

CHARTING THE PATH TO SUSTAINABILITY: A CONFIGURATIONAL STUDY OF CHINA'S LOW-CARBON PILOT INITIATIVES

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Abstract. This study examines how China's low-carbon pilot cities improve urban ecological welfare performance to promote green urban transformation, offering valuable insights for sustainable urban development. By employing the entropy method, this study constructs an evaluation system for ecological welfare performance. Additionally, a comprehensive framework integrating government, market, technology, and resource endowments is developed using fuzzy set qualitative comparative analysis (fsQCA) and necessary condition analysis (NCA). Scientific and educational support, industrial structure, and environmental quality are identified as key elements that constrain improvements in ecological welfare performance. Drawing on panel data from 71 Chinese low-carbon pilot cities from 2013 to 2023, three key performance improvement mechanisms are identified: market-resource-technology linkage, market-resource endowment advantage embedding, and government-market-technology-resource synergy. The enhancement of ecological welfare performance in low-carbon pilot cities is driven by four key pathways: (1) integrating high-quality resources with a robust industrial base, (2) coordinating government and market forces guided by market principles, (3) boosting ecological welfare performance through investment in science and education under catch-up pressure, and (4) boosting ecological welfare performance through technological innovation under catch-up pressure. This study argues that low-carbon pilot cities should capitalize on their distinctive resource endowments to identify viable green transformation pathways, prioritizing industrial structure optimization, market mechanism enhancement, and green innovation as critical policy levers for sustainable development.

Keywords: *low-carbon pilot cities, environmental welfare performance, qualitative comparative analysis, necessary condition analysis, institutional logics*

Introduction

China's commitment to carbon peaking and carbon neutrality presents formidable challenges for reconciling economic development, environmental protection, and quality-of-life improvements during its rapid urbanization. Back in 2010, China designated its first batch of low-carbon pilot cities in order to explore pathways for low-carbon urban development. According to the National Low-Carbon City Pilot Programme Progress Assessment Report: Between 2017 and 2022, 95% of pilot cities achieved significant reductions in carbon intensity, supporting an average annual GDP growth rate of 5.8% alongside a carbon emissions growth rate of just 1.3%. The Chinese government advances Beautiful City development with a focus on green and low-carbon transition, ecological livability, safety and health, and smart efficiency. This signifies a paradigm shift from economic primacy to coordinated people-society-environment development and enhanced public welfare. Ecological welfare performance reflects the conversion efficiency from natural resource inputs to human well-being. Analyzing its temporal dynamics under the dual carbon framework is essential for sustainable, high-quality urban development in China.

The concept of ecological welfare performance (EWP) stems from Daly's (1974) steady-state economic theory, which emphasizes the welfare improvement per unit of

natural resource consumption. Subsequently, researchers have employed the Ecological Footprint, Environmental Intensity of Human Well-being (EIWB), and Environmental Efficiency of Well-being (EWEB) to evaluate the ecological welfare performance (EWP) and sustainable development across various nations (Rees, 1992; Dietz et al., 2012; Knight and Rosa, 2011).

Zhu (2008) first employs the Human Development Index (HDI) ratio to the Ecological Footprint to measure EWP in China, uncovering an inverted U-shaped relationship between EWP and economic growth. Subsequent studies by Chinese scholars predominantly focus on elucidating the connotation of EWP (Zang et al., 2013; Feng and Yuan., 2016), measuring the level of EWP at different regional levels, and studying the law of spatiotemporal evolution (Liu and Zhuang, 2022; Du et al., 2019; Long, 2019; Wang et al., 2020; Kuang, 2021). Research indicates that environmental regulation, economic growth, industrial structure, city size, and urbanization are key determinants of EWP (Guo et al., 2020; Wang and Duan, 2023; Lin et al., 2019; Zang et al., 2022; Li et al., 2019). The gradual improvement in the ecological welfare performance of Chinese cities and urban areas in recent years is mostly due to advances in technology (Long, 2019). Empirical studies have confirmed that the implementation of low-carbon pilot policies significantly diminishes carbon emission intensity and air pollution in pilot cities (Dai and Cao, 2015; Deng, 2016; Song et al., 2019; Zhang, 2020). These findings parallel those of scholars who have examined the positive impacts of the European Low Emission Zone policy in mitigating air pollution and the environmental impacts of traffic congestion (Bernardo et al., 2021; Wolff, 2014).

From a macroscopic standpoint, empirical evidence has substantiated the salutary effects of Low-Carbon Pilot Policies (LCPPs) on urban total factor energy efficiency and regional green development (Fan et al., 2022; Zhang et al., 2021). The efficacy of low-carbon pilot policies exhibits significant intercity disparities. Generally, metropolises boasting superior infrastructure and larger scale reap more substantial green development dividends from such policies (Cheng et al., 2019). The implementation of LCPPs has significantly bolstered green development efficiency in the eastern region (Lan, 2021), yet their impact remains limited in resource-scarce cities (Zang and Sun, 2021). Government-imposed carbon reduction targets more significantly boost green innovation in southern cities than in northern ones, thereby widening the economic development gap between the two regions (Wang and Li, 2023). From a micro perspective, scholars demonstrate that LCPPs facilitate enterprises' green technology innovation, enhance their environmental and social governance performance, and exert a beneficial influence on the coordination of economic efficiency and social benefits (Wang and Wang, 2022; Deng et al., 2022; Wang et al., 2023).

Scholars have generally acknowledged prior research which has identified the heterogeneity of urban EWP ecological welfare performance in China across temporal and spatial dimensions. Industrial structure and technological innovation have been identified as key mechanisms through which environmental regulation affects ecological welfare performance (Gu and Chen, 2020; Wang and Luo, 2021). On the other hand, fiscal decentralization (Li et al., 2022), environmental decentralization (Cheng and Wang, 2022) and population agglomeration (Chen and Liu, 2023) are also significant factors contributing to the differentiated characteristics of EWP. Spanning all Chinese provinces, municipalities, and autonomous regions, low-carbon pilot cities vary in resource endowments, economic foundations, industrial structures, and city sizes. Promoting high quality urban development and enhancing resident welfare constitute the fundamental

objectives of China's people-centered vision for creating innovative, livable, beautiful, resilient, civilized, and smart modern cities. The low-carbon pilot city program, as a comprehensive environmental initiative, plays a pivotal role in fostering green urban transformation and improving public well-being. Its implementation represents a complex process requiring local governments to align governance objectives with market conditions, technological capabilities, and resource endowments to advance EWP.

