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Evaluation of urban energy transition and identification of barrier factors under the "dual carbon" goals: an empirical study of the Yangtze River economic belt

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The Yangtze River Economic Belt is a critical strategic region for China's economic development. Accurately assessing the energy transition level of the Yangtze River Economic Belt and identifying key barriers in the region are essential for achieving China's carbon neutrality goals. Currently, technical assessments of urban-scale energy transitions are limited, with insufficient consideration of the comprehensive contributions of supporting transformations to the broader energy transition. This study develops a comprehensive evaluation framework for urban energy transition based on six dimensions: environmental pollution, energy consumption, environmental governance, resource endowment, technological innovation, and policy guidance. Through the integrated index model and barrier degree model, a quantitative analysis is conducted to explore the dynamics and potential mechanisms of energy transition in the Yangtze River Economic Belt. The results show: (1) The overall level of urban energy transition increased by 35.86%, with persistent inter-city disparities, though their intensity has been alleviated. Over time, spatial differentiation has gradually weakened, transitioning from a core-periphery pattern to a more balanced distribution. (2) The sample cities were categorized based on four criteria: geographical region, urban size, energy transition level, and the developmental stages of resource-based cities. Under each of these four criteria, the city types with the highest energy transition performance were identified as eastern cities, large cities, high-level energy transition cities, and regenerated cities. (3) Within the entire sample, the contributions of environmental governance, resource endowment, and policy guidance to the resistance of the transition are 20.64%, 18.75%, and 18.34%, respectively. The obstacle degree value for environmental pollution is the lowest, indicating that progress in this area could further support urban energy transition efforts. This study establishes an analytical framework for evaluating urban-scale energy transitions and provides the first systematic assessment of energy transition in the Yangtze River Economic Belt, offering valuable insights applicable to other regions of China and countries or regions with similar socio-economic and developmental contexts.

KEYWORDS

urban energy transition, obstacle degree analysis, regional disparities, energy governance, Yangtze River economic belt

1 Introduction

Since the late 1970s, the diminishing contributions of fossil fuel industries to urban economic health have significantly impacted urban social structures and residential environments. Cities play a crucial role in global energy consumption and greenhouse gas emissions, accounting for two-thirds of global energy use and approximately 75% of carbon emissions (Khan et al., 2022; Cheung et al., 2023). The rapid advancement of urbanization, combined with the introduction of carbon neutrality goals, urban energy transition has become one of the key issues in current research (Argyriou, 2020; Koepke et al., 2021; Sillak et al., 2021). In response to global climate change and environmental challenges, China announced its phased "2030 carbon peaking" and "2060 carbon neutrality" goals in 2020. These targets have positioned low-carbon development and energy transition at the core of national high-quality development strategies (Cheng et al., 2022; Yang and Zhao, 2024). Under the framework of the "Dual Carbon" goals, a refined assessment of the status and inherent developmental logic of regional energy transitions within China can facilitate the comprehensive realization of the country's sustainable development objectives.

Under the carbon neutrality targets, urban energy transition aims to promote the decarbonization of urban energy structures, enhance energy efficiency, and increase human wellbeing (Escario-Chust et al., 2023). In the early 21st century, Jacobsson and Johnson (2000) proposed the Technological Innovation System (TIS) theory to explore the driving mechanisms of low-carbon transitions in energy systems. Kanger (2021) optimized TIS theory through a multi-layered perspective, integrating evolutionary economics with science and technology. Huang and Broto (2018) argued that research in this area should consider three critical dimensions of energy transition: socio-technical experimentation, urban political processes, and socio-spatial reconfiguration. Bukovszki et al. (2020) developed a technical model for energy community assessments by integrating a multi-layered approach with the Urban Building Energy Modeling (UBEM) framework, filling a significant gap in energy consumption evaluation tools at the urban planning scale. Subsequently, Frantzeskaki (2022) introduced the concepts of Social Energy Nodes (SEN) and transition management theory, applying them to the study of the sustainability of urban energy system low-carbon transitions. Current research on urban energy systems primarily centers on technological breakthroughs in quantitative assessment modeling. On one hand, simulations of the future sustainability of urban energy systems are conducted by constructing models and setting diverse future scenarios to explore potential development pathways (Turnheim et al., 2015). On the other hand, an indicator system encompassing energy, economic, social, and environmental dimensions is employed to assess regional energy transition levels and short-term dynamics (Cheung and Ossenbruegge, 2020). Moreover, a few studies have sought to investigate energy transition processes at a more micro-scale level. Cała et al. (2021) conducted an empirical study on mining towns to assess their development models and challenges, exploring the implications of green policies in such locales and evaluating the feasibility of implementing greening initiatives to foster the towns' sustainable transformation.

The Yangtze River Economic Belt (YREB) serves as a pivotal nexus for regional coordinated development and ecological civilization. As China's core economic and energy hub, the YREB bears a significant responsibility in spearheading the country's Dual Carbon targets. Spanning three major geographical regions of China, the YREB accounts for over two-fifths of the national population and economic output. However, its persistently high greenhouse gas emissions stem from a high-carbon development model and the agglomeration of chemical and dyeing industries (Zha et al., 2022; Han et al., 2024). High-level regional development conferences have underscored the need to enhance upstream-downstream energy cooperation within the YREB to facilitate transformative breakthroughs, particularly in integrating traditional energy sources with emerging renewables such as wind, solar, and hydrogen energy (Mao and Niu, 2024). Due to multidimensional heterogeneity in both geographic and socio-economic contexts, the performance of the energy system and the barriers to its optimization exhibit pronounced inconsistencies. Less-developed regions remain constrained by an excessive reliance on conventional energy sources (Sun et al., 2024). Achieving energy conservation and emission reduction while reversing the economic slowdown of the YREB is pivotal to China's long-term low-carbon development strategy and the realization of its "30·60" commitment.

The downscaling of geographical regions in energy transition assessments and the integrity of analytical frameworks remain critical challenges, both of which hinder the formation of external cognition regarding regional energy transitions. Most existing studies focus on the national scale, yet their findings reveal substantial internal heterogeneity in transition dynamics. Theoretically, while advanced economies benefit from dual advantages in innovation diffusion and specialized financing, persistent imbalances exist at the regional and sectoral levels in their transition processes (Wan et al., 2025). For instance, the European Union's *Green Deal* provides a systematic blueprint for low-carbon development; however, significant disparities remain among member states in optimizing energy structures and achieving greenhouse gas reduction targets (Bakkar et al., 2025). India, as a representative emerging economy, has made notable progress in energy transition through large-scale solar energy projects and an ambitious renewable energy strategy. Nevertheless, weak infrastructure and the generally low adaptability of regional governments to policy implementation undermine the long-term benefits of the transition (Motiwala et al., 2024). Li et al. (2022) examined Tangshan, a typical resource-based city in China, demonstrating the facilitating effect of renewable energy substitution strategies on urban energy transition and advocating for the active deployment of carbon capture and storage technologies to trade off economic costs for environmental benefits. However, quantitative studies at the urban level remain relatively scarce and lack generalizability, exacerbating the challenges of understanding the heterogeneity of energy transition across different city types and their intrinsic evolutionary logic. Meanwhile, existing assessment frameworks tend to overemphasize decarbonization of energy structures and environmental governance performance while oversimplifying—or even neglecting—the operational foundations of energy systems. Although Shen et al. (2023) made a marginal contribution to addressing these issues by focusing on demographic and innovation-related support factors, the role of targeted policies in energy transition remains unexamined. These cases underscore the necessity of refining energy transition assessments and rendering the significance of enabling endowments more explicit in technological analyses. Moreover, to accurately evaluate transition progress and map parameterized results onto local policy-making processes, it is imperative to incorporate regional inequality as a critical perspective in research.

The YREB exhibits highly differentiated urban development trajectories, offering a unique opportunity to examine energy transitions across diverse city types. This study contributes to the literature by using the YREB as a case study to evaluate urban energy transitions, providing insights applicable to other regions in China and to countries and areas with comparable socio-economic and developmental contexts. Balancing energy system performance with transition enablers, this study constructs a comprehensive evaluation framework for urban energy transition based on six dimensions: environmental pollution, energy consumption, environmental governance, resource endowment, technological innovation, and policy guidance. A quantitative assessment of the spatial-temporal evolution patterns and transition barriers further elucidates the dynamics and underlying mechanisms of energy transformation. The parameter results presented in this study offer policy implications for advancing the sustainable development of the YREB and contribute empirical evidence with regional specificity to the global discourse on energy transition.

2 Literature review

The fossil fuel-dominated energy structure has long been a key source of global greenhouse gas emissions, posing significant threats to the security of global ecosystems and economic health. This energy usage model contradicts the principles of resource efficiency and low emissions advocated by sustainable development theory, thereby making the enhancement of energy system sustainability a central issue in global energy governance. As Mishra et al. (2022) emphasize, regional-specific transformations are not only technological shifts but also entail the collaborative reconfiguration of institutions, markets, and behaviors. Under the carbon neutrality target, energy transformation is inherently a complex interaction process across technical, economic, and social dimensions, involving deep optimization of energy structures, systemic reconstruction of policy frameworks, and the accelerated dissemination of technological innovations (Shen et al., 2023). From this perspective, energy transition is not only a necessary response to climate change but also provides an opportunity for the low-carbon transformation of the economy, thereby promoting industrial restructuring and social equity.

