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WHAT DRIVES THE EFFICIENCY OF GREEN TECHNOLOGY INNOVATION IN INDUSTRIAL SECTORS? AN ANALYSIS BASED ON THE TOE FRAMEWORK USING NCA AND FSQCA

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Abstract: As the nexus of the "innovation-driven" and "green development" national strategies, green technology innovation resonates with China's dual carbon targets and represents an essential pathway toward achieving high-quality development. Existing literature has seldom employed a holistic framework to investigate the complex causal mechanisms through which technological, organizational, and environmental conditions influence green technology innovation efficiency, thereby largely overlooking the configurational effects among these antecedent conditions. To further advance green technology innovation and enhance its efficiency, this study examines China's industrial sectors. Drawing on the Technology-Organization-Environment (TOE) framework, we utilize both Necessary Condition Analysis (NCA) and fuzzy-set Qualitative Comparative Analysis (fsQCA) on a sample of 38 industrial sectors above a designated size. The analysis explores how six antecedent conditions across the technological, organizational, and environmental dimensions combine to impact green technology innovation. The findings are threefold. First, no single antecedent condition is necessary for achieving high green technology innovation efficiency, although technological factors exert a relatively strong constraint. Second, three distinct configurational pathways lead to high efficiency: a "technology-led, government-supported" path, a "technology-led, independent-innovation" path, and an "environment-technology-organization synergy" path. Third, in an otherwise favorable market environment, ill-suited environmental regulations can suppress innovation efficiency, a context where even strong market demand fails to be effective, suggesting that the impact of organizational conditions is subject to a threshold.
Keywords: Green technology innovation efficiency; TOE framework; Fuzzy-set qualitative comparative analysis (fsQCA); Necessary condition analysis (NCA); Configurational analysis

1 INTRODUCTION

As an advancement of traditional technological innovation, green technology innovation is defined as a valuable creative activity that promotes green technological development under specific constraints, including non-pollution, low energy consumption, and recyclability [1]. The research landscape in this field covers two primary areas. The first is the measurement of its efficiency, which predominantly employs parametric methods, such as Stochastic Frontier Analysis (SFA), and non-parametric methods, like Data Envelopment Analysis (DEA). Initially proposed separately by Aigner et al. and Meeusen and van den Broeck, SFA has been expanded upon by subsequent scholars. However, DEA has emerged as the predominant method for assessing green technology innovation efficiency, largely due to its flexibility in assuming either constant or variable returns to scale. The second area concerns its influencing factors, with existing literature focusing on two levels: the firm and the government. At the firm level, studies have examined determinants such as financial performance, capital investment, executive characteristics, and corporate governance. At the government level, research has centered on factors like environmental regulations and financial subsidies. Based on its definition and the scope of research, it is clear that green technology innovation is not created in a vacuum; it must be built upon the foundation of traditional technological innovation, achieving a synergistic development of green principles and technological advancement.

At present, China has yet to achieve optimal synergy between its "innovation-driven" and "green development" mandates. This disconnect is particularly severe in the industrial sectors, which are the primary contributors to excessive carbon emissions and environmental pollution, highlighting a significant imbalance between the quantity and quality of innovation. In absolute terms, industrial sectors have progressively increased their investment in green technology innovation to facilitate their green transformation and pursue high-quality development. In relative terms, however, industrial sectors above a designated size exhibit high inputs but yield low outputs in green technology innovation efficiency. Furthermore, while the literature on green technology innovation is extensive, studies on its measurement and its influencing factors have remained largely disconnected. This separation has led to an insufficient consideration of the interplay between measurement indicators and determinants, as well as the configurational effects arising from resource allocation.

To address these gaps, this study first employs a super-efficiency Slacks-Based Measure (SBM) DEA model, incorporating undesirable outputs and assuming variable returns to scale, to measure the two-stage green technology innovation efficiency of 38 major Chinese industrial sectors from 2016 to 2020 in a more scientific and robust manner.

Second, grounded in the Technology-Organization-Environment (TOE) framework, this study integrates Necessary Condition Analysis (NCA) with fuzzy-set Qualitative Comparative Analysis (fsQCA). This approach allows for a comprehensive necessity and configurational analysis of the selected antecedent conditions, exploring both the necessity of individual factors and the combined effects that multiple conditions exert on the efficiency of green technology innovation in these sectors. This research not only establishes a tighter linkage between innovation efficiency and its determinants but also remedies the deficiency of studies that consider these factors in isolation, thereby offering effective pathways for enhancing the green technology innovation efficiency of China's industrial sectors.

2 LITERATURE REVIEW AND RESEARCH FRAMEWORK

2.1 Literature Review

As efforts to achieve China's "dual carbon" targets intensify, green technology innovation has emerged as a critical driver for industrial transformation and a focal point for domestic scholars. A universally accepted definition of green technology innovation remains elusive, primarily because it amalgamates two concepts rich in connotation: technological innovation and green principles. Initially, Brawn and Wield provided one of the earliest systematic conceptualizations [2], defining green technology as a collection of technologies for recycling and environmental purification, which served as a precursor to the modern concept of green technology innovation. This foundation was subsequently enriched and expanded by numerous scholars. For instance, Qiaoling et al. broadened its scope to include innovations in energy conservation, resource recovery, green products, and environmental assessment [3]. Later, Shu et al. integrated the concept with corporate operations, defining it as the process of achieving the greening of processes or products through science and technology to foster coordinated economic and environmental development [4]. Drawing on this international scholarship, Chinese academics have also contributed new perspectives. Cheng Wenqiong et al. posit that green technology innovation aims for mutual sustainability of the environment and the economy by conserving resources and promoting waste recycling, thereby pursuing co-generation of socioeconomic and environmental benefits [5]. Furthermore, Qu Yanfen et al. aligned the concept with China's national context, proposing that it encompasses all innovations in production processes, manufacturing techniques, and product design that aim to enhance resource efficiency, reduce pollution, and maintain ecological balance, all within the constraints of economic and ecological sustainability [6].

