Research on the Group Paths of Green Technology Innovation in China

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Abstract. In the context of global warming, the pursuit of an ecological economy has intensified, with Green Technological Innovation (GTI) playing a pivotal role. However, most existing studies tend to focus on the impact of individual technological or environmental regulatory factors on GTI, often overlooking the synergistic effects of multidimensional factors. Based on the TOE theoretical framework, we used fuzzy set qualitative comparative analysis (fsQCA) to deal with the data of relevant indicators of Chinese provinces in 2022, analyzed the conditional groupings of high green technological innovation levels from the grouping perspective and came up with the following results: (1) There are five types of groupings to achieve high GTI including technology-government-talent joint-driven, technology integration-led, technology innovation-economic structure double-driven, technology-economy double-driven and government-talent double-driven. (2) Technology Application Capability, University Research Capacity and Talent Reservation are necessary conditions to constitute a high GTI level. The results of the study show the technological, organizational and environmental factors driving high GTI, with a view to providing China and even worldwide countries with locally unique paths to improve GTI.

Keywords: Green Technology Innovation, TOE, fsQCA, Configurational Theory.

1. Introduction

Since the beginning of the Industrial Revolution, the global productivity has developed rapidly, and technological innovation has gradually become a key element of world economic growth. Concomitantly, the environmental pollution and other events have also become a hot issue of global concern. From international environmental law to "the Paris Agreement" and the resolution of "the United Nations Climate Change Conference (2021) ", countries around the world are actively practicing the goals of "carbon emission reduction" and "carbon neutrality", seeking a balance between environmental protection and economic development. Countries around the world are actively practicing “carbon reduction” and "carbon neutrality", seeking a balance between environmental protection and economic development. China has jumped to the second largest economy in the world since its reform and opening up. However, at the same time, Chinese environmental problems are also prominent. 2024 "Environmental Performance Index (EPI)" list shows that China ranks 156th out of 180 countries around the world, with a score of only 35.4 points. Therefore, exploring the influencing factors of China's regional Green Technological Innovation (GTI) is of great significance to promote Chinese green development, the development of global eco-environmental protection and the realization of global sustainable development goals.

Despite the green development becomes a common vision for all humankind, the formulation of local solution paths to promote GTI is still an urgent issue to be resolved. GTI was firstly proposed by Braun and Wield (1994) [1], which refers to "the whole process of green technology from the source of research and development to the transformation of results and final marketisation". As we can see from the categorization of existing studies, scholars have explored the influencing factors of GTI mainly from the three aspects of technology, organization and system. However, scholars mostly analyze the impact of individual factors on GTI within enterprises or industries lacking a regional perspective. Besides, the research is limited to analyzing the linear correlation between GTI and its influencing factors lacking a comprehensive and holistic analysis of the influencing factors.

Therefore, we follow the suggestion of Fan et al. (2023) [2] to focus on the synergistic effect of multiple factors on regional GTI and use the fuzzy set qualitative analysis and comparison method (fsQCA) to analyze the core conditions and grouping types of GTI in China, attempting to explore solution paths for the development of regional GTI.

2. Research Background

The TOE theoretical framework, first proposed by Tornatzky et al. (1990) [28], aims to systematically analyze the diffusion and application of technological innovation through the three dimensions of Technology, Organization and Environment. The core idea of TOE is that the technological innovation is not the result of a single factor but a complex process of multiple factors interacting with each other, which coincides with the research of GTI. As GTI is a key part of the technological innovation, it certainly applies to the application of TOE. In practice, GTI requires a comprehensive consideration of technological feasibility, organizational capacity and support from the external environment. TOE framework can provide a systematic analytical tool for policymakers, businesses and researchers to help them identify key factors and develop targeted strategies. A number of scholars have conducted in-depth studies on the impact of GTI in three dimensions of TOE.

2.1. Impact of the Technological Dimension on GTI

Existing researches on the impact of the technological dimension on GTI is characterized by the efficiency of R&D inputs and outputs, mainly concentrating on three aspects: social innovation capacity, R&D human resources and R&D investment intensity. First, Wang et al. (2024) [3] argued that good innovation capacity can improve enterprises GTI efficiency. Second, GTI efficiency requires not only the input of technological resources, but also related human resources. Their combination is an effective way to improve GTI efficiency (Lafuente et al., 2023) [4]. Finally, the study of XU et al. (2020) [5] demonstrated that the increase in the proportion of R&D investment can significantly improve the GTI performance of enterprises. Therefore, we summarize indicators according to the action process of R&D in the technological dimension as Technology Integration Capability(TIG), Technology Innovation Capability(TIV) and Technology Application Capability(TAP) with a regional perspective.

