UNRAVELING CAUSAL PATHWAYS WITH DYNAMIC PANEL QCA: HOW POLICY MIXES DRIVE CARBON EMISSIONS REDUCTION IN CHINA UNDER THE TOE FRAMEWORK

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Abstract. Identifying key factors that can improve the efficiency of efforts to reduce carbon emissions against the backdrop of policy superposition is essential to achieving China’s dual carbon goals, namely reaching its carbon emissions peak before 2030 and becoming “carbon neutral” before 2060. Using the technology-organization-environment framework to construct the dimensions of influencing factors and panel data from China’s 30 provinces from 2001 to 2021, we use the dynamic panel Qualitative Comparative Analysis method to analyze the multi-factor configuration of carbon emissions reduction. We find that while no single factor can be regarded as a necessary condition for achieving high carbon emissions reductions, the importance of green technology innovation, green finance, human capital, changes in the industrial structure, and energy consumption increases year by year over the sample period, revealing the presence of a time effect. We identify five configuration paths for achieving high carbon emissions reduction, which can be further refined into three driving models, namely, green innovation-led organizational collaboration, green finance-led organizational collaboration, and green innovation-led human capital collaboration. Among these, the green innovation-led human capital collaboration approach is the most common. The between consistency adjusted distance and within consistency adj-distance of these three driving models are below the threshold value of 0.2, indicating they have no significant time or regional effects, and have strong explanatory ability and universally adaptable values. These results indicate a diversified driving path for carbon emissions reduction across China's provinces.
Keywords: *policy superposition, carbon emissions reduction, TOE framework, dynamic panel QCA, China's provinces*

List of abbreviations. BECONS: Between Consistency; CER: Carbon Emissions Reduction; ECS: Energy Consumption Structure; EDGAR: Emissions Database for Global Atmospheric Research; GFDL: Green Finance Development Level; GTIL: Green Technology Innovation Level; HC: Human Capital; IE: Income Equilibrium; ISC: Industrial Structure Change; NCA: Necessary Condition Analysis; POCONS: Pooled Consistency; POCOV: Pooled Coverage; QCA: Qualitative Comparative Analysis; TOE: Technology-Organization-Environment; UNFCCC: United Nations Framework Convention on Climate Change; WICONS: Within Consistency

Introduction

The past century has witnessed profound changes in the global climate system, largely attributable to anthropogenic emissions of greenhouse gases from fossil fuel combustion. As the principal contributor, carbon dioxide (CO_2) has been identified as the key driver of this transformation. The consequences are increasingly evident through the rising frequency and severity of extreme weather events—including droughts, hurricanes, tornadoes, and wildfires—coupled with shifts in fundamental meteorological patterns such as temperature, radiation, precipitation, and wind speed. These alterations not only

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amplify atmospheric pollutant levels and their dispersal but also intensify regional air pollution, thereby challenging sustainable development and human security. In this context, climate change emerges as one of the most critical global issues of our time.

While international awareness of climate mitigation has heightened in recent decades, and the growth rate of global CO_2 emissions has shown some moderation, aggregate emissions continue their upward trajectory. Illustratively, global carbon emissions in 2023 exceeded 2022 levels by 0.1% (Liu et al., 2024a). Consequently, implementing effective carbon emissions reduction (CER) strategies has become an urgent common agenda for nations worldwide. China, as the largest global emitter of CO_2, plays a decisive role. The fulfillment of its national emission targets and commitments under the United Nations Framework Convention on Climate Change (UNFCCC) is therefore pivotal to the success of international climate efforts.

China's pursuit of CER is marked by distinct challenges. Its economic structure remains heavily dependent on secondary industries, which are characterized by high energy consumption, substantial carbon emissions, and relatively low energy efficiency. Compounding this, the ongoing expansion of energy-intensive sectors and a continued reliance on fossil fuels—constituting 84.1% of the energy mix in 2020 (Xu et al., 2024)—present considerable obstacles to achieving its "dual carbon" goals of peaking emissions by 2030 and reaching carbon neutrality by 2060. Nonetheless, China has progressively integrated climate response into its national development agenda, elevating climate adaptation to a strategic priority. A series of policy initiatives underscore this commitment, including the *National Plan for Tackling Climate Change (2014–2020)*, the *uidance on Building a Green Financial System* 2016), *esponding to Climate Change: China's Policies and Actions*, the *ction Plan for Carbon Dioxide Peaking Before 2030* 2021), and a comprehensive energy conservation and emissions reduction framework within the14th Five-Year Plan 2022. These measures have yielded discernible progress in China's CER trajectory and contributed meaningfully to global climate governance. Within this policy-dense environment, understanding the drivers of CER, their specific effects, and their interactive mechanisms has become a pressing concern for researchers and decision-makers.

Literature review on CER drivers and analytical approaches

Carbon emissions reduction is integral not only to global sustainability but also to China's transition towards high-quality economic development (Broadstock et al., 2021). This dual significance has stimulated extensive scholarly work, which can be broadly classified into two analytical streams: one examining the net effects of single factors, and another investigating the configurational effects of multiple factors.

Single-factor net effect research

This strand of literature assesses the independent influence of individual drivers on CER. A considerable body of evidence underscores the role of green innovation, which appears to reduce carbon emissions both within a region and in neighboring areas via knowledge and technology spillovers (Shan and Shao, 2024; Zhang et al., 2024; Mardyana and Mahata, 2024). Other factors identified as effective include new urbanization, optimized urban planning, and the reallocation of resources toward lower emission intensities (Li et al., 2023a; Xiang et al., 2024). Public environmental concern has also been shown to exert pressure on governments and firms to adopt greener practices (Wang et al., 2024a). Furthermore, synergistic shifts in energy and industrial

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structures—such as transitioning from coal to renewables and scaling down high-emission industries—have demonstrated significant potential for emission reduction (Lin and Liao, 2023).

Human capital represents another critical driver. Studies by Khan (2020), Yao et al. (2021), and Zhang et al. (2023) suggest that human capital—often proxied by education and skill levels—not only directly promotes CER but also facilitates the shift to a low-carbon economy by enhancing innovative capacity. Income distribution also plays a part; Yan et al. (2023a) and Hou et al. (2024) find that narrowing urban–rural income inequality can help decouple economic growth from carbon footprint expansion, positing that a larger middle class tends to exhibit stronger environmental preferences and demand for green products.

Financial and digital dimensions have attracted comparable attention. Green finance, implemented through policy tools such as preferential loans and green credit, directly lowers emissions while also stimulating industrial upgrading and technological innovation (Ran and Zhang, 2023; Jiang et al., 2024; Li and Xu, 2024; Lu and Xia, 2024; Yin et al., 2024). Similarly, digital inclusive finance improves small and medium-sized enterprises' access to green investment, further supporting emission reduction. The digital economy and its underlying infrastructure—including 5G and big data—also contribute by optimizing industrial structures, adjusting energy mixes, and strengthening environmental regulation (Chen et al., 2023; Pan et al., 2023; Peng et al., 2024).

Multi-factor configuration effect research

Recognizing that CER is seldom driven by isolated factors, a growing body of research adopts a systemic perspective, analyzing how multiple factors combine to produce outcomes. Methods such as qualitative comparative analysis (QCA) are frequently employed. Xiong and Sun (2023), applying fuzzy-set QCA (fsQCA), identified three distinct pathways to reduce corporate carbon emissions through configurations of green innovation, green insurance, green investment, and industrial structure. Cao and Chen (2023) used fsQCA to study ecological civilization construction, revealing three effective configurational paths: eco-economy-led, eco-environmental protection-led, and land space optimization-led.

