



Exploring the role of digitalization in enhancing urban energy resilience: Evidence from Chinese cities

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ARTICLE INFO

Keywords:

Digitalization
Energy resilience
Digital governance
Green innovation
Threshold effects
Spatial spillover effects

ABSTRACT

Amid intensifying climate extremes, geopolitical shocks, and market volatility, enhancing energy resilience has become a critical challenge for sustainable urban development. While digitalization is increasingly viewed as a key enabler of resilience, its specific role in enhancing the resilience of urban energy systems, particularly in rapidly developing cities, remains unclear. Using panel data from 298 Chinese cities from 2011 to 2022, this study constructs multidimensional indices for digitalization and energy resilience and empirically examines the impact of digitalization and its mechanisms. The findings provide robust evidence that digitalization significantly enhances urban energy resilience, particularly in western, resource-based, and capital cities. Three mechanisms are identified: reducing energy misallocation, improving digital governance, and promoting green innovation. Moreover, digitalization's main effect shows a threshold impact on energy resilience, improving resistance, recovery, and regeneration capacities, and generating spatial spillover effects that enhance resilience in neighboring areas. This study underscores the role of digitalization as a strategic resource for cities to better withstand energy shocks and sustain energy security. Ultimately, this study offers both theoretical insights and actionable policy recommendations, highlighting pathways for cities globally to leverage digitalization to enhance energy resilience and accelerate the transition to a low-carbon future.

1. Introduction

With the acceleration of global warming and the increasing frequency of extreme events, the vulnerability of urban energy systems has become more evident. Traditional efficiency-oriented energy systems have demonstrated severe shortcomings when confronted with large-scale blackouts, cross-regional supply chain disruptions, or cyber-attacks (Busby et al., 2021). At the same time, digital technologies such as artificial intelligence (AI), the Internet of Things (IoT), and blockchain are being deeply embedded in energy production, transmission, and consumption, reshaping system operations and carbon reduction strategies (IEA, 2025). In this context of escalating risks and rapid technological transformation, a critical question arises as to how digitalization can enhance the resilience and adaptive capacity of urban energy systems. This issue has become a pressing agenda for ensuring energy security and advancing low-carbon transitions worldwide, particularly in rapidly developing cities.

In China, the objective of “strengthening energy system resilience”

has been elevated to a national strategic priority under the overarching “dual carbon” goals (State Council Information Office, 2024). Large-scale investments in smart grids, renewable energy bases, and digital infrastructure are accelerating this agenda. According to the National Bureau of Statistics (2025), the value added of core digital industries already accounts for nearly 10% of GDP. Meanwhile, overall energy resilience has steadily improved, but pronounced regional disparities persist. Eastern regions maintain an advantage due to diversified supply and advanced technologies, while western regions are catching up rapidly by leveraging resource endowments and industrial upgrading (Nepal et al., 2024). The uneven distribution of digital dividends and policy investments poses differentiated challenges to enhancing energy resilience across regions and urban contexts.

Existing research has examined the drivers of energy resilience from multiple perspectives. First, engineering hardening and operational optimization, including grid reinforcement, energy storage deployment, and dispatch optimization, are considered the most direct measures to improve the physical defense and recovery capacity of energy systems

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<https://doi.org/10.1016/j.scs.2026.107397>

Received 1 January 2026; Received in revised form 25 March 2026; Accepted 11 April 2026

Available online 12 April 2026

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(Panteli et al., 2017; Kim & Dvorkin, 2019; Oikonomou et al., 2025). Second, external risks such as climate change, natural disasters, and geopolitical conflicts have been identified as fundamental causes of energy system vulnerability (Sharifi & Yamagata, 2016; Cao, 2025; Ma et al., 2026). Third, institutional governance plays a pivotal role since policy design, regulatory frameworks, and governance capacity determine system performance under shocks (Busby et al., 2021; Guarascio et al., 2025). Fourth, green finance contributes to resilience by mobilizing low-carbon investments and providing financial support for clean energy development (Liu et al., 2022; Shi & Yang, 2025). Finally, technological innovation serves as a long-term driver of resilience by advancing energy transition and improving system adaptability and flexibility (Zhang et al., 2024a; Zhao et al., 2025; Chen et al., 2025). Despite the growing body of research that has enriched the theoretical and practical understanding of energy resilience, studies examining the relationship between digitalization and energy resilience remain relatively scarce, which provides the central research motivation for this study.

To fill these gaps, this study adopts the resource-based view and resilience theory as analytical frameworks and employs panel data from 298 Chinese cities from 2011 to 2022. Building on established approaches, we construct multidimensional indices of digitalization and energy resilience that are tailored to the Chinese urban setting. The study systematically examines the impacts of digitalization on energy resilience, focusing on its overall effect, underlying mechanisms, threshold, multidimensional characteristics, and spatial spillover effects. This study makes three main contributions. First, it provides city-level empirical evidence on the relationship between digitalization and energy resilience in China, and further reveals its nonlinear and spatial characteristics. Second, it opens the mechanism black box by showing how digitalization may enhance urban energy resilience through reducing energy misallocation, improving governance capacity, and promoting green innovation. Third, it extends the literature from broad regional and national discussions to differentiated urban contexts by identifying heterogeneous patterns across geography, resource endowments, and administrative hierarchy, thereby offering a more targeted basis for resilience-oriented urban policy design.

The remainder of this paper is organized as follows. Section 2 reviews the related literature. Section 3 develops the theoretical framework and research hypotheses. Section 4 presents the research design, including model specification, variable definitions, and data sources. Section 5 reports the empirical results. Section 6 discusses policy implications and future perspectives. Section 7 concludes.

2. Literature review

2.1. Consequences of digitalization

Digitalization is not merely a process of technological iteration but a systemic restructuring that encompasses organizations, institutions, and industrial structures (Matt et al., 2015; Loebbecke & Picot, 2015). In recent years, a growing body of research has systematically revealed the multifaceted consequences of digitalization from the perspectives of resource allocation, technological progress, green transition, and potential risks.

First, resource allocation and efficiency improvement. Studies have shown that digital infrastructure and digital finance can significantly enhance total factor energy efficiency by optimizing the allocation of resources and capital (Liu & Zhang, 2025). At the supply chain level, digitalization promotes innovation and collaboration, thereby improving stability and resilience (Aslam et al., 2025; Gu et al., 2025). At the regional level, smart city policies have been found to enhance energy resistance capacity through resource optimization (Wang & Hao, 2024) and to alleviate energy misallocation (Lai & He, 2025).

Second, technological advances and governance transformation. Emerging technologies such as artificial intelligence, blockchain, and

deep learning have been widely applied in energy systems, enhancing grid redundancy and operational flexibility while supporting the energy transition through green data centers (Mollah et al., 2021; Elsisi et al., 2024). The Internet of Things (IoT) and digital twins contribute to improving operational efficiency in urban governance and enhancing forecasting and decision-making precision (Li et al., 2022). At the governance level, digitalization has driven platformization in information infrastructure, with cross-sectoral integration accelerating the flow of data and services (Van Dijk, 2021). Meanwhile, although research on artificial intelligence in public governance remains largely exploratory and conceptual, it has demonstrated potential in areas such as public participation, risk management, and performance evaluation (Zuiderwijk et al., 2021).

Third, green transition and environmental governance. Digitalization advances green transition and environmental governance by enhancing the effectiveness of urban green development attention. Empirical evidence shows that attention to urban green development effectively alleviates energy resource misallocation, primarily through stronger environmental regulation, stimulation of green technological innovation, and the greening of industrial structure; moreover, the development of the digital economy amplifies these effects (Lai & He, 2025). At the same time, digital technologies are considered essential for alleviating environmental pressures and improving urban operational efficiency (Silva et al., 2018). Furthermore, with the widespread deployment of digital technologies in environmental governance, data infrastructures have come to be regarded not only as tools for policy-making and ecological monitoring but also as embedded within specific power relations, offering new perspectives for understanding how digitalization reshapes environmental governance (Nost & Goldstein, 2022).

Finally, risks and structural constraints. The effects of digitalization also exhibit a clear duality. On the one hand, cyber-physical systems can contribute to decarbonization and enhance flexibility, but they may also generate new systemic risks and uncertainties (Inderwildi et al., 2020). On the other hand, digital factor misallocation has been shown to significantly constrain urban resilience (Zhang et al., 2024b). Additional studies further reveal that the impact of digital infrastructure on energy efficiency follows a nonlinear pattern, shifting from inhibition to promotion at different stages of development (Wang & Shao, 2024). Moreover, digitalization in the energy sector is accompanied by emerging challenges such as cybersecurity, data privacy, and labor market disruptions (Nazari & Musilek, 2023).