Decarbonization of the energy structure and improvements in energy efficiency are the primary focal points of energy transformation. The United States' experience in decarbonizing its energy structure highlights the synergy between technological innovation and market mechanisms, with the rise of the electric vehicle industry serving as a global model for driving the shift toward cleaner energy consumption patterns (Min, 2025). In response to the surge in fossil fuel imports caused by nuclear accidents, the Japanese government has expanded photovoltaic applications while tapping into the potential of hydrogen technologies to build a more sustainable energy system (Assareh et al., 2025). Enhancing energy efficiency is also a critical pathway for energy transformation. The green transformation of production processes, the establishment of smart grids, and the promotion of green buildings can effectively reduce energy consumption per unit of economic output. Jiangsu Province, a major energy consumer in China, has focused on the penetration of efficient motors, waste heat recovery, and energy-saving production processes in energy-intensive industries under the guidance of its "Green Factory" initiative, with the goal of reducing energy consumption per unit of output (Rong et al., 2023). The London City Council's implementation of the Zero Carbon London program has successfully reduced building energy consumption through smart building management systems and green design standards, thereby enhancing overall energy efficiency. Simultaneously, the integration of smart grids and electric vehicle infrastructure has helped London overcome challenges related to optimizing electricity distribution and reducing energy consumption in transportation (Liu et al., 2024). Moreover, thanks to technological advancements and declining costs, renewable energies such as wind, solar, and biomass are increasingly becoming integral components of the energy structure in many regions (Fu et al., 2017). The penetration of new energy sources in societal operations not only reduces fossil energy consumption but also promotes the overall optimization of resource allocation through substitution effects and industrial upgrading (Fathi et al., 2021). It is important to note that the complexity and long-term nature of energy transformation place higher demands on governance models, particularly the coordination between regional governance actions and specialized regulatory policies.

Energy transition is profoundly linked to urban sustainable development. As hubs of economic activity and residential life, cities' intrinsic energy patterns directly influence regional and national energy structures and greenhouse gas emission levels (Xu, 2024). Advancing the optimization of energy structures, improving energy utilization efficiency, and accelerating the application of green technologies can yield multiple benefits, including industrial optimization, green economic growth, and enhanced resource utilization efficiency, while simultaneously reducing urban greenhouse gas emissions intensity. A notable example is Copenhagen, Denmark, which has achieved efficient energy system operations and balanced the relative share of energy-intensive industries and emerging sectors through the establishment of a smart energy network (Bager and Mundaca, 2017). Urban energy transition is inherently a multidisciplinary issue that intersects geography, economics, and ecology (Qiu et al., 2022; Zhao et al., 2023; Xu, 2024). Traditional economic theories posit that abundant natural resources provide a material foundation for development, while structural shifts in urban economies facilitate transitions from resource-intensive to sustainable growth modes (Gouveia et al., 2021). Industrial transitions anchored in innovation, along with the upgrading of traditional industries and the development of emerging sectors, further accelerate comprehensive urban transformations (Zhang et al., 2020). Policy interventions, human capital investments, and dynamic market environments are also pivotal to the urban transition process. Recent studies advocate for diversified approaches to urban sustainability, emphasizing optimized industrial structures, improved green total factor productivity, and enhanced low-carbon technology innovation (Sridhar et al., 2022; Abderrahim et al., 2023; Meng et al., 2024). Furthermore, the heterogeneity of urban energy transition strategies is explored as a means to achieve diversified development pathways (Deng et al., 2020).

From the perspective of energy transition assessment methods, multidimensional integrated evaluation systems and driving factor identification models are widely applied to capture the dynamic performance and key bottlenecks of regional energy transitions. Comprehensive evaluation frameworks typically include dimensions such as environmental pollution, energy structure, and government governance, which directly influence the performance of energy systems (Ma et al., 2023). Driving factor identification models provide scientific foundations for scenario forecasting and policy formulation by quantifying the impacts of potential factors on the transition process, with the econometric regression paradigm being a typical example (Zhou et al., 2024). To capture the trajectory of energy transition, spatiotemporal analysis frameworks have been incorporated into the research process. Chinese urban agglomerations provide a case reference, with energy transition levels exhibiting significant spatial agglomeration features. Cities with higher transition levels can effectively drive energy transitions in surrounding cities through technological diffusion (Shen et al., 2023). In addition to helping reveal the evolutionary differences in energy transitions across various groups, spatiotemporal analysis offers crucial insights into the spatial adaptability of policy outcomes. A study on India showed that although the development of solar parks has achieved significant success in the more economically developed western regions, technological diffusion has been impeded by lagging infrastructure development, severely limiting the actual benefits of energy transition in the central and eastern regions (Haldar et al., 2024). To foster collaborative mechanisms between member states with different energy structures and economic foundations, the European Union has built on the Green Deal, providing follow-up guarantees for the coordination and adaptability of regional policy implementation through carbon emission trading mechanisms and green finance tools (Bruch et al., 2024).

Existing research has made considerable progress in regional-level energy transition assessments, spatiotemporal feature identification, and causal inference. However, there remain notable gaps. Research at the urban level is relatively scarce, and the samples used lack broad applicability, with most existing studies relying on statistical data at the national or industry scale. Another area for improvement lies in the current static perspective on energy transition barriers, which lacks sufficient identification and discussion of the dynamic driving effects of potential factors. Furthermore, research into the heterogeneity of energy transition levels and development mechanisms across different types of cities needs to be deepened to enhance the specificity and generalizability of research conclusions.

3 Materials and methods

3.1 Construction of the energy transition index system

The urban energy transition under the "Dual Carbon" goals is a process aimed at energy substitution and comprehensive reduction of urban greenhouse gas emissions. Based on China's "3,060" policy documents and the development goals reflected in the 14th Five-Year Plan for energy at the city level, urban energy transition index (ETI) can be conceptualized as a multi-indicator comprehensive assessment, primarily focused on energy while also considering its externalities. By employing frequency analysis, this study selects key indicators from existing research on urban energy development, statistically analyzing their applicability. In addition, the "Energy Trilemma" (World Energy Council, 2024) and the energy development index proposed by the World Economic Forum (2024) were incorporated. The development of the preliminary indicator system follows principles of scientific rigor, practical operability, and future sustainability of application. Furthermore, this system was subjected to expert discussions and technical consultations, during which adjustments were made based on professional feedback, ultimately resulting in the final version of the evaluation framework.

As shown in Table 1, six primary indicators were selected to form the criterion layer of the urban energy transition evaluation system: environmental pollution (EP), energy consumption (EC), environmental governance (EG), resource endowment (RE), technological innovation (TI), and policy guidance (PG). Each primary indicator is further divided into secondary and tertiary indicators. The environmental pollution layer focuses on the scale and status of urban pollution emissions; the energy consumption layer reflects the total energy consumption, consumption structure, and efficiency; the environmental governance layer reflects investments in and effectiveness of environmental pollution control; the technological innovation layer includes support for and feedback from innovation; and the policy guidance layer evaluates the level and intensity of low-carbon energy policies. The incorporation of the resource endowment dimension into the indicator system represents a key contribution of this study, as it fundamentally shapes the structural foundation of energy production, consumption, and policy implementation, thereby serving as a critical support for the energy transition process.

TABLE 1 Urban energy transition evaluation system.

Primary indicators	Secondary indicators	Tertiary indicators	Symbol	Attribute	Unit
Environmental pollution	Pollution emissions	Industrial wastewater discharge	x1	–	10^4 tons
		Carbon emissions	x2	–	10^4 tons
		Annual average concentration of inhalable particulate matter	x3	–	μg/m^3
Energy consumption	Total consumption	Total energy consumption	x4	–	10^2 tons of standard coal
		Total electricity consumption	x5	–	10^4 kW h
		Industrial electricity consumption	x6	–	10^4 kW h
	Consumption structure	Proportion of coal consumption	x7	–	%
	Consumption efficiency	*Per capita* energy consumption	x8	–	10^2 tons of standard coal per 10^4 people
		Energy intensity	x9	–	10^2 tons of standard coal per 10^8 yuan
		Per capita electricity consumption	x10	–	kWh per person
Environmental governance	Governance investment	Energy conservation and environmental protection expenditure	x11	+	10^4 yuan
	Governance performance	Green coverage ratio in built-up areas	x12	+	%
		Comprehensive utilization rate of industrial solid waste	x13	+	%
		Industrial wastewater discharge compliance volume	x14	+	10^4 tons
		Centralized treatment rate of wastewater treatment plants	x15	+	%
Resource endowment	Resource base	Resident population	x16	+	10^4 people
		GDP	x17	+	10^8 yuan
	Economic potential	GDP growth rate	x18	+	%
Technological innovation	Innovation input	Intensity of research and development expenditure	x19	+	%
	Innovation performance	Number of patent applications	x20	+	Cases
Policy guidance	Transition policies	Intensity of command-and-control energy transition policies	x21	+	—
		Intensity of market-oriented energy transition policies	x22	+	—
		Intensity of comprehensive energy transition policies	x23	+	—

Specifically, population size influences labor supply, market potential, and energy demand, structuring the spatial dynamics of technological diffusion and industrial transformation. The total economic output directly reflects economic strength, determining the capacity for energy technology investment and infrastructure development. The growth rate of economic output serves as an indicator of economic vitality, with high-growth scenarios driving structural transformations in capital accumulation and policy adaptation, while low-growth conditions tend to sustain the inertia of regional development trajectories.

The six dimensions outlined earlier effectively capture the key aspects of energy transition, particularly the incorporation of foundational transformation factors and specific policies, which enhances the traditional assessment framework. However, it is important to recognize the inherent potential for improvement within the evaluation framework. While environmental pollution and energy consumption serve as core indicators, offering a direct reflection of energy efficiency and environmental impact during the transition process, they fail to fully account for the socio-economic complexity and regional disparities that cities face during transformation. Certain cities may encounter unique challenges in industrial structure or energy supply that cannot be adequately addressed through these existing indicators alone. Technology innovation and policy guidance are critical drivers of energy transition, but their effects are often contingent upon local government capacity, technological acceptance, and regional resource endowments, which may distort their ability to accurately reflect the actual performance of technological diffusion and policy implementation across different cities. Furthermore, the potential of renewable energy should be more accurately integrated into the resource endowment dimension in future iterations, going beyond merely considering population and economic indicators. In conclusion, while the inclusion of novel dimension layers in this study helps mitigate the shortcomings of individual indicators or incomplete information in the comprehensive assessment, future research should continue to advance technical breakthroughs and develop original datasets to improve both the precision and completeness of the evaluation framework. Indicators with discontinued publication or significant data gaps during the research period were excluded from the study. The specific indicators presented in Table 1 are continuously updated and widely applied in academic research, providing a solid foundation for the future application of this framework in assessing ongoing transformation.

