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Comprehensive Evaluation of the Resilience of China's Oil and Gas Industry Chain: Analysis and Thinking from Multiple Perspectives

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Abstract

Enhancing the resilience of the oil and gas industry chain is essential for achieving sustainable energy development amid global industrial restructuring and the accelerating low-carbon transformation. This study identifies the core contradictions in the development of China's OGI and constructs a comprehensive evaluation index system to assess the resilience of the industry from the four sustainability-aligned dimensions of resistance, recovery, innovation, and transformation. Using the entropy weight comprehensive evaluation model, obstacle degree model, and coupling coordination degree model, the resilience performance of China's OGI chain is evaluated from 2001 to 2022. The results show a significant upward trend in overall resilience, with evident stage characteristics. Resistance remains relatively stable, recovery shows the most improvement, innovation steadily increases, and transformation accelerates after 2019, particularly in response to China's dual carbon goals. Key barriers include limited CCUS deployment and insufficient downstream innovation capacity. The improved coupling coordination among resilience subsystems highlights enhanced systemic synergy. These findings offer valuable implications for strengthening the sustainability and security of energy supply chains under climate and geopolitical pressures.

Keywords: oil and gas industry chain; resilience evaluation; sustainable development; obstacle degree; coupling coordination degree

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1. Introduction

Driven by rising international trade protectionism and escalating geopolitical tensions, the global energy market has experienced severe volatility, with external uncertainties intensifying and crises occurring frequently. The global oil and gas industry (OGI) chain is undergoing significant disruptions and is being rapidly restructured. China's OGI is currently facing numerous challenges. First, China has a high degree of dependence on foreign OGI resources, making it highly susceptible to fluctuations in the international oil and gas market. Second, China's domestic energy supply and demand system is undergoing a rapid transformation. As a foundational industry critical to national economic and social development, the OGI sector is constantly exposed to unforeseeable risks and challenges posed by various "black swan" events during this period of change. The critical role of the OGI as the "anchor" of national energy security is becoming increasingly prominent. Scientifically assessing the resilience level of the OGI chain, deeply revealing

the patterns of resilience changes, and scientifically planning development pathways are of great significance for enhancing energy security, ecological security, and industrial security.

Resilience theory is widely applied across multiple fields, including ecology [1], psychology, disaster science, and economics [2]. The conceptual framework and research framework for system resilience are relatively well-established. System resilience exhibits the following characteristics: (1) the system can withstand a series of changes while maintaining control over its functions and structure, i.e., equilibrium; (2) the system has the ability to self-organize, i.e., self-organization [3]; (3) the system possesses the capacity to establish and promote learning and adaptation [4]. Based on these characteristics, a fundamental theoretical framework for resilience research has been established. Walker (2004) proposed the "3R" theoretical framework, which includes resistance, recovery, and creativity [5]. Martin (2012) expanded this into a "4R" analytical framework, encompassing resistance, recovery, renewal, and repositioning [6].

The resilience of industrial chains is a new field of research in economic resilience. Analyzed from multiple dimensions, such as supply and demand chains [7], value chains [8], and enterprise chains [9], global industrial chains and value chains are developing in the direction of "regionalization," "segmentation," "localization," and "digitalization" [10]. The risk of international "chain breaks" is intensifying, and global industrial chains and value chains are in a state of unbalanced development and are accelerating their restructuring [3,11].

Research findings in the fields of resilience measurement, evolutionary patterns, and influencing factors are relatively abundant. Resilience measurement methods can be categorized into three types: single-indicator methods, sensitivity analysis methods, and comprehensive analysis methods. Comprehensive analysis methods are widely applied, including the coefficient of variation comprehensive evaluation method [12], the dynamic combination weighting–TOPSIS method [13–16], the dynamic evaluation of basic gray correlation degrees [17], and the entropy value comprehensive evaluation method [18,19]. Regarding the evolutionary patterns of industrial chain resilience, the main methods include kernel density estimation, Dagum Gini coefficient decomposition, the σtest, and the Theil index. In terms of system association and attribution in industrial chain resilience, the main methods used are the coupling coordination model and the multi-matrix autoregressive model, which are used to analyze internal system associations and inter-system associations [20,21].