2.2. Determinants of energy resilience

The concept of resilience was originally derived from material mechanics, emphasizing the capacity of systems to rebound after disturbances (Holling, 1973). It was later extended to ecology and complex systems research, where resilience is understood not only as the ability to return to an initial state but also as the capacity for adaptation, regeneration, and transformation (Wears, 2006; Haines, 2009). Against this background, existing studies have explored the determinants of energy resilience, which can be broadly categorized into three dimensions.

First, engineering hardening and digital applications provide the foundation for enhancing the physical resilience of energy systems. Research shows that engineering and operational measures such as grid reinforcement, microgrids, distributed generation, energy storage deployment, network reconfiguration, and emergency repair can maintain critical load supply and shorten recovery time after disruptions (Panteli et al., 2017; Kim & Dvorkin, 2019; Oikonomou et al., 2025). Renewable energy and battery storage have also been proven to play an important role in improving cost-effectiveness and recovery capacity (Shafiei et al., 2024). In parallel, digital technologies are increasingly regarded as vital support for resilience. Green data centers serve as strategic infrastructure for energy transition and system stability (Lei

et al., 2025). Blockchain has been applied to improve grid redundancy (Mollah et al., 2021). The integration of deep learning and the Internet of Things enhances adaptive capacity when systems face adversarial conditions (Elsisi et al., 2024). Artificial intelligence contributes to greater flexibility and resilience in both energy production and consumption (Jiang & Yu, 2025).

Second, institutional governance serves as a crucial safeguard against external risks. Extreme climate events, natural disasters, and geopolitical conflicts frequently test the stability and recovery of energy systems (Sharifi & Yamagata, 2016; Oikonomou, 2025; Cao, 2025). Governance frameworks, policy tools, and administrative capacity largely determine whether energy systems can withstand shocks and recover effectively, linking regulatory effectiveness and governance quality directly to system resilience (Busby et al., 2021). Existing studies argue that conventional energy security approaches focus heavily on fossil fuel supply, while paying insufficient attention to resilience and adaptability at the system level. This highlights the need to identify key institutional parameters and improve policy design to promote sustainable and robust governance (Molyneux et al., 2016). From the perspective of policy coordination and structural adjustment, institutional arrangements, industrial policies, and technological support must proceed simultaneously to generate synergies for resilience enhancement (Guarascio et al., 2025). This is particularly evident in cross-regional electricity transmission, where improved interregional coordination can strengthen urban energy resilience, but may also generate distributional tensions when compensation and benefit-sharing mechanisms remain inadequate (Yang & Zhou, 2025).

Third, technological innovation and green transition are widely recognized as important drivers of energy resilience. Existing studies show that green technological innovation can enhance the stability, efficiency, and sustainability of energy systems (Zhang et al., 2024a; Zhao et al., 2025). In particular, digital and intelligent technologies, such as digital twins, artificial intelligence, and cyber-physical systems, improve real-time monitoring, operational optimization, and adaptive control, thereby strengthening the capacity of energy systems to respond to disruptions while supporting decarbonization (Inderwildi et al., 2020; Khan et al., 2025). At the same time, green transition pathways, including virtual power plants, renewable energy integration, and the coordination of storage systems, have been shown to enhance system flexibility, reduce operational costs, and improve the ability of energy systems to cope with multiple uncertainties and extreme events (Zadehbagheri et al., 2025; Wang et al., 2025a). Taken together, these studies suggest that technological innovation and green transition not only improve the operational performance of energy systems, but also provide critical support for their long-term resilience and low-carbon transformation.

2.3. Research gap

Although research on digitalization and energy resilience has expanded in recent years, several important gaps remain. First, the relationship between digitalization and energy resilience has not been comprehensively examined with systematic city-level empirical evidence, particularly in terms of its overall effects and potential heterogeneity across urban contexts. While prior studies have documented the economic and social consequences of digitalization, its role in strengthening urban energy resilience remains insufficiently understood. Second, although the determinants of energy resilience and the broader impacts of digitalization have been widely discussed, the mechanisms linking the two are still unclear. In particular, limited attention has been paid to mediating channels such as energy misallocation, governance capacity, and green innovation, which constrains a deeper understanding of how digitalization may enhance resilience. Third, existing studies have mainly focused on broad regional or national perspectives, with insufficient consideration of city-level heterogeneity in geography, resource endowments, and administrative

hierarchy. This limits the development of more targeted urban strategies for strengthening energy resilience. To address these gaps, this study develops an integrated analytical framework to examine the effects of digitalization on urban energy resilience, with particular attention to mediating mechanisms, heterogeneous patterns, nonlinear characteristics, and spatial spillovers. In doing so, it contributes new empirical evidence on how digitalization can support resilience-oriented urban governance.

3. Theoretical analysis and research hypotheses

The resource-based view (RBV) posits that actors operating in turbulent environments rely on scarce, inimitable, and transferable resources to sustain competitive advantages (Barney, 1991). Resilience theory, in turn, emphasizes that complex systems must possess dynamic responsiveness and continuous adaptability to maintain stable long-term operations under external shocks (Wears, 2006; Haimes, 2009). Taken together, these perspectives provide a logical framework for understanding the relationship between digitalization and energy resilience, as depicted in Fig. 1.

3.1. Direct effects of digitalization on energy resilience

As a strategic resource, digitalization can significantly enhance resilience across three key dimensions: resistance, recovery, and regeneration.

Resistance capacity represents the first line of defense of energy resilience, referring to the system's ability to maintain stable operations under external shocks. Digitalization strengthens this capacity through two channels: anticipatory sensing and proactive defense. On the one hand, digital tools improve the timeliness of risk identification, enabling systems to take precautionary measures before potential threats evolve into actual disruptions, thereby reducing vulnerability (Zhou & Liu, 2024). On the other hand, digitalization enhances information security and institutional safeguards, reinforcing system stability in the face of external attacks and disturbances (Wang & Hao, 2024). Although applications of digitalization may entail risks due to regional or technological differences (Chen et al., 2024a), overall, it effectively bolsters the resistance capacity of energy systems, laying the foundation for stronger resilience.

Recovery capacity constitutes the core dimension of energy resilience, reflecting the ability of systems to quickly restore essential functions and maintain flexible adaptation after a disruption. Digitalization reinforces this capacity primarily through resource integration and dynamic scheduling. On the one hand, it improves the efficiency and stability of supply-demand matching, enabling faster coordination of cross-regional resources and shortening recovery time (Gu et al., 2025). On the other hand, digitalization supports dynamic scheduling mechanisms that enhance system adjustments in the aftermath of disturbances, ensuring smoother energy flows and reducing delays and uncertainties (Mollah et al., 2021). From the perspective of recovery, digitalization accelerates resource integration and improves scheduling flexibility, thereby providing a solid safeguard for enhancing energy resilience.

Regeneration capacity represents the deeper dimension of resilience, referring to a system's ability to achieve long-term sustainability through self-regeneration and evolutionary processes after disruptions. Digitalization contributes to this capacity through iterative upgrading and continuous optimization. On the one hand, it provides experimental and simulation environments that enable systems to accumulate experience in virtual scenarios and continuously refine operational logic, thereby strengthening long-term adaptive potential (Shaukat et al., 2018). On the other hand, data-driven feedback mechanisms allow energy systems to continuously learn and adjust in operation, gradually developing greater complexity and diversity, and demonstrating higher stability in contexts of distributed energy integration and network evolution (Cicilio et al., 2021). From the perspective of regeneration,