Other studies focus on specific thematic domains. Yin and Wang (2024) examined the alignment of ambidextrous green innovation strategies, external policy environments, and slack resource structures, concluding that successful CER depends on their coordinated interaction. Zhang and Liao (2024) analyzed the digital economy using fsQCA, identifying four configuration paths: digital technology-led, digital finance-led, industrial digitalization-led, and digital industrialization-led. Zhao and Feng (2024) adopted dynamic QCA to show that deep integration of digital finance, scientific innovation, and environmental regulation significantly improves emission reduction efficiency. Chen et al. (2024a) combined fsQCA with necessary condition analysis (NCA) across six dimensions—energy consumption, industrial structure, technological innovation, government support, economic development, and demographic factors—finding that configurations dominated by economic growth or low energy consumption achieve high CER performance.

A limited but growing number of studies apply the Technology–Organization–Environment (TOE) framework to CER. Shi and Wang (2024) used the TOE framework with fsQCA to identify three configuration paths for agricultural low-carbon transitions: machinery-leading, machinery–structure collaboration, and structure–environment

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collaboration. Wang et al. (2024b) further established that the presence of at least 80% of TOE factors constitutes a critical threshold for effective CER and noted a “Matthew effect” in carbon reduction, whereby initial advantages in drivers tend to accumulate over time.

Research gaps and adapted TOE framework

Identification of research gaps

Despite these contributions, three significant research gaps remain, particularly salient in the context of China's “policy superposition”—the concurrent implementation of multiple CER policies. (1) Fragmented Factor Analysis. redominant single-factor studies focus on net effects, while multi-factor research often examines partial configurations (e.g., limited to digital economy or ecological civilization factors), rather than integrating drivers across technological, organizational, and environmental dimensions. This fragmented approach obscures the systemic and interdependent nature of CER, leaving the holistic picture of multi-factor synergy inadequately understood. (2) Insufficient Dynamic and Contextual Analysis. ew studies employ dynamic methods to trace how multi-factor linkages evolve temporally, especially under policy superposition. Moreover, individual heterogeneity across Chinese provinces and the influence of China's unique institutional context—such as central–local policy coordination and state-owned enterprise dominance—remain underexplored, limiting explanations for temporal and spatial variations in CER outcomes. (3) Inadequate Adaptation of the TOE Framework. Although the TOE framework is well-suited to analyzing multi-level drivers of technological adoption, its application to regional CER in China remains underdeveloped. Existing studies often apply the framework generically without contextual refinement, or define its core dimensions too broadly, failing to cleanly map CER-specific factors onto technological, organizational, and environmental contexts. This reduces the framework’s explanatory power for China's distinctive CER challenges.

Construction of a TOE framework for China's CER

Originally proposed by Tornatzky and Fleischer (1990), the TOE framework analyzes technological adoption through three contexts: the *technological* (tools and innovations enabling change), the *organizational* (internal structures and capacities), and the *environmental* (external conditions shaping behavior). Its explanatory power and adaptability have been demonstrated across diverse technological scenarios (Chen et al., 2024b; Wang et al., 2024b). The framework aligns naturally with CER research, as key drivers identified in the literature readily map onto these three dimensions, with green technology innovation at the core (Su et al., 2022). To address the identified gaps, this study adapts the TOE framework to China’s context by defining six CER-specific factors across the three dimensions: (1) Technological: Enterprises stand as central actors in achieving CER targets. Through green innovation technologies, they can enhance energy utilization efficiency and strengthen their CER engagement via positive spillovers such as cost savings and reputational gains (Su et al., 2022). Green finance—a policy-oriented financial instrument—complements this process by providing credit support and preferential interest rates to environmentally sound enterprises. This channeling of credit toward low-carbon and clean production sectors (Han et al., 2023) raises the share of green production capacity and indirectly pressures high-energy-consuming firms toward green transformation through tightened financial constraints (Zhang et al., 2021), thereby collectively advancing CER. (2) Organizational: Organizational factors encompass the

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social structures and human capacities underpinning CER. First, balanced income distribution is crucial. Magnani (2000) contends that the environmental preferences of middle-income groups prove decisive in environmental policy formation, as a larger middle class boosts demand for green products and policies. A widening income gap shrinks this group, dampening environmental demand and raising emissions. Conversely, greater income equality correlates with lower per capita CO_2 emissions and facilitates the implementation of energy conservation policies (Rojas-Vallejos and Lastuka, 2020; Yan et al., 2023a). Second, human capital serves as a key driver of long-term endogenous growth, enhancing energy efficiency and underpinning sustainable development. Khan (2020) observes that higher human capital levels strengthen the capacity of economic development to reduce CO_2 emissions; Yao et al. (2021) identify a long-term negative correlation between human capital (propelled by a younger, highly educated labor force) and emissions; and Gao et al. (2022) show that human capital accumulation lowers energy consumption via economic restructuring and technological innovation. Bie and Zhou (2024) further emphasize that high-quality human capital is indispensable for adjusting industrial structures and achieving the green technological progress necessary to reach carbon peaking. (3) Environmental: Environmental factors refer to external structural conditions shaping the CER landscape. Industrial structure upgrading—through rationalization (raising the share of low-emission tertiary industries) and advancement (adopting high-tech, low-carbon technologies)—reduces emissions by decoupling economic growth from energy-intensive secondary sectors (Yuan and Sun, 2020), promoting low-carbon R&D, and optimizing the allocation of innovative resources (Zhao et al., 2022). Energy consumption structure adjustment is equally critical. Zhang et al. (2022) find that reducing fossil fuel dependence (e.g., by increasing renewable energy share) exerts a significant negative impact on carbon emissions, and Li et al. (2023b) confirm that such adjustments directly curb energy-related CO_2 emissions. In summary, CER in China constitutes a synergistic process driven by six factors distributed across the technological, organizational, and environmental dimensions of the TOE framework. This study investigates whether these factors represent necessary conditions for high CER performance and analyzes their configurational effects under policy superposition. The research model is illustrated in *Figure 1*.

Research objectives and questions

Against the backdrop of policy superposition and the identified research gaps, this study sets out to systematically analyze the complex mechanisms of CER in China using a context-adapted TOE framework. The core research objectives are as follows: (1) To uncover synergistic effects among the six TOE-based drivers—green technology innovation, green finance, income equilibrium, human capital, industrial structure upgrading, and energy consumption structure adjustment—under policy superposition. (2) To examine whether these drivers exhibit time effects (temporal variation in influence) or individual effects (provincial heterogeneity). (3) To identify key configuration paths of multi-factor collaboration that lead to high CER performance across Chinese provinces. To achieve these objectives, the study addresses two core research questions: (1) What synergistic effects characterize the drivers of CER in the context of China's policy superposition? (2) Do these drivers exhibit temporal or provincial heterogeneity, and if so, how do such heterogeneities shape CER outcomes?