In the OGI field, scholars have concentrated on diverse aspects such as the resource curse and industrial development issues [22], the driving forces of industrial development [23], and the evolutionary paths of industrial development [24]. Additionally, they have explored the return on energy investment in the OGI [25], ecological benefit evaluation and the analysis of influencing factors of the OGI [26], the impact assessment of carbon emission reduction constraints on China's OGI development [27], the relationship between green financial assets and petroleum industry development [28], and supply–demand forecasts for the OGI under different scenarios [29]. However, research on the OGI from the perspective of resilience remains underdeveloped. For instance, Wu Wenjie (2024) [30] applied the entropy method to measure the resilience level of the oil industry and its supply chain from 2002 to 2022. Furthermore, the DEMATEL-ISM model was employed to identify the key factors influencing resilience. External indicators such as GDP and GDP per capita have been used as critical metrics for assessing the economic resilience of the oil industry [30].

The primary objective of this study is to establish a robust theoretical foundation for an evaluation framework and employ rigorous scientific methods to conduct a comprehensive assessment of the resilience of China's OGI chain. The marginal contributions of this paper are as follows:

(1) Based on Martin's "4R" resilience theory framework, a comprehensive evaluation indicator system for the resilience of the OGI is constructed from four dimensions: resistance, recovery, innovation, and transformation. Based on the principles of resilience formation, it identifies the primary risk sources and impact points within the oil and gas industry chain, and develops a set of secondary and tertiary indicators for the multi-level evaluation system.

(2) An objective weighting method is applied to build a suite of analytical models, including a comprehensive evaluation model, an obstacle degree model, and a coupling coordination degree model, thereby enabling a systematic diagnosis of the resilience level of China's OGI chain.

(3) A multi-dimensional assessment of the resilience of China's OGI chain is conducted for the period from 2001 to 2022. The study systematically analyzes key obstacle factors, the severity of their occurrence, and the structural causes that constrain improvements in resilience.

2. Materials and Methods

2.1. Comprehensive Evaluation Index System for Resilience of OGI

Based on Martin's "4R" resilience analysis framework, an evaluation index system for the resilience of the oil and gas industry (OGI) chain is constructed across four dimensions: resistance, recovery, innovation, and transformation. Drawing on relevant research findings and adhering to the principles of comprehensiveness, scientific rigor, representativeness, and data availability, the system includes 4 first-level indicators, 13 second-level indicators, and 35 third-level indicators. This comprehensive evaluation framework for OGI chain resilience is detailed in Table 1 [31,32].

The indicators were selected based on the following considerations:

(1) Resistance Dimension: Resistance refers to a system's ability to maintain stability and continuous operation in the face of external shocks and disturbances—that is, its capacity to cope with uncertainty. Over the past two decades, China's oil and gas industry (OGI) has encountered several major challenges arising from risk shocks, including insufficient domestic supply, high external dependency, import shortages, and price volatility caused by fluctuations in the international market. Additional pressures include the industrial chain impacts of the energy structure transition and the dual carbon control targets (i.e., total carbon emissions and carbon intensity).

In response, this study identifies three secondary indicators under the resistance dimension—resource guarantee capability, product supply capability, and price buffer capability—which collectively reflect the OGI chain's capacity to withstand external shocks. The ability to manage carbon emission constraints is discussed under the transformation dimension.

From the perspective of energy security and the "two markets (domestic market and international market)", this article selects four level 3 indicators to measure the resource security capacity of the OGI: recoverable reserves of oil, recoverable reserves of natural gas, dependence on oil imports, and dependence on natural gas imports.