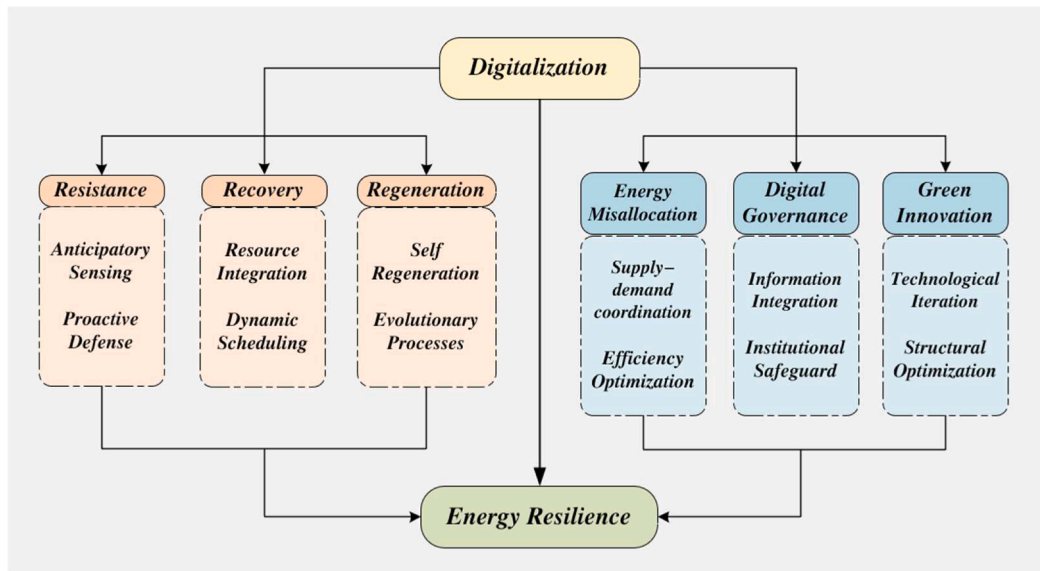


Fig. 1. Theoretical influencing mechanism diagram.

therefore, digitalization offers a vital source of momentum for the sustainability and evolution of energy resilience.

In summary, we propose Hypothesis 1: Digitalization significantly enhances energy resilience.

3.2. Indirect effects of digitalization on energy resilience

Energy misallocation is one of the root causes of energy system vulnerability, as it leads to resource waste and structural shortages, making systems more prone to imbalance under external shocks. The development of digitalization provides effective solutions to mitigate misallocation. From the perspective of supply–demand coordination, digitalization improves the precision of energy allocation through information integration and predictive scheduling, enabling more efficient matching of resources across production, transmission, and consumption. This reduces instability caused by structural distortions and enhances the system’s ability to maintain balance during disruptions (Xue et al., 2022; Sun et al., 2024). From the perspective of efficiency optimization, digitalization promotes transparency and intelligence in energy flows, reduces redundancy and bottlenecks, and improves overall system performance. Such efficiency gains allow systems to cope with greater uncertainty using fewer resources, thereby reinforcing resilience (Liu & Zhang, 2025). Thus, we put forward the following hypothesis:

H2a: Digitalization reduces energy misallocation, and the reduction in energy misallocation, in turn, enhances energy resilience.

Government governance capacity is another critical institutional safeguard for energy resilience, and digitalization injects new momentum into it. Energy resilience depends not only on the internal technical efficiency of the system but also on whether governance structures can provide timely responses and institutional guarantees under shocks. Digitalization strengthens information integration, as e-government platforms break down departmental and regional silos to consolidate data from power grids, markets, and the environment. This enhances risk identification and early warning, reducing information asymmetry in governance processes (Zuiderwijk et al., 2021; Chen et al., 2024b). Moreover, digitalization improves institutional safeguards by embedding into public governance systems, increasing policy enforcement and rule transparency. This allows systems to restore order more quickly after disruptions and gradually develop long-term adaptability (Tang et al., 2025). Therefore, we propose the following hypothesis:

H2b: Digitalization improves digital governance, and the improvement in digital governance, in turn, enhances energy resilience.

Green innovation serves as a critical driver through which digitalization enhances energy resilience. According to the resource-based view, green technologies and low-carbon industries are strategic resources that are scarce, difficult to imitate, and capable of providing long-term competitive advantages. Digitalization facilitates green innovation in two main ways. First, from the perspective of technological iteration, digitalization reduces the cost of knowledge flows and collaborative R&D, thereby accelerating the development and diffusion of green technologies, which improves energy efficiency and the level of decarbonization (Wu et al., 2024). Second, from the perspective of structural optimization, green innovation accelerates the integration of clean and distributed energy, making the energy structure more diversified and flexible, and reducing reliance on a single energy pathway. This, in turn, strengthens the stability and adaptability of the energy system under external shocks (Wang et al., 2022; Ran et al., 2023). Accordingly, we propose the following hypothesis:

H2c: Digitalization promotes green innovation, and the promotion of green innovation, in turn, enhances energy resilience.

4. Research design

4.1. Modelling

To examine the effect of digitalization on energy resilience, we specify the following baseline two-way fixed-effects model:

$$ER_{it} = \alpha_0 + \alpha_1 Dig_{it} + \alpha_c Controls_{it} + \mu_i + \delta_t + \varepsilon_{it} \quad (1)$$

Where ER_{it} denotes the level of energy resilience of city i in year t , Dig_{it} represents the degree of digitalization, $Controls_{it}$ is a set of control variables; μ_i captures city fixed effects, δ_t controls for year fixed effects, and ε_{it} is the idiosyncratic error term.

To examine the mediating roles of energy misallocation, digital governance, and green innovation, we follow the mediation testing framework of Baron and Kenny (1986) and estimate the following equations:

$$M_{it} = \beta_0 + \beta_1 Dig_{it} + \beta_c Controls_{it} + \mu_i + \delta_t + \varepsilon_{it} \quad (2)$$

$$ER_{it} = \gamma_0 + \gamma_1 Dig_{it} + \gamma_2 M_{it} + \gamma_c Controls_{it} + \mu_i + \delta_t + \varepsilon_{it} \tag{3}$$

Where M_{it} denotes the mediating variable. β_1 captures the effect of digitalization on the mediator, and γ_2 captures the effect of the mediator on energy resilience. If both β_1 and γ_2 are statistically significant, this provides evidence consistent with a mediating effect.

Furthermore, to test for potential nonlinear effects of digitalization on energy resilience, we further employ a panel threshold model following Hansen (1999):

$$ER_{it} = \phi_0 + \phi_1 Dig_{it} \cdot I(q_{it} \leq \theta) + \phi_2 Dig_{it} \cdot I(q_{it} > \theta) + \phi_c Controls_{it} + \mu_i + \delta_t + \varepsilon_{it} \tag{4}$$

Where q_{it} is the threshold variable, θ is the estimated threshold, and $I(\cdot)$ is the indicator function that equals 1 if the condition holds and 0 otherwise. This model is used to test whether the effect of digitalization on energy resilience differs across regimes.

Given that digitalization may affect urban energy resilience not only within a city but also across cities through infrastructure connectivity, information diffusion, and factor mobility, we further employ a spatial Durbin model with two-way fixed effects to examine potential spatial

spillover effects, following Liu et al. (2024).

$$ER_{it} = \rho \sum_j w_{ij} ER_{jt} + \beta_1 Dig_{it} + \beta_2 \sum_j w_{ij} Dig_{jt} + \beta_m \sum_{m=1}^n Controls_{it} + \beta_{m'} \sum_j \sum_{m=1}^n w_{ij} Controls_{jt} + \mu_i + \delta_t + \varepsilon_{it} \tag{5}$$

where ρ denotes the spatial autoregressive coefficient and w_{ij} denotes the spatial weight matrix. Since the coefficients of the spatial Durbin model cannot be interpreted directly as marginal effects, the estimation results are further decomposed into direct, indirect, and total effects. This study uses the economic-geographic distance matrix as the baseline spatial weight matrix. To further examine the distance sensitivity of spatial spillovers, geographic-threshold matrices are additionally constructed, including the 200 km threshold matrix and the 300 km threshold matrix.

4.2. Variables

(1) Energy Resilience (ER)

Drawing on Wang et al. (2025b) and adapting the framework to the prefecture-level city context, this study constructs a multidimensional index of urban energy resilience for 298 prefecture-level and above

Table 1
Indicator system of urban energy resilience in China.