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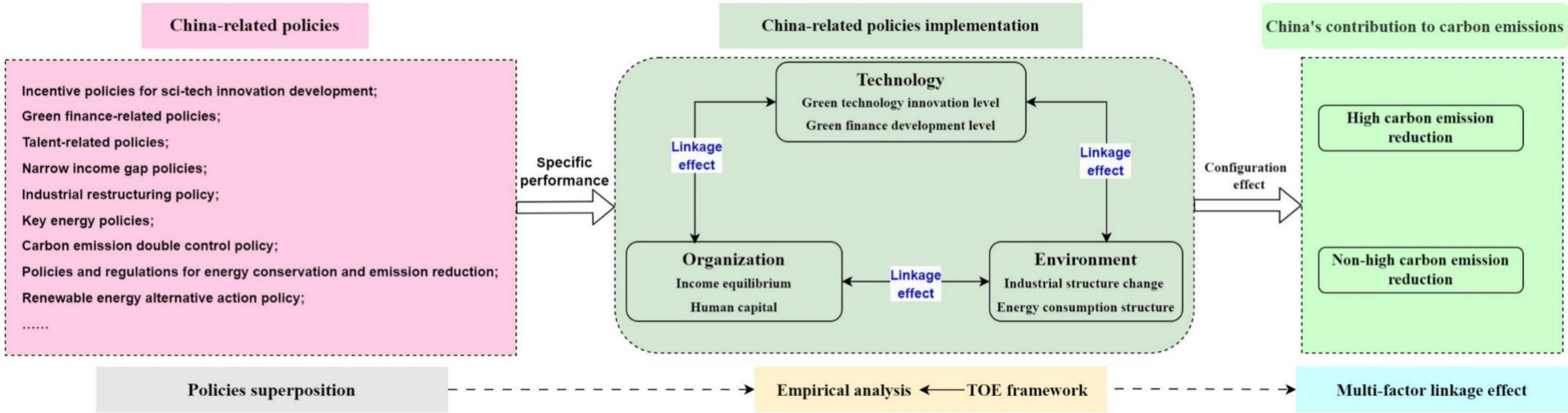

Figure 1. *Research ideas and TOE integration framework of factors influencing carbon emissions reduction*

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To answer these questions, we utilize panel data from 30 Chinese provinces (excluding Tibet, Hong Kong, Macao, and Taiwan due to data availability) covering the period 2001–2021. We construct the context-adapted TOE framework and apply dynamic QCA to analyze configurational effects and complex causal relationships. The findings aim to offer theoretical insights and practical strategies for optimizing CER policy in China.

Materials and methods

Materials

Data sources

To ensure the continuity, soundness, relevance, and availability of our data, we select panel data on China's 30 provinces (excluding Hong Kong, Macao, Taiwan, and Tibet) from 2001 to 2021. CO_2 emissions data is from the Emissions Database for Global Atmospheric Research (EDGAR). The original data was formatted as txt grid data, which was processed by ArcGis. We aggregated and extracted CO_2 emissions panel data on all fossil fuel sources of CO_2, including fossil fuel combustion, non-metallic mineral processing (e.g., cement production), metal (ferrous and non-ferrous) production processes, urea production, and agricultural lime and solvent use. Relevant antecedent condition data comes from the China Statistical Yearbook, China Science and Technology Statistics Yearbook, China Energy Statistics Yearbook, Provincial statistical yearbook, Statistical Bulletin of National Economic and Social Development from each province, and the China Human Capital Report (compiled by the Central University of Finance and Economics) from 2001~2021. Missing data is filled in using an ARIMA model using the same province data during 2001~2021.

Variable selection and calibration

(1) Variable selection. Outcome variable: Based on previous studies (Guo and Wang, 2023; Ahmed et al., 2024), CO_2 emission is the outcome variable in this study. Antecedent condition variables: *Green technology innovation level (GTIL).* We use the number of green patents granted to measure the level of green technological innovation (Gao et al., 2022; Miao and Zhao, 2023). *Green finance development level (GFDL).* Following Chen and Chen (2021) and Wang et al. (2023), we use the entropy value method to assess the level of green finance development in each Chinese province across the following seven dimensions: green credit, green securities, green investment, green insurance, green funds, green supports, and green rights and interests. *Income equilibrium (IE).* Income equality in a given area is frequently expressed using the Gini coefficient (Oanh and Ha, 2023). We calculate the Gini coefficient using the method proposed in Tian (2012). *Human capital (HC).* There is currently no standard measure of HC. The China Human Capital Report from the Central University of Finance and Economics uses the J–F approach (Jorgenson and Fraumeni, 1989; Fraumeni et al., 2019) which provides a useful indicator of HC stock. We use this measure of real per capita human capital stock in prices from the year 2000, published in the 2022 edition of this report. *Industrial structure change (ISC).* We use the ratio of the value of tertiary industries output to secondary industries output to measure the optimization of a province's industrial structure (Liang et al., 2023). *Energy consumption structure (ECS).* This measure incorporates data available at the prefecture-level cities. Electricity consumption from natural gas and clean energy are selected as representative energy uses, and energy consumption structure is measured as

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a proportion of total energy consumption from these two sources. The size of the proportion represents the proportion of clean energy in the energy consumption structure, reflecting the reasonable degree of energy consumption structure (Liu et al., 2024b). *Table 1* shows variable descriptions, measurements, and data sources.

Table 1. *Variable descriptions, measurements, and data sources*

Variable	Description	Measurement	Unit	Source
CO_2 emissions	Carbon dioxide emissions	Total CO_2 emissions from fossil fuels and industrial processes	tons	EDGAR database
GTIL	Green technology innovation level	Number of green patents granted	count	China Statistical Yearbook
GFDL	Green finance development level	Entropy value index from seven dimensions	index	China Statistical Yearbook
IE	Income equilibrium	Gini coefficient	coefficient	Calculated based on Oanh and Ha (2023)
HC	Human capital	Real per capita human capital stock (J-F method)	CNY	China Human Capital Report 2022
ISC	Industrial structure change	Ratio of tertiary to secondary industry output value	Ratio	China Statistical Yearbook
ECS	Energy consumption structure	Share of natural gas and clean energy in total consumption	%	China Energy Statistics Yearbook

(2) Variable calibration. Following existing QCA research, we perform a data calibration using objective quantiles. We define the 95th, 50th and 5th quantiles of the antecedent condition variables and the outcome variable as the anchor points of “full membership”, “cross point”, and “completely unaffiliated”, and calibrate the data to a membership degree of 0 to 1 (Du et al., 2021, 2022; Zhang and Ma, 2023). At the same time, fuzzy membership, a value of 0.500 is changed to 0.499 or 0.501 to avoid classification difficulties (Fiss, 2011; Crilly et al., 2012). *Table 2* shows the final calibration results and descriptive statistics for each variable.

Table 2. *Calibration results and descriptive statistics*

Variable type	Variable	Fuzzy sets calibration			Descriptive statistics			
		Full membership	Cross point	Completely unaffiliated	Mean	SD	Min	Max
Outcome variable	*CER*	20413.583	5754.409	1039.644	7331.249	5459.450	241.688	27409.624
Technology factors	*GTIL*	9782.550	512.500	16.450	2128.887	4510.483	1.000	45359.000
	GFDL	0.853	0.646	0.452	0.652	0.129	0.420	0.899
Organization factors	*IE*	0.501	0.427	0.356	0.428	0.047	0.344	0.520
	HC	29400.400	7766.000	974.550	10498.806	9510.981	274.000	54682
Environment factors	*ISC*	2.161	0.900	0.605	1.072	0.597	0.494	5.297
	ECS	24.871	8.740	3.740	10.960	7.757	0.383	50.166

Research method

Qualitative Comparative Analysis, an approach to configuration analysis based on Boolean logic and algebra, explores multiple concurrent causality relationships between multiple antecedent conditions (Ragin, 2008). However, traditional QCA primarily uses cross-sectional data to analyze problems from a static perspective. Given that it lacks a

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time dimension it is limited in terms of the configurations it can produce, as deviations in a sample over time are common. Thus, a traditional QCA can draw configuration conclusions based on unstable conditions, creating controversy over the validity of the approach. To make up for this shortcoming, Garcia-Castro and Ari (2016) propose a dynamic QCA method based on panel data, which includes the concepts of “between consistency (BECONS) ”, “within consistency (WICONS) ” and “pooled consistency (POCONS) ”, allowing researchers to observe the degree of change and resulting effect of a given configuration in both the time dimension and individual dimension (Guedes et al., 2016; Beynon et al., 2020), to determine whether the case involves time or individual effects and its stability, based on consistency- adjusted distances. Using the R package’s SetMethods (Oana and Schneider, 2018), in this study we apply the dynamic QCA method with panel data to explore multiple configuration paths of China's CER under the background of policy superposition.