Existing studies commonly employ static models such as the dynamic panel spatial Durbin model (Zhang et al., 2024) and the difference-in-differences (DID) model and other methods to examine the economic and environmental impacts of individual factors on low-carbon pilot cities. These approaches fail to capture the multifactorial interactions inherent in the development of low-carbon cities, thus being inadequate for explaining how different low-carbon pilot cities enhance EWP. Understanding how these factors interact and synergies to improve EWP clarifies the various ways in which low-carbon pilot cities can achieve sustainable urban development.

Compared with existing literature, the marginal contribution of this paper is mainly reflected in the following aspects. Firstly, existing literature mainly focuses on the environmental and economic effects of low-carbon pilot policies, while there is a lack of discussion on the impact of low-carbon pilot policies on sustainable urban development and people's livelihood. This study proposes an EWP indicator system adapted to Chinese contextual conditions with an objective method to evaluate the changes in the EWP of pilot cities. The study improves the evaluation of the effectiveness of these policies, thus offering a more comprehensive assessment. Secondly, existing studies often concentrate on the isolated impact of a single factor on EWP, thereby overlooking the reality of the joint effect of multiple factors in the promotion of low-carbon pilot policies. This study employs a multi-level institutional logics framework, integrating the various institutional logics that affect EWP into the overall analytical structure. It offers significant support for local governments to enhance the efficacy of low-carbon pilot policies, adapting them to specific local conditions. Thirdly, this study summarizes the various institutional configurations of LCPPs to promote EWP and reveals the different pathways for enhancing EWP in low-carbon pilot cities. These pathways offer valuable insights for further summarizing and disseminating best practices to achieve sustainable urban development nationwide.

Theoretical analysis

Multi-institutional logic of building a low-carbon pilot city

Ecological welfare performance serves as a crucial metric for assessing a city's capacity for sustainable development. Low-carbon pilot cities (LCPCs) have taken on the role of trailblazers in mapping out a path for the green transformation of urban economies and societies. This initiative is propelled by the goal of attaining sustainable urban economic growth, improving environmental quality, and enhancing the well-being of residents, creating a mutually beneficial situation where economic, environmental, and social benefits are achieved in a balanced way. Literature predominantly evaluates low-carbon pilot policies' effectiveness in carbon reduction and environmental governance, yet human well-being impacts remain underexplored. While LCPPs' positive effects on urban EWP and spatial spillovers are confirmed (Ge et al., 2024), systematic investigation of multi-factor interactions in Low-carbon Pilot City construction effectiveness remains scarce.

Institutional logic theory posits that organizations are influenced by the coexistence of multiple institutional logics within a given institutional framework, and that organizational

behavior and strategic decisions are inextricably linked to the organization's social position and its perception of that position (Thornton et al., 2012). In recent years, there has been a gradual shift in the dominant logic from a single-system orientation to a multiple-systems approach. This shift reflects a recognition of the need to accommodate individual differences and the interconnections between systems (Tu and Guo, 2024). In the absence of explicit emission reduction targets for pilot cities from the central government, the formulation of low-carbon pilot policy measures is left to the discretion of local governments. Pilot cities integrate their distinctive resource endowments, economic foundations, market environments, technology levels, and other institutional contexts to implement a range of concrete measures. In the development of LCPCs, government policies interact with economic, environmental, and social factors to shape local EWP. These interactions enhance EWP in adjacent regions via policy spillovers, thereby fostering the comprehensive enhancement of EWP across Chinese cities.

Ecological welfare performance under the symbiosis of government, market, technology, and resource endowment logics

The government governance factor constitutes an important institutional logic in the context of low-carbon city pilots. This factor represents the government's capacity to leverage its authority for the purpose of regulation and resource allocation. China's environmental governance paradigm has been predominantly characterized by a system of regional decentralization (Xu, 2011), through which local governments have been influenced by various incentives, including promotion incentives, financial incentives (Tie et al., 2020; Pan et al., 2017; Liu, 2015), and preferential access to resources in other fields from the central government. Local governments, as principal environmental governance agents, mobilize central support to secure competitive advantages through environmental quality improvements. They deploy green R&D subsidies, tax rebates, and other fiscal incentives to stimulate corporate emission reductions and clean technology investment. Concurrently, public health campaigns promote low-carbon lifestyles, curbing residential emissions and resource consumption. Strategic investments in infrastructure and healthcare further enhance urban livability and elevate population well-being. The interaction of factors such as fiscal decentralization, local government competition, vertical fiscal disequilibrium, and environmental regulation factors on EWP become the focus of scholarly debate (Xie and Chen, 2022; Liu and Xue, 2021; Guo and Chen, 2021). The studies reveal that the impact of governmental governance factors on EWP is marked by regional heterogeneity.

Market mechanisms are essential in constructing low-carbon pilot cities, as higher consumption levels and more rational industrial structures, driven by larger market sizes, significantly enhance EWP (Li and Hu, 2023). Previous studies show that pilot carbon emission trading schemes have improved energy efficiency, lowered production costs (Hu et al., 2020), and spurred the rapid development of green technological innovation (Shao et al., 2022). Moreover, such initiatives have facilitated the optimization of industrial structures within designated pilot cities (Guo and Ou, 2023). The pilot carbon emission permit policy promotes the clean transformation of energy consumption structures and intensifies market-incentive environmental regulations, thereby significantly enhancing EWP (Yang et al., 2023).

The imperative for energy-saving and emission-reducing technologies in developing low-carbon pilot cities has expedited the adoption of green technological innovations. The interaction between environmental regulation and technological innovation drives

the overall improvement of EWP (Xiao and Xiao, 2022). Technological innovation enables the transformation of government functions and enhances governance efficiency. Propelled by digital technology innovation, the digital economy significantly boosts EWP through economic scale expansion, industrial upgrading, and technological advancement (Xia et al., 2024).

Research indicates that the resource endowment characteristics of cities significantly influence EWP. Studies show that setting carbon peak targets is particularly effective for low-carbon transitions in non-resource-based cities (Zhang et al., 2024). The low-carbon pilot policy notably promotes the coordination of economic growth with ecological sustainability, especially in eastern China, non-resource-based cities, and larger cities (Zhang and Yan, 2023). There is a significant relationship between the administrative level and city size and EWP (Zang et al., 2022).