With the continuous advancement of green technology innovation, issues concerning its input-output relationship and the measurement of its effectiveness have garnered increasing scholarly attention. As early as 2016, Luo Liangwen and Liang Shengrong proposed that green technology innovation efficiency is a key metric for gauging its development, a view further elaborated by others [7]. Liang Zhong et al. defined this efficiency as the ratio reflecting the utility between inputs and outputs in the green innovation process [8], establishing a general consensus on the standard for its measurement. However, due to the lack of a uniform definition of green technology innovation itself, the methodologies for measuring its efficiency are diverse. Wang Zhiping et al. used an SFA model to measure the green technology efficiency of China's provinces from 2001 to 2010, analyzing its regional disparities and their causes [9]. In contrast, Liang Zhong et al. employed a more mainstream method, using an SBM-DEA model to measure green technology innovation efficiency based on provincial panel data from 2005 to 2016 [8]. Compared to SFA, the DEA model, which can segment green technology innovation into a research input stage and a results transformation stage, has progressively become the mainstream methodology. Its ability to accommodate multiple output indicators through various extensions and its relative operational simplicity have contributed to its popularity and ongoing refinement.

As measurement methodologies have matured, scholarly focus has shifted towards identifying the determinants of green technology innovation efficiency to enhance it. Cheng Qiongwen et al. identified average firm size, degree of marketization, foreign openness, and the intensity of environmental regulation as primary drivers, noting that the technological environment primarily influences the R&D stage [10]. Li Danqing and Zhong Chenlin further disaggregated environmental regulation into government support for science and technology and the stringency of environmental protection, examining their effects in conjunction with other factors like foreign openness [11]. More recently, Wang Wan et al. were the first to employ fuzzy-set Qualitative Comparative Analysis (fsQCA), identifying pathways such as a "government-industry-academia synergy model" under a quadruple helix framework [12]. Subsequently, Jia Jianfeng et al. innovatively proposed an institutional configuration perspective to explore the tripartite influence of government, market, and society on green technology innovation efficiency [13]. Furthermore, other scholars have demonstrated that specific factors such as green credit [14], digital new infrastructure [15], carbon emission efficiency [16], environmental regulation coupled with foreign direct investment [17], as well as regional economic levels and the science and technology innovation environment [18], all positively contribute to green technology innovation.

2.2 Research Framework

The extensive body of research on green technology innovation has evolved from defining "what it is," to "how to measure it," and now to "how to improve it," continuously driving its development. However, current research on improving its efficiency predominantly analyzes influencing factors independently or in simple complementary pairs. This approach often fails to uncover the complex causal relationships and configurational effects inherent in the input-output process of green technology innovation. Therefore, building on prior research and grounded in the TOE framework, this study integrates a two-stage super-efficiency SBM-DEA measurement with NCA and fsQCA. Based on the current state of green technology innovation, we construct a research framework to analyze its determinants (as shown in Figure 1). The objective is to identify the necessary conditions and the configurational effects among multiple antecedent conditions, thereby proposing effective pathways to enhance the green technology innovation efficiency in industrial sectors and achieve high-quality development.

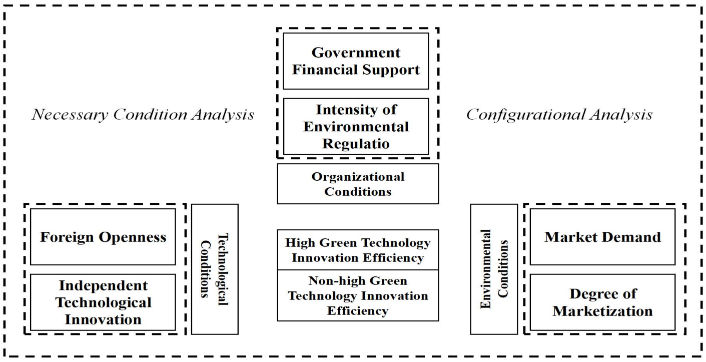

Figure 1 Research Framework

3 RESEARCH DESIGN

3.1 Research Methods

Data Envelopment Analysis (DEA) is a non-parametric efficiency analysis method used to evaluate the relative efficiency of multiple decision-making units (DMUs) with multiple inputs and outputs [19]. To overcome the limitations of traditional DEA models, such as the slackness of variables and errors in radial measurement, Tone (2001) introduced the non-radial, non-oriented Slacks-Based Measure (SBM) model [20]. Furthermore, since traditional DEA is unable to differentiate and rank multiple units that are all deemed equally efficient, Tone (2002) subsequently developed the super-efficiency SBM model [21]. Drawing upon this body of work and relevant research in green technology innovation, this study employs the super-efficiency SBM-DEA model to measure the innovation efficiency of 38 major industrial sectors.

Qualitative Comparative Analysis (QCA), developed by Ragin et al., utilizes configurational analysis combined with cross-case comparison to explore the combinations of conditions that lead to an outcome [22]. Among its variants—crisp-set QCA (csQCA), multi-value QCA (mvQCA), and fuzzy-set QCA (fsQCA)-this study employs fsQCA. Compared to the others, fsQCA accommodates continuous variables by calibrating them into membership scores within the interval [23], allowing for more nuanced assessments. Recognizing that the panel data in this study spans several years, it is crucial to incorporate a temporal dimension into the analysis. Among the three types of Time-Series QCA (TS-QCA)-namely, pooled QCA, fixed-effects QCA, and time-difference QCA-this study adopts a fixed-effects fsQCA approach. This is operationalized by calibrating the data for each case relative to its own mean value, thereby controlling for time-invariant, case-specific effects (Hino, 2009) and enabling a dynamic configurational analysis.

Necessary Condition Analysis (NCA) is a technique specifically designed to identify necessary relationships, determining whether an antecedent condition is essential for an outcome to occur [24]. Unlike the qualitative assessment of necessity within fsQCA, NCA quantifies the degree to which a condition is necessary, thus compensating for a key limitation in fsQCA (Vis et al., 2018). This allows us to precisely determine if any single factor constitutes a necessary condition for high green technology innovation efficiency.