Primary Indicator	Secondary Indicator	Tertiary Indicator	Calculation	Unit	Attribute	Explanation	
Resistance Capacity	Ecological Load	Carbon dioxide emissions intensity	Carbon emissions/GDP	Tons/10,000 CNY	-	Ecological Load reflects resistance capacity by capturing the environmental pressure and disaster-related exposure faced by the energy system. A heavier ecological load increases system vulnerability under external shocks and weakens resistance capacity.	
		SO ₂ emissions per capita	SO ₂ emissions / Total population	Tons/person	-		
		Disaster losses	Total economic losses from natural disasters	Billion CNY	-		
	Energy Consumption	Low-carbon energy use	Share of low-carbon energy in total energy consumption	Share of low-carbon energy in total energy consumption	%	+	Energy Consumption reflects resistance capacity by capturing the intensity, efficiency, and dependence of energy use. Higher energy consumption intensity and stronger dependence on energy place greater pressure on the system and weaken its ability to withstand disturbances.
			Energy consumption per GDP	Total energy consumption / GDP	Tons/10,000 CNY	-	
			Energy consumption per capita	Total energy consumption / Population	Tons/person	-	
Recovery Capacity	Energy Endowment	Energy investment	State-owned enterprises energy fixed asset investment / Total fixed asset investment	%	+	Energy Endowment reflects recovery capacity by capturing the resource and infrastructural basis for post-shock restoration. Greater investment in energy infrastructure and better access to renewable energy and gas systems facilitate recovery capacity and contribute to overall energy resilience.	
		Renewable power per capita	Installed renewable capacity / Population	kW / person	+		
		Gas pipeline length	Length of natural gas pipelines	Kilometers	+		
	Environmental Governance	Industrial waste utilization	Comprehensive utilization of general industrial solid waste	Comprehensive utilization of general industrial solid waste / Total generation of general industrial solid waste	%	+	Environmental Governance reflects the recovery capacity by evaluating industrial waste utilization, environmental regulation, and green space. While better waste utilization and more green spaces facilitate recovery, the impact of environmental regulation on energy resilience is uncertain, as it can both support and hinder recovery depending on its strength and implementation.
			Pollution treatment investment	Pollution treatment investment / Secondary industry output	%	-	
			Green space ratio	Forest area / Land area	%	+	
Regeneration Capacity	External Security	Energy import dependence	Net energy import / Total energy consumption	%	-	External Security reflects regeneration capacity by capturing a city's exposure to external energy dependence and the extent to which its economic structure can buffer external shocks. Lower dependence on imported energy and a more advanced industrial structure contribute to long-term regeneration capacity and support overall energy resilience.	
		Industrial output per GDP	Industrial output / GDP	%	+		
		Tertiary industry ratio	Tertiary industry value added / GDP	%	+		
	Internal Drivers	Energy transition	Renewable installed capacity	Renewable installed capacity / Total installed capacity	%	+	Internal Drivers reflect regeneration capacity by capturing the internal conditions that support energy-system transition and long-term adaptation, including energy transition, diversity, self-sufficiency, and the internal support base of the energy sector. These factors strengthen the system's ability to regenerate and adapt over time, thereby contributing to overall energy resilience.
			Energy diversity	Energy production diversity index	-	+	
			Energy self-sufficiency	(Gas production + Power generation) / Energy consumption	%	+	
		Energy employment	Employment in electricity, gas, and heating supply / Population	%	+		

cities in China. Based on the literature review and expert consultation, energy resilience is defined along three core dimensions, namely resistance capacity, recovery capacity, and regeneration capacity, together with their corresponding tertiary indicators (see Table 1). After standardizing the original data, indicator weights are objectively determined using the entropy weight method. The TOPSIS method is then employed to calculate the overall energy resilience index as well as the scores for each of the three dimensions for each city.

(2) Digitalization (Dig)

To measure the level of digitalization across cities, this study constructs a composite urban digitalization index by drawing on the measurement framework of Zhang and Bai (2023) and adapting it to the data availability of prefecture-level and above cities in China. The index comprises three dimensions, namely digital infrastructure, digital users, and digital applications, which capture the foundational support, user penetration, and application intensity of urban digitalization, respectively. The specific indicators are reported in Table 2.

To ensure comparability, all raw indicators are standardized, and the entropy weight method is employed to determine indicator weights. Based on these weights, a composite digitalization index is calculated for each city.

(3) Energy Misallocation (EM)

Following the distortion coefficient approach proposed by Hsieh and Klenow (2009), this study measures the degree of energy misallocation across Chinese prefecture-level cities by examining the relative deviation between energy input and output. Specifically, the index is constructed based on the deviation of each city’s actual share in total output and energy consumption from its theoretical share under an “optimal” allocation. A larger value of EM indicates a higher degree of distortion in the allocation of energy factors within the city.

(4) Digital Governance Capacity (Gov)

This study uses the China Local Government Open Data Index released by the Digital and Mobile Governance Laboratory of Fudan University to measure digital governance capacity. The index is constructed from multiple sub-indicators covering dimensions such as local identification, readiness, platform development, data openness, and data utilization, and is aggregated through weighted synthesis. It reflects the overall capability of local governments in information transparency, data sharing, public service delivery, and governance effectiveness. A higher score indicates stronger digital governance capacity in terms of open data provision, cross-departmental information integration,

Table 2
Digitalization indicator system.

Primary Indicator	Secondary Indicator	Tertiary Indicator	Attribute
Composite Digitalization Index	Digital infrastructure	Share of employment in the computer services and software industry	+
		Total volume of telecommunication services per capita	+
	Digital users	Number of Internet users per 100 persons	+
		Number of mobile phone users per 100 persons	+
	Digital applications	Digital Inclusive Finance Index of China	+
		Domain name share	+
		E-commerce transaction volume (billion yuan)	+

resource coordination, and emergency response.

(5) Green Innovation (GI)

Drawing on Lee et al. (2023), green innovation is proxied by the annual number of authorized green patents in each prefecture-level city. To construct a continuous GI variable, one is added to the patent count before taking its natural logarithm. This treatment provides an intuitive measure of regional green technological innovation activity, mitigates the high skewness of patent counts, and ensures computability when the patent count is zero.

(6) Control Variables (Controls)

To improve the explanatory power and reliability of the empirical model, six key control variables are included with reference to prior studies on energy resilience and digitalization. Specifically, urbanization rate (UrbRate) reflects the degree of urbanization; financial development (FinDev) captures the level of financial support; higher education ratio (HighEdu) measures human capital; government scale (GovScale) reflects the scale of public resource allocation; R&D input (RDInput) captures innovation input intensity; and railway mileage (Railway) measures the length of urban railway operation. Detailed definitions and formulas are reported in Table 3.

Variance inflation factor (VIF) tests were conducted for all independent variables. The results show that the VIF values of all variables are below 5 (average VIF = 3.62), which is well below the critical threshold of 10 for severe multicollinearity. Therefore, multicollinearity is not a serious concern in the model.

To further assess the relationships among the main variables, we present the correlation matrix below. Table 4 provides a more intuitive understanding of the interactions between the variables and complements the VIF analysis.

4.3. Data sources

Considering data availability and research needs, this study constructs a balanced panel dataset of 298 prefecture-level and above cities in China from 2011 to 2022, including 294 prefecture-level cities and 4 municipalities directly under the central government. The year 2011 is selected as the starting point because it marks the beginning of China’s 12th Five-Year Plan, which explicitly emphasized optimizing the energy structure and building a modern energy system that is secure, stable, economical, and clean. The raw data are obtained from the China Energy Statistical Yearbook, China Electric Power Yearbook, China E-Commerce Yearbook, China City Statistical Yearbook, the National Intellectual Property Administration, and other official datasets used to construct the digitalization and governance indicators. Interpolation is applied to fill sporadic missing values in certain variables, while cities with substantial missing data are excluded from the sample. Descriptive statistics are reported in Table 5.

Table 3
Control variables.

Variable name	Definition	Calculation method or formula
UrbRate	Urbanization rate	Registered urban population / total population
FinDev	Financial development	Balance of deposits and loans of financial institutions/city GDP
HighEdu	Higher education ratio	Number of higher education students / total population
GovScale	Government scale	General public budget expenditure/city GDP
RDInput	R&D input intensity	R&D expenditure / general public budget expenditure
Railway	Railway mileage	Length of urban railway operation

Table 4
Correlation matrix of main variables.

Variables	ER	Resistance	Recovery	Regeneration	Dig	EM	Gov	GI
ER	1.0000							
Resistance	0.7357***	1.0000						
Recovery	0.6474***	0.1603***	1.0000					
Regeneration	0.7844***	0.2750***	0.4561***	1.0000				
Dig	0.0353**	0.0270	0.0183	0.0297*	1.0000			
EM	-0.0624***	-0.0069	-0.0943***	-0.0554***	-0.3259***	1.0000		
Gov	0.0320*	0.0367**	0.0413**	0.0048	0.2591***	-0.1158***	1.0000	
GI	0.3908***	0.1349***	0.3624***	0.4039***	0.0531***	-0.0179	0.0172	1.0000

Notes: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. The full correlation matrix is in the Appendix.

