

Research on Digital-Green Integration Boosting the Construction of Modern Urban Energy Systems in China

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Abstract: Based on panel data from 277 prefecture-level cities (2014–2023), this paper examines the impact, pathways, and regional differences of digital-green integration on urban modern energy system construction using entropy-weighted TOPSIS, coupling coordination degree, and two-way fixed effects, mediation, and moderation models. The results show that digital-green integration significantly promotes urban modern energy system development. Green technological innovation serves as a mediating mechanism, while industrial structure upgrading plays a positive moderating role. Moreover, these effects exhibit notable regional heterogeneity.

Keywords: Digital-green integration; Modern energy system; Green technological innovation; Industrial structure upgrading.

1. Introduction

To coordinate green and sustainable development, China has established the carbon peaking and carbon neutrality strategic goals and integrated them into the overall framework of ecological civilization construction. At present, China has successively issued policies such as the Several Opinions on Accelerating the Digital and Intelligent Development of Energy, aiming to break through the bottlenecks of traditional energy systems and build intelligent and green urban modern energy systems. However, the energy transition still faces challenges such as insufficient intelligence, uneven regional development, and lagging efficiency in green technology commercialization, which constrain the comprehensive construction of the energy system. Focusing on how digital-green integration promotes the construction of urban modern energy systems, this paper conducts theoretical analysis and empirical testing to explore its impact effects, pathways, and regional differences, thereby providing references for deepening digital-green synergistic transformation in the energy sector.

2. Literature Review

In the research domain concerning the synergistic development of digitalization and green transformation, early studies predominantly focused on the unidirectional empowerment of digitalization upon green development, generally recognizing digital technologies as the core driver of urban green transition. In recent years, however, the research perspective has progressively shifted toward a bidirectional synergistic framework. Specifically, Zhou and Qiao (2023) constructed a coupling framework at the city level that integrates digital empowerment and green traction [1], while Yang (2022) identified, from an industrial perspective, a bidirectional constraint-improvement relationship between digital infrastructure and renewable energy development [2]. Regarding the measurement of synergy levels, the coupling coordination degree model has been adopted as the core methodology, supplemented by various auxiliary approaches. Liu et al. (2025) found that the overall level of digital-green integration in China has exhibited an upward trend, with absolute regional disparities

continuously narrowing [3]. In terms of impact effects, Ma et al. (2022) confirmed that the digital economy exerts a direct driving effect on the green development of cities in emerging economies [4].

With respect to research on modern energy systems, early studies primarily emphasized the security and economic viability of energy supply. Solomon et al. (2011) underscored the critical influence of energy efficiency, smart grids, and related policies on energy system development [5]. As research has progressively deepened, the scholarly understanding of the connotation of modern energy systems has been considerably enriched. Du (2020) emphasized that a modern energy system should be characterized by holism, systematization, and intelligence, with due attention to multi-energy synergistic development [6]. Huang et al. (2021) stressed the necessity of focusing on three key aspects: energy resource development, import control, and the construction of security defense lines [7].

However, limitations remain: the internal mechanisms of digital-green integration are insufficiently explored, systematic empirical evidence on modern energy system construction is lacking, and urban-level disparities have received inadequate attention. To address these gaps, this paper centers on digital-green integration promoting urban modern energy system construction and conducts research from both theoretical and empirical dimensions.

3. Theoretical Analysis and Research Hypotheses

3.1. The Impact Effect of "Digital-Green Integration" on the Construction of Urban Modern Energy Systems

Digital-green integration is a new development paradigm featuring deep coupling of digitalization and greening. Grounded in sustainable development theory and synergetics, it achieves bidirectional synergy through technological integration, data empowerment, and energy system optimization. On the energy supply side, digital technologies enable renewable energy development and conventional energy upgrading; on the consumption side, they promote intensive energy use in industry, construction, and other sectors; on the governance side, they enable refined and

intelligent collaborative management. Accordingly, Hypothesis 1 is proposed:

Digital-green integration has a significant positive impact on the construction of urban modern energy systems.

3.2. The Mediating Effect of Green Technology Innovation

The deep integration of digital and green technologies drives the iterative upgrading of green technologies. The technological empowerment advantages generated by digital-green integration need to be transmitted and transformed through green technological innovation, providing a low-carbon technological foundation and intelligent allocation models for the energy system. Accordingly, Hypothesis 2 is proposed:

Green technological innovation plays a mediating role in the impact of digital-green integration on the construction of urban modern energy systems.