The above multiple factors and their interactive effects together constitute the multiple institutional logics of ecological welfare performance in low-carbon pilot cities, as shown in *Figure 1*.

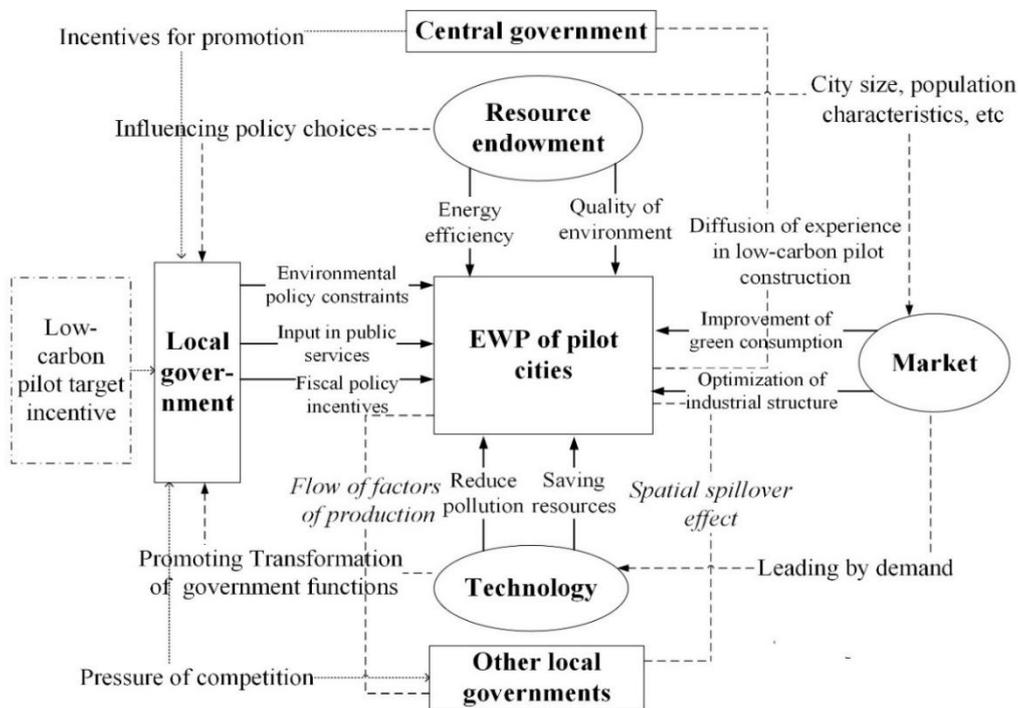


Figure 1. Multi-institutional logical analysis framework for LCPCs

Methods, samples, and variables

Research methodology

Enhancing the EWP of LCPCs involves addressing complex systemic issues and navigating a multitude of concurrent causal relationships. These relationships are characterized by the interplay of various institutional logics. Researchers predominantly use regression analysis as a methodological framework to investigate the determinants of EWP. However, regression analysis can only assess the net effect of a single variable. Consequently, it is unable to elucidate the intricate causal relationships between multiple variables that collectively constitute a configuration. This paper uses qualitative

comparative analysis (QCA) and necessary condition analysis (NCA) to examine the mechanism by which groups are formed in the construction of low-carbon pilot cities, with the aim of enhancing EWP.

The QCA approach is a case-oriented research method used to examine how antecedent grouping patterns affect outcomes. The method integrates the strengths of qualitative and quantitative analysis, focusing on the necessary and sufficient conditions for results (Cooper and Glaesser, 2016). This study employs fuzzy set qualitative comparative analysis (fsQCA) to elucidate the complex causal configurations in the low-carbon pilot construction process that enhance EWP. Further, necessary condition analysis (NCA) quantitatively identifies the essential prerequisites and potential bottlenecks for EWP improvement, complementing the fsQCA findings by pinpointing key institutional factors in LCPCs and their impact on EWP.

Samples and data

The QCA method generally adheres to the theoretical sampling principle in the selection of cases, contingent upon the fulfillment of two criteria: the presence of sufficient homogeneity within each group and maximal heterogeneity across groups. This approach is predicated on the expectation that it will yield conclusions that are externally valid and sufficiently comparable between cases (Tang et al., 2021).

Low-carbon Pilot Cities (LCPCs) represent an experimental urban development initiative promulgated by Chinese governments at the city level. This initiative is distinguished by three integrated characteristics. First, it adopts a low-carbon economy as both the developmental paradigm and strategic orientation. Second, it cultivates citizens' low-carbon consciousness as guiding values and behavioral norms. Third, it establishes a low-carbon society as the governance blueprint and institutional archetype for public administration. These cities function as policy laboratories, meticulously designed to systematically explore, codify, and disseminate replicable low-carbon development experiences for subsequent national-scale application.

Since the establishment of the inaugural group of low-carbon pilot cities in 2010, China has established a total of 87 low-carbon provincial and municipal pilot cities. From the second batch onward, cities have constituted the primary units for low-carbon pilot implementation. Even during the first batch of pilots when provinces were initially responsible for implementation, significant disparities within provinces effectively shifted policy execution to municipal governments. Therefore, 6 provincial pilots of the first batch were excluded, leaving a total of 81 low-carbon city pilots.

Observations from seven county-level cities, two specially administered regions¹, and Lhasa were excluded because disclosed statistical data for relevant indicators were unavailable. Specifically, Lhasa was excluded because data were missing for over half of the study period across multiple key indicators—including per capita urban built-up land area, water resources, industrial wastewater discharge, industrial SO₂ emissions, industrial soot emissions, and total electricity consumption in society.

¹ The excluded seven county-level cities and two specially administered regions include: Jiyuan in Henan Province, and Daxing'anling Prefecture, which is a prefecture-level administrative divisions under Heilongjiang Province in the second batch of Low-carbon Pilot Cities. Qiongzong in Hainan Province, Xunke in Heilongjiang Province Changyang in Hubei Province, Changji, Hetian, Yijing in Xinjiang autonomous region, Xinjiang Production and Construction Corps which is a state-designated, separate-planning provincial-level special administrative regions of the People's Republic of China in the third batch of Low-carbon Pilot Cities.