Scholars usually choose to use the "number of importing countries" and "import concentration" to reflect an OGI's resistance to imported crises. Although such indicators can reflect the degree of risk, they cannot accurately reflect the ability to cope with risks. Therefore, this article chooses to use "Price buffering capacity of upstream and downstream of the industrial chain" to reflect the OGI's ability to resist huge shocks caused by import shortages or international oil and gas price fluctuations.

Table 1. Comprehensive Evaluation Index System for Resilience of China's OGI.

First-Level Indicators	Second-Level Indicators	Third-Level Indicators		Type	Weight
Resistance	Resource Guarantee Capability	Ultimate Recoverable Reserves of Oil	A1	Maximum	0.0297
		Ultimate Recoverable Reserves of Natural Gas	A2	Maximum	0.0292
		Oil Import Dependence	A3	Minimum	0.0269
		Natural Gas Import Dependence	A4	Minimum	0.0394
	Product Supply Capability	Crude Oil Production	A5	Maximum	0.0181
		Natural Gas Production	A6	Maximum	0.0341
		Pipeline Cargo Turnover	A7	Maximum	0.0365
	Price Buffer Capability	Price Buffer Capability of Upstream Industry Chain	A8	Median	0.0067
		Price Buffer Capability of Downstream Industry Chain	A9	Median	0.0058
Recovery	Industrial Base	Pipe Length	B1	Maximum	0.0295
		Number of Upstream Enterprises in the Industry Chain	B2	Maximum	0.0352
		Number of Downstream Enterprises in the Industry Chain	B3	Maximum	0.0474
	Element Base	Upstream Capital Stock of the OGI	B4	Maximum	0.0284
		Downstream Capital Stock of the OGI	B5	Maximum	0.0342
		Upstream Labor Stock of the OGI	B6	Maximum	0.0289
		Downstream Labor Stock of the OGI	B7	Maximum	0.0296
	Investment Capacity	Upstream Investment in the OGI	B8	Maximum	0.0278
		Downstream Investment in the OGI	B9	Maximum	0.0272
	Economic Foundation	Main Operating Revenue per 100 Yuan of Assets of Large-Scale Enterprises	B10	Maximum	0.0177
		Return on Total Assets of Industrial Enterprises Above Designated Size	B11	Maximum	0.0159
Innovation	Innovation Investment	Funding for R&D Investment in the Upstream OGI to Develop New Products	C1	Maximum	0.0212
		Funding for R&D Investment in the Downstream OGI to Develop New Products	C2	Maximum	0.0380
	Innovation Output	Number of Invention Applications from Upstream Oil and Gas Companies	C3	Maximum	0.0370
		Number of Invention Applications from Downstream Oil and Gas Companies	C4	Maximum	0.0663
	Technology Improvement	Refining Rate	C5	Maximum	0.0270
		Efficiency of Energy Conversion	C6	Maximum	0.0158

Table 1. *Cont.*

First-Level Indicators	Second-Level Indicators	Third-Level Indicators		Type	Weight
Transformation	Structural Transformation	The Proportion of Crude Oil Consumption in the Chemical Raw Materials and Chemical Products Manufacturing Industries	D1	Maximum	0.0183
	Low-carbon Transformation	CO_2 Emissions—Oil	D2	Minimum	0.0239
		CO_2 Emissions—Natural Gas	D3	Minimum	0.0176
		Carbon Emission Intensity of Oil	D4	Minimum	0.0174
		Carbon Emission Intensity of Natural Gas	D5	Minimum	0.0305
		Sulfur Dioxide Emissions from Upstream of the Industrial Chain	D6	Minimum	0.0059
		Sulfur Dioxide Emissions from Downstream of the Industrial Chain	D7	Minimum	0.0448
		Annual Storage of CO_2 by CCUS	D8	Maximum	0.0719
	Extension and Integration of The Industrial Chain	Number of Downstream Enterprises in the Industrial Chain	D9	Maximum	0.0162

$$Price\ buffer\ capacity\ of\ upstream\ industry\ chain = \frac{Upstream\ price\ index\ of\ the\ industrial\ chain}{International\ oil\ price\ fluctuations} \quad (1)$$

$$Price\ buffer\ capacity\ of\ downstream\ industry\ chain = \frac{Downstream\ price\ index\ of\ the\ industrial\ chain}{International\ oil\ price\ fluctuations} \quad (2)$$