Therefore, this study integrates NCA with a fixed-effects fsQCA. This combined approach, while accounting for temporal dynamics, allows for a robust investigation into both the necessity of single antecedent conditions and the configurational effects of multiple conditions, thereby uncovering the deeper causal pathways to high-quality green technology innovation in China's industrial sectors.

3.2 Sample Selection and Data Sources

The initial data for this study were compiled from indicators published by the National Bureau of Statistics and from the major industrial sector categories listed in the China Industrial Statistical Yearbook, published by the China Statistics Press. First, to account for the inherent time lags in the innovation process, the data for all antecedent conditions and the outcome variable were defined as the five-year average from 2016 to 2020. Second, after excluding sectors with missing data, anomalous values, or other exceptional circumstances, a final sample of 38 industrial sectors above a designated size was obtained. The sample of cases is presented in Table 1.

Table 1 The 38 Industrial Sectors in the Sample

No.	Industrial Sector	No.	Industrial Sector
1	Coal Mining and Washing	20	Pharmaceutical Manufacturing
2	Petroleum and Natural Gas Extraction	21	Chemical Fiber Manufacturing
3	Ferrous Metal Mining and Dressing	22	Rubber and Plastic Products
4	Non-ferrous Metal Mining and Dressing	23	Non-metallic Mineral Products
5	Non-metallic Mineral Mining and Dressing	24	Smelting and Pressing of Ferrous Metals
6	Processing of Agricultural and Sideline Food Products	25	Smelting and Pressing of Non-ferrous Metals
7	Food Manufacturing	26	Metal Products
8	Manufacture of Wine, Beverages and Refined Tea	27	General-Purpose Equipment Manufacturing
9	Tobacco Products	28	Special-Purpose Equipment Manufacturing
10	Textile Industry	29	Automobile Manufacturing
11	Textile, Apparel, and Accessories	30	Manufacture of Railway, Shipbuilding, Aerospace and Other Transport Equipment
12	Manufacture of Leather, Fur, Feather and Related Products and Footwear	31	Manufacture of Electrical Machinery and Equipment
13	Wood Processing and Manufacture of Wood, Bamboo, Rattan, Palm and Straw Products	32	Manufacture of Computers, Communication and Other Electronic Equipment
14	Furniture Manufacturing	33	Manufacture of Measuring Instruments and Machinery
15	Papermaking and Paper Products	34	Other Manufacturing
16	Printing and Reproduction of Recording Media	35	Repair of Metal Products, Machinery and Equipment
17	Manufacture of Articles for Culture, Education, Arts and Crafts, Sports and Entertainment	36	Production and Supply of Electric Power and Heat Power
18	Processing of Petroleum, Coal and Other Fuels	37	Production and Supply of Gas
19	Manufacture of Raw Chemical Materials and Chemical Products	38	Production and Supply of Water

The data for measuring green technology innovation efficiency, such as patent statistics, were sourced from the *China Industrial Statistical Yearbook*, the *China Labor Statistical Yearbook*, the *China Environment Statistical Yearbook*, the *China Economic Census Yearbook*, and the China Research Data Service Platform (CSMAR). Data for analyzing the influencing factors, such as industrial "three wastes" emissions, the number of new product development projects, and R&D expenditures, were obtained from the *China Industrial Statistical Yearbook*, the *China Economic Census Yearbook*, the CSMAR platform, the *China Environment Statistical Yearbook*, and the *China Science and Technology Statistical Yearbook*. The interpolation method was used to address a small amount of missing data.

3.3 Variable Description

3.3.1 Measurement of green technology innovation efficiency

There is a general consensus in the existing literature regarding the selection of indicators, which are typically categorized into two stages: the green technology R&D stage and the green technology commercialization stage, each with distinct input and output indicators.

(1) Green Technology R&D Stage

Based on the research of Luo Liangwen et al. [7] and Qian Li et al. [25], and taking into account the specific characteristics of the industrial sectors, this study selects three input indicators for the R&D stage: R&D expenditure, the full-time equivalent of R&D personnel, and expenditure on new product development. Following prior research, the output indicators for this stage are the number of patent applications and the number of invention patents granted.

(2) Green Technology Commercialization Stage

For the commercialization stage, the inputs bear a resemblance to the outputs of the R&D stage. Drawing on the work of Yang Shidi et al. [26] and Zhao Lu et al., [27] this study uses the number of patent applications, the number of invention patents granted, the number of new product development projects, and enterprise energy consumption as input indicators. For the outputs of this stage, based on the research of Zhang Liao et al. [28] and Li Lin et al. [29], the desirable output is defined as sales revenue from new products, while the undesirable output is defined as the emissions of the "three wastes" from the industrial sectors.

The names and definitions of all variables are presented in Table 2.

Table 2 Definition of Variables for Green Technology Innovation Efficiency Measurement

Stage	Category	Variable Name and Definition
Green Technology R&D Stage	R&D Input	T1: R&D Expenditure (CNY 10,000)
		T2: Full-Time Equivalent of R&D Personnel (person-year)
		T3: Expenditure on New Product Development (CNY 10,000)
	Intermediate Output	M1: Number of Patent Applications (units)
		M2: Number of Invention Patents Granted (units)
Green Technology Commercialization Stage	Commercialization Input	C1: Number of Patent Applications (units)
		C2: Number of Invention Patents Granted (units)
		C3: Number of New Product Development Projects (items)
		C4: Industry Energy Consumption (10,000 tons of standard coal)
	Desirable Output	E1: Sales Revenue from New Products (CNY 10,000)
	Undesirable Output	U1: Industrial Wastewater Discharge (cubic meters)
		U2: Waste Gas Emissions (cubic meters)
		U3: Solid Waste Generation (tons)

3.3.2 Antecedent conditions for green technology innovation efficiency

(1) Technological Conditions

This study examines two technological conditions from both external and internal perspectives: foreign openness and independent technological innovation. In the new era, technological innovation is often characterized by transnational and cross-disciplinary collaboration. Liu Zhibiao argues that China must leverage its new pattern of comprehensive openness to acquire global innovation resources, thereby advancing innovation in key areas [30]. Similarly, Guo Wei et al. suggest that the degree of open innovation significantly impacts an industry's innovative capacity by promoting industrial restructuring and accelerating the international flow of innovation factors [31]. Conversely, independent technological innovation is the process through which an industry improves and innovates its internal technologies using its own resources. It is crucial for firms to maintain control during the innovation process to avoid over-reliance on foreign technology, which can lead to a loss of market competitiveness and industrial creativity.