3.3. The Moderating Effect of Industrial Structure Upgrading

Industrial structure upgrading breaks the path dependence of traditional energy systems and unleashes scale effects and structural dividends. Digital-green integration provides external impetus for industrial upgrading, while industrial upgrading in turn amplifies the enabling effects of digital-green integration by expanding technology application scenarios and optimizing factor allocation. Accordingly, Hypothesis 3 is proposed:

Industrial structure upgrading plays a positive moderating role in the impact of digital-green integration on the construction of urban modern energy systems.

4. Research Design

4.1. Model Specification

(1) Two-Way Fixed Effects Model

To ensure the precision and reliability of the empirical conclusions, this paper employs a two-way fixed effects model for analysis. This model simultaneously incorporates both regional and temporal fixed effects to examine the comprehensive impact of digital-green integration on urban modern energy systems. After fully accounting for other factors that may influence urban modern energy systems, the following model is specified:

$$HE_{it} = \beta_0 + \beta_1 D_{it} + \beta_2 X_{it} + \mu_i + \gamma_t + \varepsilon_{it} \quad (1)$$

(2) Mediation Effect Model

As a critical component of empirical research, mediation effect testing facilitates a more in-depth examination of the underlying mechanisms through which variables interact. Based on the preceding theoretical derivation, it can be preliminarily ascertained that green technology innovation serves a mediating transmission function in the process through which digital-green integration affects the construction of urban modern energy systems. To empirically test whether this mediating effect holds, green technology innovation is designated as the mediating variable, and the following mediation effect model is accordingly specified:

$$GTI_{it} = \alpha_0 + \alpha_1 D_{it} + \alpha_2 X_{it} + \mu_i + \gamma_t + \varepsilon_{it} \quad (2)$$

(3) Moderation Effect Model

To test the positive moderating role of industrial structure upgrading in the process through which digital-green

integration promotes the construction of urban modern energy systems, the following moderation effect model is specified:

$$HE_{it} = \beta_0 + \beta_1 D_{it} + \beta_2 Ind_{it} + \beta_3 (D_{it} \times Ind_{it}) + \sum \beta_k X_{it} + \mu_i + \gamma_t + \varepsilon_{it} \quad (3)$$

4.2. Variable Specification

(1) Dependent Variable: Urban Modern Energy System Development Level (HE)

Urban modern energy system development level, measured through a comprehensive indicator system comprising four dimensions: low-carbon energy supply and demand, green environmental protection, energy technological innovation, and energy openness and sharing, using the entropy-weighted TOPSIS method.

(2) Core Explanatory Variable: Digital-Green Integration (D)

Digital-green integration level, measured by constructing separate digitalization and greening indicator systems and calculating the coupling coordination degree using the coupling coordination degree model. The specific algorithm is as follows:

$$C = 2 \times \frac{\sqrt{f_{\text{digital}}(x)f_{\text{green}}(y)}}{(f_{\text{digital}}(x) + f_{\text{green}}(y))^2} \quad (4)$$

$$T = \alpha f_{\text{digital}}(x) + \beta f_{\text{green}}(y) \quad (5)$$

$$D = \sqrt{C \times T} \quad (6)$$

To construct a digitalization evaluation system, which adopts six dimensions—internet employment scale, internet industry output, digital inclusive finance, mobile phone penetration rate, internet penetration level, and digital policy support intensity—to systematically measure the effectiveness of urban digital construction. Meanwhile, a greenization evaluation system is constructed from three dimensions: pollution emission intensity, environmental governance level, and green living environment. Specifically, pollution emission intensity is measured by carbon dioxide emissions, industrial sulfur dioxide emissions per unit of GDP, and industrial soot and dust emissions per unit of GDP; environmental governance level is measured by the centralized treatment rate of sewage treatment plants and the household waste treatment rate; and green living environment is measured by per capita daily domestic water consumption, per capita park green area, and green coverage rate in built-up areas.

(3) Control Variables

To mitigate model estimation bias while accounting for data availability at the city level, this study introduces a series of control variables as follows: Fiscal investment intensity (FI), financial development level (FD), urbanization rate (Urb), government intervention (Gov), population density (Pd), and human capital level (Hr).