3.2 Comprehensive index method

This study employs the comprehensive index method to quantify the level of urban energy transition. In practice, the first step involves standardizing the indicator data using the range-based normalization approach. The standardization process for positive and negative indicators is as follows:

$$y_{ij} = \frac{x_{ij} - x_j^{\min}}{x_j^{\max} - x_j^{\min}} \tag{1}$$

$$y_{ij} = \frac{x_j^{\max} - x_{ij}}{x_j^{\max} - x_j^{\min}} \tag{2}$$

Where y_{ij} represents the normalized value of indicator for city, and x_{ij} is the original value of indicator for city.

This study integrates the widely applied entropy method and the CRITIC method to calculate indicator weight coefficients. The entropy method objectively quantifies the information uncertainty of each indicator based on data variability, thereby minimizing subjective cognitive bias to the greatest extent possible (Dzanic and Witherden, 2022; Chen et al., 2023). The CRITIC method, in contrast, incorporates the interrelationships among indicators as a critical dimension, allowing for a more precise capture of each indicator's contribution to the overall evaluation (Wang H. J. et al., 2022). In other words, while the entropy method emphasizes the intrinsic informational properties of individual indicators without considering their interactions, the CRITIC method is inherently influenced by data distribution characteristics. Therefore, the inherent limitations of both methods can be effectively mitigated through methodological integration. Theoretically, the fusion of the entropy and CRITIC methods can be further justified within the framework of Multi-Criteria Decision Analysis, which emphasizes the simultaneous consideration of multiple interrelated evaluation factors and optimizes indicator weight allocation under the dual principles of information entropy theory and decision trade-off mechanisms (Wanore et al., 2023). Existing studies suggest that the integration of information entropy and correlation analysis maximizes information gain in weight computation for complex systems, thereby enhancing the stability of evaluation outcomes (Che et al., 2025). Accordingly, this methodological integration is theoretically grounded, ensuring data-driven objectivity while enhancing the rigor and reliability of urban energy transition assessments. Moreover, this approach offers methodological insights that may serve as a reference for future research in related domains.

3.3 Obstacle degree model

The obstacle degree model is a tool used to analyze the interaction among influencing factors within a system. It aids in identifying key obstacles and provides targeted strategies to overcome them (He and Liu, 2022; Wang H. L. et al., 2022). By clarifying the barrier factors that hinder urban energy transition, the model helps pinpoint constraints on sustainable urban development. Obstacle degrees are assessed through single-indicator and criterion-layer analyses, where the latter aggregates results from the former. The formulas used for calculating obstacle degrees are as follows:

$$I_j = 1 - Y_{ij} \tag{3}$$

In this formula, Y_{ij} represents the normalized value of a single indicator.

$$o_j = I_j \times F_j \Big/ \sum_{j=1}^{m} I_j \times F_j \tag{4}$$

In this formula, o_j denotes the obstacle degree of an individual indicator, and F_j represents the weight of the indicator. The overall obstacle degree for criterion-layer indicators is calculated as:

$$O_j = \sum o_j \tag{5}$$

In this formula, O_j is the obstacle degree for a specific criterion layer.

3.4 Study area and data source

This study focuses on 107 cities within the YREB as defined by the *Outline of Yangtze River economic belt development*. Cities were selected based on representativeness and the availability of relevant data (Figure 1).

Since China has experienced more profound regional transformation trends post-2010, particularly within the YREB, this study focuses on the changes within YREB from 2010 to 2020. This study selects data from three time points—2010, 2015, and 2020—based on the following considerations. First, existing research suggests that urban transition processes often exhibit long-term characteristics, and the precise identification of transition states requires a sufficiently extended observation window (Zhou et al., 2025). Second, the dynamics of energy transition are jointly influenced by policy cycles, industrial restructuring, and technological diffusion (Gao et al., 2022). A five-year interval, as a typical policy evaluation window, helps mitigate the interference of

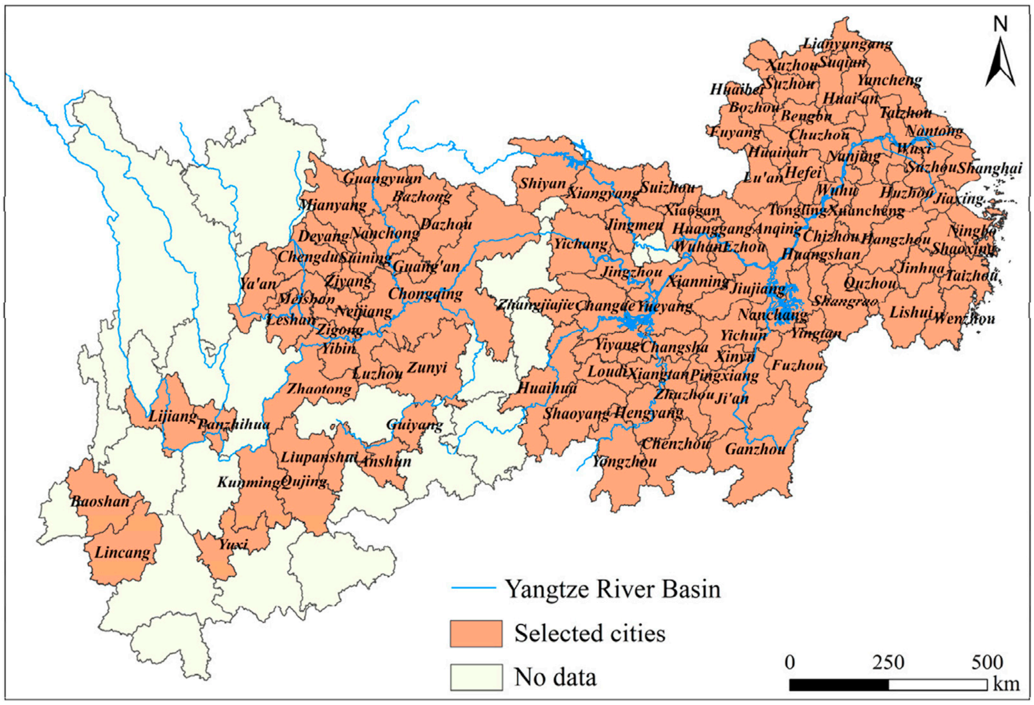

FIGURE 1
Overview of the study area.

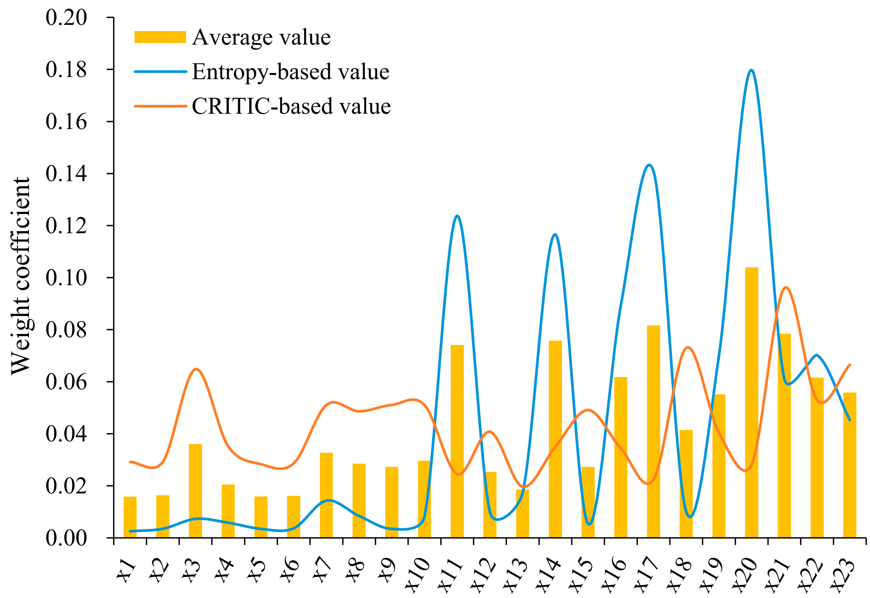

FIGURE 2
Results of indicator weights.

short-term fluctuations, thereby facilitating the identification of structural transition trends. Third, data availability and consistency are critical to the robustness of time-series analysis. A five-year interval ensures data completeness and comparability, thereby enhancing measurement accuracy. Accordingly, the selection of time points in this study aligns with both theoretical understandings of urban transition and the logic of policy practice, ensuring the scientific rigor and robustness of the analysis while balancing data availability and the need to capture dynamic evolution. The majority of the primary data used in this study is sourced from the China Energy Statistical Yearbook, China City Statistical Yearbook, China Environmental Statistical Yearbook,

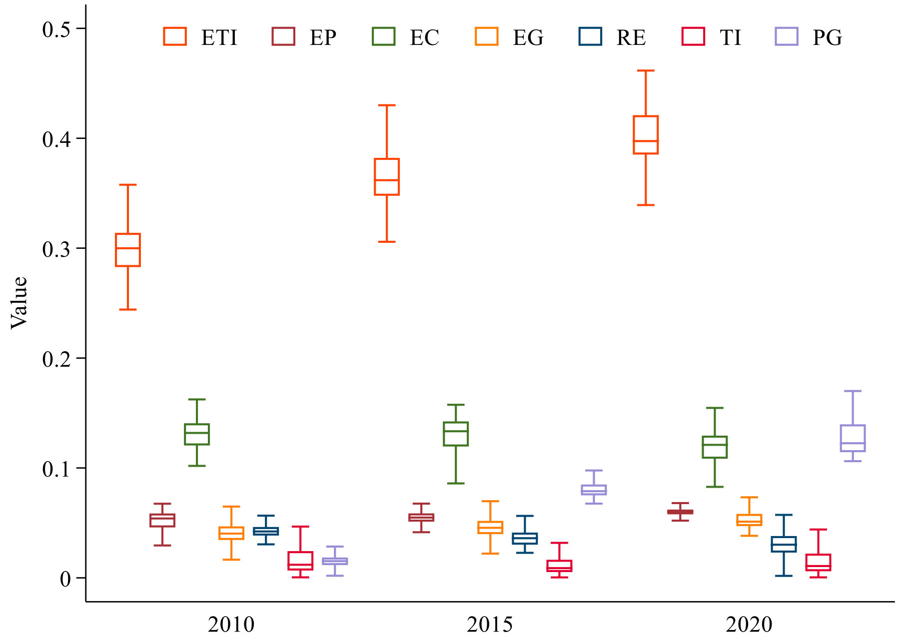

FIGURE 3
Box-whisker distribution of Urban ETI and its components.