(2) Recovery Dimension: Recovery refers to the ability of the OGI chain to rapidly return to normal operations after experiencing a shock. Industrial foundation, factor endowments, investment intensity, and economic performance form the basic conditions for the industrial chain to regain equilibrium following disruptions. This study selects four secondary indicators and eleven tertiary indicators to reflect the OGI chain's system restoration capabilities.

(3) Innovation Dimension: Maintaining technological innovation capacity is essential for achieving dynamic equilibrium in industrial development. When confronted with challenges and opportunities, the OGI chain can enhance its sustainability and competitiveness through technological, product, and managerial innovations. The selected secondary indicators under this dimension include innovation input, innovation output, and technological innovation.

(4) Transformation Dimension: Transformation reflects the OGI chain's ability to proactively adjust its industrial structure and achieve upgrading in response to changes in the external environment and internal development needs. This study identifies three secondary indicators—structural transformation, low-carbon transformation, and industrial chain extension and integration—as well as nine tertiary indicators to capture the transformation capacity of the OGI chain.

Drawing on the "14th Five-Year Plan for a Modern Energy System" and the reform and development practices of domestic and international energy industries, the OGI chain demonstrates several key trends: raw materialization, low-carbonization, integration, diversification, digitalization, and toolization. This study focuses on three major aspects: raw materialization, low-carbonization, and integration. Specifically, raw materialization is used to reflect structural transformation; under the "dual control" system of carbon emissions, seven indicators—including carbon dioxide emissions, emission intensity, and

annual CO_2 storage through CCUS—are selected to reflect the level of decarbonization. The number of enterprises extending downstream within the industrial chain is used to indicate the degree of integration in terms of industrial development.

2.2. Evaluation Method

2.2.1. Resilience Comprehensive Evaluation Model

The key to comprehensive evaluation of multiple indicators lies in the reasonable determination of indicator weights to reflect the importance of each indicator to the overall system. There are two main methods for weight setting: the subjective weighting method and the objective weighting method. In order to avoid the influence of human subjective bias, this paper chooses the objective weighting method. Common objective weighting methods include the entropy weight method, mean square error method, and dispersion method. The entropy weight method was chosen to determine the indicator weights.

The entropy weight method is an objective weighting method based on information entropy theory. In multi-attribute decision analysis, different indicators carry different amounts of information and have different degrees of influence on the overall evaluation results. The core idea of this method is to determine the indicator weight by calculating the degree of discreteness (information entropy) of the indicator data. The smaller the entropy value, the greater the amount of information it carries.

(1) Data standardization. The original data is standardized and converted into dimensionless pure values to eliminate the dimensional effects between different indicators. Among them is the original value of the *j*-th indicator in the i-th year, as are the minimum and maximum values of the *j*-th indicator, respectively, which are the standardized data.

