). Once additional control variables enter the specification in Column (2), that figure shifts to -0.983 ($p < 0.01$), evidence that the digital economy exerts a clear reducing effect on energy intensity, which lends support to Hypothesis H1. Turning to the controls: energy structure (ES) and industrial structure (TS) post a significantly positive coefficient; environmental regulation intensity (ER) is significantly negative. No statistical significance is detected for the remaining control variables. The results show that model with strong explanatory power.

Table 2. Baseline Regression

	EI	EI
Digital	-0.836*** (-5.883)	-0.983*** (-7.250)
TS		1.534*** (6.419)
ES		6.322*** (3.669)
ER		-8.060*** (-2.680)
Pop		0.027 (0.927)
ln_GTI		-0.220 (-1.354)
ln_GTFP		0.015 (0.287)
_cons	0.882*** (25.029)	0.302 (0.683)
N	388.000	388.000
r2_a	0.935	0.944

3.3 Endogeneity Analysis

Concerned about potential endogeneity, we employ several instrumental variable strategies. Regardless of the specification, the coefficient on digital remains significantly negative. That consistency told us that the observed negative relationship between digital economy and energy intensity is unlikely to be an artifact of endogeneity. Turning to control variables, energy structure (ES_pct) posts a positive and significant sign maybe with the reason that higher coal consumption indeed raises energy intensity. Both green technology innovation (ln_GTI) and green total factor productivity (ln_GTFP) are significantly negative, supporting technological progress in energy saving. After mitigating endogeneity, the core finding holds, and consistent with baseline results.

Table 3. Endogeneity Analysis

	EI	EI	EI	EI
Digital	-1.186*** (0.008)	-0.556** (0.019)	-1.439* (0.050)	-0.647*** (0.009)
TS	1.550**	-0.891	-0.248	-0.887

	(0.012)	(0.304)	(0.856)	(0.345)
ES	6.750*			
	(0.078)			
ER	-7.226			
	(0.238)			
Pop	0.107			
	(0.257)			
ln_GTI	0.045	-1.142**	-0.827	-1.094**
	(0.900)	(0.016)	(0.164)	(0.029)
ln_GTFP	-0.149	-0.358*	-0.298*	-0.402*
	(0.186)	(0.064)	(0.093)	(0.058)
ES_pct		0.075***	0.084***	0.075***
		(0.000)	(0.000)	(0.000)
ER_pct		0.130	0.127	0.126
		(0.464)	(0.493)	(0.480)
ln_Pop		-0.175***	-0.189***	-0.179***
		(0.000)	(0.000)	(0.001)
_cons	-0.077	3.552***	2.797*	3.469***
	(0.932)	(0.003)	(0.080)	(0.007)
N	334.000	309.000	302.000	277.000
r2	0.698	0.765	0.715	0.749
province	YES	YES	YES	YES
year	YES	YES	YES	YES

3.4 Robustness Analysis

Several robustness checks confirm the findings. Replacing the explanatory variable (talent_lq: -1.106, $p < 0.05$) or the dependent variable (CEI: -1.593, $p < 0.05$) still yields negative digital coefficients. A one-period lag of Digital (L_Digital) is negative at the 1% level (-1.331). Excluding four municipalities gives -1.334 ($p < 0.01$). Thus, digital economy development consistently reduces energy intensity, confirming baseline robustness.

Table 4. Robustness Analysis

	EI	CEI	EI	EI
talent_lq	-1.106**			
	(0.024)			
TS	1.406**	3.888***	1.517***	1.622**

	(0.032)	(0.000)	(0.009)	(0.013)
ES	8.803*	11.685	5.761	6.317*
	(0.069)	(0.249)	(0.236)	(0.089)
ER	-2.821	10.464	-7.149	-8.811
	(0.674)	(0.223)	(0.168)	(0.145)
Pop	0.102	0.396*	0.082	0.103
	(0.376)	(0.051)	(0.408)	(0.269)
ln_GTI	-0.028	-1.214*	0.222	0.172
	(0.955)	(0.095)	(0.625)	(0.661)
ln_GTFP	-0.149	-0.225	-0.160	-0.162
	(0.249)	(0.365)	(0.150)	(0.158)
Tech	-0.405	1.903	1.074	0.768
	(0.647)	(0.302)	(0.146)	(0.375)
Digital		-1.593**		-1.334***
		(0.019)		(0.005)
L_Digital			-1.331***	
			(0.004)	
_cons	-0.143	2.013	-0.363	-0.302
	(0.911)	(0.277)	(0.749)	(0.748)
N	301.000	320.000	295.000	320.000
r ²	0.634	0.881	0.666	0.706
province	YES	YES	YES	YES
year	YES	YES	YES	YES

3.5 Mediation Analysis

Mediation analysis shows a negative total effect of the digital economy on energy intensity, and it also boosts the technology market. Yet the coefficient turns positive when both are included, which contrary to expectations. Consequently, no mediating role can be claimed. One possible explanation is that non-energy-saving technologies dominate market transactions. Another possibility maybe that existing a time lag in the diffusion of energy-saving technologies. Even so, the digital economy's direct negative effect on energy intensity remains intact.