2.2. Impact of the Organizational Dimension on GTI

Existing studies on the impact of the organizational level on GTI mostly focus on the internal of enterprises or industries and the results of the studies are specific, not widely applicable to study the GTI level in the whole regions. For example, enterprises can enhance their green innovation efficiency by creating a green and innovative organization culture (Alshammari et al., 2023.) [6]. The manufacturing industry and the resource-based industry have a more urgent need for green technology innovation, (Liu, 2024) [7]. However, several scholars have also preliminarily explored the roles of universities, government and society. Jaffe et al. (1993) [8] found that university research outputs significantly contribute to green technology development by spilling to firms. The research by Udeagha and Muchapondwa (2023) [9] in South Africa shows that moderate fiscal decentralization can promote green technology innovation through optimal resource allocation. Xu and Huang (2021) [10] indicates that the talents concentration can significantly promote regional green development. Therefore, we summarize the indicators in the organizational dimension as Universities Research Capacity(URC), Governmental Fiscal Decentralization Degree(FDD), and Talent Reservation(TR) with a regional perspective.

2.3. Impact of the Environmental Dimension on GTI

Existing studies on the impact of the environmental dimension on GTI are mainly categorized into political environment, market environment, economic environment and innovation environment. The political environment is mainly about environmental regulations where the relevant studies have

been more complete. Liu et al. (2020) [11] concluded that environmental regulation has a positive U-shaped relationship with urban green innovation efficiency. Besides, the market environment is mainly about market segmentation which affects the regional GTI by restricting the free flow of technological resources (Wang et al., 2024) [12]. Moreover, the economic environment focuses on the industrial structure. Long and Zhang (2012) [13] pointed out that industrial concentration and specialization have a significant role in promoting GTI. Lastly, the innovation environment focuses on regional technological cooperation. Sun and Yang (2024) [14] found that the green technology cooperation network can enhance the regional green low-carbon technology innovation. Therefore, we summarize the indicators in the environmental dimension as Market Segmentation(MS), Economic Structure(ES) and Innovation Environment(IE) with a regional perspective.

2.4. Literature Review

To sum up, existing articles have carried out quite a lot of researches on the influencing factors of GTI. However, firstly in terms of the main body, the researches only analyze the influencing factors of GTI within enterprises or industries, lack of the research of the regional perspective, which makes it difficult to form a locally-adapted solution path based on the unit of the province. Secondly, in terms of variables, there is lack of theoretical, systematic and logical synthesis of these indicators. Thirdly, in terms of methodology, the studies are merely limited to analyze the linear correlation between GTI and its factors, having not taken the cases of multiple factors acting together into account. Therefore, this paper will take a regional perspective, construct the indicators system of condition variables that affect regional GTI based on the TOE theoretical framework, use fsQCA method to conduct group analysis, generalize the necessary conditions and multiple group types of regional GTI.

3. Research Method

Qualitative Comparative Analysis (QCA) is a case-oriented, multilogical analysis approach that combines qualitative and quantitative analysis, created by sociologist Ragin in 1987. It is based on three assumptions: concurrent causality, equipotentiality and asymmetry. Multiple concurrent causality indicates multiple causes and outcomes without one-to-one correspondence. Equipotentiality indicates multiple paths for the same outcome. Asymmetry indicates the outcome with different causes, application and effects. QCA methods have three types including clear set (csQCA), multivalent set (mvQCA) and fuzzy set (fsQCA). The csQCA and mvQCA are only suitable for dealing with the category problems, while fsQCA mainly assigns values to the variables from 0 to 1 by means of the "fuzzy set score".

There are four main reasons for this paper to choose fsQCA to study the influencing factors of GTI. Firstly, compared with the traditional regression method, fsQCA uses Boolean arithmetic to form a algebraic set, which can reduce the loss of information during the data processing making the conclusions more refined and reliable. Secondly, fsQCA is suitable for small and medium samples. This paper selects data samples from 31 provinces in China as research cases, which meets the requirements. Thirdly, fsQCA is able to reveal the configuration effect of the linkage and matching of different driving factors rather than ideally assume that only one factor makes effects. Fourthly, fsQCA can deal with the asymmetric phenomenon of causality and explore the causal chains of the single result caused by multiple grouping paths, so as to better solve the problem of continuous variables. Therefore, this paper adopts the fsQCA method to analyze the linkage effect of multiple factors in order to explore the realistic path of regional GTI in line with the development principle.