(2) Organizational Conditions

The two organizational conditions are government financial support and intensity of environmental regulation. Research by Li et al. finds that governments, in pursuit of sustainable development and environmental protection, often encourage firms to engage in green technology innovation. Government R&D funding can enhance the efficiency of corporate green innovation, while green credit policies can strengthen the motivation for it [32]. Therefore, this study measures this condition using the proportion of R&D expenditure sourced from the government. Regarding the intensity of environmental regulation, a study by Yao et al. posits that the pressure of industrial pollution can compel heavy-polluting industries (e.g., oil refining, chemical manufacturing, and primary metals) to accelerate their green innovation R&D, thereby enhancing their environmental legitimacy [33]. Consequently, this study uses the emissions of the industrial "three wastes" as a proxy for the intensity of environmental regulation.

(3) Environmental Conditions

The environmental conditions consist of market demand and degree of marketization [34]. Zhang Dunjie asserts that market consumption demand has a pronounced impact on green technology innovation. Furthermore, Denicolò notes that market profits and competition are primary incentives for firms to undertake such innovation [35]. Therefore, we adopt the number of new product development projects in industrial sectors as the measure for market demand. Regarding the degree of marketization, as China's market economy system matures, the allocative role of the market becomes more prominent, intensifying competition and amplifying the incentive for innovation [36]. Research by Feng Zongxian et al. demonstrates that the degree of marketization has a significant positive effect on the technical efficiency of innovation [37]. Additionally, Wu Lianghai et al. find that a higher degree of marketization helps enhance information transparency and reduce information asymmetry between investors and managers [38], enabling firms to send positive signals to the market about their high-level innovation capabilities [39]. Thus, building on prior research, this study measures the degree of marketization by the proportion of non-state capital in the industry's paid-in capital.

The specific calculation method for each variable is shown in Table 3.

Table 3 Calculation of Variables for the Antecedent Conditions

Variable Name	Symbol	Calculation Method
Green Technology Innovation Efficiency	GTIE	Five-year average of the two-stage green technology innovation efficiency
Foreign Openness	FO	Proportion of foreign capital in paid-in capital
Independent Technological Innovation	ITI	Proportion of internal expenditure in total R&D expenditure
Government Financial Support	GFS	Proportion of R&D funds sourced from the government
Intensity of Environmental Regulation	IER	Emissions of the industrial "three wastes"
Market Demand	MD	Number of new product development projects
Degree of Marketization	DM	Proportion of non-state capital in paid-in capital

4 DATA ANALYSIS AND EMPIRICAL RESULTS

4.1 Measurement of Green Technology Innovation Efficiency

To incorporate the temporal dimension into the NCA and fsQCA analyses, this study first calculated the two-stage green technology innovation efficiency for each of the 38 industrial sectors for each year from 2016 to 2020. Subsequently, the five-year average efficiency was computed for each sector. This approach effectively creates a single, time-averaged data point for each case, thereby controlling for case-specific time effects. The results are presented in Table 4.

Table 4 Five-Year Average Green Technology Innovation Efficiency of the 38 Industrial Sectors (2016-2020)

Industrial Sector	Green Technology Innovation Efficiency	Industrial Sector	Green Technology Innovation Efficiency
Coal Mining and Washing	0.258	Pharmaceutical Manufacturing	0.477
Petroleum and Natural Gas Extraction	0.456	Chemical Fiber Manufacturing	0.459
Ferrous Metal Mining and Dressing	0.849	Rubber and Plastic Products	1.153
Non-ferrous Metal Mining and Dressing	0.551	Non-metallic Mineral Products	2.171

Non-metallic Mineral Mining and Dressing	0.472	Smelting and Pressing of Ferrous Metals	0.547
Processing of Agricultural and Sideline Food Products	0.335	Smelting and Pressing of Non-ferrous Metals	0.413
Food Manufacturing	25.848	Metal Products	0.668
Manufacture of Wine, Beverages and Refined Tea	52.062	General-Purpose Equipment Manufacturing	0.800
Tobacco Products	0.863	Special-Purpose Equipment Manufacturing	0.772
Textile Industry	0.452	Automobile Manufacturing	0.599
Textile, Apparel, and Accessories	0.448	Manufacture of Railway, Shipbuilding, Aerospace and Other Transport Equipment	4.660
Manufacture of Leather, Fur, Feather and Related Products and Footwear	0.398	Manufacture of Electrical Machinery and Equipment	2.955
Wood Processing and Manufacture of Wood, Bamboo, Rattan, Palm and Straw Products	0.399	Manufacture of Computers, Communication and Other Electronic Equipment	1.172
Furniture Manufacturing	0.800	Manufacture of Measuring Instruments and Machinery	0.826
Papermaking and Paper Products	2.301	Other Manufacturing	0.956
Printing and Reproduction of Recording Media	0.957	Repair of Metal Products, Machinery and Equipment	0.436
Manufacture of Articles for Culture, Education, Arts and Crafts, Sports and Entertainment	0.517	Production and Supply of Electric Power and Heat Power	1.390
Processing of Petroleum, Coal and Other Fuels	0.448	Production and Supply of Gas	0.858
Manufacture of Raw Chemical Materials and Chemical Products	0.677	Production and Supply of Water	1.946

4.2 Data Calibration

Before applying the direct calibration method [22] (Ragin, 2008), we first calculated the five-year average for each antecedent variable for every case (industry). This step ensures that time-varying effects within each case are controlled for, aligning with the fixed-effects approach. In the absence of clear theoretical or external standards to guide the calibration of the antecedent conditions and the outcome variable, this study follows the precedent of prior research [40] and uses the descriptive statistics of the sample itself to set the calibration thresholds [23]. Specifically, the three anchors for calibration—the threshold for full membership, the crossover point, and the threshold for full non-membership—are set at the 75th, 50th, and 25th percentiles of the data distribution for each variable, respectively. The resulting calibration anchors are presented in Table 5.