Table 5. Mediation Analysis

	EI	Tech	EI
Digital	-0.983***	0.057*	-1.152***
	(0.009)	(0.081)	(0.003)

TS	1.534*** (0.005)	0.056 (0.257)	1.566*** (0.006)
ES	6.322* (0.071)	0.192 (0.578)	5.885* (0.086)
ER	-8.060 (0.181)	0.371 (0.306)	-9.834* (0.081)
Pop	0.027 (0.678)	-0.001 (0.913)	0.031 (0.575)
ln_GTI	-0.220 (0.458)	-0.097** (0.024)	0.023 (0.934)
ln_GTFP	0.015 (0.785)	0.006 (0.408)	0.007 (0.896)
Tech			1.771* (0.069)
_cons	0.620 (0.508)	0.167 (0.137)	0.134 (0.871)
N	388.000	372.000	372.000
r2	0.696	0.583	0.716
province	Yes	Yes	Yes
year	Yes	Yes	Yes

3.6 Heterogeneity Analysis

Heterogeneity analysis reveals regional and resource-based differences. In the eastern provinces, the coefficient is negative but not significant. The central region behaves differently: the sign turns positive though still insignificant. Only in the western area does the coefficient become negative at a statistically significant level. A similar split appears along resource lines. Provinces endowed with abundant natural resources show a negative but non-significant coefficient, however, the coefficient of non-resource provinces is both negative and significant. Putting together, these results show that the energy-reducing effect of the digital economy is stronger in western and non-resource provinces, which call for the need for region-specific energy transition policies.

Table 6. Heterogeneity Analysis

	Regional Heterogeneity			Resource Heterogeneity	
	Eastern region	Central region	Western region	Resource-based	Non-resource-based
Digital	-0.479	1.075	-1.304**	-0.391	-1.121***

	(0.187)	(0.292)	(0.027)	(0.289)	(0.009)
TS	0.170	1.743***	0.937	0.723	2.009
	(0.526)	(0.008)	(0.220)	(0.438)	(0.125)
ES_pct	0.015	0.010	0.266***	0.300***	0.020
	(0.526)	(0.825)	(0.002)	(0.006)	(0.492)
ER_pct	-0.129*	0.099	-0.070	-0.089	-0.039
	(0.064)	(0.346)	(0.324)	(0.361)	(0.524)
ln_Pop	-0.132	-2.450**	-3.376**	-2.452**	0.065
	(0.796)	(0.018)	(0.033)	(0.015)	(0.874)
ln_GTI	-0.636	1.362**	-0.321	0.737	-0.273
	(0.129)	(0.031)	(0.414)	(0.435)	(0.498)
ln_GTFP	-0.145*	-0.342**	-0.177	-0.329	-0.029
	(0.082)	(0.033)	(0.108)	(0.102)	(0.849)
_cons	2.318*	-0.433	-0.359	-2.733	0.638
	(0.078)	(0.658)	(0.783)	(0.292)	(0.525)
N	108.000	109.000	117.000	92.000	242.000
r2	0.804	0.879	0.810	0.782	0.768
province	YES	YES	YES	YES	YES
year	YES	YES	YES	YES	YES

4. Results

The analysis leads to several key conclusions. First, a consistent finding is that digital development reduces energy intensity. Various robustness checks including variable substitution and one-period lags had supported this conclusion. Second and rather unexpectedly, technology market growth fails to serve as a transmission channel; it does not mediate the relationship. Third, resource endowment matters. Non-resource-based provinces achieve meaningful energy reductions, while their resource-rich counterparts do not. A plausible explanation lies in the latter's heavy reliance on fossil fuels and a narrowly structured industrial base. Fourth, regional disparities surface. A sharp decline in energy intensity appears in the western region, but not in the eastern or central areas. Different stages of digitalization, along with the rebound effect, likely account for this gap. Endogeneity tests further confirm that the core findings remain robust.

5. Conclusions

From the results above, here are some policy directions. Expanding digital infrastructure is key because it helps unlock energy savings. Green technology incentives should be strengthened to keep the transmission channel open. A one-size-fits-all approach does not work. Resource-based provinces need to accelerate digital transformation in traditional industries; the central region, in contrast, must

guard against the rebound effect. At the same time, refining environmental regulation can better align digitalization with greening.

A few limitations deserve mention. The time span of data is relatively short, which may affect generalizability. Measurement of the digital economy could be extended along more dimensions. Micro-level mechanisms remain underexplored. Future research might turn to firm-level evidence or explore new digital business forms.

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