The configuration development in this study is theoretically grounded in the TOE framework, which posits that technological adoption and implementation outcomes are determined by the interplay of factors at three levels: technological, organizational, and environmental. This framework suggests that no single factor can adequately explain complex phenomena like carbon emissions reduction; rather, it is the configuration of multiple factors that leads to desired outcomes. Our approach builds on set-theoretic methods that allow for equifinality—the idea that multiple distinct configurations can lead to the same outcome. This theoretical foundation enables us to move beyond net effects thinking and examine how different combinations of conditions work together to produce high carbon emissions reduction.

Results

Necessary analysis of single condition

Before conducting the conditional configuration analysis we must test the necessity of each antecedent condition. In analyzing QCA panel data, we first test whether a single antecedent condition (including its non-membership) constitutes a necessary condition for the outcome variable (i.e., carbon emissions). The criteria for concluding that the antecedent condition is a necessary condition for the outcome variable are usually that the consistency coefficient is greater than 0.9 and the coverage degree is greater than 0.5 (Schneider and Wagemann, 2012). At the same time, we also consider the adjusted distances of BECONS and WICONS; when these distances are greater than 0.2 it indicates the antecedent conditions may have time or region effects, which must be further explored (García-Castro and Ariño, 2016).

Table 3 summarizes the results of the necessary condition analysis for high CER and non-high CER. As can be seen in *Table 3*, although POCOV (pooled coverage) for the six antecedent conditions is greater than 0.5, the POCONS is below 0.9, indicating the six antecedent conditions are not necessary conditions for high and non-high CER. At the same time, we can see the adjustment distances of BECONS and WICONS for the six antecedent conditions are greater than 0.2, indicating these conditions may have time or regional effects. Given the absence of any single necessary condition, we therefore proceed to a sufficiency analysis using fsQCA to identify which combinations of these antecedent conditions are sufficient for achieving high CER.

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Table 3. *Necessity test results for single antecedent conditions*

Antecedent condition	High carbon emissions reduction						Non-high carbon emissions reduction					
	POCONS	POCOV	BECONS distance	WICONS distance	BECONS adjusted distance	WICONS adjusted distance	POCONS	POCOV	BECONS distance	WICONS distance	BECONS adjusted distance	WICONS adjusted distance
GTIL	0.715	0.828	0.078	0.045	0.449	0.259	0.430	0.574	0.121	0.068	0.696	0.391
~ GTIL	0.632	0.491	0.075	0.056	0.431	0.322	0.871	0.779	0.042	0.024	0.242	0.138
GFDL	0.764	0.701	0.091	0.033	0.523	0.190	0.556	0.588	0.122	0.010	0.702	0.058
~ GFDL	0.551	0.519	0.121	0.039	0.696	0.224	0.717	0.778	0.107	0.032	0.615	0.196
IE	0.645	0.608	0.021	0.039	0.121	0.224	0.625	0.671	0.019	0.032	0.109	0.184
~ IE	0.646	0.599	0.032	0.042	0.184	0.242	0.635	0.679	0.025	0.032	0.144	0.184
HC	0.821	0.833	0.019	0.049	0.109	0.282	0.489	0.572	0.077	0.084	0.443	0.483
~HC	0.578	0.496	0.061	0.072	0.351	0.414	0.857	0.847	0.027	0.029	0.155	0.167
ISC	0.608	0.629	0.074	0.062	0.426	0.357	0.601	0.716	0.071	0.052	0.408	0.299
~ ISC	0.725	0.612	0.063	0.046	0.362	0.265	0.689	0.670	0.042	0.059	0.242	0.339
ECS	0.631	0.644	0.065	0.063	0.374	0.362	0.593	0.697	0.074	0.071	0.426	0.408
~ ECS	0.702	0.599	0.057	0.059	0.328	0.339	0.697	0.685	0.033	0.069	0.190	0.397

Note: “~” indicates conditional absence. POCONS, POCOV, BECONS, and WICONS indicates pooled consistency (or overall consistency), pooled coverage, between consistency, and within consistency, respectively. GTIL, GFDL, IE, HC, ISC, and ECS indicates green technology innovation level, green finance development level, income equilibrium, human capital, industrial structure change, and energy consumption structure, respectively. Abbreviations are used consistently throughout all following tables and figures

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Fig. 2 and *Fig. 3* shows the BECONS and WICONS changes for the six antecedent conditions in the high CER category. *Fig. 2* shows the overall BECONS of the six antecedent conditions is less than 0.9, indicating that none are necessary conditions for achieving a high CER. Aside from the fluctuation of income equality consistency around 0.654, the BECONS for the remaining factors show an overall upward trend, and BECONS adj-distance is greater than 0.2, indicating these factors affecting high CER are heterogeneous over time, with a significant time effect. As seen in *Fig. 3*, the simultaneous presence of full WICONS (equals 1) together with low consistencies indicates some clustering in the data. The WICONS adj-distance is well above the 0.1 and 0.2 thresholds (García-Castro and Ariño, 2016), indicating the existence of strong differences across groups of regions. The WICONS values are highly polarized with a few subgroups of regions displaying very high consistencies (equal to 1) over time-e.g., the *ISC* for Beijing is sufficient to belong in high CER while in another subgroup of Henan with an extremely low WICONS value (equal to 0.276), *ISC* is not sufficient for high CER. In the high CER group (*Table 3*), the BECONS distances for *GTIL, GFDL, ISC,* and *ECS* are greater than their WICONS distance, implying that time effects dominate over regional effects, while the WICONS distances for *IE* and *HC* are greater than their BECONS distance, implying that regional effects dominate over time effects, as confirmed by *Fig. 2*.