(4) Mediating Variable

Green Technology Innovation (GTI): Green technological innovation, measured by the number of green invention patent applications per 10,000 urban residents.

(5) Moderating Variable

Industrial Structure Upgrading (Ind): this paper employs the following formula to measure industrial structure upgrading:

$$Ind = T1 \times 1 + T2 \times 2 + T3 \times 3 \quad (7)$$

Where T1, T2, and T3 represent the proportions of value

added of the primary industry, secondary industry, and tertiary industry, respectively, in the gross regional product.

4.3. Data Sources

The panel dataset covers 277 prefecture-level cities from 2014 to 2023. Raw data are obtained from the National Bureau of Statistics, China City Statistical Yearbook, China Energy Statistical Yearbook, and other authoritative yearbooks, as well as data from the Peking University Digital Financial Inclusion Research Center. Missing values are supplemented using interpolation methods.

Table 5-1. Descriptive Statistics of Key Variables

Variable Type	Variable Name	Mean	Std. Dev.	Min	Max	N
Core Explanatory Variable	D	0.2551	0.0903	0.0000	0.9487	2770
Dependent Variable	HE	0.1124	0.0968	0.0362	0.8397	2770
Control Variable	FD	2.8230	1.2805	0.7167	21.3015	2770
	FI	6.5674	4.8792	0.0103	41.6771	2770
	Urb	0.4130	0.2204	0.0750	1.0000	2770
	Gov	0.2051	0.0934	0.0439	0.7044	2770
	Pd	5.7721	0.9297	1.7462	8.1756	2770
	Hr	0.0217	0.0262	0.0002	0.1848	2770

5.2. Baseline Regression Analysis

As shown in Table 5-2, the two-way fixed effects model results show that, regardless of whether control variables are included, the regression coefficient of digital-green integration on urban modern energy system construction is 0.251 and significant at the 1% level, confirming Hypothesis 1. The model fit (R^2) increases from 0.638 to 0.643. further confirming that Hypothesis 1—digital-green integration exerts a significant positive driving effect on the construction of urban modern energy systems—is supported.

Table 5-2. Baseline Regression Results

	(1)	(2)
Variables	HE	HE
D	0.251***	0.251***
	(5.44)	(5.32)
N	2770	2770
R2	0.643	0.638
Year FE	Yes	Yes
City FE	Yes	Yes
Control Variables	Yes	No

5.3. Robustness Tests

(1) To rule out the possibility that the observed association between digital-green integration and urban modern energy system construction is driven by time trends or stochastic factors, this paper conducts a placebo test by randomly generating fictitious digital-green integration indicators. The regression coefficients of the random samples are symmetrically distributed around zero, with the mean significantly different from the baseline coefficient of 0.521. Moreover, the vast majority of p-values exceed 0.1. These findings confirm the robustness of the main regression results, effectively excluding interference from time trends and unobserved incidental factors.

Changing the Sample Period. To mitigate the interference of external shocks, this paper adjusts the sample interval by excluding the COVID-19 pandemic period. The original

5. Empirical Analysis

5.1. Descriptive Statistical Analysis

As shown in Table 5-1, both the digital-green integration level and the urban modern energy system development level have relatively low mean values of 0.2551 and 0.1124, respectively, indicating both remain at early development stages. The mean variance inflation factor is 1.54, suggesting no severe multicollinearity.

sample includes 2020 and subsequent years; however, the 2020 outbreak constitutes an exogenous public health emergency. To eliminate its interference, the study restricts the final sample period to 2014–2019 and re-estimates the regressions based on the adjusted sample.

Adding Other Control Variables. Additional controls—population size (Pop), fiscal pressure (Fiscal), opening-up level (Open), and education expenditure (Edu)—are included, and the baseline regression is re-estimated.

Digital-green integration retains a significant positive effect on urban modern energy system construction after both sample period adjustment and the inclusion of additional controls, further supporting Hypothesis 1. These results align closely with the baseline findings, confirming the robustness and reliability of our conclusions. Due to the limited journal-page space, several figures and tables are omitted in the published version. The complete charts and tables are available upon request.