Table 5 Calibration Anchors for Antecedent Conditions and the Outcome

Condition / Outcome	Full Membership (75%)	Crossover Point (50%)	Full Non-Membership (25%)
Green Technology Innovation Efficiency	1.026	0.609	0.354
Foreign Openness	0.122	0.084	0.036

Independent Technological Innovation	0.984	0.972	0.948
Government Financial Support	0.032	0.018	0.013
Intensity of Environmental Regulation	305,687.451	117,035.422	31,647.918
Market Demand	21,449.850	5,899.800	2,340.300
Degree of Marketization	0.936	0.893	0.675

4.3 Necessary Condition Analysis (NCA)

NCA identifies necessary conditions by analyzing the necessity effect size and statistical significance of individual antecedent variables. It also employs bottleneck analysis to evaluate the required level of an antecedent condition needed to achieve a specific level of the outcome [41]. The significance of the necessity is determined using a Monte Carlo simulation with permutation tests. NCA utilizes two estimation techniques, ceiling regression (CR) and ceiling envelopment (CE), to handle both continuous and discrete data [42]. The results of the necessity analysis are presented in Table 6.

Table 6 Necessity Analysis of Individual Antecedent Conditions

Antecedent Condition	Method	Accuracy	Ceiling Zone	Scope	Effect Size (d)	p-value
Foreign Openness	CR	100%	0.001	0.94	0.001	0.738
	CE	100%	0.002	0.94	0.002	0.733
Independent Technological Innovation	CR	97.4%	0.003	0.96	0.003	0.745
	CE	100%	0.004	0.96	0.004	0.759
Government Financial Support	CR	100%	0.001	0.95	0.002	0.705
	CE	100%	0.003	0.95	0.003	0.696
Intensity of Environmental Regulation	CR	100%	0.000	0.93	0.000	1.000
	CE	100%	0.000	0.93	0.000	1.000
Market Demand	CR	100%	0.000	0.93	0.000	0.848
	CE	100%	0.000	0.93	0.000	0.848
Degree of Marketization	CR	100%	0.000	0.94	0.000	0.667
	CE	100%	0.000	0.94	0.000	0.667

Notes: a. Calibrated fuzzy membership scores. b. The permutation test in the NCA analysis (number of permutations = 10,000).

Table 6 presents the results of the necessity analysis for each antecedent condition under both estimation methods. A condition is typically identified as necessary when its effect size (d) is greater than 0.1 and the p-value indicates statistical significance ($p < 0.05$) [42-45]. According to the NCA results, the necessity effects for foreign openness, independent technological innovation, government financial support, intensity of environmental regulation, market demand, and degree of marketization are all non-significant ($p > 0.05$), and their effect sizes (d) are all well below the 0.1 threshold. Therefore, we conclude that no single antecedent condition, when considered in isolation, constitutes a necessary condition for high green technology innovation efficiency.

Furthermore, the bottleneck analysis from NCA, as summarized from Table 7 (not shown), provides additional insights. It reveals that while no condition is strictly necessary, some exert a minor constraint. For example, to achieve an efficiency level of 80%, a government financial support level of at least 0.3% is required. This indicates a very small constraining effect. Across the full spectrum of outcomes (0% to 100% efficiency), except for the intensity of environmental regulation which exhibits "condition inefficiency" (Dul, 2016), the other variables show some level of constraint at the highest efficiency levels, but their constraining power is minimal. Although no factor qualifies as a necessary condition, the analysis suggests that the technological conditions (foreign openness and independent technological innovation) exert a relatively stronger constraint compared to the other factors.

Table 7 Bottleneck Analysis of Necessary Conditions (%)

Green Technology Innovation Efficiency	Foreign Openness	Independent Technological Innovation	Government Financial Support	Intensity of Environmental Regulation	Green Technology Innovation Efficiency	Foreign Openness
0	NN	NN	NN	NN	NN	NN
10	NN	NN	NN	NN	NN	NN
20	NN	NN	NN	NN	NN	NN
30	NN	NN	NN	NN	NN	NN
40	NN	NN	NN	NN	NN	NN
50	NN	NN	NN	NN	NN	NN
60	NN	NN	NN	NN	NN	NN
70	NN	NN	NN	NN	NN	NN
80	NN	NN	0.3	NN	NN	NN
90	NN	NN	0.7	NN	NN	NN
100	10.3	13.0	1.0	NN	1.0	2.1

Note: Results are based on the CR method. "NN" indicates "Not Necessary" at the given level of the outcome.

To further probe the necessity of the antecedent conditions, we next employed fsQCA to test whether any single condition (or its negation) is necessary for achieving high or non-high green technology innovation efficiency. Following the guideline proposed by Schneider et al. (2012), a condition is considered necessary if its consistency score is greater than 0.9 [46]. As shown in the necessity analysis results in Table 8, the consistency scores for all individual antecedent conditions are below the 0.9 threshold. This holds true for both the presence and absence of each condition in relation to both high and non-high efficiency outcomes. This confirms the NCA findings and underscores the need to proceed with a sufficiency analysis to explore how combinations of these conditions lead to the outcome.