Based on the theoretical analysis above, this paper identifies the key driving factors of regional GTI from the three dimensions of technology, organization, and environment to summarize nine factors including Technology Integration Capacity, Technology Innovation Capacity, Technology Application Capacity, University Research Capacity, Government Fiscal Decentralization Degree, Talent Reservation, Market Segment, Economic Structure and Innovation Environment. Finally, we

adopts fsQCA methods based on the configurational theory to derive the five basic paths of high GTI forming the grouping model as shown in Figure 1.

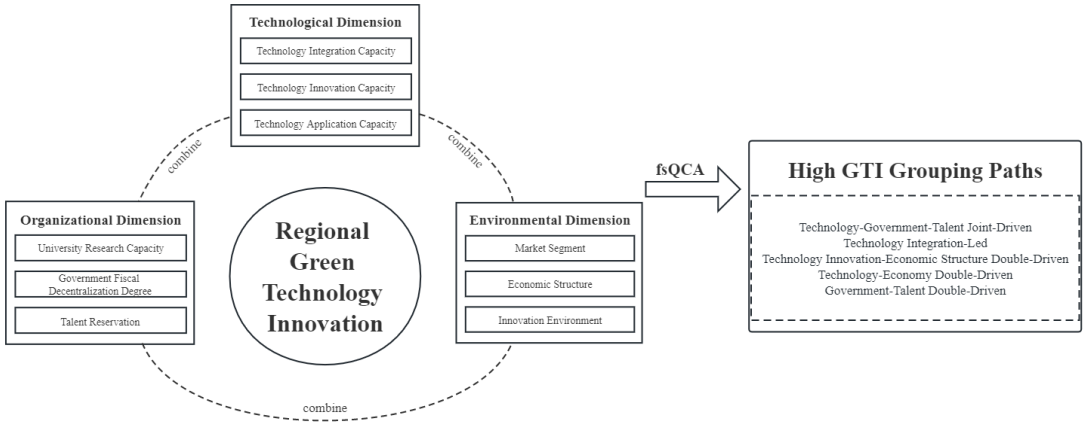

Figure 1: Grouping Model

4. Research Design

4.1. Variables Selection and Measurement

4.1.1 Outcome Variable

GTI is used as the outcome variable. This paper uses the number of green patent applications to indicate GTI, which is mainly because green patents are an important tool for measuring GTI, especially in assessing the contribution of different countries or regions to green technology on a global scale (Schultz, F.C. et al., 2024) [15]. Relevant data are from the Chinese Research Data Services Platform.

4.1.2 Condition Variables

In this paper, we refer to papers by Liu, Bao, Huangfu (2024) [17],et al. to derive a condition variable indicators system, as shown in Table 1.

Table 1 Condition Variable Indicators System

Condition Variable		Definition	Data Resource	Reference
Technology Dimension	Technology Integration Capacity(TIG)	Ratio of R&D personnel to employed population	*China Statistical Yearbook*	Liu, Bao, Huangfu (2024) [17]
	Technology Innovation Capacity(TIV)	R&D investment intensity	*China Statistical Yearbook*	Zhu, Lai, Zhu,Zhang (2022) [24]
	Technology Application Capacity(TAP)	Technology market turnover		Du, Zhang (2020) [16]
Organization Dimension	University Research Capacity(URC)	Number of R&D topics in universities	*China Science Statistical Yearbook*	Zhang, Lin, Zhang (2015) [18]
	Government Fiscal Decentralization Degree(FDD)	Regional per capita fiscal expenditure to the overall reginonal and central level	*China Statistical Yearbook*	Li, Sun (2024) [19]
	Talent Reservation(TR)	Number of persons with academic qualifications at college, bachelor's degree and above		Wang, Xue, Xie (2025) [20]
Environment Dimension	Market Segment(MS)	Retail commodity price index	*China Statistical Yearbook*	Chen (2024) [21]
	Economic Structure(ES)	Ratio of tertiary value added to GDP		Wang, Song (2025) [22]
	Innovation Environment(IE)	Innovation environment utility value	*Evaluation Report on China's Regional Innovation Capability*	Jia (2017) [23]