China Electric Power Statistical Yearbook, and publicly available government reports on social development. Carbon emission data was obtained from the publicly available projects of the China Urban Greenhouse Gas Working Group. The low-carbon policy intensity indicator was derived using the framework and calculation procedures established by Dong et al. (2024). For missing data within individual cities, linear interpolation was applied to fill the gaps. In the case of rare but objectively present instances where data for certain indicators were entirely missing for specific cities over the study period, the hot deck imputation method was employed.

4 Results and discussion

4.1 Indicator importance evaluation

The weight coefficients of indicators are shown in Figure 2, with the criterion-layer indicators ranked in the order of importance as, EG > PG > RE > EC > TI > EP. This ranking highlights the critical roles of environmental governance in shaping urban ETI levels. Specialized energy policies and resource endowments have often been overlooked in previous studies (Hoeben and Posch, 2021; Liao and Li, 2022; Opoku et al., 2024), despite contributing 19.59% and 18.50%, respectively, to the overall ETI calculation. This underscores the critical role of transformational support in urban energy transitions.

4.2 Temporal characteristics of urban ETI

The development and internal disparities of the criterion layer of urban ETI are illustrated in Figure 3. During the baseline period of the study, the energy consumption status played a leading role in the development of the ETI. However, from 2015 onwards, this role was increasingly supplanted by the intensity of policy implementation. Over the 10-year period, the development levels of environmental pollution, environmental governance, and policy guidance have all improved, positively correlating with urban energy transition performance. Energy consumption, resource endowment, and technological innovation, however, are the criterion layers to show a decline in its development level, and it exhibits a negative correlation with urban energy transition performance. In recent years, the Chinese government has promulgated and implemented a series of policy initiatives to reinforce the policy-driven momentum for the region's cities to transition towards low-carbon and resource-conserving development models. Under the influence of these policies, the status of urban energy systems, environmental governance, and transition support systems has undergone significant transformation, with urban energy transition activities advancing steadily. For example, cities with more developed economies, such as Suzhou, have leveraged industrial diversification adjustments and stricter environmental regulations to support their ecological development.

The equilibrium state of transformation levels serves as an external manifestation of the effectiveness of regional resource allocation. Quantifying regional inequalities in urban energy transitions helps identify potential structural issues. This study employs the Gini coefficient to measure the uneven characteristics of transformation performance and decomposes it for analysis (Figure 4). The overall Gini coefficient (G) initially declined before rising, from 0.0584 in 2010 to 0.0567 in 2020. This suggests that while the energy transition in the YREB region has made overall progress, regional disparities have somewhat diminished. Concurrently, the intra-group disparity coefficient (Ga), calculated based on provincial administrative divisions, decreased from 0.0056 in 2010 to 0.0044 in 2020, indicating a

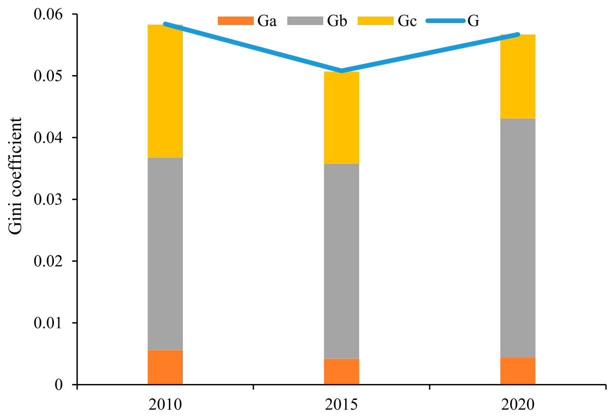

FIGURE 4
Gini coefficient of the Urban ETI.

reduction in the energy transition disparity within provinces. This phenomenon reflects the relative equilibrium of cities within provinces in terms of resources, policies, and population mobility. On one hand, the coordinated development of major urban clusters within provinces has promoted spillover effects in regional central cities, helping to narrow the transformation gaps between cities. On the other hand, the coordination of local governments in the allocation of public resources and industrial layout has also alleviated intra-provincial transformation imbalances to some extent. In contrast, the inter-group disparity coefficient (Gb) has shown an increasing trend, indicating a significant widening of energy transition gaps between provinces. Differences in resource endowments, economic foundations, and policy support across provinces result in divergent dynamics and patterns of energy transition. This finding reveals that although overall disparities in the YREB region are narrowing, structural issues in local development remain prominent, particularly as the transformation potential of underdeveloped provinces has yet to be fully realized, necessitating further attention to inter-regional imbalances. The super-variance density (Gc), reflecting the interaction between intra-regional and inter-regional disparities, has consistently declined over the study period, indicating a relatively favorable linkage between internal and external factors in the energy transition over the past decade.

The top 40 cities based on urban ETI values, both for cross-sectional and overall study periods, are presented in Figure 5. The results indicate that municipalities directly under the central government and regional economic hub cities consistently rank highest in terms of ETI levels. This suggests that cities with higher political status and economic development are at more advanced stages of energy transition compared to other cities. These types of cities are often prioritized as pilot areas for national strategies, benefiting from increased fiscal support and access to technological resources, which in turn facilitates the optimization of regional energy structures and the application of low-carbon technologies. The capital accumulation and market vitality stemming from economic strength also provide a foundation for green investment and renewable energy development. The inter-city transition gap in high-ETI cities is notably significant. For instance, the ETI gap between the top-ranking and tenth-ranking cities increased from 0.102 in 2010 to 0.246 in 2020. In summary, cities with high ETI levels have continued to develop throughout the study period, particularly those cities that have benefited from favorable policy support and optimal resource allocation.

4.3 Spatial characteristics of urban ETI

Based on the natural breaks method and the average ETI values of sample cities over the study period, this study classifies urban ETI

2010	Chongqing	Chengdu	Nanjing	Suzhou	Shanghai	Hangzhou	Wuxi	Mianyang	Nantong	Changsha
	0.458	0.428	0.396	0.378	0.376	0.374	0.373	0.363	0.358	0.356
	Wuhan	Hefei	Shaoxing	Taizhou	Nanchang	Zhenjiang	Deyang	Changde	Yancheng	Changzhou
	0.355	0.353	0.335	0.328	0.327	0.325	0.325	0.323	0.322	0.320
	Jingdezhen	Dazhou	Xiangyang	Wenzhou	Yingtan	Wuhu	Yibin	Zhuzhou	Kunming	Ningbo
	0.319	0.319	0.318	0.317	0.317	0.315	0.314	0.314	0.314	0.313
	Hengyang	Bazhong	Jingmen	Zigong	Shiyan	Zunyi	Suining	Shangrao	Ziyang	Yueyang
	0.313	0.313	0.313	0.312	0.312	0.311	0.310	0.310	0.308	0.308
2015	Chongqing	Shanghai	Suzhou	Chengdu	Hangzhou	Wuxi	Nanjing	Wuhan	Nantong	Hefei
	0.543	0.518	0.486	0.481	0.476	0.453	0.449	0.436	0.430	0.413
	Yancheng	Changsha	Changzhou	Taizhou	Zhenjiang	Ningbo	Shaoxing	Mianyang	Huai'an	Wenzhou
	0.410	0.406	0.404	0.396	0.395	0.395	0.394	0.392	0.389	0.388
	Suqian	Nanchang	Yangzhou	Yichang	Xuzhou	Deyang	Changde	Lianyungang	Kunming	Jiaxing
	0.387	0.386	0.384	0.384	0.383	0.383	0.382	0.378	0.377	0.377
	Yibin	Xiangyang	Ganzhou	Zunyi	Suining	Jingmen	Luzhou	Bazhong	Jingdezhen	Huzhou
	0.373	0.373	0.373	0.373	0.372	0.371	0.371	0.370	0.369	0.368
2020	Shanghai	Chongqing	Hangzhou	Suzhou	Chengdu	Nanjing	Wuhan	Wuxi	Hefei	Nantong
	0.706	0.599	0.574	0.574	0.531	0.527	0.521	0.500	0.462	0.460
	Changzhou	Changsha	Ningbo	Yichang	Xuzhou	Mianyang	Yancheng	Shaoxing	Yangzhou	Taizhou
	0.457	0.456	0.456	0.456	0.445	0.445	0.434	0.434	0.433	0.432
	Wenzhou	Suqian	Yibin	Ganzhou	Xiangyang	Kunming	Nanchang	Zhenjiang	Huai'an	Zigong
	0.429	0.429	0.426	0.424	0.423	0.421	0.421	0.420	0.420	0.420
	Luzhou	Jiaxing	Lianyungang	Jingzhou	Shiyan	Suining	Guiyang	Taizhou	Zunyi	Huzhou
	0.419	0.417	0.416	0.414	0.413	0.412	0.412	0.409	0.409	0.409

FIGURE 5
List of the top 40 cities by ETI level.