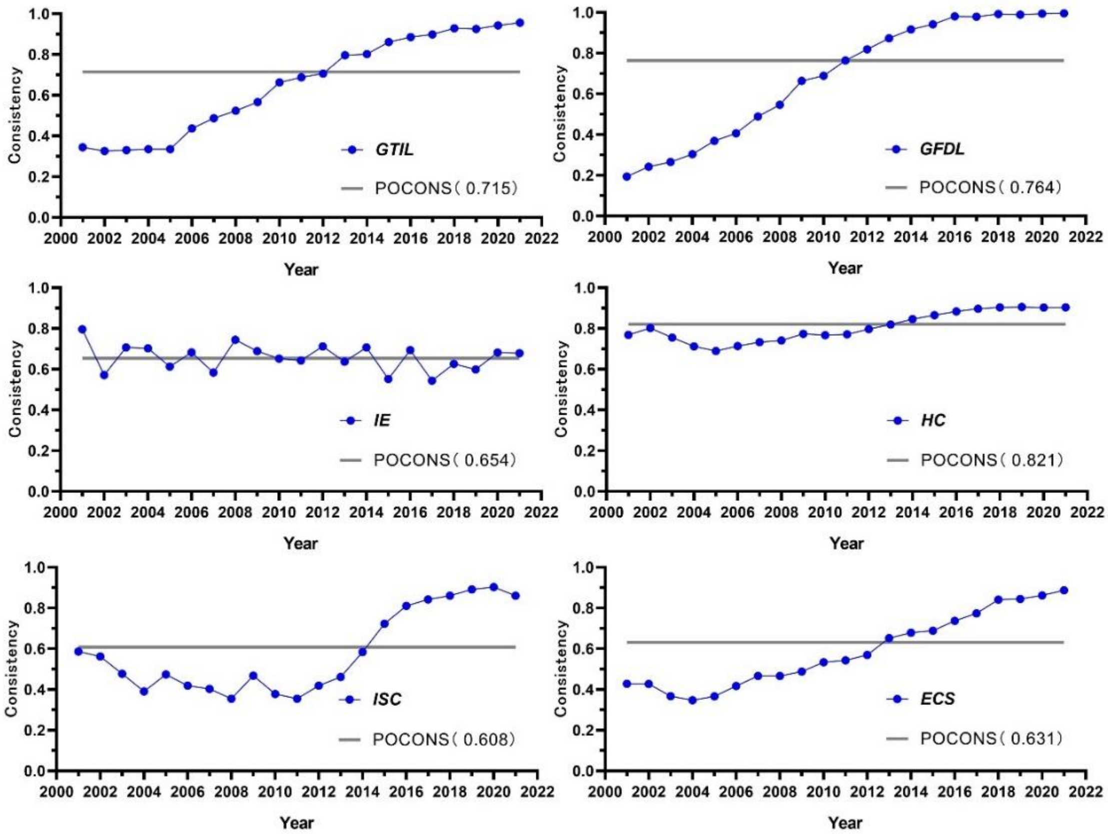

Figure 2. *BECONS changes in "technology-organization-environment" conditions for high carbon emissions reduction*

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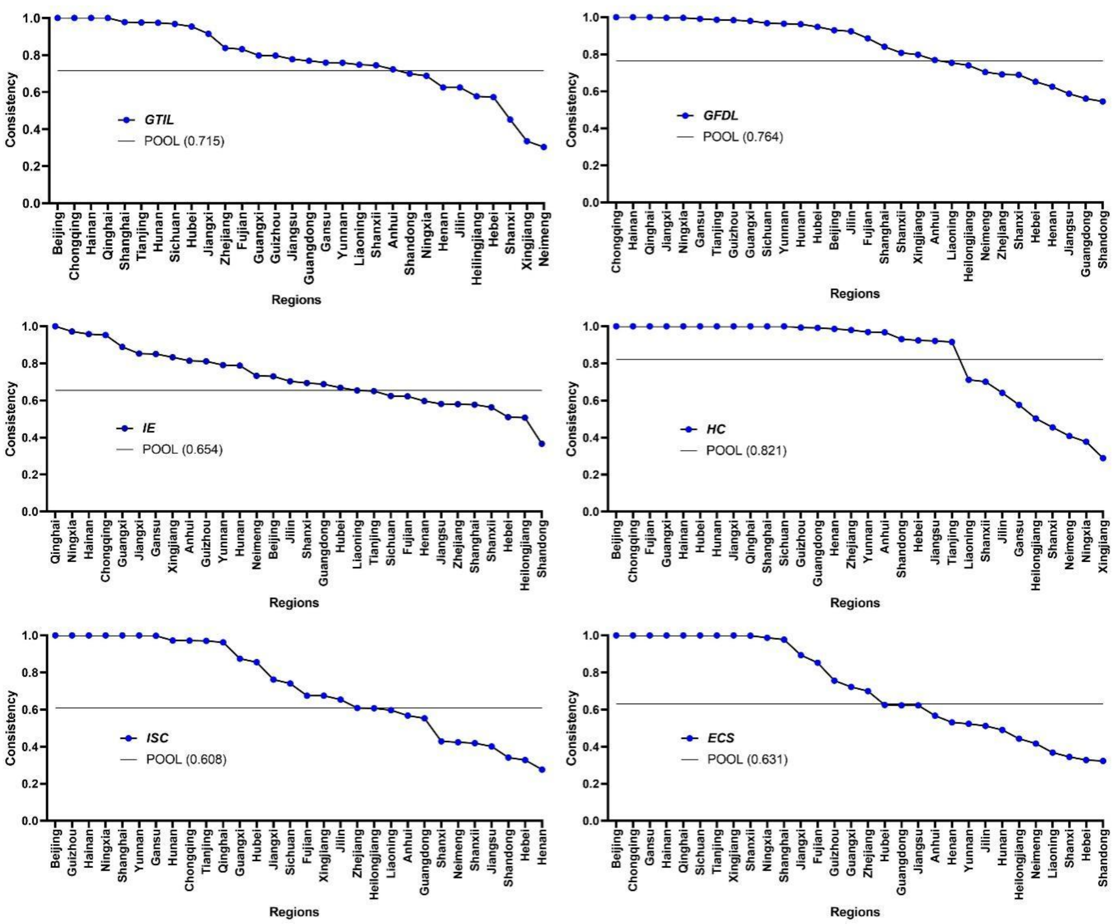

Figure 3. *WICONS changes in "technology-organization-environment" conditions for high carbon emissions reduction*

Sufficiency analysis of conditional configuration

A sufficiency analysis of a conditional configuration is an important part of the dynamic QCA method. In this study, we use a consistency threshold of 0.8, a PRI threshold of 0.75, and a case frequency threshold of 1.0 to construct a truth table. We apply a Boolean algebra method to standardize the truth table to obtain a complex solution, parsimonious solution, and an intermediate solution. Lastly, we identify the core and peripheral conditions for each solution through the nested relationship between the parsimonious and intermediate solutions. Specifically, we use the intermediate solution to determine number of configurations and their inclusion conditions, then use the results of the parsimonious solution to determine the most important core conditions of a given configuration. The conditions in the parsimonious solution are the core conditions for a given configuration, indicating a strong causal relationship between these conditions and the results obtained. The remaining antecedent conditions that appear in the intermediate solution but not in the parsimonious solution are peripheral conditions, indicating a weak causal relationship between these remaining antecedent conditions and the results obtained (Du et al., 2020; Pappas and Woodside, 2021). The configurations that achieve high CERs are shown in *Table 4*.