Table 5
Descriptive statistics.

Variable Category	Variable Name	Obs	Mean	Std. Dev.	Min	Max
Explained Variables	ER	3576	0.8199	0.1550	0.4865	2.2551
	Resistance	3576	0.5672	0.0852	0.3487	0.9697
	Recovery	3576	0.0888	0.0529	0.0203	0.5840
	Regeneration	3576	0.1639	0.0740	0.0584	0.8548
	Dig	3576	0.3517	0.2231	0.0573	0.9577
Core Explanatory Variable	Dig	3576	0.3517	0.2231	0.0573	0.9577
	EM	3576	-0.0034	0.3521	-0.7519	1.9316
Mediating Variables	Gov	3576	3.2379	11.6756	0.0000	82.8800
	GI	3576	0.1647	0.0288	0.0660	0.4002
	UrbRate	3576	0.5740	0.0996	0.2281	0.8960
Control Variables	FinDev	3576	2.8894	0.8464	1.1540	7.4360
	HighEdu	3576	0.0901	0.0072	0.0592	0.1221
	GovScale	3576	0.2404	0.1560	0.1058	1.3792
	RDInput	3576	0.0165	0.0110	0.0037	0.2007
	Railway	3576	0.4675	0.1993	0.0438	1.4200

5. Empirical results analysis

5.1. Benchmark regression

We estimate the effect of digitalization on urban energy resilience using a two-way fixed-effects model that controls for both city and year fixed effects. As reported in Table 6, digitalization (Dig) exerts a significantly positive effect on urban energy resilience (ER). Across columns (1)–(3), control variables are added progressively, and the coefficient on digitalization remains positive and significant at the 1% level, with estimated coefficients of 1.5281, 0.8302, and 0.7705, respectively. Although the magnitude of the coefficient declines after

Table 6
Estimation results of the benchmark regression.

Variables	(1)	(2)	(3)
Dig	1.5281*** (0.0587)	0.8302*** (0.0490)	0.7705*** (0.0456)
UrbRate	—	0.0056*** (0.0007)	0.0042*** (0.0008)
FinDev	—	0.0715*** (0.0048)	0.0738*** (0.0051)
HighEdu	—	—	2.9761*** (0.8991)
GovScale	—	—	-0.7481*** (0.0660)
RDInput	—	—	5.2941*** (0.4131)
Railway	—	—	0.0642** (0.0292)
Constant	0.6170*** (0.0075)	0.1705*** (0.0221)	0.0076 (0.0783)
City FE	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
R ² (within)	0.8156	0.9462	0.9601
Observations	3576	3576	3576

Notes: Robust standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. The notation applies similarly to the following table.

additional controls are introduced, the positive association remains robust. Meanwhile, the within R² increases from 0.8156 to 0.9601, indicating an improvement in explanatory power.

The estimated effects of the control variables are also broadly consistent with theoretical expectations. Urbanization rate (UrbRate), financial development (FinDev), higher education ratio (HighEdu), R&D input (RDInput), and railway mileage (Railway) are significantly positive, whereas government scale (GovScale) shows a significantly negative coefficient. This negative coefficient suggests that excessive government expansion may be associated with lower urban energy resilience, potentially reflecting inefficiencies in resource allocation and coordination.

5.2. Robustness checks

To assess the robustness of the benchmark results, we conduct four additional tests, as reported in Table 7. First, we re-estimate the baseline model using city-level clustered robust standard errors. Second, all continuous variables are winsorized at the 1% level to mitigate the influence of extreme values. Third, we replace the composite digitalization index (Dig) with the number of digital patents as an alternative proxy for digitalization. Digital patents are commonly used to capture digital technological advancement (Huang et al., 2023). The coefficient remains significantly positive at 0.7602 ($p < 0.01$), indicating that the main result is not sensitive to alternative measurement. Fourth, to address potential endogeneity and dynamic persistence, we estimate a dynamic panel model using the System GMM estimator. The lagged dependent variable is significantly positive, and the coefficient on digitalization remains positive and significant. Moreover, the AR(2) test ($p = 0.3120$) and the Hansen test ($p = 0.2560$) support the validity of the model specification and instrument set. Overall, the results across all four robustness checks confirm the robustness of the baseline findings.

5.3. Mediation mechanism tests

To further uncover the mechanisms through which digitalization

Table 7
Estimation results of robustness tests.

Variables	Dependent variable: ER			
	Clustered SE (1)	Winsorization (2)	Alternative Dig (3)	System GMM (4)
L.ER	—	—	—	0.9284*** (0.2087)
Dig	0.7711*** (0.0456)	0.8102*** (0.0423)	0.7602*** (0.0901)	3.0012*** (0.4125)
UrbRate	0.0056*** (0.0007)	0.0044*** (0.0007)	0.0042*** (0.0006)	-0.0215** (0.0053)
FinDev	0.0715*** (0.0048)	0.0717*** (0.0042)	0.0712*** (0.0064)	0.0193*** (0.0085)
HighEdu	2.9761*** (0.8991)	2.7314*** (0.8593)	2.9075*** (1.2115)	2.5372*** (0.9753)
GovScale	-0.7481*** (0.0660)	-0.7162*** (0.0651)	-0.7385*** (0.0931)	-0.4972** (0.1425)
RDInput	5.2941*** (0.4131)	5.3876*** (0.4071)	5.2951*** (0.6467)	4.5512 (3.7201)
Railway	0.0642** (0.0292)	0.0699*** (0.0213)	0.0725** (0.0386)	0.1234* (0.0851)
Constant	0.0076 (0.0783)	0.0102 (0.0721)	0.0055 (0.0794)	0.0105 (0.0221)
City FE	Yes	Yes	Yes	—
Year FE	Yes	Yes	Yes	—
Observations	3576	3576	3576	3278
R ² (within)	0.9462	0.9331	0.9780	—
AR(2) test p-value	—	—	—	0.3120
Hansen test p-value	—	—	—	0.2560

enhances energy resilience, three mediating variables are introduced: energy misallocation (EM), digital governance (Gov), and green innovation (GI). Stepwise regression and Bootstrap methods are employed, with the results presented in Table 8.

5.3.1. Energy misallocation mechanism

As shown in Table 8, Column (1) reports the benchmark regression,

Table 8
Mediation analysis.

Variables	ER (1)	EM (2)	ER (3)	Gov (4)	ER (5)	GI (6)	ER (7)
Dig	0.7705*** (0.0456)	-0.8736*** (0.1424)	0.6997*** (0.0327)	1.1370*** (0.1364)	0.6538*** (0.0531)	1.0317*** (0.1147)	0.6754*** (0.0352)
EM	—	—	-0.0810*** (0.0061)	—	—	—	—
Gov	—	—	—	—	0.1026*** (0.0083)	—	—
GI	—	—	—	—	—	—	0.0922*** (0.0051)
UrbRate	0.0042*** (0.0008)	-0.0019 (0.0017)	0.0037*** (0.0007)	0.0195*** (0.0023)	0.0049*** (0.0007)	3.1156 (0.9872)	0.0073*** (0.0006)
FinDev	0.0738*** (0.0051)	0.0231* (0.0122)	0.0531*** (0.0062)	0.0261** (0.0117)	0.0713*** (0.0052)	0.0201*** (0.0017)	0.0532*** (0.0046)
HighEdu	2.9761*** (0.8991)	3.2217 (2.3572)	2.5871*** (0.5633)	2.1136 (2.3583)	2.7236*** (0.8778)	0.0007 (0.642)	0.5312 (0.4471)
GovScale	-0.7481*** (0.0660)	0.9204*** (0.1625)	-0.6671*** (0.0542)	0.5836*** (0.1632)	-0.7136*** (0.0665)	-0.2553* (0.1521)	-0.3742*** (0.0451)
RDInput	5.2941*** (0.4131)	2.2963*** (1.1326)	5.0936*** (0.3642)	8.4600*** (1.1391)	5.4623*** (0.5137)	0.5311 (1.1342)	0.3517 (0.3775)
Railway	0.0642** (0.0292)	0.0264 (0.0537)	0.0683** (0.0533)	0.2634** (0.0731)	0.0632** (0.0249)	0.1351** (0.0562)	0.0293 (0.0165)
Constant	0.0076 (0.0783)	-0.2355 (0.1896)	0.0261 (0.0472)	-0.8315*** (0.2319)	-0.0077 (0.0831)	-0.3569** (0.1832)	0.2188*** (0.0463)
City FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R ² (within)	0.9601	0.9534	0.9713	0.9532	0.9610	0.9368	0.9617
Observations	3576	3576	3576	3576	3576	3576	3576
Indirect effect ab	—	0.0705	—	0.1167	—	0.0983	—
Bootstrap Robustness Test	—	[0.0130, 0.1800]	—	[0.0420, 0.2550]	—	[0.0291, 0.2107]	—