Table 8 fsQCA Necessity Analysis

Antecedent Condition	High Green Technology Innovation Efficiency		Non-high Green Technology Innovation Efficiency	
	Consistency	Coverage	Consistency	Coverage
Foreign Openness	0.548	0.534	0.651	0.559
~Foreign Openness	0.556	0.565	0.509	0.549
Independent Technological Innovation	0.469	0.469	0.740	0.584
~Independent Technological Innovation	0.632	0.624	0.409	0.496
Government Financial Support	0.581	0.595	0.529	0.511
~Government Financial Support	0.537	0.519	0.409	0.496
Intensity of Environmental Regulation	0.355	0.359	0.760	0.712
~Intensity of Environmental Regulation	0.742	0.725	0.380	0.371
Market Demand	0.465	0.471	0.689	0.634
~Market Demand	0.662	0.648	0.487	0.484
Degree of Marketization	0.462	0.447	0.764	0.646
~Degree of Marketization	0.661	0.676	0.431	0.474

4.4 Sufficiency Analysis of Configurational Paths

Having established that no single condition is necessary, we now proceed with the sufficiency analysis to identify which combinations of conditions are sufficient for achieving high green technology innovation efficiency. The analysis parameters were set as follows: following standard practice, the consistency threshold was set to 0.8 [40]. The case frequency threshold was set to 1, ensuring that the resulting configurations account for at least 75% of the observed cases. To minimize potential logical contradictions, the Proportional Reduction in Inconsistency (PRI) consistency threshold was set to 0.7 [41]. The analysis generated three types of solutions: complex, parsimonious, and intermediate. In line with conventional QCA reporting, the intermediate solution is presented as the primary result, with the parsimonious solution used as a reference to distinguish between core and peripheral conditions (i.e., core presence, core absence, peripheral presence, and peripheral absence) [41]. The results of this analysis are presented in Table 9.

Table 9 Configurations for High and Non-high Green Technology Innovation Efficiency

Antecedent Conditions	High Green Technology Innovation Efficiency				Non-high Green Technology Innovation Efficiency			
	H1	H2	H3	H4	U1	U2	U3	U4
Foreign Openness	●	•	⊗	●		●	⊗	•
Independent Technological Innovation		●	●	⊗	•	●	•	⊗
Government Financial Support	•	•	⊗	●	⨂		⊗	•
Intensity of Environmental Regulation	⊗	⨂	⨂	⨂	●	●	●	●
Market Demand	⨂		⊗	•	●	•	⨂	⨂
Degree of Marketization (DM)	⨂	⨂	⨂	●	•	•	●	●
Raw Coverage	0.103	0.095	0.086	0.190	0.175	0.378	0.186	0.094
Unique Coverage	0.052	0.011	0.073	0.138	0.041	0.188	0.068	0.016
Consistency	0.929	0.923	1.00	0.823	0.941	0.904	0.936	0.877
Overall Solution Consistency	0.899				0.914			
Overall Solution Coverage	0.362				0.525			

Note: ● *indicates the presence of a core condition;* • *indicates the presence of a peripheral condition;* ⨂ *indicates the absence of a core condition;* ⊗ *indicates the absence of a peripheral condition. Blank spaces indicate a "don't care" condition.*

As shown in Table 9, there are four configurations (paths) that lead to high green technology innovation efficiency. The overall solution consistency is 0.899, which is well above the established 0.8 threshold, confirming that these four paths collectively represent sufficient conditions for achieving high efficiency [47]. The overall solution coverage is 0.362, indicating that these four paths together explain a substantial proportion of the cases exhibiting high green technology innovation efficiency [22]. Paths H1 and H2 show strong individual consistency scores of 0.929 and 0.923, respectively, with raw coverage scores of 0.103 and 0.095. This confirms that both are valid sufficient pathways, each explaining a meaningful share of the outcome cases. In these paths, either foreign openness or independent technological innovation acts as the core driver, consistently supported by government funding, while other conditions function as "don't care." We therefore label this pathway type "Technology-led, Government-supported." Path H3 has a perfect consistency of 1.000 and a raw coverage of 0.086, establishing it as a sufficient condition that explains a distinct set of cases. Here, independent technological innovation is the sole core driver, while the other conditions are marked by core or peripheral absence. This signifies that their absence is crucial for this path to be effective. Consequently, we name Path H3 "Technology-led, Independent-innovation." Path H4, with a consistency of 0.823 and the highest raw coverage of 0.190, is also a sufficient path explaining a significant number of cases. It is characterized by the synergy of multiple factors, with foreign openness, government financial support, and the degree of marketization all acting as core conditions. We therefore label this path "Environment-Technology-Organization Synergy."

4.4.1 Configurations for high green technology innovation efficiency

The Technology-led, Government-supported Path (H1 and H2). Path H1 as shown in Figure 2 indicates that a combination of high foreign openness (core presence), coupled with the core absence of high marketization and high market demand, leads to high green innovation efficiency. This is peripherally supported by the presence of government funding and the absence of high environmental regulation. Similarly, Path H2 as shown in Figure 3shows that high independent technological innovation (core presence), also combined with the core absence of high marketization and high environmental regulation, achieves the same outcome, with foreign openness and government support acting as peripheral conditions. Synthesizing these two paths reveals a key insight: high green technology innovation efficiency is achievable even in the face of low environmental regulatory pressure and unfavorable market conditions. This can be accomplished by leveraging either foreign openness or independent innovation to advance an industry's technological level, particularly when coupled with government financial support. This is exemplified by cases such as the "Metal Products, Machinery and Equipment Repair," "Other Manufacturing," and "Special-Purpose Equipment Manufacturing" industries. These sectors often exhibit low market demand elasticity and are order-driven, making their innovation activities less sensitive to broad market fluctuations. In other words, for these industries, the primary driver of high efficiency is the enhancement of their internal technological capabilities—either by attracting foreign capital and technology (FO) or by strengthening independent innovation (ITI). In this context, government financial support acts as a crucial catalyst, prompting these industries to intensify their green innovation efforts.