For positive indicators (maximum), the normalized processing formula is

$$z_{ij} = \frac{x_{ij} - x_j^{\min}}{-x_j^{\min}} \tag{3}$$

For negative indicators (maximum), the normalized processing formula is

$$z_{ij} = \frac{x_j^{\max} - x_{ij}}{x_j^{\max} - x_j^{\min}} \tag{4}$$

For intermediate indicators, the normalized processing formula is

$$z_{ij} = \begin{cases} 1 - \frac{a - x_{ij}}{\max\left(a - x_j^{\min},\ x_j^{\max} - b\right)} & , x_{ij} < a \\ 1 & , a \le x_{ij} \le b \\ 1 - \frac{x_{ij} - b}{\max\left(a - x_j^{\min},\ x_j^{\max} - b\right)} & , x_{ij} > b \end{cases} \tag{5}$$

(2) Calculate the proportion of the value of the *i*-th object under the *j*-th indicator to the indicator P_{ij}. The standardized matrix Z at this time is

$$Z = \begin{bmatrix} z_{11} & z_{12} & \cdots & z_{1m} \\ z_{21} & z_{22} & \cdots & z_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ z_{n1} & z_{n2} & \cdots & z_{nm} \end{bmatrix} \tag{6}$$

Then

$$P_{ij} = z_{ij} / \sum_{i=1}^{n} z_{ij},\ (j = 1, 2, \ldots, m) \tag{7}$$

(3) Calculate the entropy value E_j of the j-th indicator. When $P_{ij} = 0$, $P_{ij}\ln P_{ij} = 0$.

$$\mathrm{E_j} = -\frac{1}{\ln \mathrm{n}}\sum_{\mathrm{i=1}}^{\mathrm{n}} \mathrm{P_{ij}}\ln \mathrm{P_{ij}}, (\mathrm{j} = 1, 2, \ldots, \mathrm{m}) \quad (8)$$

(4) Calculate the coefficient of variation G_j of the $_j$-th indicator

$$G_j = 1 - E_j \quad (9)$$

(5) Calculate the weight W_j of the j-th indicator

$$W_j = G_j / \sum_{j=1}^{m} G_j \quad (10)$$

Calculate the comprehensive resilience score of the OGI

$$F_i = \sum_{i=1}^{m} w_j z'_{ij} \quad (11)$$

$$F_z = F_a + F_b + F_c + F_d \quad (12)$$

In these equations, F_z represents the comprehensive resilience level of the OGI chain, and F_a, F_b, F_c, and F_d represent the scores of the four dimensions of resistance, recovery, innovation, and transformation, respectively.

2.2.2. Obstacle Factor Diagnosis Model

In order to better explore the key factors that inhibit the improvement of the resilience level of the OGI chain, the influence of each subsystem and each indicator within each subsystem on the improvement of the resilience of China's OGI chain was examined, and the key factors affecting the improvement of the resilience of the industry chain were identified.

Referring to relevant research findings, this paper selects the obstacle degree model to identify the shortcomings that inhibit its development [33,34].

The obstacle model is a method to identify key constraints by quantifying the degree of deviation of each indicator from the system goal. The core idea is that the greater the gap between the current value of a certain indicator and the ideal target, and the higher the importance (weight) of the indicator in the system, the stronger the obstacle effect of the indicator on the development of the system.

The method of using the obstacle model to identify the main obstacles to improving the resilience of China's OGI is as follows:

(1) Calculate the factor contribution F, which reflects the expected contribution of the indicator to the system goal, usually equal to the weight $\mathrm{W_j}$.

(2) Calculate the indicator deviation, which represents the gap between the actual value of the indicator and the optimal value.

$$I = 1 - Z \quad (13)$$

(3) Calculate the obstacle degree Oij of each layer indicator.

$$O_{ij} = \frac{W_j I_{ij}}{\sum_{j=1}^{n} W_j I_{ij}} \quad (14)$$

2.2.3. Coupling Coordination Degree Model (CCD Model)

According to the research of Martin, Ahmadi, and others, from an evolutionary perspective, the resilience of the industrial chain is a dynamic evolutionary process of interaction and self-regulation among various links, elements, and subsystems within the industrial system under the impact of external risks. From the perspective of resilience genesis, the resistance, recovery, innovation, and transformation capabilities—formed by the industrial chain in the face of risk shocks—promote and restrict each other, and have a typical interactive coupling relationship. Referring to relevant research findings, the CCD model has been used to analyze the relevant coupling coordination relationship between the subsystems in the urban resilience system and the copper industry resilience system [35]. This paper introduces a coupling coordination model to evaluate and grade the coupling relationships between the resistance, resilience, innovation, and transformation capabilities of the resilience system of the OGI chain.