Ten cities with substantial missing data were excluded, yielding a final sample of 71 low-carbon pilot cities. This satisfies the case requirements of the QCA methodology (Castro and Ariño, 2016). The second batch of low-carbon pilot cities was established near the end of the year on November 26, 2012, so 2013 was chosen as the starting point for the research timeframe of this paper. Consequently, the research samples encompass a total of 71 low-carbon pilot cities' data from 2013 to 2023.

In this study, the 71 low-carbon pilot cities are dispersed across 26 provincial-level administrative units and China's three major regions: eastern, central, and western. These cities, which include prefecture-level cities, provincial capitals, and municipalities directly under the central government, exhibit significant heterogeneity in economic development, resource endowments, market environments, and governmental governance capabilities. The policy measures implemented during the low-carbon pilot construction process also vary markedly, and initial ecological welfare performance levels differ substantially across cities. Configurational analysis methods are particularly well-suited for examining the complex interactions among a large number of variables with substantial heterogeneity in both conditions and outcomes. By identifying combinations of different variables, these methods can effectively elucidate the diverse pathways through which ecological welfare performance can be enhanced.

Figure 2 illustrates the spatial distribution of China's three batches of low-carbon pilot cities. The first batch comprised few cities concentrated in select northern, central, and southwestern locations. Subsequent batches progressively expanded coverage into central and eastern regions. By the third batch, pilot cities were distributed systematically across China's eastern, central, and western macro-regions, substantively encompassing all provincial-level administrative units. The 71 pilot cities thus exhibit extensive geographical distribution and robust representativeness.

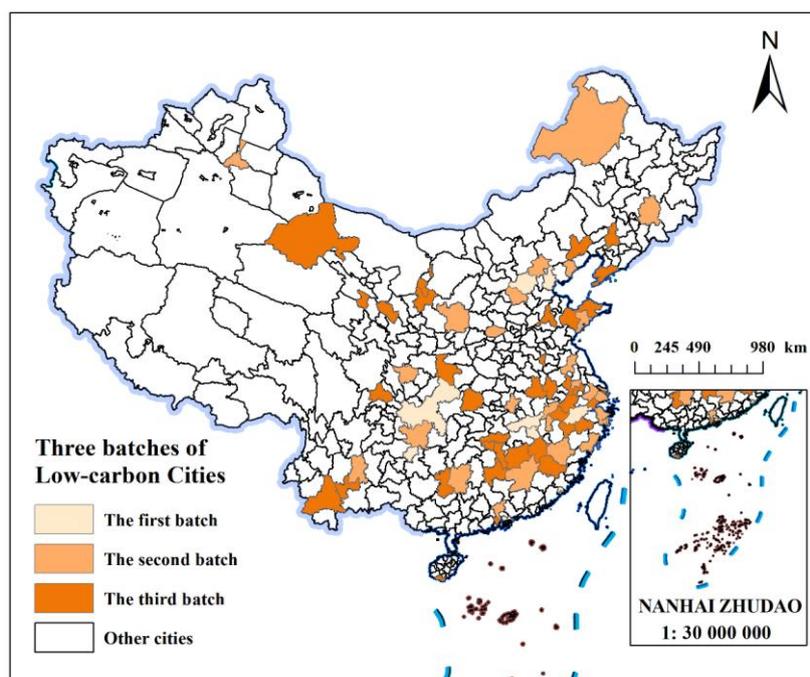


Figure 2. Geographical distribution of China's three batches of Low-Carbon Pilot Cities. This figure is produced using the standard map (approval number: GS(2023)2767) from the Standard Map Service of the Ministry of Natural Resources, with no modifications made to the base map boundaries

All the data are obtained from China Urban Statistical Yearbook, China Urban Construction Statistical Yearbook, and provincial statistical yearbooks. Some of the missing data are supplemented by checking the corresponding statistical yearbook of each city and the statistical bulletin of national economic and social development in the corresponding years.

Variables and calibration

Outcome variable

The outcome variable of this study is EWP, and comprehensive indicators are constructed to assess EWP from an input-output perspective. The evaluation system of EWP is constructed with resource consumption as the input, welfare level as the desired output, and environmental pollution as the undesired output, as shown in *Table 1*. This system is constructed based on the idea of indicator construction of Xiao and Ji (2018) and Long (2019).

Table 1. *Ecological well-being performance evaluation indicator system*

Category	Primary indicators	Secondary indicators	
Input indicators	Land	Per capita urban built-up land area	
	Water	Per capita water resources	
	Energy	Per capita energy consumption	
Expected outputs	Living standards of the population	Average wage of employees	
		Retail sales of consumer goods per capita	
		Registered urban unemployment rate	
Expected outputs	Level of public services	Engel's coefficient	
		Basic urban pension coverage	
		Number of college students per 10,000 people	
Expected outputs	Environmental quality	Doctors per 10,000 population	
		Centralized treatment rate of municipal wastewater	
		Green coverage rate of built-up area	
Non-expected outputs	Waste water	Per capita area of mechanized road sweeping and cleaning	
		Exhaust gas	Per capita industrial wastewater discharge
			Per capita industrial SO ₂ emissions
		per capita industrial soot emissions	

Data source: most data is from or calculated from China Urban Statistical Yearbook, yearbooks of provinces, autonomous regions, and municipalities directly under the central government, and a small amount of missing data calculated from municipal statistical bulletins

Pertaining to resource input indicators, the selection encompassed three key resource consumption metrics: land, water, and energy. Determinants of welfare level output indicators, including income, employment, old-age pension, consumption, and social public services (quality education, medical conditions, and environmental quality), significantly correlate with urban residents' living standards and well-being in China. To avoid subjective bias from arbitrary weight assignment, this study uses the entropy value method (Li and Zhang, 2014) to determine the ecological welfare performance of each city. Descriptive statistics of relevant variables are shown in *Table 2*.

Table 2. Descriptive statistics of variables

Variable	Observations	Mean	Standard deviation	Minimum	Maximum
EWP for all cities in China	3003	0.5949	0.0392	0.4124	0.7371
EWP of LCPCs	782	0.5984	0.0370	0.4707	0.7371
EWP of resource-based cities	1199	0.5873	0.0403	0.4707	0.6844

Table 2 shows that among the 71 low-carbon pilot cities over a decade, the EWP values range from 0.4707 to 0.7371, with an average of 0.5984 and a standard deviation of 0.0370, highlighting significant variations in EWP across cities. The mean and minimum EWP values of the pilot cities exceed those of all cities in China, with a smaller standard deviation, suggesting that the EWP of low-carbon pilot cities is generally higher and exhibits less variation compared to other cities. Conversely, resource-based cities have a lower mean EWP and greater intercity disparity.