4.2. Data Calibration

Calibration is the process of converting the raw values of antecedent and outcome conditions into pooled affiliation scores. This process is a crucial part of performing QCA. In this paper, the direct calibration method is used to convert each variable to a fuzzy affiliation value between 0~1.Ragin(2008) [25] originally recommended using 90% as fully affiliated points, 10% as fully unaffiliated points and 50% as crossover points, a setting that was widely applied in subsequent studies. Simultaneously, many scholars like Schneider and Wagemann(2012) [26], Thiem and Duşa(2013) [27] and so on thought this setup clearly distinguished the affiliation degree of the samples to the condition and benefited for the robustness of results. Therefore the thresholds for three calibration points of full affiliation, intersection, and no affiliation at all are respectively set to 90%, 50%, and 10% for calculation. The calibration result is shown in Table 2.

Table 2 Variables Calibration

Variable	Full Affiliation	Intersection	No Affliation
GTI	12647	2456	563
TIG	0.018	0.006	0.002
TIV	0.053	0.019	0.007
TAP	32318349	7338839	315522
URC	94787	40113	10252
FDD	0.365	0.243	0.110
TR	1167	588	140
MS	103.2	102.7	102.1
ES	0.600	0.505	0.437
IE	42.99	24.8	18.24

5. Research Results

5.1. Individual Conditional Necessity Analysis

The necessity analysis of individual conditions is a prerequisite for the analysis of fuzzy set truth table procedures. Usually, the consistency value is a necessary condition to assess whether a certain variable is an outcome condition. When the consistency value exceeds 0.9, the condition variable is considered to be a necessary condition for constituting the outcome variable. The results of the necessity analysis of high and non-high GTI are shown in Table 3. It shows that TAP, URC and TR are necessary conditions for constituting a high GTI level, while non-high TIG is necessary for constituting a non-high GTI level.

Table 3 Analysis of Necessary Conditions

Condition Variable	GTI		~GTI	
	Consistency	Coverage	Consistency	Coverage
TIG	0.882	0.887	0.409	0.463
~TIG	0.466	0.412	0.900	0.896
TIV	0.862	0.852	0.414	0.461
~TIV	0.455	0.409	0.867	0.876
TAP	0.911	0.889	0.368	0.403
~TAP	0.388	0.353	0.898	0.919
URC	0.965	0.894	0.426	0.444
~URC	0.400	0.382	0.898	0.967
FDD	0.891	0.823	0.464	0.482
~FDD	0.439	0.421	0.830	0.896
TR	0.945	0.838	0.465	0.464
~TR	0.396	0.397	0.838	0.945
MS	0.681	0.598	0.671	0.662
~MS	0.615	0.624	0.593	0.677
ES	0.797	0.775	0.523	0.571
~ES	0.559	0.510	0.794	0.815
IE	0.858	0.842	0.464	0.512
~IE	0.503	0.455	0.857	0.871

Note: "~" means that the condition is missing.

5.2. Configuration Analysis

In this paper, the fsQCA method is used to examine the antecedent group state of GTI level in provinces. Firstly, referring to the practice of Ragin (1987) [17], the threshold amount of the frequency of the sample cases in the portfolio is set to 1.5% of the total number of cases and the frequency threshold is set to 1 in the establishment of the truth table. Secondly, the original consistency threshold is set to 0.8. Lastly, due to the lack of the exact theory and proof that shows the conditions affecting the results direction, this paper chooses the option of "presence or absence" in the factual analysis of each condition, which ultimately produces the complex solution, parsimonious solution and intermediate solution. In this paper, we focus on reporting the intermediate solutions, determining the conditions that appear in the intermediate and parsimonious solutions at the same time as the core conditions and the conditions that appear in the intermediate solutions only as the edge conditions. Table 4 below reports the grouping results, combining the seven grouping paths into five types of high GTI groupings based on the same core conditions. The consistency level of all groupings is greater than 0.8, the overall solution consistency is 0.857 and the overall solution coverage is 0.833, which has strong explanatory power and robustness.