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Table 4. *Configuration results achieving high carbon emissions reductions*

Configuration	**High carbon emissions reduction**				
	HCER1	HCER2	HCER3a	HCER3b	HCER3c
GTIL	●	⊗	●	●	●
GFDL	◦	●	◦	◦	○
IE	●	●	⊗	⊗	⊗
HC	●	●	●	●	●
ISC	◦	○	○	◦	◦
ECS	◦	○	◦	○	◦
Consistency	0.914	0.957	0.932	0.936	0.951
PRI	0.783	0.816	0.795	0.782	0.799
Raw coverage	0.483	0.388	0.477	0.475	0.353
Unique coverage	0.071	0.026	0.019	0.017	0.003
BECONS adj-distance	0.052	0.029	0.040	0.040	0.035
WICONS adj-distance	0.133	0.083	0.113	0.128	0.093
Overall solution consistency	0.923				
Overall solution PRI	0.795				
Overall solution coverage	0.641				

Notes: ● indicates the core condition exists; ⊗ indicates the core condition does not exist; ○ indicates the auxiliary condition exists; ◦ indicates the auxiliary condition does not exist. Variable abbreviations as in *Table 3*. HCER1, HCER2, HCER3a, HCER3b, HCER3c indicates configuration type of high carbon emissions reduction (HCER)

As shown in *Table 4*, the overall consistency is 0.923, which is above the acceptable threshold of 0.8, indicating that across these five configurations, 92.3% of provinces present a high CER level. Overall coverage is 0.641, indicating that these five configurations explain 64.1% of cases where provinces have a high CER level. The overall PRI is 0.795, indicating there is a 79.5% probability these outcomes do not occur due to a “same-cause-different-effect” problem. The BECONS adj-distance and WICONS adj-distance of per configuration are below 0.2, indicating the five configuration paths obtained can be regarded as a sufficient condition for a province-level high CER. At an individual level, the coverage for the five configurations is 0.483, 0.353, 0.477, 0.475 and 0.388, respectively, and each one has a high consistency level (0.914, 0.951, 0.932, 0.936, 0.957, respectively), and a high PRI (0.783, 0.799, 0.795, 0.782, 0.816, respectively), indicating the five configurations obtained have high explanatory power.

Taking green technology innovation plus human capital (*GTIL+HC*) as our theoretical guidance, we use set-analytic theory to evaluate whether the above configuration intersection is consistent with our theoretical guidance and find the consistency between the high CER configurations and the theory (*GTIL+HC*) is 0.902, PRI is 0.775, and raw coverage is 0.616, indicating our theoretical position is valid. In contrast, the consistency between no-high CER configurations and the theory (*~GTIL+~HC*) is 0.498, PRI is 0.206, and raw coverage is 0.661, indicating the theoretical guidance is not valid in these cases (Sager and Thomann, 2017; Schneider and Maerz, 2017).

Configuration 1 (HCER1): Green innovation-led organization, collaborative-driven high CER. This path indicates that income equality, human capital, and green technology innovation play decisive roles as core conditions in the process of achieving a high

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regional CER. In the HCER1 configuration, raw coverage was 0.483 and unique coverage was 0.071, indicating that HCER1 can explain 48.3% of the high regional CER cases, of which about 7.1% can be explained only by the HCER1 configuration path (*Table 4*). Typical cases (selected based on membership degree greater than 0.5) are seen in Jiangsu_2014, Jiangsu_2020, Jiangsu_2021, Shandong_2020, Shandong_2021, Guangdong_2021, and others, as shown in *Fig. 4*.

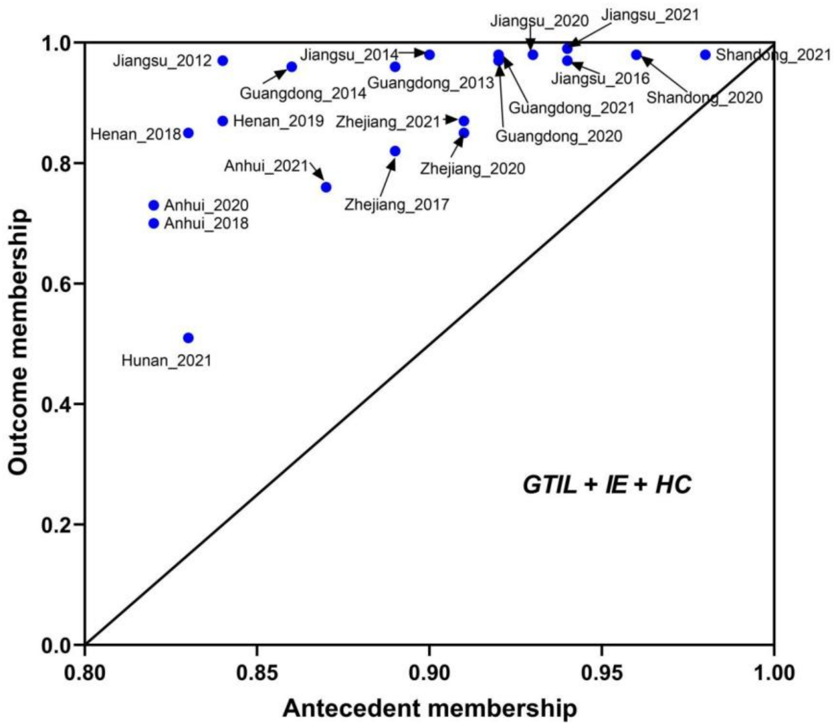

Figure 4. *Explanation of Configuration 1. Note: With antecedent membership as the horizontal axis and outcome membership as the vertical axis, a membership degree greater than 0.5 indicates a typical case that can be explained by the configuration (Ding, 2023)*

Configuration 2 (HCER2): Green finance-led organization, collaborative-driven high CER. This path indicates that income equality, human capital, and green finance play decisive roles as core conditions in the process of achieving a high regional CER, with changes in industrial structure and energy consumption structure as auxiliary conditions. In HCER2, raw coverage is 0.388 and unique coverage is 0.026, indicating that HCER2 can explain 38.8% of the high CER of regional cases, of which about 2.6% can only be explained by the HCER2 configuration path (*Table 4*). Typical cases (selected based on membership degree greater than 0.5) include Hebei_2011, Hebei_2015, Hebei_2016, and others (see *Fig. 5*).

Configuration 3 (HCER3): Green innovation-led human capital collaborative- driven high CER. *Table 4* shows the core conditions of configuration HCER3a, HCER3b, and HCER3c are the same, constituting a second-order equivalent configuration (Fiss, 2011) that is merged into one class. This path indicates green technology innovation and human capital play decisive roles as core conditions in the process of high regional CER, with industrial structure change (HCER3a), energy consumption structure (HCER3b), and green finance (HCER3c) as auxiliary conditions, respectively. In the HCER3a

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configuration, raw coverage is 0.477 and unique coverage is 0.019, indicating that HCER3a can explain 47.7% of the high regional CER cases, of which about 1.9% can only be explained by the HCER3a configuration path (see *Table 4*). Typical cases (selected based on membership degree greater than 0.5) include Shandong_2011, Shandong_2012, Shandong_2013, Jiangsu_2010, Jiangsu_2011, and others (*Fig. 6A*). In HCER3b, raw coverage is 0.475 and unique coverage is 0.017, indicating HCER3b can explain 47.5% of the high regional CER cases, of which about 1.7% can be explained only by the HCER3b configuration path (see *Table 4*). Typical cases (selected based on membership degree greater than 0.5) include Shandong_2011, Shandong_2012, Shandong_2013, Shandong_2014, and others (*Fig. 6B*). In HCER3c, raw coverage is 0.353 and unique coverage is 0.003, indicating HCER3c can explain 35.3% of the high regional CER cases, of which about 0.3% can only be explained by the HCER3c configuration path (*Table 4*). Typical cases (selected based on membership degree greater than 0.5) include Guangdong_2008, Guangdong_2009, Shandong_2009, Shandong_2010, Shandong_2011, Jiangsu_2009, and others (*Fig. 6C*).