The CCD model is mainly used to analyze the coordinated development level of things. Generally, there are mutual influences and couplings between multiple subsystems.

(1) Calculate the coupling degree C

$$C = \left(\frac{\prod_{i=1}^{n} U_i}{\left(\frac{1}{n} \sum_{i=1}^{n} U_i \right)^n} \right)^{\frac{1}{n}} \tag{15}$$

where the number of subsystems is the value of each subsystem, and the distribution range is [0, 1]. That is, after standardization, the coupling degree C value range is also [0, 1]. The larger the C value, the smaller the discreteness between subsystems and the higher the coupling degree; conversely, the lower the coupling degree between subsystems.

(2) Calculate the comprehensive coordination index T

$$T = \sum_{i=1}^{n} \alpha_i \times U_i \quad , \quad \sum_{i=1}^{n} \alpha_i = 1 \tag{16}$$

where α_i is the weight of the i-th subsystem, which is generally set to the same weight.

(3) Calculate CCD index D

$$D = \sqrt{C \times T} \tag{17}$$

2.3. Data Sources and Processing

The indicator data required for this article mainly come from the "China Statistical Yearbook", "China Industrial Statistical Yearbook", "China Energy Statistical Yearbook", "China Environmental Statistical Yearbook", and "China Climate Change Yearbook" from the 2002 to 2023 editions. Among them, the data related to carbon emissions in the OGI comes from the China Emission Accounts and Datasets (CEADs), and the data related to carbon capture, utilization, and storage (CCUS) in the OGI comes from the CCUS Project Database (2024) of the International Energy Agency (IEA). Since some indicators were missing during the data collection process, a linear regression interpolation method was used to supplement them.

3. Results Analysis

3.1. Analysis of the Results of the Resilience Evaluation of China's OGI Chain

3.1.1. Comprehensive Index Analysis

Equations (3)–(12) are applied to calculate the comprehensive evaluation indexes of China's OGI chain resilience, and the results are shown in Figure 1.

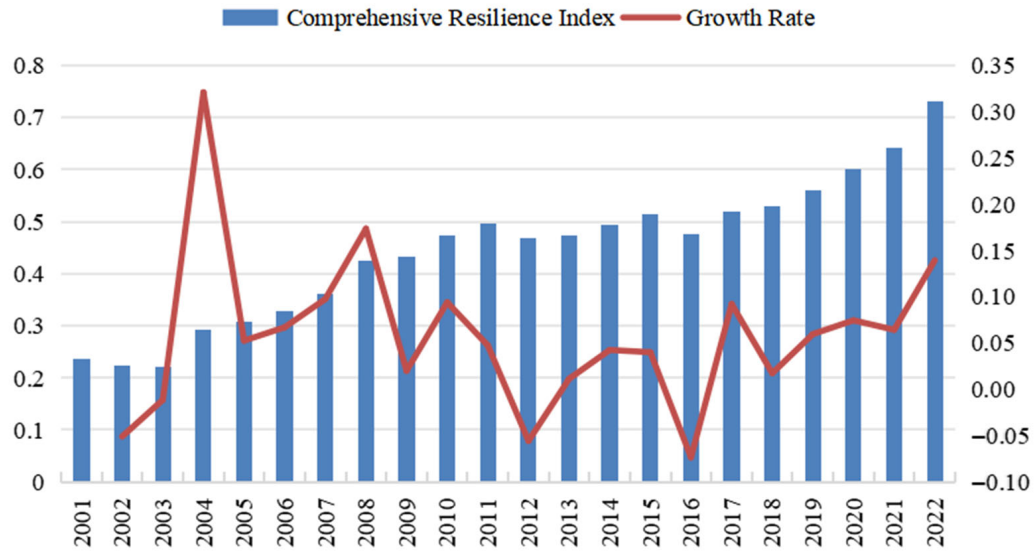


Figure 1. Resilience Index and Trend of China's OGI from 2001 to 2022.