Notes: The bootstrap test is based on 1000 resamples. The indirect effect (ab) is reported, and the values in brackets indicate the corresponding 95% confidence intervals.

indicating that digitalization significantly enhances energy resilience. Column (2) shows that digitalization reduces energy misallocation. Column (3) further demonstrates that energy misallocation exerts a negative effect on resilience, while the coefficient of digitalization decreases, suggesting a partial mediation effect. These results indicate that digitalization is associated with lower energy misallocation, and lower energy misallocation is associated with higher energy resilience. Energy misallocation often results in rigidities and distortions in resource flows, which weakens the stability and adaptability of energy systems under external shocks (He et al., 2024). Digitalization alleviates these inefficiencies by integrating supply–demand information, enabling accurate matching, and supporting dynamic scheduling, thereby enhancing overall system efficiency and resilience (Lai & He, 2025). These results confirm that reducing energy misallocation is a vital pathway through which digitalization enhances resilience, supporting Hypothesis 2a.

5.3.2. Digital governance mechanism

As shown in Column (4), digitalization significantly improves governance capacity. Column (5) shows that governance capacity positively contributes to energy resilience, while the coefficient of digitalization decreases, confirming a partial mediation effect. These results suggest that digitalization is associated with stronger governance capacity, and stronger governance capacity is associated with higher energy resilience. Improved governance capacity implies that cross-departmental and cross-regional data integration is more effective, information asymmetry is reduced, and risk identification and early warning are more timely (Wang & Hao, 2024). Moreover, embedding digitalization into governance enhances regulatory enforcement and policy implementation, allowing energy systems to restore order and adapt more rapidly under shocks (Shahbaz et al., 2022). This indicates that governance capacity not only amplifies the benefits of digitalization but also underscores the institutional foundation of energy resilience, supporting Hypothesis 2b.

5.3.3. Green innovation mechanism

As shown in Column (6), digitalization significantly promotes green

innovation, while Column (7) shows that green innovation enhances resilience. This confirms that green innovation is an important mediator in the digitalization–resilience nexus. These results suggest that digitalization is associated with higher green innovation, and higher green innovation is associated with stronger energy resilience. By facilitating the development and diffusion of clean technologies, green innovation promotes low-carbon transition and enhances the adaptability and sustainability of energy systems in the face of external shocks (Wu et al., 2024). Furthermore, the interaction between digital infrastructure and green innovation promotes technological clustering and industrial upgrading, which accelerates green urban transformation and generates heterogeneous effects across regions and development stages (Qin et al., 2024). This mechanism not only strengthens the low-carbon adaptability of the system but also reinforces its recovery and long-term sustainability under uncertainties. Therefore, green innovation serves as a critical channel through which digitalization enhances energy resilience, supporting Hypothesis 2c.

5.3.4. Robustness tests

To verify the robustness of the findings, this study employs Bootstrap estimation with 1000 resamples. The results confirm that the indirect effects of energy misallocation, digital governance, and green innovation are all statistically significant, indicating that the three mediating pathways are stable. Among them, digital governance exerts the strongest mediating effect, highlighting the pivotal role of institutional effectiveness in amplifying the contribution of digitalization to resilience.

5.4. Heterogeneity analysis

5.4.1. Geographical heterogeneity

To examine whether the effect of digitalization varies across regions, this study follows Jiang et al. (2024) and divides the sample into the eastern, central, and western regions of China. Table 9 reports the results of grouped fixed-effects regressions, together with F-tests comparing the central and western regions with the eastern region. The results show that digitalization significantly enhances urban energy resilience in all three regions. In terms of point estimates, the effect is largest in the central region (1.0372, $p < 0.01$), followed by the western region (0.8764, $p < 0.01$) and the eastern region (0.5469, $p < 0.01$). However,

Table 9
Geographical heterogeneity.

Variables	Eastern Region	Central Region	Western Region
Dig	0.5469*** (0.0539)	1.0372*** (0.1171)	0.8764*** (0.0852)
UrbRate	0.0062*** (0.0017)	0.0055*** (0.0021)	0.0053*** (0.0016)
FinDev	-0.0087 (0.0102)	-0.1362*** (0.0237)	0.0919*** (0.0082)
HighEdu	4.7354*** (1.5963)	-3.1362** (1.611)	2.1367 (1.7913)
GovScale	-1.6299*** (0.2033)	1.1054*** (0.2689)	-0.7358*** (0.1142)
RDInput	1.7132*** (0.5581)	9.7519*** (1.6426)	7.8806*** (1.5732)
Railway	0.1079** (0.0532)	0.0935 (0.0781)	0.0311 (0.0465)
Constant	-0.6135*** (0.1761)	0.6742*** (0.1577)	0.0890 (0.1479)
City FE	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
R ² (within)	0.9362	0.9513	0.8864
Observations	1068	1080	1428
F-test: Central vs Eastern	3.1500 ($p = 0.1423$)		
F-test: Western vs Eastern	12.9800*** ($p = 0.0012$)		

the inter-group tests show that the effect in the western region is significantly larger than that in the eastern region ($F = 12.9800$, $p = 0.0012$), whereas the difference between the central and eastern regions is not statistically significant ($F = 3.1500$, $p = 0.1423$). This pattern may reflect differences in regional energy endowments, digital foundations, and the marginal returns to digitalization. In particular, the western region, which is characterized by relatively abundant energy resources but comparatively lower levels of digitalization, may have greater room for improvement, thereby generating larger marginal gains. By contrast, the eastern region already has a relatively strong digital foundation, which may reduce the incremental benefits of further digitalization.

5.4.2. Resource endowment heterogeneity

To investigate whether resource endowment shapes the effect of digitalization on energy resilience, this study follows Jiang et al. (2024) and classifies cities into resource-based and non-resource-based categories according to the National Sustainable Development Plan for Resource-Based Cities. Table 10 reports the results of the grouped fixed-effects regressions. The results show that digitalization significantly enhances urban energy resilience in both groups, but the magnitude of the effect differs substantially. Specifically, the coefficient on digitalization is 1.0500 ($p < 0.01$) for resource-based cities and 0.5621 ($p < 0.01$) for non-resource-based cities. The inter-group difference is statistically significant ($F = 25.7800$, $p = 0.0003$), indicating that digitalization exerts a stronger marginal effect in resource-based cities. This pattern may reflect differences in energy-system foundations and the marginal returns to digitalization across city types. In resource-based cities, a stronger local energy-resource base and higher dependence on energy-related industries may allow digitalization to generate larger gains in system coordination and operational efficiency. In non-resource-based cities, more diversified economic structures and weaker direct dependence on resource-based energy systems may reduce the marginal gains from digitalization, although its effect remains significantly positive.

5.4.3. Administrative level heterogeneity

To examine whether the effect of digitalization varies across administrative levels, this study follows Shi and Hu (2023) and divides the sample into capital cities and non-capital cities. Capital cities include 27 provincial capitals and municipalities directly under the central government, together with 4 sub-provincial cities (Dalian, Qingdao, Ningbo, and Shenzhen), for a total of 31 cities. All remaining cities are

Table 10
Resource endowment heterogeneity.