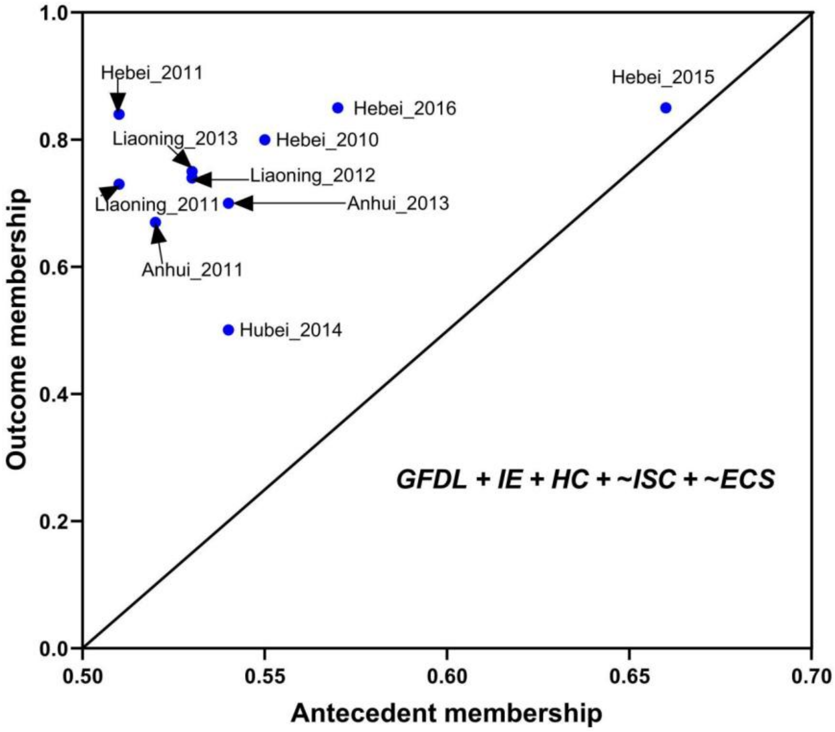

Figure 5. *Explanation of Configuration 2. Note: With antecedent membership as the horizontal axis and outcome membership as the vertical axis, a membership degree greater than 0.5 indicates a typical case that can be explained by the configuration (Ding, 2023)*

Table 4 shows the BECONS adj-distance and WICONS adj-distance of Configuration 1, Configuration 2, and Configuration 3 are both below the threshold value of 0.2, so there are no significant time or regional effects in the three configurations, indicating that these three configuration paths for regional CER have a strong explanatory ability and universally adaptable values, which is useful for factor-based research on CER (Zhao and Feng, 2025).

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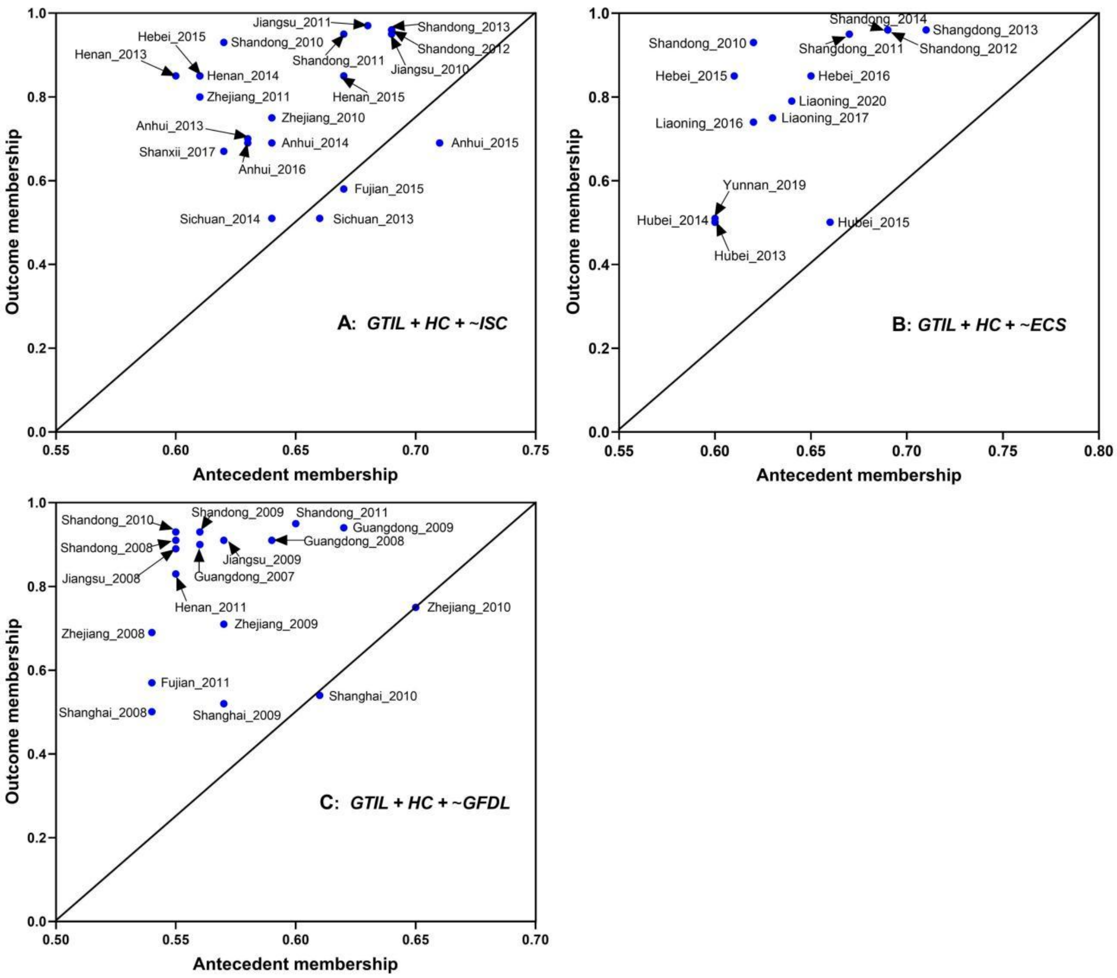

Figure 6. *Explanation of Configuration 3. Note: With antecedent membership as the horizontal axis and outcome membership as the vertical axis, a membership degree greater than 0.5 indicates a typical case that can be explained by the configuration (Ding, 2023)*

Robustness test

The QCA model offers complex, new solutions, and its robustness must be tested to ensure the validity of its results. When the operation is adjusted slightly there is a subset relationship between the obtained outcomes but if the substantive explanation of the research findings does not change, the robustness of the original results is supported (Zhang and Du, 2019; Du et al., 2020). Based on previous studies, (Du and Jia, 2017; Du et al., 2022; Chen et al., 2024c), we use three methods to test the robustness of the different configurations of high CER in this study. First, we raise the consistency threshold from 0.8 to 0.9, and adjust the PRI threshold from 0.75 to 0.80, with no significant changes in the results (*Table 5*). Second, we raise the case frequency threshold from 1 to 2 and the four configurations obtained are consistent with the four solutions in the baseline results (*Table 5*). Third, we use the 92nd, 45th, and 13th quantiles to calibrate the anchor points as a robustness test and find a clear subset relationship between the obtained configuration and the original configuration, indicating the robustness of the original research results (*Table 5*). Based on this, we find the original empirical conclusions to be reliable.