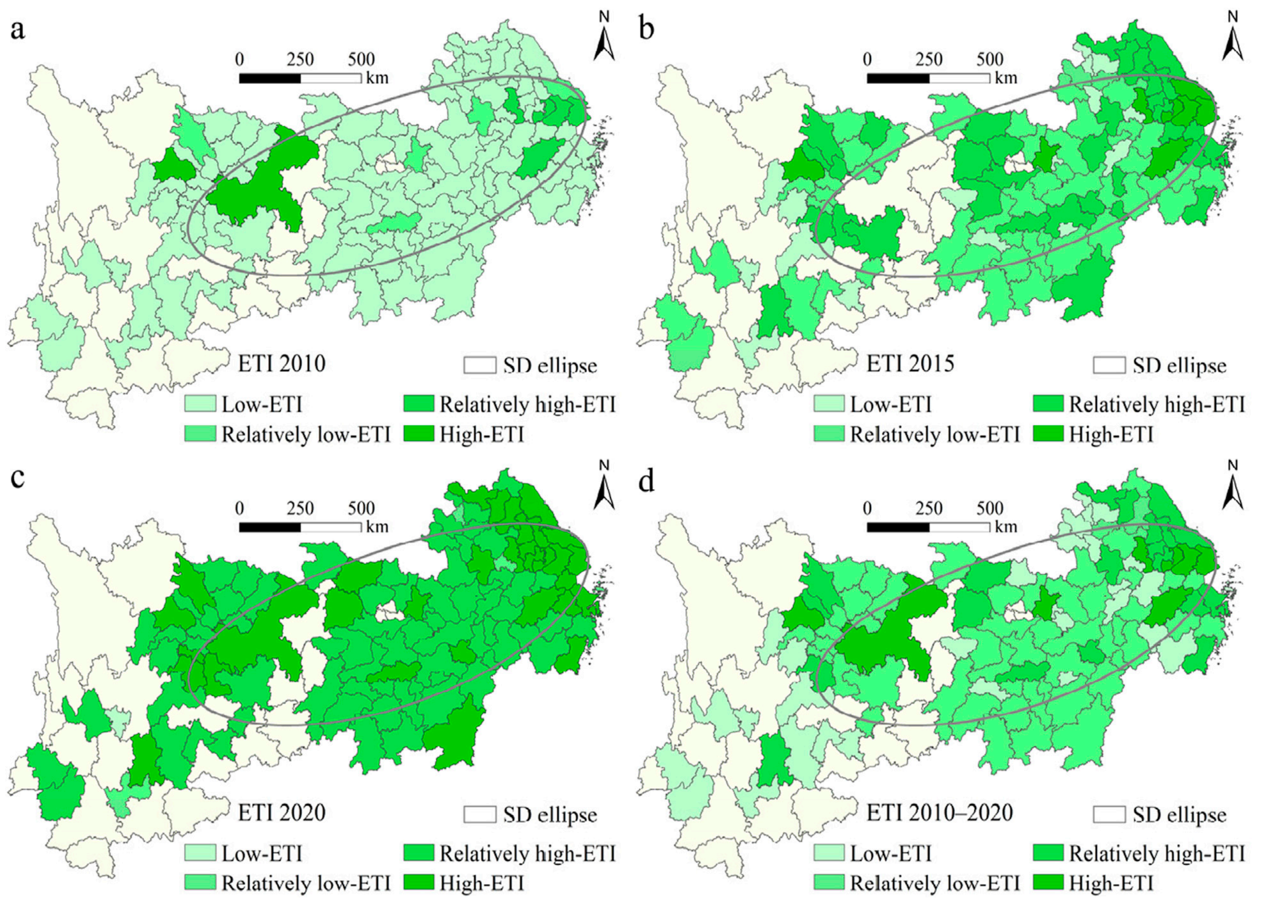

FIGURE 6
Spatial distribution and evolutionary characteristics of Urban ETI. **(a)** ETI 2020 **(b)** ETI 2015 **(c)** ETI 2020 **(d)** ETI 2010-2020.

levels into four distinct tiers and visualizes the results (Figure 6). The findings reveal that in 2010, a high-ETI cluster existed in the lower reaches of the Yangtze River, and Chongqing's ETI significantly higher than that of surrounding cities. The geographical distribution of urban ETI at this time closely mirrored the overall status throughout the study period, indicating the advanced energy transition of cities in the Yangtze River Delta region. From 2010 to 2015, most cities showed improvements in their ETI, particularly those in the midstream region of the Yangtze River. However, geographical differentiation in ETI values remained relatively distinct. By 2020, as the majority of cities achieved the highest or second-highest ETI levels, the spatial heterogeneity of ETI distribution in the study area had diminished. Low-ETI cities were predominantly located in the upper reaches of the Yangtze River, such as Panzhihua, Zhoushan and Maanshan City. These changes were influenced by a combination of policy orientation, regional catch-up effects, economic development disparities, and resource endowments. The Yangtze River Delta and Chongqing maintained their leading positions in the transition due to policy and economic advantages, while central cities rapidly caught up through resource integration and technology adoption. In contrast, some western cities lagged in energy transition progress due to insufficient infrastructure and limited resource endowments. Ultimately, the spatial differentiation of urban ETI gradually weakened, with the distribution shifting from a core-periphery mode to a more balanced distribution. The level of urban energy transition within the YREB exhibits clear regional inequalities, a finding that is consistent with research conducted in other regions. For instance, the development of solar energy parks has significantly accelerated energy transition in Western India, whereas it has had minimal impact in the infrastructure-poor central and eastern regions (Haldar et al., 2024). Similarly, despite the existence of the European Green Deal, substantial disparities in energy transition processes persist across EU member states, shaped by variations in energy structures and economic foundations (Bruch et al., 2024).

The results of the global and local spatial autocorrelation tests for urban energy transition are presented in Figure 7. Over the study period, the intensity of global spatial autocorrelation for urban energy transition has increased and consistently remained significant at the 1% level, indicating a strong spatial dependence of the energy transition status within the YREB. The positive value of the statistic further suggests that this spatial dependence is positive in nature. Local significant clusters predominantly consist of high-high clusters, followed by low-low clusters, with relatively fewer low-high and high-low clusters, reflecting the uneven pattern of energy transition. Coastal cities in the eastern region with high energy transition values gradually extend their developmental advantages to

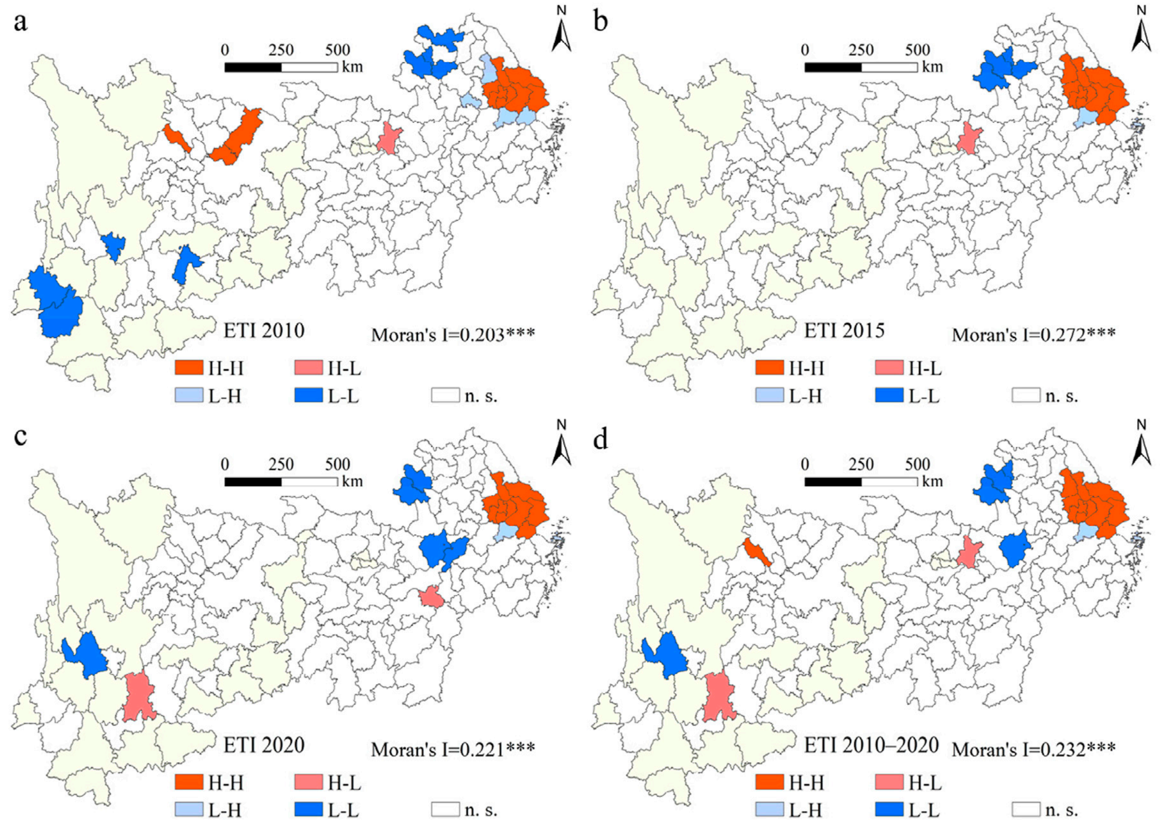

FIGURE 7
Spatial autocorrelation of Urban ETI. **(a)** ETI 2020 **(b)** ETI 2015 **(c)** ETI 2020 **(d)** ETI 2010-2020.

surrounding cities, forming relatively stable high-value city clusters. High-high significant clusters in Shanghai, Suzhou, and Nantong are consistently present in each cross-sectional time point, which aligns closely with the spatial distribution structure of energy transition. Benefiting from policy support, several key cities in the central and western regions have also started to play a significant role in the energy transition process, exhibiting a local phenomenon of adjacent high and low energy transition values.

4.4 Heterogeneity of ETI based on city types

This study conducts a comprehensive comparative analysis of urban ETI development across four dimensions: geographical region, urban size, energy transition level, and the developmental stages of resource-based cities. Cities are grouped based on their geographical regions into eastern, central, and western cities, with corresponding codes A1–C1; based on population size, they are categorized into large, medium, and small cities, with codes A2–C2; based on transition levels, cities are classified into high-ETI, relatively high-ETI, relatively low-ETI, and low-ETI, with codes A3–D3; and based on developmental stages, resource-based cities are grouped into growing, mature, declining, and regenerating cities, with codes A4–D4. The visualized results of urban ETI value grouping are shown in Figure 8.