Variables	Resource-based Cities	Non-resource-based Cities
Dig	1.0500*** (0.0821)	0.5621*** (0.0550)
UrbRate	0.0049*** (0.0011)	0.0037*** (0.0009)
FinDev	0.0780*** (0.0062)	0.0892*** (0.0073)
HighEdu	1.8450 (1.3523)	4.3100*** (1.1289)
GovScale	-0.5800*** (0.0952)	-0.9510*** (0.1123)
RDInput	6.7840*** (0.8630)	5.1500*** (0.7281)
Railway	0.0191* (0.0392)	0.0504** (0.0386)
Constant	0.2300* (0.1167)	-0.0500 (0.1035)
City FE	Yes	Yes
Year FE	Yes	Yes
R ² (within)	0.8932	0.9189
Observations	1356	2220
F-test: Resource vs Non-resource	25.7800*** ($p = 0.0003$)	

classified as non-capital cities. Table 11 reports the grouped fixed-effects regression results. The findings show that digitalization significantly enhances urban energy resilience in both groups. The coefficient on digitalization is 0.9124 ($p < 0.01$) for capital cities and 0.7101 ($p < 0.01$) for non-capital cities, and the inter-group difference is statistically significant ($F = 10.7200$, $p = 0.0018$). This pattern may reflect differences in digital foundations, policy support, and governance coordination across city types. Capital cities typically possess more advanced digital infrastructure, stronger concentrations of talent and innovation resources, and greater administrative capacity, which enable digital technologies to be embedded more effectively in energy monitoring, interdepartmental coordination, and emergency response systems. As a result, digitalization can generate larger marginal gains in energy resilience. In non-capital cities, by contrast, the positive effect of digitalization remains significant, but relatively weaker digital foundations and tighter resource constraints may reduce the extent of these resilience gains.

5.5. Further analysis

5.5.1. Threshold effect analysis

To examine the potential nonlinear effect of digitalization on urban energy resilience, this study employs the panel threshold regression model proposed by Hansen (1999). Digitalization is used as the threshold variable, and the significance of the threshold effect is tested using a bootstrap procedure with 1000 replications. The results are reported in Table 12.

As shown in Table 12, the single-threshold model is statistically significant, with an F-statistic of 96.3421 and a p-value of 0.0024, indicating significance at the 1% level. By contrast, the double-threshold model is not statistically significant, as its F-statistic (30.8542) does not exceed the 10% critical value and the corresponding p-value is 0.1902. Therefore, the subsequent analysis is based on the single-threshold specification. The estimated threshold value is 0.1187, with a 95% confidence interval of [0.1072, 0.1195].

Based on this estimated threshold, the sample is divided into two regimes for further analysis, as reported in Table 13. When $Dig < 0.1187$, the estimated coefficient of digitalization on energy resilience is 0.2824 and is significant at the 1% level. When $Dig \geq 0.1187$, the coefficient increases to 0.9105, also significant at the 1% level. These results suggest that the positive effect of digitalization on energy resilience becomes substantially stronger once digitalization surpasses the threshold level, indicating a clear nonlinear enhancement effect.

Table 11
Administrative level heterogeneity.

Variables	Capital Cities	Non-capital Cities
Dig	0.9124*** (0.0683)	0.7101*** (0.0490)
UrbRate	0.0051*** (0.0012)	0.0045*** (0.0009)
FinDev	0.0841*** (0.0076)	0.0912*** (0.0068)
HighEdu	3.4532** (1.2856)	4.0156*** (1.1672)
GovScale	-0.8745*** (0.1076)	-1.1041*** (0.1152)
RDInput	6.5147*** (0.8820)	4.9032*** (0.5327)
Railway	0.0492** (0.0369)	0.0637** (0.0331)
Constant	-0.0992 (0.1076)	-0.0954 (0.1071)
City FE	Yes	Yes
Year FE	Yes	Yes
R ² (within)	0.8782	0.9243
Observations	372	3204
F-test: Capital vs Non-capital	10.7200***($p = 0.0018$)	

5.5.2. Dimension-specific effects

To further clarify how digitalization influences various dimensions of energy resilience, this study conducts a dimension-specific analysis encompassing three core capacities: resistance, recovery, and regeneration. The results are presented in Table 14. First, digitalization significantly strengthens the resistance dimension of the energy system. The estimated coefficient (0.5720, $p < 0.01$) indicates that digitalization enhances front-end risk identification and forecasting through big data analytics, intelligent monitoring, and platform integration. These capabilities optimize resource allocation and mitigate load imbalance risks, thereby reinforcing the system’s first line of defense. Second, digitalization substantially improves the recovery dimension. With a coefficient of 0.0854 ($p < 0.01$), the findings suggest that digitalization promotes stronger coordination and information symmetry, which accelerates fault detection, localization, and restoration processes, enhancing the system’s ability to rebound from disruptions. Third, digitalization promotes the regeneration dimension. The coefficient of 0.1312 ($p < 0.01$) demonstrates that digital infrastructure and green applications jointly facilitate the diffusion of low-carbon technologies, driving the energy system’s transformation toward a greener and smarter configuration. This process strengthens its long-term structural adaptability and regenerative capacity. Overall, the results indicate that digitalization exerts the greatest influence on the resistance dimension, followed by the regeneration and recovery dimensions.

5.5.3. Spatial spillover effect analysis

To examine the spatial spillover effects of digitalization on urban energy resilience, this study estimates a spatial Durbin model with two-way fixed effects under alternative spatial weight matrices. Table 15 reports the estimated direct, indirect, and total effects under the baseline matrix, the 200 km threshold matrix, and the 300 km threshold matrix.

The results show that the direct effect of digitalization is significantly positive under all three specifications, with coefficients ranging from 0.0355 to 0.0796, indicating that digitalization contributes significantly to the improvement of local urban energy resilience. The indirect effect is also significantly positive, with estimated values of 0.1902, 0.2659, and 0.9806, respectively, suggesting that digitalization generates positive spillover effects on spatially connected cities. In other words, the benefits of digitalization are not confined to the local city, but may also extend to nearby cities through channels such as infrastructure connectivity, inter-city information flows, and factor mobility. Correspondingly, the total effect remains significantly positive across all three specifications, ranging from 0.2257 to 1.0602.

To further examine the distance sensitivity of the spillover effects, Fig. 2 plots the estimated indirect effects under a series of geographic thresholds from 100 km to 1000 km, together with their 90% confidence intervals. The results show that the spillover effect is strongest around the 300 km threshold and gradually weakens as the geographic threshold expands, indicating that the positive externalities of digitalization are more pronounced within relatively close spatial ranges and diminish with distance.

6. Discussion

This study systematically examines the impact of digitalization on energy resilience and its underlying mechanisms. The results indicate that digitalization significantly enhances the energy resilience of Chinese cities, consistent with existing studies on the roles of green finance (Nepal et al., 2024), artificial intelligence-driven technological innovation (Jiang & Yu, 2025; Nepal et al., 2025), and supply chain digitalization (Fahad et al., 2025; Gao et al., 2025) in strengthening energy resilience. However, unlike previous research that has primarily focused on a single dimension or mechanism, this study extends the literature in three major aspects. First, it develops a city-level measurement framework for energy resilience, systematically evaluates the overall effect of digitalization, identifies its threshold characteristics under varying

Table 12
Test results of the threshold effect.

Threshold variable	Model type	F-statistic	p-value	10% critical value	5% critical value	1% critical value	Threshold value	Confidence interval
Digitalization	Single threshold	96.3421***	0.0024	79.1345	85.4299	93.6821	0.1187	[0.1072, 0.1195]
	Double threshold	30.8542	0.1902	41.2012	50.4673	56.3825	0.5832	—

Table 13
Results of the panel threshold regression model.

Threshold variable	Regime division	Estimated coefficient	Significance level
Digitalization	Dig < 0.1187	0.2824	***
	Dig ≥ 0.1187	0.9105	***

Table 14
Dimension-specific effects.

Variables	Resistance	Recovery	Regeneration
Dig	0.5720*** (0.0371)	0.0854*** (0.0152)	0.1312*** (0.0189)
UrbRate	-0.0042*** (0.0006)	0.0012** (0.0003)	0.0042*** (0.0002)
FinDev	0.0410*** (0.0037)	-0.0021*** (0.0015)	0.0423*** (0.0019)
HighEdu	-1.6542** (0.7033)	1.9107*** (0.4085)	3.6720*** (0.5897)
GovScale	-0.7563*** (0.0526)	0.1627*** (0.0205)	-0.2210*** (0.0213)
RDInput	6.6537*** (0.2886)	-0.3856*** (0.1241)	1.7513*** (0.1598)
Railway	0.0736*** (0.0213)	0.0045 (0.0075)	-0.0054 (0.0090)
Constant	0.7625*** (0.0600)	-0.2481*** (0.0223)	-0.5234*** (0.0294)
City FE	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
R ² (within)	0.9335	0.9257	0.8893
Observations	3576	3576	3576

Table 15
Regression results of the spatial spillover effects.