Conditional variable

(1) The logic of government governance

This study employs local government investment preferences and competition intensity as proxies for governance logic, which is primarily manifested in the government's role in resource allocation and regulation. Amid the growing embrace of green development, local governments face the challenge of balancing economic growth with environmental protection. Through the implementation of various policy measures, LCPCs have achieved energy-saving and emission-reduction targets, thereby promoted sustainable development and enhanced urban livability. Consequently, these cities have secured greater competitive advantages in urban competition. The enhanced EWP of pilot cities is likely to prompt neighboring cities to emulate these practices through competitive pressures. Recent studies indicate that green technological innovation has been pivotal in enhancing urban EWP (Long, 2019). Local governments' preference for investing in technological innovation reflects their prioritization of long-term development goals, using the ratio of expenditure on science and education to local general budgetary expenditures. The competitive dynamics among cities are characterized by a dual motivation to catch up with and surpass both neighboring cities and national benchmark cities. Accordingly, this paper employs the practice of Miao et al. (2017) and utilizes the economic catch-up level collectively determined by the dimensions of neighboring cities and benchmark cities as the proxy variable for local government competition. Reflecting the stratified nature of urban competition, this study categorizes all city samples into four groups: first-tier cities, municipalities, provincial capitals, and prefecture-level cities. The highest per capita GDP of each group each year is used as the benchmark for that category. For instance, when calculating Tianjin's economic catch-up level, the national highest per capita GDP is determined by the highest per capita GDP among municipalities directly under the Central Government for that year.

$$\text{Economic catch-up level} = \frac{\text{Highest GDP per capita in neighboring cities}}{\text{GDP per capita of the city}} \times \frac{\text{Highest urban GDP per capita in the country}}{\text{GDP per capita of the city}} \quad (\text{Eq.1})$$

(2) The logic of the market

Market logic is assessed through industrial structure and market size. In this study, the industrial structure is measured by the ratio of value added in the tertiary to the secondary industry, while market size is indicated by per capita consumption of retail goods.

(3) The logic of technology

Green technology innovation exhibits dual externalities and is pivotal to the green transformation of production and consumption. To eliminate the impact of city size differences, this study employs the ratio of authorized green technology invention patents to all authorized invention patents as a proxy for technological logic.

(4) The logic of resource endowment

To evaluate urban resource endowments, this study selects indicators measuring both energy consumption and urban environmental quality. On one hand, the ratio of total electricity consumption to GDP in each city is used to measure energy intensity, which reflects the efficiency of converting energy inputs into economic outputs. Cities rich in energy resources typically have lower energy prices and higher consumption, leading to higher energy intensity and greater challenges for green transitions. On the other hand, aesthetically pleasing urban environments enhance residents' well-being and quality of life, making cities more attractive to high-quality talent. This, in turn, facilitates the environmentally conscious transformation of production and consumption. Accordingly, this study adopts the per capita area of green space in parks as a proxy for urban environmental quality.

Variable calibration

To ensure the objectivity and accuracy of the calibration process, this study employs the direct calibration method to establish thresholds for the transformation of fuzzy set membership scores. Specifically, the 95th, 50th, and 5th percentile values are designated as the qualitative anchor points for full membership, crossover point, and full nonmembership, respectively. The calibration results are presented in *Table 3*.

Table 3. Calibration of conditions and results

Conditions and results		Calibrate anchor		
		Full affiliation (95%) intersection point	Crossover point (0.5)	Completely unaffiliated (0.05)
Outcome variable	EWP	0.6569	0.5975	0.5398
Government governance	Support for science and education	0.2647	0.1903	0.1315
	Catch-up pressure	30.0879	5.6010	0.9464
Market	Industrial structure	2.4475	1.0984	0.5692
	Market size	12.0063	11.0452	5.1491
Technology	Green innovation	0.2042	0.1058	0.0424
Resource endowment	Energy intensity	0.2169	0.0661	0.0328
	Environmental quality	20.2349	14.0990	9.8420

Analysis of results

Analysis of necessary conditions

(1) QCA analysis

Within the QCA framework, a condition is deemed necessary for the outcome variable if its consistency level exceeds 0.9. As illustrated in *Table 4*, the consistency levels of all antecedent variables fall below 0.9, indicating that neither high nor low levels of any single condition are necessary for high or low outcomes, thus confirming the absence of a single necessary condition for the generation of high EWP in cities. This finding underscores the multifaceted and systemic nature of urban EWP enhancement, necessitating the application of conditional group generation analysis to elucidate the underlying mechanisms.

Table 4. QCA results of the necessity analysis

Conditional variable	High EWP		Non-high EWP	
	Consistency	Coverage	Consistency	Coverage
High support for science and education	0.6620	0.6853	0.6262	0.6359
Non-high support for science and education	0.6482	0.6387	0.6901	0.6670
High catch-up pressure	0.5782	0.6732	0.5924	0.6765
Non-high catch-up pressure	0.7221	0.6436	0.7138	0.6241
High industrial development	0.7306	0.7845	0.5424	0.5713
Non-high industrial development	0.6007	0.5723	0.7954	0.7434
High market size	0.7260	0.6560	0.7364	0.6527
Non-high market size	0.6157	0.7042	0.6119	0.6866
High green innovation	0.6218	0.6367	0.6786	0.6816
Non-high green innovation	0.6891	0.6861	0.6383	0.6234
High energy intensity	0.5857	0.6522	0.6648	0.7262
Non-high energy intensity	0.7541	0.6963	0.6816	0.6174
High environmental quality	0.6519	0.6747	0.6293	0.6389
Non-high environmental quality	0.6512	0.6417	0.6796	0.6570

(2) NCA analysis

This study employs the NCA method for necessity analysis, with results presented in *Table 5*. Under both the Ceiling Envelopment (CE) and Ceiling Regression (CR) capping techniques, no institutional element exhibits an effect size greater than 0.1 with a significant p-value. This indicates that no single institutional factor is sufficient to produce high EWP in low-carbon pilot cities. Moreover, the results demonstrate that science and education support, as well as industrial structure, have a relatively strong influence.