The resilience of China's oil and gas industry (OGI) chain has exhibited a fluctuating upward trend over the past two decades. The comprehensive resilience index rose from 0.23652 in 2001 to 0.72977 in 2022, with an average annual growth rate of 5.51%, indicating a sustained improvement in the resilience of China's OGI chain.

To further analyze the evolution of the resilience index, the period from 2001 to 2022 is divided into five stages, aligned with China's national Five-Year Plans for economic and social development:

Phase I (2001–2005) corresponds to the 10th Five-Year Plan. During this period, the resilience of the OGI chain exhibited a "V"-shaped trajectory—initially declining and then rebounding. This was primarily due to the rapid growth in domestic demand for oil and gas resources driven by accelerated economic expansion. However, the sharp increase in international oil prices in 2003 exerted considerable supply–demand and cost pressures on the domestic industry, leading to a decline in resilience. In response, China intensified its efforts in oil and gas exploration and development while actively expanding overseas cooperation. Meanwhile, with China's accession to the World Trade Organization, the OGI sector gradually opened up to international markets. The three major state-owned enterprises—China National Petroleum Corporation (CNPC), China Petrochemical Corporation (SINOPEC), and China National Offshore Oil Corporation (CNOOC)—completed their shareholding reforms and were listed on overseas stock markets. As market competition diversified, the resilience of the industry improved significantly.

Phase II (2006–2010) corresponds to the 11th Five-Year Plan. During this period, the resilience of China's OGI chain steadily improved. With continued economic growth, demand for oil surged, leading to a rising dependence on foreign oil and intensifying the imbalance between domestic crude oil supply and demand. To mitigate the risks associated with oil shortages, China began accelerating the construction of a national oil reserve system. The country's first oil reserve base was completed in 2006, and the National Petroleum Reserve Center was officially established in 2007. This strategic reserve system enhanced the industry's capacity to respond to sharp fluctuations in international oil prices. This is evidenced by the resilience performance in 2008: although global oil prices reached historic highs before plummeting sharply, the resilience of China's OGI chain continued to improve. Meanwhile, domestic exploration achieved significant breakthroughs, and the refining and petrochemical industries experienced rapid expansion—both of which were key drivers of the sustained improvement in resilience.

Phase III (2011–2015) corresponds to the 12th Five-Year Plan. During this period, the resilience of China's OGI chain once again followed a "V"-shaped pattern, first declining and then recovering. The decline in 2012 was primarily due to persistently low international oil prices, which created uncertainty in investment decisions. Additionally, China's economic growth slowed, leading to a deceleration in oil and gas demand growth and a decline in the overall profitability of the domestic OGI. However, from 2013 to 2015, resilience steadily improved as the industry entered a phase of transformation and upgrading. First, market-oriented reforms in the oil and gas sector deepened, including the relaxation of price controls, which promoted competition and improved resource allocation efficiency. Second, significant breakthroughs were made in the exploration and development of unconventional oil and gas resources such as shale gas, creating new growth drivers. Third, international cooperation became more diversified, expanding beyond traditional regions like the Middle East and Africa to include new partnerships in Latin America, Central Asia, and other regions.