5.4. Endogeneity Test

Table 5-3. Endogeneity Test Results

	(1)	(2)
Variables	D	HE
L.D	0.520***	
	(30.777)	
D		0.265***
		(5.531)
_cons	0.118***	-0.103***
	(7.818)	(-4.353)
N	2493	2493
R ²	0.357	0.276
Year FE	Yes	Yes
City FE	Yes	Yes
Control Variables	Yes	Yes

Using the first-order lag of the core independent variable as an instrumental variable and employing the two-stage least squares (2SLS) method, both the identification test and weak instrument test are passed. The results continue to show a

significant positive impact of digital-green integration on urban modern energy system construction. The specific test results are presented in Table 5-3.

5.5. Mechanism Tests

(1) Mediation Effect Analysis
The regression results are presented in Table 5-4. The regression coefficient of digital-green integration on green technological innovation is 18.63 (significant at 1%), and the coefficient of green technological innovation on urban modern energy system construction is 0.0136 (significant at 1%), confirming the mediating role of green technological innovation and validating Hypothesis 2.

Table 5-4. Mediation Effect Test Results

Variables	(1) GTI	(2) HE
D	18.63*** (5.76)	-0.00323 (-0.32)
GTI		0.0136*** (39.30)
_cons	-74.21*** (-3.73)	0.613*** (4.69)
N	2770	2770
R ²	0.140	0.882
Year FE	Yes	Yes
City FE	Yes	Yes
Control Variables	Yes	Yes

(2) Moderation Effect Analysis
As shown in Table 5-5, the coefficient of the interaction term D×Ind is significantly positive at the 1% level, indicating that industrial structure upgrading positively moderates the impact of digital-green integration on urban modern energy system construction, validating Hypothesis 3.

Table 5-5. Moderation Effect Test Results

Variables	(1) HE	(2) HE
D	0.252*** (0.018)	0.207*** (0.017)
Ind	0.000*** (0.000)	-0.000*** (0.000)
D _{it} × Ind _{it}		0.000*** (0.000)
_cons	-0.125 (0.164)	-0.037 (0.153)
City FE	YES	YES
Year FE	YES	YES
Control Variables	Yes	Yes
N	2770	2770

5.6. Heterogeneity Analysis

As shown in Table 5-6, the sample is divided into eastern, central, and western regions based on geographic location. The regression coefficient for eastern cities is 0.473 (significant at 1%), showing the strongest driving effect; for central cities it is 0.163 (significant at 5%); and for western cities it is 0.068 (significant at 10%), showing the weakest effect. The pattern exhibits a gradient of East > Central > West,

attributable to regional differences in digital infrastructure, industrial maturity, and resource endowments.

Table 5-6. Heterogeneity Analysis Results

	(1) Eastern Cities	(2) Central Cities	(3) Western Cities
D	0.473*** (0.095)	0.163** (0.073)	0.068* (0.037)
_cons	0.146 (0.452)	-0.079 (0.214)	-0.653* (0.352)
N	1000	980	790
City FE	YES	YES	YES
Year FE	YES	YES	YES
Control Variables	Yes	Yes	Yes

6. Research Conclusions and Policy Recommendations

Based on panel data from 277 prefecture-level cities in China from 2014 to 2023, this paper employs the entropy weight TOPSIS method, the coupling coordination degree model, and two-way fixed effects, mediation effects, and moderation effects models, arriving at the following core conclusions:(1) Digital-green integration significantly and positively promotes the construction of urban modern energy systems. (2) Green technological innovation plays a mediating transmission role. (3) Industrial structure upgrading exerts a positive moderating effect. (4) The impact effect exhibits significant regional heterogeneity, with a gradient pattern of East > Central > West.

Based on the above conclusions, the following policy recommendations are proposed:(1) At the top-level design level, incorporate digital-green integration into urban energy planning and dual carbon strategies, and build an intelligent, dispatchable, and secure energy digital foundation. (2) At the mechanism activation level, leverage the mediating role of green technological innovation and rely on industrial structure upgrading to amplify energy transition effectiveness. (3) At the differentiated implementation level, eastern cities should deepen pilot demonstrations, central cities should promote industrial upgrading and regional coordination, and western cities should address digital infrastructure gaps. (4) At the policy guarantee level, improve fiscal subsidies, green credit, and other support systems; refine standards for energy data security and carbon emission accounting; and establish cross-departmental coordination mechanisms and special assessments to accelerate the construction of urban energy systems suited to Chinese-style modernization.

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