The ETI levels of eastern cities are relatively high and exhibit a stable growth trend, primarily attributable to their well-developed infrastructure, advanced industrialization, and robust economic foundations. These cities benefit from greater support for technological innovation and favorable policy interventions, which collectively foster the progress of energy transition. In contrast, the ETI levels of central cities lag behind, largely due to the region's continued reliance on traditional industries, limited industrial diversification, and weaker links to external markets and technological advancements, which slow down the energy transition process. Western cities consistently exhibit the lowest ETI values, owing to the region's delayed economic development, reliance on traditional energy structures, and dependence on high-polluting and inefficient energy forms such as coal. Despite recent policy efforts, the vast geography, underdeveloped infrastructure, and scarcity of skilled labor and technological resources pose significant challenges to energy transition in the western region. When analyzed from the perspective of urban scale, large cities outperform smaller ones in terms of energy transition performance, with regional economic hubs such as Nanjing and Wuhan standing out. These cities not only dominate in economic output but also have greater access to policy support, technological innovation, and financial resources, enabling them to effectively drive energy transition. In contrast, medium-sized cities experience steady but slower progress in their energy transition activities, as they face relative shortages of resources, technological capabilities, and policy support. Small cities, due to insufficient financial resources, technical expertise, and industrial foundations, exhibit the lowest ETI values and face more significant challenges in the transition process. Across the annual cross-

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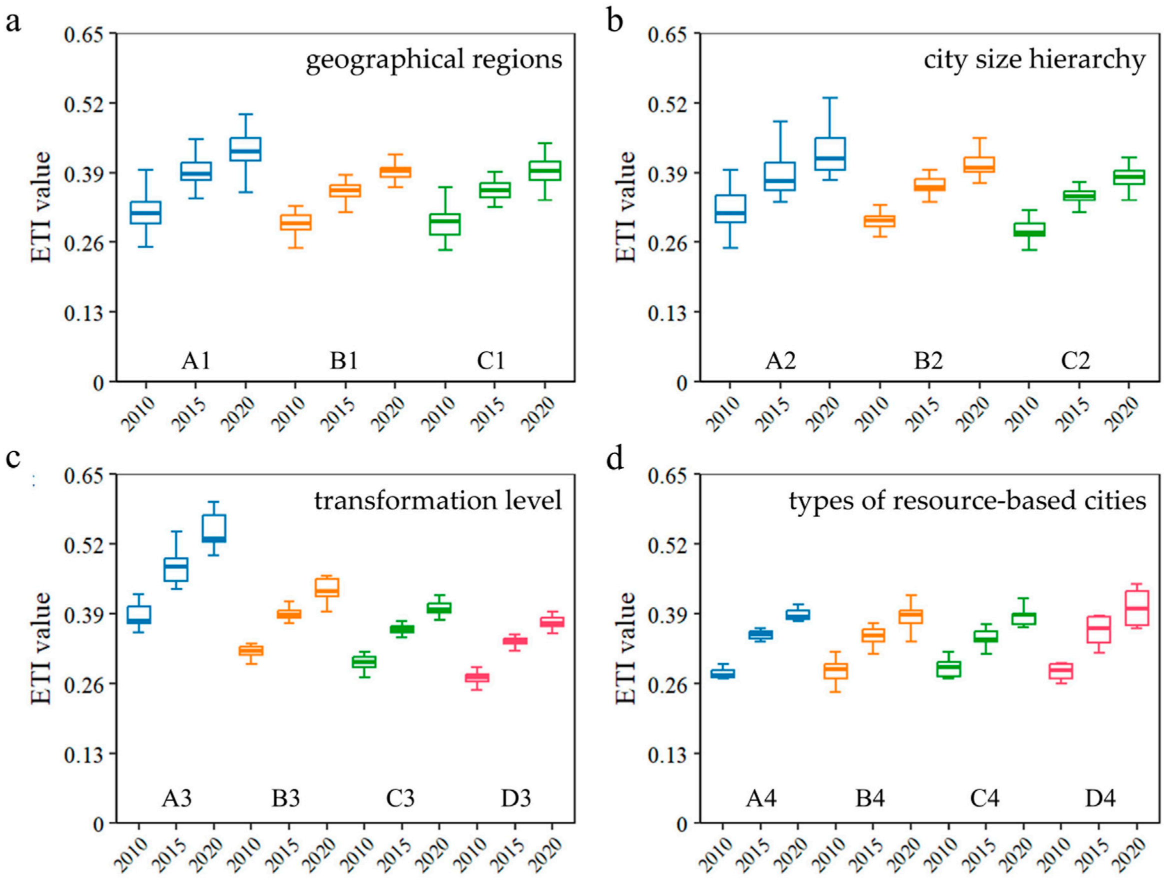

FIGURE 8
ETI levels based on city type grouping. **(a)** geographical regions; **(b)** city size hierarchy; **(c)** transformation level; **(d)** type of resource-based cities.

sectional data, the energy transition levels of high-ETI, relatively high-ETI, relatively low-ETI, and low-ETI cities show a gradual decline, indicating a relatively stable internal ETI ranking structure within the sample. This trend reflects the path dependence and inertia experienced by different cities in the energy transition process. Despite varying stages of development and differing transition speeds, the direction and general pace of transformation remain consistent across these cities. The disparities in ETI values between resource-based cities are relatively small, particularly in 2010, when declining cities exhibited higher ETI values, and mature and regenerating cities had similar levels, while emerging cities lagged in transition performance. However, since 2015, regenerating cities have seen a rapid rise in ETI, widening the gap with mature cities. This shift can be attributed to the reduction in resource dependence, industrial structure optimization, and the adoption of proactive green transformation strategies in regenerating cities. These cities have become pioneers in energy transition by fostering innovation, strengthening environmental policy enforcement, and upgrading industries.

These findings reveal that cities within the YREB are influenced by a complex interplay of geographical location, urban scale, resource dependence, and industrial structure, resulting in differentiated transition pathways and outcomes.

4.5 Identification of barrier factors impeding urban ETI improvement

The obstacle degree values for various indicators were calculated using the obstacle factor model to identify the primary contributing factors and offer targeted recommendations to enhance urban ETI levels. Environmental governance, resource endowment, and policy guidance constitute the three primary barriers to urban energy transition. Within the entire sample, the contributions of environmental governance, resource endowment, and policy guidance to the resistance of the transition are 20.64%, 18.75%, and 18.34%, respectively. The high associated with environmental governance highlights the significant challenges of pollution control and ecological restoration, particularly in cities with a heavy industrial base, where governance pressures are especially pronounced. The obstacle degrees of energy consumption and technological innovation rank fourth and fifth, each at approximately 17.60%, indicating that the optimization of energy consumption structures and advancements in technological innovation remain critical constraints to energy transition. Notably, the relatively low obstacle degree of environmental pollution across the six dimensions signals a positive development, suggesting that progress in this area may provide further support for the transition process.

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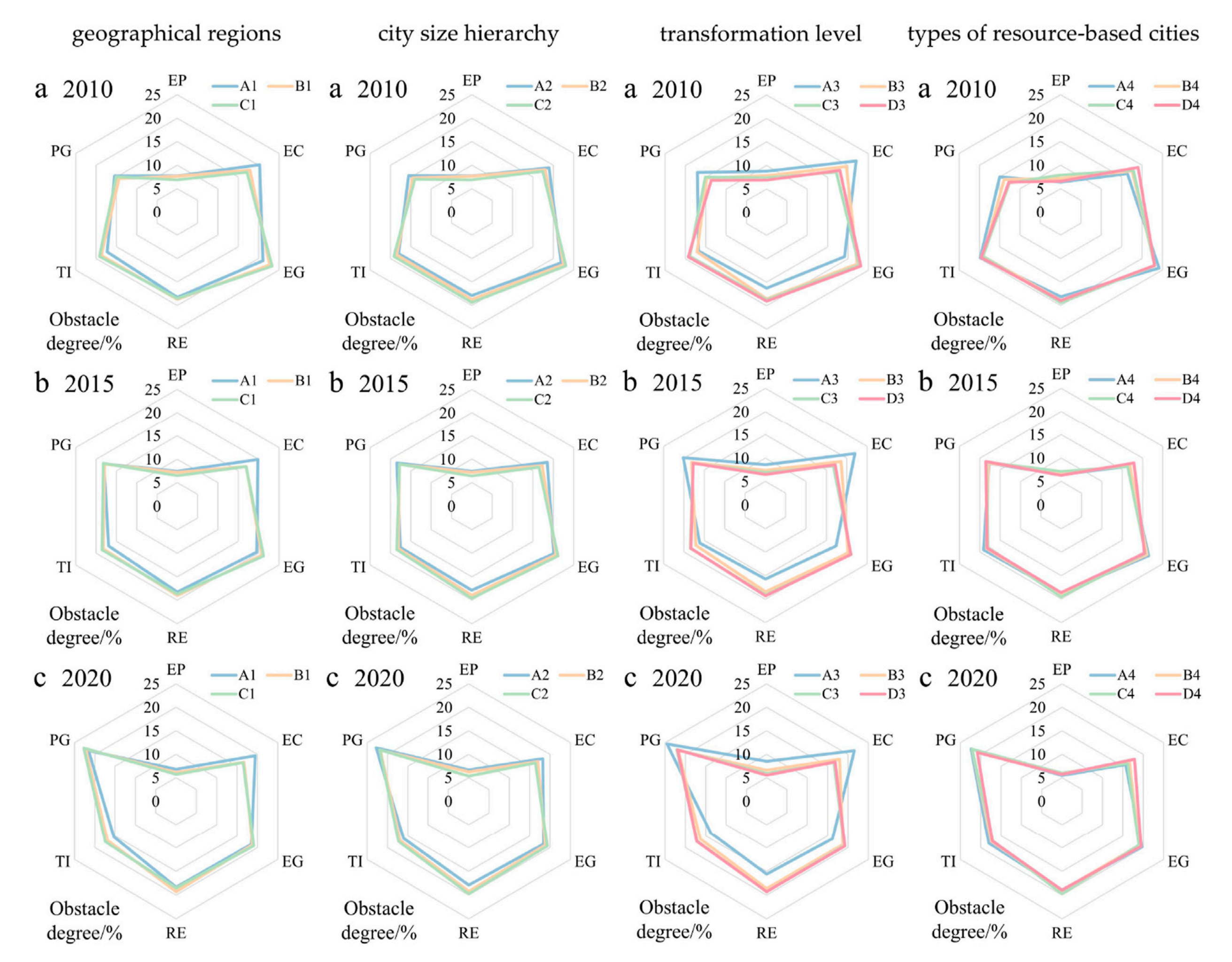

FIGURE 9
Obstacle degree of primary indicators based on city type grouping.

The results of the barrier factor assessment based on urban typology are illustrated in Figure 9. The factors ranked in the top two positions for barrier severity are defined as key barriers.