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Table 5. *Robustness test results of achieving high carbon emissions reduction*

Configuration	**Increase the consistency and PRI thresholds**					**Increase the case frequency**				**Adjust the calibration anchor points**			
	HCER1	HCER3c	HCER3a	HCER3b	HCER2	HCER1	HCER3a	HCER3c	HCER3b	HCER1	HCER3a	HCER3b	HCER2
GTIL	●	●	●	●	⊗	●	●	●	●	●	●	●	⊗
GFDL	○	◯	○	○	●	○	○	◯	○	○	○	○	●
IE	●	⊗	⊗	⊗	●	●	⊗	⊗	⊗	●	⊗	⊗	●
HC	●	●	●	●	●	●	●	●	●	●	●	●	●
ISC	○	○	◯	○	◯	○	◯	○	○	○	◯	○	◯
ECS	○	○	○	◯	◯	○	○	○	◯	○	○	◯	◯
Consistency	0.920	0.955	0.967	0.945	0.951	0.914	0.936	0.955	0.934	0.863	0.919	0.876	0.928
PRI	0.788	0.847	0.853	0.795	0.836	0.783	0.820	0.764	0.785	0.767	0.828	0.784	0.807
Raw coverage	0.451	0.368	0.329	0.372	0.371	0.483	0.475	0.288	0.439	0.624	0.412	0.537	0.302
Unique coverage	0.074	0.004	0.021	0.022	0.019	0.071	0.029	0.004	0.019	0.030	0.034	0.008	0.013
BECONS adj-distance	0.058	0.029	0.023	0.040	0.029	0.052	0.040	0.035	0.046	0.081	0.040	0.035	0.040
WICONS adj-distance	0.133	0.093	0.079	0.088	0.113	0.133	0.128	0.088	0.113	0.231	0.177	0.216	0.137
Overall solution consistency	0.912					0.903				0.852			
Overall solution PRI	0.789					0.775				0.752			
Overall solution coverage	0.599					0.616				0.697			

Notes: indicates the core condition exists; ⊗ indicates the core condition does not exist; ◯ indicates the auxiliary condition exists; ○ indicates the auxiliary condition does not exist. Variable abbreviations as in *Table 3* and *Table 4*

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Discussion

This study systematically deciphers the complex causal mechanisms underpinning carbon emissions eduction (CER) across Chinese provinces by integrating a context-adapted Technology-Organization-Environment (TOE) framework with dynamic panel Qualitative Comparative Analysis (QCA). Our findings provide robust, configuration-based evidence that addresses the identified research gaps regarding fragmented factor analysis, insufficient dynamic contextualization, and the need for a tailored analytical framework in the context of China's policy superposition.

A pivotal finding is the absence of any single necessary condition for high CER performance. This result fundamentally challenges reductionist, single-factor policy approaches and underscores the inherent multi-dimensionality and systemic nature of carbon mitigation (Ragin, 2008; Fiss, 2011). It confirms that CER success is not about identifying a "silver bullet" but about understanding how factors combine. While green technology innovation and human capital consistently emerge as powerful core elements, their efficacy is contingent upon synergistic combinations with other conditions. For instance, the HCER1 and HCER3 pathways demonstrate that the emissions reduction potential of green innovation is fully activated only when coupled with strong organizational foundations (human capital) or facilitated by an enabling environmental context (industrial structure upgrading). This configurational perspective moves the discourse beyond the isolated examination of net effects, revealing the critical "combinatorial advantages" that define successful CER outcomes.

Our dynamic analysis further elucidates the temporal and spatial complexities of these drivers. The significant time effects (BECONS distances >0.2) and regional heterogeneity (WICONS distances >0.2) observed in most antecedent conditions validate the context-dependent nature of CER policies (García-Castro and Ariño, 2016). The pronounced regional variation in income equality and human capital, in particular, mirrors China's vast socio-economic disparities. A crucial insight, however, is that despite this underlying heterogeneity at the factor level, the three overarching driving models we identified exhibit remarkable stability across both time and space (BECONS and WICONS adjusted distances <0.2). This implies that while the specific manifestation of individual drivers may vary, the fundamental "architecture" or "success formula" for achieving high CER is universal and replicable across diverse provincial contexts. This finding is of paramount importance for policymakers, suggesting that strategic efforts should focus on constructing these proven, stable configurations rather than pursuing isolated factors.

The contextual adaptation of the TOE framework proved highly effective in capturing the multi-level interactions driving CER in China (Tornatzky and Fleischer, 1990; Wang et al., 2024b). Our findings not only reinforce the catalytic role of technological factors like green innovation and finance but also elevate the importance of organizational foundations—specifically human capital (Khan, 2020; Yao et al., 2021) and income distribution—as essential social underpinnings for a sustainable low-carbon transition. The prevalence of the green innovation-human capital synergy (HCER3) suggests this combination is a particularly potent and widely applicable strategy within China's current innovation-driven development paradigm.

When situated within the broader literature, our results show both convergence and distinctiveness. The critical role of green technology innovation aligns with findings from developed economies, while the prominent configuration of organizational factors highlights the influence of China's unique socio-institutional context. The identified pathways extend the work of Xiong and Sun (2023) and Cao and Chen (2023) by

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demonstrating the dynamic stability of these configurational patterns across a broader regional and temporal scale.

Methodologically, this study underscores the significant advantages of dynamic panel QCA for analyzing complex socio-ecological systems (García-Castro and Ariño, 2016; Oana and Schneider, 2018). The approach adeptly captures equifinality and causal complexity while providing a rigorous assessment of the temporal and cross-sectional robustness of the solutions—a substantial advancement over static analytical methods prevalent in environmental policy research.

Conclusions

This study leverages a dynamic panel QCA approach within a tailored TOE framework to unravel the pathways to high carbon emissions reduction across China's provinces. The principal conclusions are threefold.

(1) The quest for a single, universally necessary condition for CER is futile. Our analysis confirms that no individual factor—be it technological, organizational, or environmental—constitutes a bottleneck for reducing carbon emissions in China. This necessitates a paradigm shift from siloed policy interventions to a more holistic, systems-based approach.

(2) We identify three robust and stable configuration models that effectively drive high CER: ① Green innovation-led organizational collaboration, ② Green finance-led organizational collaboration, and ③ Green innovation-led human capital collaboration. The stability of these models across time and regions indicates their value as reliable blueprints for policy design.

This study leads to three clear and actionable policy recommendations for achieving high carbon emission reduction. Policymakers should:

(1) Prioritize synergistic policy mixes that strategically combine elements across the technological, organizational, and environmental dimensions, rather than optimizing single-policy instruments in isolation.

(2) Leverage organizational foundations as key enabling conditions. Investing in human capital development and promoting income equality can powerfully complement technological advancements and create a more resilient social foundation for the low-carbon transition.

(3) Adopt a flexible, pathway-oriented implementation strategy. Provincial governments should diagnose their local resource endowments and factor conditions to select and adapt the most suitable configuration path, rather than applying a one-size-fits-all model.

Limitations and future research

This study, while comprehensive, is subject to certain limitations that present avenues for future inquiry. First, although the TOE framework incorporated six critical factors, other potentially influential variables—such as the quality of local institutions, the degree of marketization, international technology transfer, or cultural factors—were not included. Future research could expand the analytical framework to incorporate these elements for a more nuanced explanation of regional CER disparities. Second, the use of provincial-level data, while appropriate for a national analysis, may mask significant variations at the city or district level. The inherent time lags between policy implementation and observable effects also warrant a longer-term perspective. Subsequent studies could,

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therefore, employ prefecture-level city panel data and extend the research period to enhance the granularity and temporal depth of the findings (Du et al., 2022). Finally, to disentangle universal principles from context-specific patterns, future work should employ a comparative international design. Applying the same adapted TOE framework and dynamic QCA methodology to data from other major economies could help identify which configuration paths are generalizable and which are unique to China's institutional and developmental context.

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