Table 4 Configuration Analysis

Condition Variables	GTI Groupings						
	S1		S2	S3	S4	S5	
	P1	P2				P1	P2
TIG	●	●	●	○	●	○	○
TIV	●	●	○	●	●	○	○
TAP	•	•	○	○	•	•	•
URC	•	•	○	○	○	○	•
FDD	●	●	○	○	○	●	●
TR	●	●	○	○	○	●	●
MS	•		○	⊗	⊗	○	•
ES		•	○	●	●	○	○
IE	•	•	○	○	○	•	•
Raw Coverage	0.558	0.626	0.212	0.260	0.221	0.217	0.273
Unique Coverage	0.042	0.124	0.008	0.035	0.010	0.013	0.013
Consistency	0.999	1.000	0.883	0.803	0.831	1.000	0.994
Overall Coverage	0.833						
Overall Consistency	0.857						

Note: ● or • means the condition exists, ⊗ or ○ means the condition does not exist, ● or ⊗ means the core condition, • or ○ for marginal conditions, blank for conditions that may or may not exist.

Overall, TIG and TIV in the technology dimension and FDD and TR in the organizational dimension have the highest number of occurrences in all groupings. TIG and TIV are core conditions in most groupings, indicating the general importance of technological factors in GTI. However, the way in which technological factors work varies among regions, for example, technological factors work synergistically with organizational and environmental factors in S1 while work independently in S2. FDD and TR are core conditions in only several groupings. For example, they are key factors in S1 and S5 while not significant in S3, which suggests significant heterogeneity in the role of organizational and environmental factors due to regional differences. Moreover, MS is a necessary condition in two groupings of S3 and S4, while it does not play a significant role in other clusters, forming the distinct regional heterogeneity. Lastly, the coverage and consistency of the different configuration paths varied considerably, indicating that the scope of application and stability of each was different. For example, S1 has the highest coverage and the widest scope of application, while S2 and S4 have lower coverage and a narrower scope of application.

For S1 (technology-government-talent joint-driven), the combination of stronger TIG, TIV, FDD and TR creates a grouping of high GTI level even when the levels of other factors are weak. The consistency of both P1 and P2 is greater than 0.9 and the original coverage is the highest among all the groupings, indicating that S1 can explain a larger number of cases and the explanation is robust

and reliable. Specific typical cases include Zhejiang, Jiangsu, Hunan, Guangdong, Shanghai and Shandong. Taking Zhejiang Province as an example, in terms of TIG, There are several industrial clusters in Zhejiang such as Hangzhou's Internet e-commerce industry and Ningbo's manufacturing industry. The in-depth integration of technologies like cloud computing, big data and the Internet of Things (IoT) realizes the clustering and exchanges of R&D manpower, material and financial resources. In terms of TIV, enterprises attach importance to R&D investment, construction of R&D centers to increase R&D efforts, for example Alibaba has built an information ecosystem to drive the overall industry productivity and innovation. In terms of FDD, the implementation of the "province directly supervise the counties" of the financial management system reform in Zhejiang contributes to the establishment of a transfer payment system rationalizing the relationship of the financial distribution of the sub-provincial government level. In terms of TR, Zhejiang Province has put forward relevant policies in the "14th Five-Year Plan for Talent Development", forming a system of introducing and cultivating high-quality talents with superimposed provincial, municipal and county policies.

For S2 (technology integration-led), in the absence of all other conditions, only a strong TIG can form a high GTI grouping. But the coverage and consistency of this grouping is not high, indicating that it has a narrow scope of interpretation. Ningxia Province is the unique case reference point. For example, with the policy and construction needs, Ningxia has taken advantage of the "east wind" of East-West scientific and technological cooperation to attract and gather 10,000 scientific and technological innovation talents from the outside to participate in the innovation activities of Ningxia, promoting the construction of the national East-West scientific and technological cooperation leading region and realizing the clustering of research personnel and the rapid growth of short-term high technological innovations.

For S3 (technology innovation-economic structure double-driven), A high GTI level can be developed regardless of the level of other conditions in the case of a high level of TIV and ES and a non-high level of MS. However, its coverage and consistency are not high, suggesting that S3 is narrowly interpreted and has the specificity of the development of Hainan as a single province. In terms of TIV, Hainan's R&D investment in 2022 reached 6.837 billion yuan and an input intensity reached 1.002% contributing to the first growth rate in the country. In terms of ES, Hainan Province, relying on the policy advantages of the free-trade port as well as its unique natural endowments, focuses on the development of the four major leading industries, such as high-tech industry, tourism and son on, which making tertiary industry's value-added climb up. Moreover, the lack of MS is due to Hainan's unique geographical location as an island, reducing market barriers which is conducive to the formation of high-level industrial integration clusters.