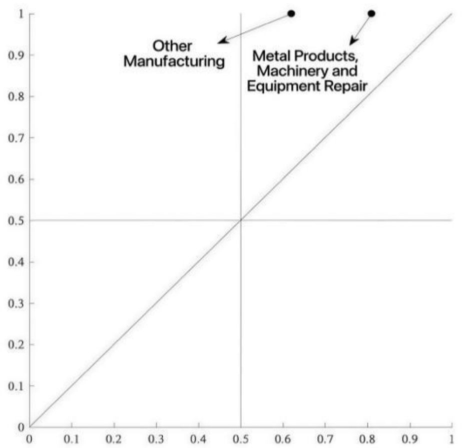

Figure 2 Configuration H1 Case

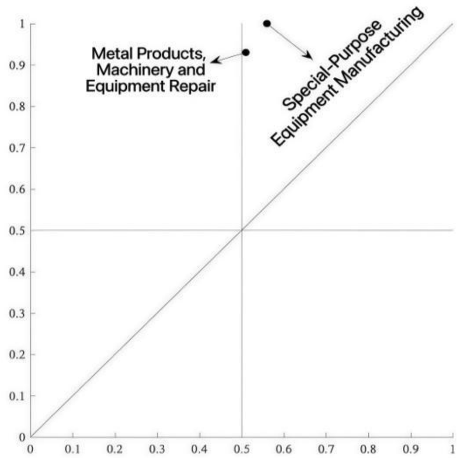

Figure 3 Configuration H2 cCase

The Technology-led, Independent-innovation Path (H3) as shown in Figure 4. Path H3 demonstrates that high green technology innovation efficiency can be achieved through a core combination of high independent technological innovation, the absence of high environmental regulation, and the absence of high marketization. This path is further defined by the peripheral absence of foreign openness, government financial support, and market demand. This configuration reveals a powerful dynamic: industries can achieve high innovation efficiency even when both organizational and environmental conditions are unfavorable. Adversities such as weak market demand or minimal government support do not fundamentally hinder the drive for green technology innovation in this pathway. The "Production and Supply of Gas" industry serves as a classic example. This sector is characterized by its broad population and regional coverage, massive service volume, and extremely low user demand elasticity, with a total industry value exceeding one trillion CNY.

Furthermore, given its significant impact on the national economy and other sectors (approaching 8% of GDP influence), this industry is predominantly state-controlled. As a critical "livelihood" sector, it bears a substantial social responsibility that transcends typical market or organizational pressures. Even without strong external support or regulatory constraints, such industries are internally motivated to continuously pursue technological innovation. This intrinsic drive propels the development of green technologies within the sector, contributing significantly to the national "dual carbon" targets.

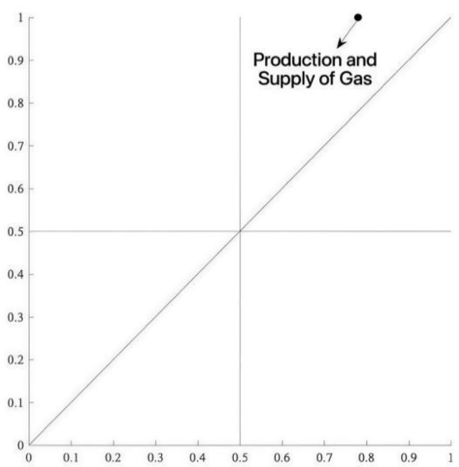

Figure 4 Configuration H3 Case

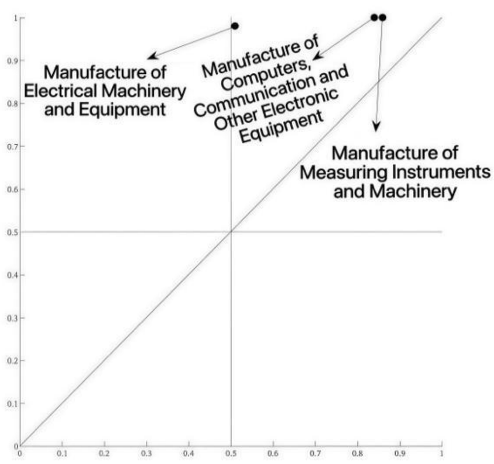

Figure 5 Configuration H4 Case

The Environment-Technology-Organization Synergy Path (H4), as shown in Figure 5. Path H4 illustrates that high green technology innovation efficiency can be achieved through a core combination of high foreign openness, a high degree of marketization, substantial government financial support, and the absence of high environmental regulation. This is peripherally supported by the presence of market demand, while independent innovation is marked by peripheral absence. This configuration demonstrates that for some industries, no single dimension—be it organizational, technological, or environmental—is sufficient on its own to drive green innovation. Instead, it is the synergistic interplay of all three that unlocks high efficiency. In a favorable market environment, high marketization and strong market demand provide the necessary resources. These resources fuel technological advancement, which is further bolstered by the support and security of government funding. Only through this tripartite collaboration can a higher level of green technology innovation be realized. This pathway is exemplified by industries such as the "Manufacture of Electrical Machinery and Equipment," "Manufacture of Computers, Communication and Other Electronic Equipment," and "Manufacture of Measuring Instruments and Machinery." These sectors are characterized by precision manufacturing, which inherently demands a high level of technology. Consequently, they do not generate significant volumes of industrial "three wastes." However, their R&D investments and capital requirements are substantial. Fortunately, these industries benefit from a high degree of marketization and a broad user base. In this context, government financial support plays a dual role: it not only assists these industries in enhancing their innovative capabilities and overcoming international technology barriers, but it also directly secures the achievement of high green technology innovation efficiency.

4.4.2 Configurations for non-high green technology innovation efficiency

The analysis of pathways leading to non-high green technology innovation efficiency also reveals four distinct configurations:

Path U1 is defined by the core conditions of high-intensity environmental regulation, the absence of strong government financial support, and high market demand. Supported by peripheral presence of marketization and independent innovation, this combination leads to non-high efficiency. This path highlights a conflict between government environmental regulations and market demand. Because industries are unable to reconcile these competing pressures effectively, government funding (or the lack thereof) fails to alleviate the industry's green innovation dilemma. In this scenario, neither internal innovation efforts nor a market-oriented environment can avert a low-efficiency outcome.