Based on the geographical grouping, energy transitions in eastern cities are primarily constrained by environmental management and energy consumption. Eastern cities typically possess a strong industrial base and high energy consumption demands, which impede the progress of energy transitions. Specifically, despite policy guidance on pollution control, traditional industries and high-carbon energy structures continue to dominate, resulting in high governance costs. In central and western cities, the primary constraints in 2010 and 2015 were environmental management and resource endowments. However, by 2020, policy guidance and resource endowments became more prominent, reflecting the increasing role of policy guidance in the central region. For eastern cities, policies should focus on enhancing support for clean energy technologies and facilitating structural changes in energy consumption, particularly in high-pollution industries and heavy industries. The government should promote technological upgrades in traditional energy enterprises through tax incentives and green credit, driving pollution control. Funding should prioritize green technology research and development, as well as green infrastructure construction, to promote the implementation of clean energy projects. In central and western cities, policies should focus on strengthening policy guidance and supporting resource endowments. The government should optimize resource allocation, foster the development of green industries, and provide fiscal subsidies and low-interest loans to support local enterprises' low-carbon transitions. Funding should be concentrated on improving energy efficiency and advancing clean energy development projects.

Large cities face dual challenges of environmental management and energy consumption during their energy transitions. Despite having advantages in terms of funding and technology, high-energy consumption patterns remain the primary constraint. Transforming energy consumption structures, especially in the sectors of buildings, transportation, and industry, is a key focus in current policies. For medium-sized cities, environmental management and resource endowments are the primary obstacles, and over time, policy guidance gradually becomes a more prominent constraint. Small cities exhibit similar trends to medium-sized cities, relying primarily on policy guidance and resource endowments to address energy transition issues. For large cities, policies should increase support for green technologies, particularly in promoting energy efficiency in the building and transportation sectors. The government should set stringent energy consumption standards to optimize traditional energy structures. Funding should prioritize investments in smart grid infrastructure, electric transportation systems, and green building initiatives. For medium-sized and small cities, policies should emphasize strengthening policy guidance, encouraging local governments to develop implementation details that align with national energy policies. Funding should prioritize resource-saving and green technology projects, helping these cities achieve low-carbon transitions, particularly in energy efficiency and clean energy applications.

The barriers to energy transitions exhibit clear differences across cities with varying transformation levels. For high-ETI cities, energy consumption and environmental management are the primary obstacles, with the role of policy guidance gradually increasing over time. For relatively high-ETI cities, environmental management and energy consumption were particularly significant in 2010 and 2015, and by 2020, the barrier of policy guidance became more apparent. For relatively low-ETI cities, environmental management and resource endowments were the main constraints in the early stages, with policy guidance becoming more effective in the later stages. Low-ETI cities demonstrate significant temporal heterogeneity in their barriers, with the relative importance of policy guidance and environmental management shifting across different time periods. For high-ETI cities, policies should focus on accelerating the application and promotion of clean energy technologies while advancing the green transformation of industrial structures. The government should incentivize companies to reduce carbon emissions and improve energy efficiency through tax credits and green credit. Funding should prioritize enhancing green technology innovation and facilitating low-carbon transitions in traditional industries. For relatively high-ETI cities, policies should strengthen the role of policy guidance through the formulation of regional policies and incentive mechanisms to optimize energy consumption. Funding should be directed toward improving energy efficiency and accelerating technological innovation in industries. For relatively low-ETI and low-ETI cities, policies should focus on resolving resource endowment issues and promoting low-carbon industrialization through technological innovation. Funding should prioritize infrastructure construction and technological innovation, ensuring these cities can achieve green transformation targets in the short term.

For resource-based cities, the transformation barriers of growth-type, mature-type, declining-type, and regenerated-type cities exhibit different characteristics. Growth-type cities faced obstacles in environmental management and technological innovation in 2010. As the transformation deepened, mature-type and declining-type cities saw their obstacles shift to resource endowments and environmental management. The obstacles in regenerated-type cities gradually shifted to policy guidance and environmental management, reflecting progress in reducing resource dependence and adjusting industrial structures. For growth-type cities, policies should primarily support technological innovation, particularly in green and environmental technologies. The government should provide innovation funding to support the research and promotion of green technologies. Funding should prioritize clean energy projects and the application of low-carbon technologies. For mature-type cities, policies should focus on promoting industrial structural transformation, strengthening green guidance for resource-based industries, and supporting the clean transformation of traditional energy sectors. Funding should support industrial upgrading and the promotion of green technologies to facilitate low-carbon transitions in resource-based cities. For declining-type cities, policies should focus on the effective utilization of resources and ecological restoration, promoting transformation through green infrastructure construction and industrial restructuring. Funding should support environmental restoration and ecological protection projects while attracting foreign capital and technology to foster green development. Regenerated-type cities should place greater emphasis on policy guidance and environmental management, with funding primarily directed toward supporting green infrastructure and regeneration projects in green industries.

The identification of influencing factors at the tertiary indicator level is presented in Figure 10. The highest OD value indicators corresponding to environmental pollution, energy consumption, environmental governance, resource endowment, technological innovation, and policy guidance are annual average concentration of inhalable particulate matter, *per capita* electricity consumption, energy conservation and environmental protection expenditure, GDP, number of patent applications, and intensity of market-oriented energy transition policies, respectively. This conclusion is largely applicable across various city types.

In the geographical regions grouping, industrial wastewater discharge compliance volume emerges as the key obstructive factor for western cities within the environmental governance dimension. In the city size hierarchy grouping, deviations from the overall findings are concentrated in the energy consumption and environmental governance dimensions. Specifically, in the former, large cities are more significantly influenced by the proportion of coal consumption, whereas in the latter, industrial wastewater discharge compliance volume plays a decisive role in shaping the transition trajectory of small cities. Under the transformation level grouping, the heterogeneity of OD values is evident in the energy consumption and policy guidance dimensions. For relatively low-ETI cities and low-ETI cities, proportion of coal consumption warrants greater attention than *per capita* electricity consumption within the energy consumption dimension. For high-ETI cities, comprehensive energy transition policies outweigh market-oriented energy transition policies as the more critical policy-related factor. Similar to the findings from the geographical regions grouping, within resource-based cities, the energy consumption patterns of growing cities and mature cities are predominantly driven by the proportion of coal consumption. Moreover, except for declining cities, the enhancement of the environmental governance dimension across the other three resource-based city types is more reliant on improvements in industrial wastewater discharge compliance volume. Overall, the parameter results at the tertiary indicator level provide deeper insights into the driving factors of energy transition in YREB cities, reinforcing the practical necessity of assessing energy transition and designing transition pathways through the lens of regional heterogeneity.

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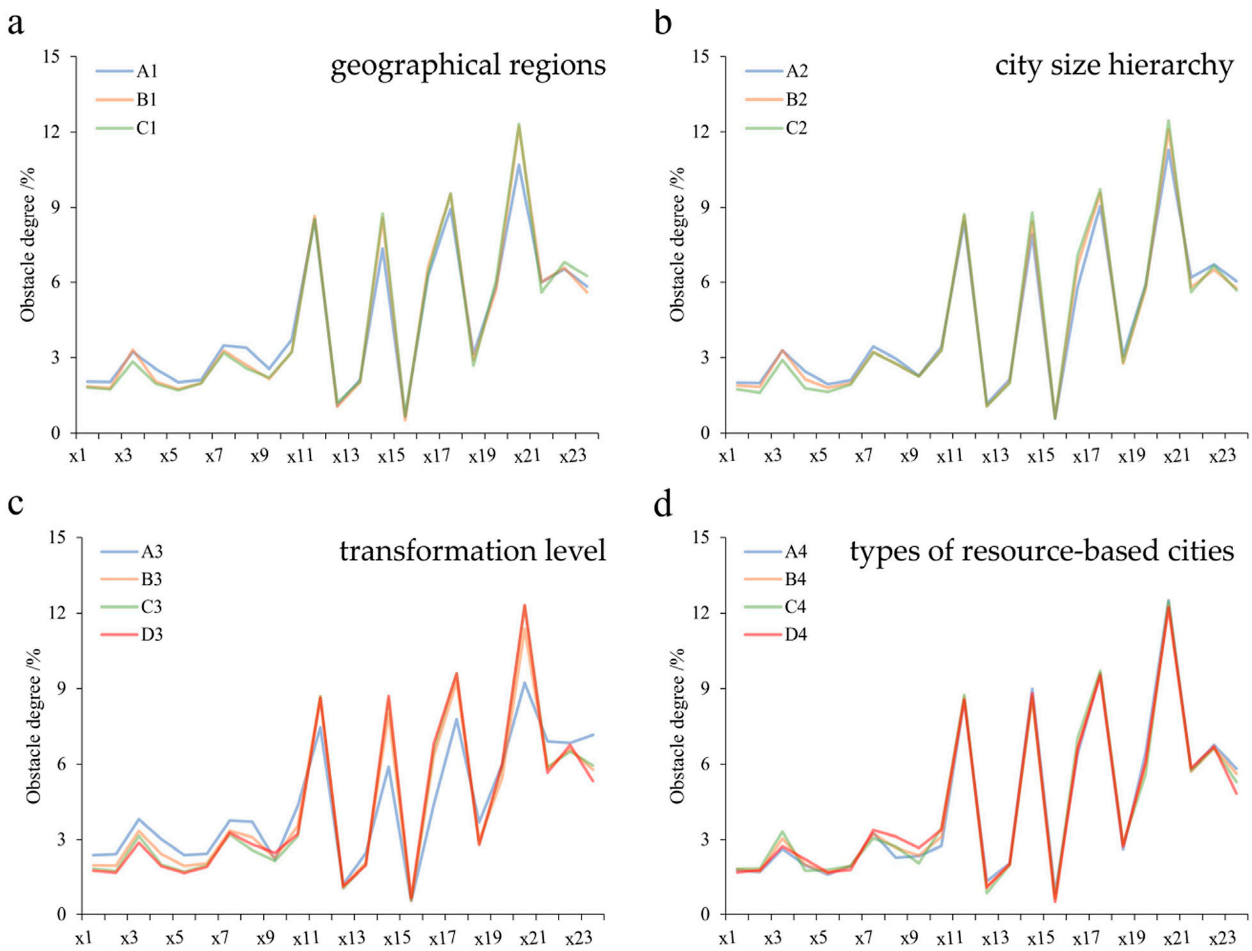

FIGURE 10
Obstacle degree of tertiary indicators based on city type grouping. **(a)** geographical regions; **(b)** city size hierarchy; **(c)** transformation level; **(d)** type of resource-based cities.