Table 6 displays the findings of the bottleneck level analysis conducted using the Ceiling Regression (CR) methodology. As urban EWP improves from moderate to high levels, industrial structure and energy intensity gradually become the most significant bottleneck factors. As EWP ascends to and sustains leading levels, robust scientific and educational support emerges as crucial. Specifically, when EWP exceeds 90%, cities must achieve minimum levels of 60.7% in science and education support, 36.1% in catch-up pressure, 51.5% in industrial development, 5.7% in market size, 33.1% in green innovation, 3.8% in

energy intensity, and 54.9% in environmental quality. These thresholds show that achieving a high level of EWP depends on various factors working together. Notably, the most critical constraints for improving EWP in low-carbon pilot cities are support from science and education, industrial structure, and environmental quality.

Table 5. NCA results of the necessity analysis

Conditional variable	Methods	Precision	Upper limit area	Effective quantity (d)	p-Value
Support for science and education	CR	97.70%	0.033	0.033	0.190
	CE	100%	0.023	0.023	0.012*
Catch-up pressure	CR	98.50%	0.012	0.013	0.180
	CE	100%	0.005	0.006	0.338
Industrial structure	CR	96%	0.077	0.077	0.009*
	CE	100%	0.046	0.046	0*
Market size	CR	99.40%	0.003	0.003	0.876
	CE	100%	0.004	0.004	0.896
Green innovation	CR	99.70%	0.008	0.008	0.322
	CE	100%	0.010	0.010	0.147
Energy intensity	CR	99.90%	0.008	0.008	0.454
	CE	100%	0.011	0.011	0.227
Environmental quality	CR	99.70%	0.010	0.010	0.726
	CE	100%	0.013	0.013	0.375

d < 0.1 Indicates low level, p indicates statistical significance, * indicates a threshold of less than 0.05

Table 6. NCA bottleneck level analysis under the CR approach (%)

High EWP	Support for science and education	Catch-up pressure	Industrial structure	Market size	Green innovation	Energy intensity	Environmental quality
0	NN	NN	NN	NN	NN	NN	NN
10	NN	NN	NN	NN	NN	NN	NN
20	NN	NN	NN	NN	NN	NN	NN
30	NN	NN	NN	NN	NN	NN	NN
40	NN	NN	NN	NN	NN	NN	NN
50	NN	NN	NN	NN	NN	NN	NN
60	NN	NN	NN	NN	NN	0	NN
70	NN	NN	0.2	NN	NN	1	NN
80	NN	NN	17.3	NN	NN	1.9	NN
90	4.6	NN	34.4	0	NN	2.9	NN
100	60.7	36.1	51.5	5.7	33.1	3.8	54.9

NN indicates not necessary

Configuration analysis

This study utilizes fuzzy-set Qualitative Comparative Analysis (fsQCA) to examine the conditional variables of EWP, thereby elucidating the complex pathways through which various conditions interact to influence urban sustainability. To minimize

contradictory groupings, the PRI consistency threshold is set at 0.75, whereas the original consistency threshold remains at the default value of 0.8. Considering the extensive dataset of 71 cities over a decade and the substantial number of cases, the frequency threshold is established at 8. The resulting conditional groupings for EWP in LCPCs are detailed in *Table 7*.

Table 7. Grouping analysis of EWP generation mechanisms in LCPCs

Prerequisites	S1	S2	S3	S4	S5
Support for science and education			●	●	⊗
Catch-up pressure				●	●
Industrial development	●	●	●	●	●
Market size		⊗	●	●	●
Green innovation	⊗		⊗	⊗	•
Energy intensity	⊗	⊗		⊗	⊗
Environmental quality	•	●	●		
Consistency	0.912	0.900	0.941	0.930	0.914
Original coverage	0.388	0.354	0.320	0.263	0.266
Unique coverage	0.014	0.015	0.028	0.011	0.034
Consistency of solutions	0.882				
Overall coverage	0.522				

● or • indicates that the condition exists, ● denote the core condition, ● denote auxiliary conditions; ⊗ indicates that the condition does not exist, ⊗ denote the core condition, ⊗ denote auxiliary conditions; Blank space indicates that the condition is optional

It is illustrated that the overall consistency of the grouping is 0.882, which exceeds the acceptable standard of 0.8 in *Table 7*. Additionally, the overall coverage is 0.522. Notably, all five groupings exhibit individual solution consistency levels above 0.9, collectively explaining over 52% of the cases. The five clusters were categorized to identify key configurations for enhancing EWP in LCPCs. *Table 7* reveals that the pathways to high urban EWP exhibit diverse characteristics. Market logic is central to urban EWP, and industrial structure significantly influences all high-performance groupings, aligning with the NCA methodology's finding that industrial structure is a bottleneck factor for EWP improvement. The configurations are further classified into three distinct categories, with detailed configurations and representative cities documented in *Table 8*.

LCPCs can be categorized into three primary types, as shown in *Table 8*: market-resource-technology logic, market-resource logic, and government-market-technology-resource logic. Based on the status of different institutional logics, these types can be further divided into five distinct groups: market-driven cities with strong resources and industries (dominated by market logic), science-education-driven cities with significant government and market involvement (dominated by government logic), and cities driven by science-education and technology respectively under catch-up pressure. Specifically, the five groups exhibit the following characteristics in enhancing EWP, as five configurations listed in *Table 8*:

Table 8. Classification of logical groupings for improving EWP in LCPCs

Configuration logics	Configuration classification	Representative cities	Representative cities
Market-resource-- technology logic: configuration 1	Market-driven “strong resources + strong industry”	Qingdao, Wuhan, Guangzhou, Shenzhen, Quzhu, Ganzhou, Fuzhou, Liuzhou	<p>Wuhan: national carbon emission rights trading market, forming the entire carbon market industry chain, including carbon trading and carbon assets</p> <p>Guangzhou: urban carbon inclusion platform with low carbon behavior data access and real-time accounting of carbon reductions</p> <p>Shenzhen: the pilot project of near-zero carbon emission zone and enterprise emission testing, and multi-level greenhouse gas testing network of “flux-concentration-emission”</p> <p>Quzhou: carbon accounting system for seven major sectors: industry, agriculture, residential, construction, energy, transportation and forestry</p> <p>Fuzhou: Carbon Conversion Application Standard for Public Institutions, the Green Family Evaluation Standard, and formulation of 13 provincial and municipal local standards</p>
Market-resource logic: configuration 2		Tianjin, Shenyang, Nanjing, Huai’an, Hefei, Huaibei, Liu’an, Chenzhou, Chongqing	<p>Tianjin: the “two high” project management accounts to conduct the categorization and disposal</p> <p>Shenyang: the pilot project of forest composite management and the reform of collective forest rights, and the investment of loans in the green field</p> <p>Nanjing: green energy in the community to promote Jiangsu “light storage charging integration” pilot application, and improved the urban shade system</p> <p>Hefei: development of strategic emerging industries and entering the first national strategic industrial clusters</p> <p>Liu’an: diversified use of hydrogen energy, and demonstration applications for urban buses and van-type logistics vehicles</p> <p>Chenzhou: “Four Waters, Eight Waters” multiple water resource management project and promoted the sustainable use of water resources to coordinate the promotion of clean energy, industrial production, air quality management</p> <p>Chongqing: the implementation plan of the Cross-Provincial “Point-to-Point” Targeted Utilization and Exemption Management of Hazardous Wastes in Sichuan and Chongqing, and constructing a solid waste big data platform</p>
Government-market- technology-resource logic: configuration 3-5	Science and education led “big government + big market”	Changzhou, Suzhou, Jiaxing, Xuancheng, Yantai,	<p>Changzhou: the first local standard for green construction “Changzhou Green Construction Evaluation Standard” industrial ecological closed cycle of “development, storage, delivery and utilization network”, promoting the application of new energy in all scenarios</p> <p>Suzhou: first market-based carbon inclusive trading system, which realizes the overlapping effects of electricity and carbon revenues through voluntary emission reduction</p>

	Weifang, Chengdu, Guiyang, Yuxi	<p>Xuancheng: “green microgrid” that integrates source, network, load and storage, partnership with universities to research key green technologies and promote the industrial transformation of innovative achievements</p> <p>Yantai: developing nuclear power, offshore wind power, offshore photovoltaic power and other green energy sources an integrated emission inventory of air pollution and carbon emissions and optimized the ecological environment access list</p> <p>Chengdu: launching specialized green and low-carbon science and technology programs formation of Tianfu Yongqing Laboratory and Green Low Carbon Industry Investment Group</p> <p>Guiyang: establishing a trading system for Guian forest carbon tickets setting up Guizhou (International) Ecological Products Trading Center, promoting the trading of forestry carbon sinks, karst carbon sinks and other ecological products</p> <p>Yuxi: the pilot project of zero-carbon demonstration zone participation of key enterprises in the joint construction of Yunnan Vaccine Laboratory and the establishment of Yunnan Pottery Industry Innovation Research Institute</p>
Science-and education-led under economic catch-up	Hangzhou, Jinan, Wenzhou	<p>Hangzhou: energy “double carbon” digital intelligence platform for real-time accurate control of key energy-using enterprises, “green building pass” to promote the whole life cycle of new buildings to decarbonize cloud computing, big data technology used to reduce traffic congestion index</p> <p>Jinan: green and low-carbon technology performance catalog to promote the promotion and application of low-carbon advanced and applicable technologies, “Carbon wise Shandong” to record individual green and low-carbon behaviors</p> <p>Wenzhou: implementation a near-zero carbon factory evaluation system to carry out a comprehensive assessment of the green transformation of enterprises group standard “General Rules for Carbon Labeling Evaluation of Electric Power Products “ to provide standardized guidance for carbon footprint evaluation and carbon labeling certification</p>
Technology-led under economic catch-up	Jiling, Dalian, Changsha, Zhuzhou Yichang Kunming	<p>Changsha: an intelligent manufacturing equipment industry cluster and the capital of advanced energy storage materials food waste biogas power generation and domestic waste incineration power generation</p> <p>Zhuzhou: the Intelligent Science Research Institute to promote the high-end, intelligent and green development of the manufacturing industry, Zhuzhou Science and Innovation Fund Port to promote the transformation of scientific and technological innovation achievements</p> <p>Kunming: promoting increased energy saving and emission reduction of common key technology research and development and production of complete sets of equipment; a base for the comprehensive utilization of industrial resources, strengthening of cogeneration and centralized heat supply</p>

(1) Group 1 and 2 consist of market-driven low-carbon cities characterized by robust resources and industries, encompassing both market-resource-technology logic and market-resource logic.

LCPCs in Group 1 corresponding to Column S1 in *Table 7*, are characterized by market-resource-technology logic, are typically major economic centers or well-developed cities. Superior infrastructure and high concentration of skilled populations of these cities effectively promote intensive energy use. These cities are notable for their initiatives in establishing a carbon market, promoting market-driven carbon pricing through carbon accounts, and advancing carbon-inclusion platforms. They also employ market mechanisms to regulate energy consumption, encouraging enterprises to adjust their usage and residents. However, given the nascent stage of carbon market development, green innovation has not yet emerged as a significant driver.

LCPCs in Group 2 corresponding to Column S2 in *Table 7*, are predominantly robust economic hubs situated in the eastern and central provinces, characterized by superior environmental quality and low energy intensity. A defining feature of these cities is the strategic alignment of LCPCs and measures with their unique local advantageous industries and resource endowments. This alignment actively catalyzes the green transformation of key local industries and the comprehensive protection and utilization of unique natural resources. For instance, the pilot understory complex operation in Shenyang, the urban tree-shade system in Nanjing, and the sustainable utilization of water resources in Chenzhou exemplify these practices. However, the positive influence of LCPCs on EWP is somewhat circumscribed by the constraints of market size.