Variables	(1) SDM	(2)w _{ij} ²⁰⁰ SDM	(3)w _{ij} ³⁰⁰ SDM
Dig	0.0223 (0.0616)	0.0264 (0.0473)	0.0339*** (0.0044)
w × Dig	0.0975*** (0.0053)	0.0637*** (0.0084)	0.2760*** (0.0125)
Direct Effect (Dig)	0.0355** (0.0093)	0.0497*** (0.0067)	0.0796** (0.0242)
Indirect Effect (Dig)	0.1902*** (0.0011)	0.2659*** (0.0579)	0.9806*** (0.0635)
Total Effect (Dig)	0.2257*** (0.0098)	0.3156*** (0.0676)	1.0602*** (0.0976)
Control Variables	YES	YES	YES
City FE	YES	YES	YES
Year FE	YES	YES	YES
ρ	0.8693***	0.9138***	0.9077***
R ² (within)	0.7503	0.7800	0.7541
Observations	3576	3576	3576

levels of digitalization, examines its effects across the three dimensions of resistance, recovery, and regeneration, and further investigates its spatial spillover effects. Second, it elucidates the internal logic of how digitalization enhances energy resilience through three mechanisms: reducing energy misallocation, improving digital governance, and promoting green innovation. Third, it incorporates the heterogeneity of geographical regions, resource endowment, and administrative hierarchy to explore regional variations in the digitalization–resilience relationship.

These findings have direct policy relevance for strengthening urban energy resilience through digitalization. In cities with weak digital foundations, priority should be given to targeted investment in energy-related digital infrastructure, including smart-grid sensing, real-time monitoring systems, and emergency dispatch platforms, so that these cities can cross the critical threshold at which digitalization begins to generate stronger resilience gains. In cities that have already reached a relatively high level of digitalization, policy emphasis should shift from basic infrastructure expansion to system integration, data interoperability, and intelligent optimization, so as to translate digital advantages into sustained resilience improvements. In practical terms, resistance capacity can be strengthened through predictive maintenance and risk-warning systems for critical energy facilities; recovery capacity can be improved by establishing cross-departmental digital dispatch and emergency coordination mechanisms; and regeneration capacity can be enhanced by applying digital twins, simulation tools, and adaptive optimization algorithms to support long-term learning and system upgrading. In addition, given the significant spatial spillover effects identified in this study, digital resilience policies should not be designed in isolation at the city level. Neighboring cities should promote data sharing, joint emergency exercises, and coordinated energy dispatch arrangements to extend the benefits of digitalization beyond administrative boundaries and improve regional energy resilience as a whole.

The mechanism analysis further suggests that policy design should focus on safeguarding the channels through which digitalization is translated into higher energy resilience. To ensure that digitalization can effectively reduce energy misallocation, governments should establish unified energy data platforms, improve data interoperability across energy production, transmission, and consumption, and institutionalize digital dispatch mechanisms for routine supply-demand coordination. These measures would help embed digital tools into resource allocation processes and thereby strengthen the capacity of urban energy systems to maintain balance and stability under shocks. To ensure that digitalization can continuously improve governance capacity, policymakers should strengthen cross-departmental data sharing, clarify coordination responsibilities among energy-related agencies, and incorporate digital governance performance into policy evaluation and emergency management systems. In this way, digital governance can provide more reliable institutional support for rapid risk identification, emergency response, and post-shock recovery. To ensure that digitalization can be effectively converted into green innovation, governments should provide sustained support through targeted R&D funding, pilot demonstration programs, green finance instruments, and intellectual property protection for digital-green technology integration. Such policy arrangements would accelerate the diffusion of renewable energy, storage technologies, and smart energy management systems, thereby improving system flexibility, diversification, and long-term adaptive capacity. Overall, the key policy task is not merely to expand digitalization itself, but to build stable institutional support for the intermediate channels through which digitalization enhances energy resilience.

The heterogeneity analysis further indicates that policies aimed at enhancing energy resilience through digitalization should be better tailored to local conditions. In the central region, where digitalization shows the strongest effect on energy resilience, policy efforts should focus on accelerating the integration of digital technologies with energy infrastructure and industrial systems, so that the region’s intermediate position in resource flows and industrial linkages can be translated into greater resilience gains. In the eastern region, where the digital foundation is already relatively strong, the policy focus should shift from

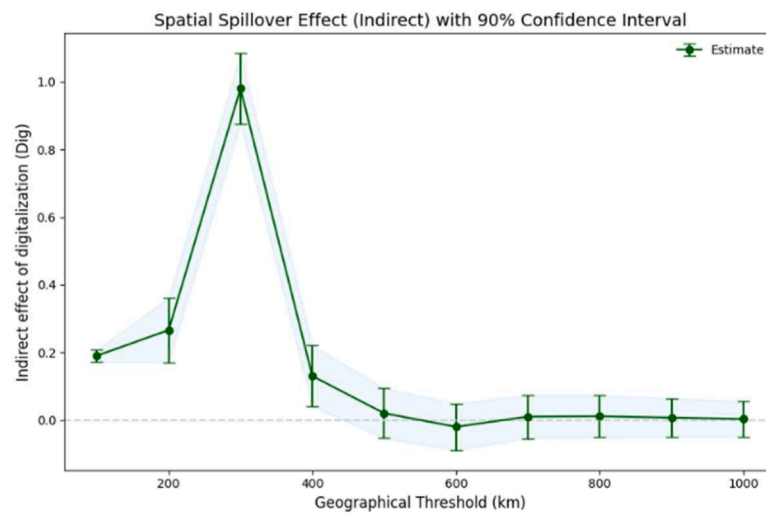


Fig. 2. Spatial spillover effect.

further expansion of basic digital infrastructure to system integration, data interoperability, and cross-regional coordination, in order to improve the efficiency and resilience effects of existing digital systems. In the western region, policies should place greater emphasis on strengthening basic digital infrastructure and improving the accessibility of digital technologies in energy production and distribution, so as to gradually narrow the digital gap and unlock future resilience potential. In resource-based cities, digitalization policies should prioritize the intelligent upgrading of traditional energy industries and the more efficient use of resource advantages, whereas in non-resource-based cities, the emphasis should be placed on cultivating digital-green industrial linkages and enhancing cross-sectoral coordination. At the administrative level, capital cities should make fuller use of their governance and innovation advantages by piloting integrated energy data platforms and regional emergency coordination systems, while general cities should strengthen functional linkages with core cities through shared digital platforms and coordinated dispatch mechanisms. Overall, the policy value of the heterogeneity findings lies in enabling more targeted digitalization strategies for different regional and urban contexts.

Drawing on evidence from a large sample over a long time horizon, this study provides robust empirical evidence and policy insights for strengthening urban energy resilience. Future research could incorporate data with higher spatial and temporal resolution and conduct cross-country comparisons to further examine how institutional settings and energy structures shape the effects of digitalization on energy resilience, thereby testing the broader applicability of the findings across different contexts.

7. Conclusion

Using panel data for 298 prefecture-level and above Chinese cities from 2011 to 2022, this study conducts a comprehensive empirical assessment of the relationship between digitalization and energy resilience. The main conclusions are as follows.

Main effect and robustness. After developing and applying a city-level energy resilience index, the estimates show that digitalization significantly enhances energy resilience. This main effect remains robust across multiple specifications, including city-level clustered robust standard errors, 1% winsorization, alternative measures of digitalization, and the dynamic panel estimation using two-step System GMM.

Mediation effects. Digitalization enhances energy resilience indirectly through three statistically significant channels: reducing energy misallocation, improving digital governance capacity, and promoting

green innovation. Among these, the governance channel is relatively stronger.

Threshold, dimension-specific, heterogeneous, and spatial spillover effects. The effect of digitalization on energy resilience exhibits a significant single-threshold pattern: once the digitalization level surpasses the critical value, its promotive effect increases markedly. Positive and significant effects are observed across the dimensions of resistance, recovery, and regeneration. The magnitude of the effect also varies by geography, resource endowment, and administrative hierarchy, and is more pronounced in western regions, resource-based cities, and capital cities. In addition, digitalization generates significant positive spatial spillover effects on urban energy resilience, with the spillover effect being strongest around the 300 km threshold and gradually weakening as geographic distance increases.

CRediT authorship contribution statement

Bingqian Zhang: Writing – original draft. **Heng Ma:** Funding acquisition. **Lawrence Loh:** Project administration. **Siliang Guo:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no competing interests.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at [doi:10.1016/j.scs.2026.107397](https://doi.org/10.1016/j.scs.2026.107397).

Data availability

Data will be made available on request.

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