For S4 (technology-economy double-driven), High levels of TIG, TIV and ES and their linkages with non-high levels of MS can form a high-level GTI grouping. The consistency and coverage of this grouping is not so high, suggesting that its interpretation is narrow and lacks reliability. Taking Tianjin as a typical case, in terms of TIG, Tianjin has established several high-tech industrial parks, such as the Tianjin Binhai Hi-tech Industrial Development Zone, which have gathered a large number of R&D personnel. In terms of TIV, Tianjin has continuously increased R&D investment and made remarkable achievements in the fields of intelligent manufacturing and new energy. In terms of ES, Tianjin has vigorously developed the financial industry and set up the Tianjin FTZ, which has increased the proportion of the tertiary industry. In terms of MS, Tianjin maintains relatively stable commodity prices and has few market barriers due to the positioning of the municipality directly under the central government and the unified market supervision system.

For S5 (government-talent double-driven), with the coordinated linkage of FDD and TR, a high GTI level can be achieved regardless of other conditions. The consistency of P1 and P2 in S5 is greater than 0.9, which indicates that this grouping is robust and reliable. While the coverage is less than 0.5, which indicates that the number of explanation cases of this grouping is small. Specific explanatory cases include Hebei and Shaanxi. In Shaanxi, in terms of FDD, based on the overall national strategic considerations like "the development of the western region" and the development

needs of its own characteristic industries like energy industry and aerospace, Shaanxi has more autonomy in financial expenditures. In terms of TR, a number of colleges and universities, such as the Xi'an Jiaotong University and the Sixth Research Institute of the China Aerospace Science and Technology Corporation(CASC), attract a large number of scientific research talents. In Hebei, based on its geographical advantage of being close to Beijing, it is affected by the policy spillover effect and the establishment of Xiongan New Area, resulting in a higher financial discretion and social talent pool.

In this paper, the results of the above configuration analysis are summarized and outlined into five different configurations categories, as shown in Table 5 below.

Table 5 Typical cases of Configuration Analysis

Configuration	Name	Province
S1	Technology-government-talent joint-driven	Zhejiang, Jiangsu, Hunan, Guangdong, Shanghai, Shandong
S2	Technology integration-led	Ningxia
S3	Technology innovation-economic structure double-driven	Hainan
S4	Technology-economy double-driven	Tianjin
S5	Government-talent double-driven	Hebei, Shaanxi

6. Research Contribution

After analyzing five types of high GTI groupings in this study, we conceptualize their deeper meanings in total. Further, we will explain the contribution of this study to the current research.

6.1. Theoretical Contribution

Firstly, this study innovatively expands the application context of the configurational theory and TOE framework, adding new dimensions to the research framework of GTI. Secondly, we specifically pay more importance on the integration of multiple antecedents based on TOE rather than single factor. Thirdly, the study uniquely concludes five grouping paths of high GTI. This paper provides new insights in the research field of GTI and it is expected that further research on the influencing factors of GTI will be conducted to promote the comprehensive development of theoretical frameworks and practical applications.

6.2. Factual Contribution

This study creatively combines the statistic results of fsQCA with the factual condition of specific provinces, making conclusions more robust and reliable. The paper not only distinctively reveals the principle of regional heterogeneity of GTI, but also provides adaptive suggestions for Chinese provinces to enhance GTI level. Further, the research provides theoretical guidance and methodological references for all countries in the world to enhance GTI. We innovatively suggest the other developing countries all over the world should strengthen the role played by the technological and organizational dimensions, taking into account the negative effects of the market environment level on high GTI.

7. Conclusion

This study aims to explore the influencing factors of regional GTI, constructs the conditional variable indicators system based on the TOE theoretical framework, uses fsQCA method to analyze the provinces showing that technology integration capacity, technology innovation capacity,

government fiscal decentralization degree and talent reservation determines the high GTI level and explaining the impact of the existence and absence of market segmentation, and finally forms five configuration categories including technology-government-talent joint-driven, technology integration-led, technology innovation-economic structure double-driven, technology-economic double-driven and government-talent double-driven.

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