(2) Group 3, 4, and 5 follow a common logic that integrates government, market, technology, and resource endowments, as listed in Column 3, 4, and 5 in *Table 7*. In this paradigm, government plays a dominant role in the development of LCPCs, while the market, technological advances, and resource endowments work together to support this initiative. Among these configurations, highly developed economies, robust industrial bases, and advanced market maturity characterize the low-carbon pilot cities in configuration 3. Furthermore, the municipal governments in these areas place a premium on cultivating talent and boosting scientific and technological investment. Consequently, these cities emerge as regional population magnets, offering highly desirable living and working environments. Predominantly situated in the eastern economic hubs and provincial capitals, as well as pivotal western economic centers, these cities are characterized by substantial financial resources. Beyond promoting incentives for technological innovation and supporting low-carbon sectors financially, governments and enterprises are actively building joint laboratories and enhancing university cooperation. This joint effort not only promotes the industrialization of scientific achievements, but also leads to the active creation and widespread application of green production, construction, and energy standards that serve as exemplary approaches. Leveraging their unique energy and resource advantages, pilot cities like Guiyang and Yantai have developed innovative carbon trading systems and renewable energy industries. Guiyang has established a forest carbon ticket trading system and the Guizhou Eco-Products Trading Center to facilitate the trading of forestry and karst carbon sinks. Yantai has aggressively expanded its offshore nuclear power, wind power, and photovoltaic industries. The governments of these LCPCs strategically invest in science and education, actively attracting and retaining talent. They skillfully integrate local resource strengths with the dual benefits of a robust regional industrial structure and expansive market scale, thereby significantly enhancing EWP.

This integrated approach initiates a virtuous cycle within these cities and exerts a positive, cascading influence on the EWP of neighboring urban areas.

(3) In the fourth and fifth Groups, LCPCs encounter intense competition and economic pressure from neighboring strong cities. Cities of Group 4, situated in the eastern provinces, possess substantial financial resources, robust industrial bases, and advantageous market conditions. Despite the necessity to align with more economically advanced neighbors, these cities demonstrate a commitment to science and education, thereby providing essential momentum for sustainable, long-term development. The deployment of data-sharing industrial internet platforms and zero-carbon factories has significantly boosted resource allocation efficiency and enhanced urban EWP. These measures not only facilitate precision governance, but also drive green production and consumption, thereby advancing urban management.

Characterized by a robust industrial base and significant market scale, LCPCs of Group 5, including Jilin, Dalian, Changsha, and Kunming, are strategically positioned in the northeast, southwest, and central economic hubs. However, these cities face challenges due to their relatively modest economic output and considerable geographic distance from advanced regions like the Yangtze River Delta and Pearl River Delta. To counteract these limitations, these cities actively develop industrial and green industrial clusters, which not only drive technological progress, but also attract capital through various channels. These efforts secure the financial support necessary for translating scientific and technological achievements into practical applications. Despite located in less developed provinces, most of these LCPCs are provincial capitals. They possess a wealth of universities and a substantial pool of talent, thus significantly boosting their innovative capacity.

Conclusions and suggestions

This study adopts a multi-institutional logic approach, employing Qualitative Comparative Analysis (QCA) and Necessary Condition Analysis (NCA) methods to examine 71 low-carbon pilot cities in China as case studies. This study explores diverse pathways to enhance urban EWP, demonstrating that government, market, technology, and resource endowment logics are interdependent rather than autonomous. Each institutional logic enhances urban EWP through unique syntheses of antecedents drawn from other logics.

Pathways for enhancing EWP in LCPCs are categorized into five groups based on three institutional logics. The first two groups operate primarily through market logic: (1) cities with robust resources and industries in the market-resource-technology logic, and (2) cities with robust resources and industries in the market-resource logic. The remaining three groups reflect government logic dominance: (3) cities driven by science and education with strong government and market support, (4) cities under catch-up pressure driven by science-education, and (5) cities under catch-up pressure driven by technology. These heterogeneous classifications reveal the diverse strategic approaches employed by low-carbon pilot cities in promoting sustainable urban development. Consequently, local governments should strategically tailor low-carbon pilot policies to local contexts by aligning them with available resources, market conditions, technological capabilities, and governance capacity. Representative cities from the five institutional groupings comprise 62.5% of top-performing LCPCs documented in the 2023 Progress Assessment Report, attesting to the study's explanatory power and representativeness. Accordingly, this study proposes policy recommendations tailored to each institutional grouping of LCPCs to enhance EWP and foster sustainable development:

Firstly, optimizing the industrial structure and establishing an effective market mechanism are crucial prerequisites for enhancing the EWP of LCPCs. Undoubtedly, market logic plays an irreplaceable role in all five institutional groupings examined in this study. The improvement of EWP hinges on fostering synergy between LCPPs and industrial policies, which is corroborated by the findings of Guo et al. (2022).

It is evidenced that industrial structure can be optimized by actively leveraging carbon emissions trading, thus boosting urban ecological welfare performance (Guo and Ou, 2023). Additionally, the market mechanism can be harnessed to concurrently achieve energy conservation and emission reduction by promoting greater enterprise engagement in the national unified carbon emission trading market, guided by governmental policies. Conversely, the crucial role of consumer markets in propelling the green transition of production must be recognized. The convergence of the digital economy with primary, secondary, and tertiary sectors can spur economic growth in financially constrained cities, thereby surmounting limitations tied to geographical location and market size.

Secondly, green technological innovation is pivotal in enhancing urban EWP. This study's findings reveal that green technological innovation is significantly underutilized in low-carbon pilot projects for sustainable urban development, primarily due to its relatively low current proportion in China.

In industrialized urban centers with stringent government oversight, green technological innovation catalyzes resource intensification benefits and pollution abatement, thereby neutralizing population density's adverse impact on EWP. Policymakers in economically advanced eastern cities should actively foster an environment conducive to green consumption, promote public awareness of green consumption, and enhance its pivotal role in driving production's green transformation. Meanwhile, cities in central and western China should leverage their inherent resource endowments and scientific and educational resources to maximize green innovation's impact on ecological governance, cleaner production, and the circular economy. This requires the optimization of industrial structure and the advancement of clean energy use, thereby furthering nationwide balanced EWP.

Thirdly, the absence of a standardized framework for sustainable urban development necessitates that pilot cities adapt their initiatives to local resource endowments and capitalize on unique regional strengths. In developed areas, pilot cities are advised to leverage their industrial and human capital advantages, harness big data platforms for enhanced urban governance precision, and upgrade urban infrastructure and environmental quality. Governments in the central region are encouraged to actively steer the green transformation of key industries, establish robust platforms for scientific and technological innovation, and facilitate the translation of scientific and educational achievements into practical applications. Cities in the western region are urged to prioritize resource conservation, strategically utilize abundant natural resources, significantly bolster the digital economy and talent attraction, and proactively tackle pollution control and energy efficiency challenges in resource development.

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