5 Policy and managerial implications

Policy guidance has gradually become the primary obstacle to urban energy transitions by the end of the study period, with this trend becoming evident as early as 2015. This shift reflects the central role of policy in driving energy transitions. Insufficient or poorly implemented policies have become key factors hindering energy transformation. Future policy interventions should focus more on institutional development and the effectiveness of policy implementation, strengthening differentiated policy support for different types of cities, especially resource-based and small- and medium-sized cities, to provide more targeted policy guidance and financial support. The cities within the YREB face distinct challenges and barriers in their energy transition processes due to variations in their economic development stages, industrial structures, and resource endowments. This section provides a comprehensive analysis of the multidimensional obstacles encountered during urban energy transitions and offers policy intervention directions to address these challenges.

As the most economically developed region, Eastern cities exhibit substantial energy consumption demands alongside significant environmental pollution pressures. Policies should further strengthen regulation of high-pollution industries by implementing stricter emission standards and environmental taxation systems to promote the cleaner transformation of traditional energy industries. Additionally, the establishment of green development funds could support the research and application of environmental technologies, thereby reducing pollutant emissions. These policies hold high applicability in other industrialized regions globally, such as major urban clusters in Europe and North America. In the central region, key obstacles to energy transition have shifted from environmental management and resource endowment to policy guidance. Policy efforts should focus on promoting the development of green industries and optimizing resource allocation. This can be achieved by implementing preferential policies to encourage investment and growth in low-carbon, green industries. Simultaneously, local governments should consider ecological carrying capacity when allocating resources, avoiding excessive reliance on traditional resource-based industries. Policies in the central region may also be relevant to resource-rich but economically underdeveloped areas, such as Southeast Asia and Latin America, which are similarly grappling with the challenge of transitioning from resource-dependent economies to green, low-carbon models. Western cities face key challenges in improving the effectiveness of policy guidance and constructing adaptable, technologically advanced green energy infrastructure. For these cities, governments should increase policy efforts and encourage local governments to develop more specific energy transition policies. Leveraging local resource advantages, the development of clean energy industries can gradually replace traditional high-pollution energy sectors. The experiences of Western cities in policy guidance and green infrastructure construction offer valuable insights for other developing economies, such as those in Africa and South Asia, where similar challenges of resource-based industry transitions and weak energy infrastructure exist.

Large cities typically encounter substantial energy consumption demands and significant environmental management pressures, requiring technological innovations and managerial strategies to optimize energy consumption structures and reduce carbon emissions. Policies should increase support for low-carbon technologies and clean energy projects, particularly in high-energy consumption sectors such as construction and transportation. Stricter energy efficiency standards should be established to guide society and businesses in implementing energy-saving and emission-reducing technologies, thus driving a gradual transition to green energy consumption. Such policies are also applicable to large cities with high energy demand and significant pollution challenges in other global regions, such as urban clusters in North America and Europe. In resource-limited and structurally homogeneous medium and small cities, the key challenge lies in how to drive energy transitions within limited resources. Medium and small cities should implement tailored energy transition pathways based on their unique resource endowments and prioritize the development of renewable energy projects suitable for local conditions. These policies can also be applied to small cities in emerging market economies.

For high-ETI cities, energy transition obstacles primarily relate to energy consumption and policy guidance, while low-ETI cities exhibit significant temporal heterogeneity in their barriers. The policy needs of these two categories of cities differ substantially during their transitions. For high-ETI cities, policies should focus on enhancing energy efficiency, fostering low-carbon technological innovation, and optimizing the existing energy consumption structure. By strengthening policy guidance, more low-carbon technologies and green industries should be promoted in the market. For low-ETI cities, policies should emphasize addressing resource endowment and environmental management issues, with an increased focus on technological innovation to gradually facilitate the transition to a green, low-carbon development model. Policy recommendations for high-ETI and low-ETI cities can be flexibly adjusted in other industrialized or emerging economies, particularly in regions where clear differences exist between urban energy consumption and policy guidance.

Resource-based cities face diverse barriers in their energy transitions but generally struggle with transitioning from resource-dependent industries to green, low-carbon sectors. Governments should use green finance, tax incentives, and other measures to support the transformation of resource-based cities into green, low-carbon industries, particularly in the fields of new energy and environmental protection industries. Strengthening environmental governance in resource-based cities to reduce pollution during resource extraction, along with promoting environmental restoration and green infrastructure development, is essential. The transition pathways of resource-based cities provide valuable lessons for other resource-dependent regions, especially in resource-based economies such as those in the Middle East, Africa, and Latin America.

Under the constraints of carbon neutrality goals, the green transition of the traditional coal power industry not only defines the scope of its sustainable transformation but also determines the stability and flexibility of urban energy systems. The functional repositioning of the coal power sector must be approached through technological innovation, policy regulation, and industrial coordination to ensure its critical role in optimizing the energy structure. Leveraging advanced intelligent technologies, coal-fired power plants can integrate artificial intelligence, big data analytics, and the Internet of Things to develop intelligent operational systems, enabling precise combustion control, dynamic load adjustment, and real-time pollutant monitoring. These advancements enhance energy efficiency while improving system adaptability in high-penetration renewable energy scenarios. The widespread deployment of ultra-supercritical coal-fired units, deep carbon capture, utilization, and storage (CCUS) technologies, as well as CO_2 mineralization and reutilization pathways, can simultaneously reduce emissions and enhance the carbon sink potential of the coal power industry, laying the groundwork for a negative-carbon emission technology framework. Targeted policy interventions play a pivotal role in driving the low-carbon transition of the coal power sector. The deepening of carbon trading markets can send price signals that incentivize high-emission enterprises to optimize asset allocation and increase investment in low-carbon technologies. Green financial instruments, such as green bonds and sustainability-linked loans, can lower financing costs for decarbonization upgrades, strengthening the sector's transition momentum. Differentiated electricity pricing mechanisms, capacity remuneration policies, and incentives for flexibility retrofits can ensure the economic viability of coal power in peak shaving and renewable energy balancing, thereby mitigating supply-demand mismatches in high-renewable penetration scenarios. The green and intelligent transformation of coal power extends beyond technological upgrades within the sector itself and requires integration into a broader energy system. Advancing a coordinated operation model that integrates coal power, renewables, and energy storage—underpinned by advanced storage technologies, hydrogen energy, and smart dispatching systems—can enhance complementarity and flexibility across energy sources. Encouraging coal power enterprises to transition into integrated energy service providers by expanding cogeneration and industrial waste heat recovery can improve overall energy efficiency and contribute to system-wide emission reductions. Ultimately, the green and intelligent evolution of the traditional coal power industry transcends sectoral transformation, emerging as a crucial pillar in the low-carbon and intelligent development of the energy system. This transition will not only facilitate the high-quality energy transformation of cities in the YREB but also help maintain a dynamic balance between energy security and carbon neutrality goals.

6 Conclusion and future directions

Accurately identifying the status and obstacles of urban energy transition is crucial for achieving China's overall climate change mitigation goals and ensuring the sustainable use of resources. This study employs a comprehensive index method and obstacle degree model to quantitatively analyze the energy transition levels and obstacle factors of 107 cities in the Yangtze River Economic Belt from 2010 to 2020. The main findings are as follows:

Over the past decade, the level of urban energy transition has significantly improved, while also exhibiting a trend of increasing polarization. The development levels of environmental pollution, environmental governance, and policy guidance have all improved, positively correlating with urban energy transition performance. Conversely, energy consumption, resource endowment, and technological innovation show declines in their development levels, and these factors are negatively correlated with urban energy transition performance.

The spatial differentiation of urban energy transition levels has weakened, and the distribution has shifted from a core-periphery model to a more balanced pattern, with the intensity of spatial positive clustering also strengthening. The sample cities were categorized based on four criteria: geographical region, urban size, energy transition level, and the developmental stages of resource-based cities. Under each of these four criteria, the city types with the highest energy transition performance are found to be eastern cities, large cities, high-ETI cities, and regenerated cities.

During the study period, the primary obstacles to urban energy transition were identified as environmental governance, resource endowment, and policy guidance. The prominence of environmental governance highlights the significant challenges of pollution control and ecological restoration, especially in cities with heavy industrial bases, where governance pressures are particularly evident. The obstacles related to energy consumption and technological innovation ranked fourth and fifth, respectively. Among the six dimensions, the obstacle degree value of environmental pollution is the lowest, suggesting that progress in this area may further support urban energy transition efforts.

The realization of urban energy transition is a systemic issue, requiring top-down policy guidance as well as bottom-up practices and feedback. This study reveals the spatiotemporal disparities in urban energy transition processes and the challenges faced by different types of cities, offering valuable insights for the design of green finance policies. By quantifying the energy transition progress across various urban types, the research facilitates policy deliberations on how financial instruments can promote the sustainable transition of small and resource-based cities. Additionally, this study provides methodological guidance and data support for international climate cooperation, particularly in developing countries, where the evaluation framework and research paradigm proposed herein can inform the design of effective policies and financial mechanisms to accelerate energy transition and address climate change. This study relies on static datasets, which do not reflect the temporal dynamics and timely execution of policies during the energy transition process. Future research should consider adopting dynamic or real-time analytical methods, utilizing higher-frequency data to monitor the evolving urban energy transition process, thereby enhancing the timeliness and accuracy of the research outcomes. Fully leveraging multi-source data will further strengthen the enabling role of digital development in urban energy transition, providing more precise decision-making support for policy interventions. Future studies could explore the application of digital technologies in urban energy transition, particularly the interaction between digital technologies and energy transition—such as how digitalization can enhance energy efficiency, optimize energy management, and foster the development of green and low-carbon industries.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found below: No.

Author contributions

HY: Conceptualization, Data curation, Formal Analysis, Methodology, Writing–original draft, Writing–review and editing. JG: Data curation, Software, Writing–review and editing. SL: Funding acquisition, Supervision, Validation, Writing–review and editing. JB: Data curation, Formal Analysis, Writing–review and editing. ZL: Software, Writing–review and editing. CM: Data curation, Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2025.1545626/full#supplementary-material

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