Path U2 shows that even with high levels of foreign openness and independent innovation, the presence of high-intensity environmental regulation leads to non-high efficiency. This is peripherally supported by market demand and marketization. In this configuration, high levels of openness and innovation fail to synergize with market forces to improve green innovation. Instead, the intense environmental regulation, rather than compelling positive change, combines with other factors to produce an unfavorable outcome. This suggests that the "Schrödinger's cat" condition of government support—its presence or absence in the model—may be a critical missing factor that could rescue these industries from low efficiency.

Path U3 demonstrates that a core combination of high-intensity environmental regulation, the absence of high market demand, and a high degree of marketization results in non-high efficiency. This is peripherally shaped by the absence of government support and foreign openness, and the presence of independent innovation. This path suggests that even within a highly marketized environment, ill-conceived environmental regulations can suppress green innovation. In this context, strong market demand not only fails to stimulate green innovation but may even perversely incentivize non-green technological innovation, thereby depressing overall green efficiency.

Path U4 shares the same core conditions as U3 but exhibits a symmetrical pattern in its peripheral conditions. It reinforces the finding that in an otherwise favorable market environment, excessive environmental regulation can stifle green innovation. The role of government financial support becomes negligible in this context. Furthermore, foreign openness—such as attracting foreign technology and investment—not only fails to mitigate the suppressive effect of the regulations but combines with it to lock the industry into a state of non-high green technology innovation efficiency.

4.5 Robustness Check

To ensure the reliability of the findings, a robustness check was conducted following established practices. This was done by increasing the stringency of the PRI consistency threshold to 0.75 [48]. The results of this re-analysis showed no significant changes; the configurations remained consistent, and the consistency and coverage scores for both the individual solutions and the overall solution were stable. This indicates that the findings of the study are robust.

5 CONCLUSION AND IMPLICATIONS

5.1 Research Conclusions

As the conflict between economic development and environmental sustainability intensifies, green technology innovation has become a cornerstone of high-quality social development. The roles of technological, organizational, and environmental conditions are undeniable. Understanding how these factors combine in synergistic configurations to achieve high efficiency is crucial for advancing green innovation. Based on the TOE framework and integrating DEA, NCA, and fixed-effects fsQCA, this study analyzed the configurational effects of these conditions on green technology innovation efficiency, leading to the following conclusions:

First, by combining NCA with fixed-effects fsQCA, we find that no single antecedent condition is necessary for achieving high green technology innovation efficiency. However, the technological conditions exert a relatively stronger constraining effect compared to others. Second, the study identifies three distinct configurational pathways to high efficiency: a "Technology-led, Government-supported" path, a "Technology-led, Independent-innovation" path, and an "Environment-Technology-Organization Synergy" path. These different configurations represent effective, alternative strategies for various industrial sectors to enhance their green innovation efficiency. Third, the analysis reveals that even within a favorable market environment, inappropriate environmental regulations can suppress innovation, highlighting that the effectiveness of organizational conditions is subject to certain limitations or thresholds.

5.2 Theoretical Contributions

This study makes several key theoretical contributions to the literature on the determinants of green technology innovation efficiency:

First, grounded in the TOE framework, this study incorporates a temporal dimension into the configurational analysis, providing a more objective investigation of the synergistic effects of technological, organizational, and environmental conditions. Previous studies have often relied on methods like pooled OLS [36], spatial econometric models [49], multiple linear regression [50], or static fsQCA [12-13], which tend to overlook temporal dynamics and the complex interplay among antecedent conditions. By using DEA-measured efficiency as the outcome and employing a combination of NCA and fixed-effects fsQCA, our research provides a more scientifically robust analysis of how configurations, not just individual factors, drive green innovation. This not only expands the research on influencing factors but also enriches the application of dynamic configurational analysis.

Second, this study constructs a multi-dimensional, two-stage measurement system for green technology innovation efficiency, advancing the research on its evaluation. Much of the prior literature has used simple proxies like the total number of green patents [19] or green patents granted [51], which neglect the input-output process and fail to capture the full picture of innovation. By using a super-efficiency SBM-DEA model to build a two-stage measurement framework with multiple inputs and outputs, this study offers a more accurate and comprehensive reference for assessing green technology innovation efficiency.

5.3 Policy Implications

Based on the research findings, this study proposes policy recommendations for different industrial sectors in China to achieve high green technology innovation efficiency, structured around the three identified pathways:

First, for the "Technology-led, Government-supported" path, the findings show that with the assurance of government funding, both attracting foreign technology and capital and pursuing independent innovation can effectively boost efficiency. Therefore, in industries with high foreign openness or strong independent innovation capabilities, the government should implement matched funding schemes tied to specific outcomes, such as attracting foreign investment or achieving milestones in indigenous innovation projects. This should be coupled with strengthened oversight of government fund utilization and the formulation of reasonable environmental policies to foster a supportive innovation ecosystem.

Second, for the "Technology-led, Independent-innovation" path, the results indicate that high efficiency is achievable through a singular focus on independent innovation, even with weak market conditions and limited government support. For industries on this path, the government should grant a degree of trust and autonomy. This involves enacting policies that stimulate independent innovation, encouraging these industries to leverage their unique characteristics and optimize resource allocation based on their strengths. However, the government must also maintain a regulatory role, supervising industry behavior and ensuring adherence to market principles to guide them toward high green innovation efficiency.

Third, for the "Environment-Technology-Organization Synergy" path, it is clear that no single dimension is sufficient; success requires the organic combination of all three. In favorable market environments, the government should increase financial support to stimulate industries to absorb foreign capital and advanced technologies, learning from global best practices to achieve rapid technological advancement. In this process, the government must act as both a "gatekeeper" and a "stabilizer," not only maintaining a healthy market order but also carefully vetting foreign technologies to adopt their strengths while discarding their weaknesses, thereby ensuring the faster and better development of green technology innovation.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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