Phase IV (2016–2020) corresponds to the 13th Five-Year Plan. After a slight decline in 2016, the resilience of China's OGI chain showed a generally upward trend throughout this period. Frequent fluctuations in international oil prices introduced operational uncertainties for oil and gas enterprises. Meanwhile, the global energy transition accelerated, and the rapid rise of new energy sources intensified competitive pressure on the traditional OGI sector. Domestically, slowing economic growth and weak demand momentum further constrained the industry. The "dual carbon" goals (carbon peaking and carbon neutrality) placed additional limits on carbon emissions from the OGI. Despite these challenges, the industry's resilience continued to improve, driven by several key factors: (1) structural adjustments and a shift toward greener development, including a gradual increase in natural gas consumption; (2) expanded oil and gas exploration into deep-sea and deep-reservoir areas, enhancing supply capacity; and (3) continuous improvement in technological innovation, with advances in intelligence and digitalization across the industry.

Phase V (2021–2022) corresponds to the initial years of the 14th Five-Year Plan. During this period, the global energy transition accelerated significantly, and the large-scale development of renewable energy exerted a substitution effect on the OGI. In addition, increasingly complex international geopolitical tensions posed challenges to oil and gas supply security. Domestically, the pursuit of carbon peak and carbon neutrality targets necessitated urgent reductions in carbon emissions within the industry. At the same time, market competition intensified, requiring enterprises to continually enhance their competitiveness. Despite these pressures, the resilience of the OGI chain continued to improve, primarily due to: (1) the National Petroleum Reserve Center fully assuming its emergency management role; (2) the rapid development of carbon capture, utilization, and storage (CCUS) technologies; and (3) a shift in oil demand, with chemical feedstocks becoming a primary driver, and natural gas consumption steadily increasing across industrial, residential, and power generation sectors.

3.1.2. Multidimensional Index Analysis

Equations (3)–(12) are applied to calculate the resilience index scores of different dimensions of China's OGI chain, as shown in Figure 2.

In Figure 2, the overall dimensions of China's OGI resilience showed a fluctuating upward trend from 2001 to 2022.

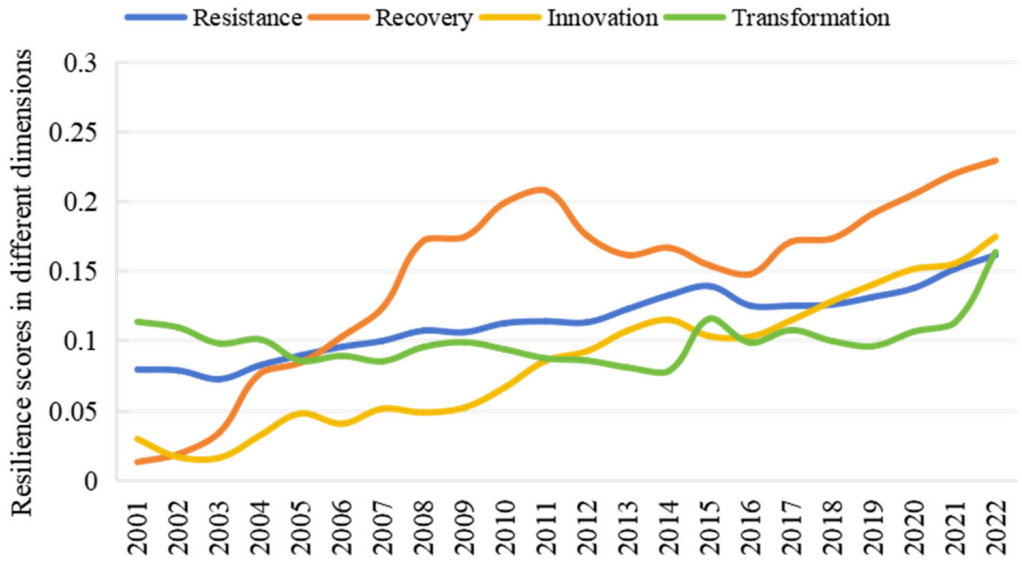


Figure 2. Trends in Resilience Index of China's OGI Chain in Different Dimensions from 2001 to 2022.

The resistance index remained relatively stable throughout the period, indicating that China's oil and gas industry experienced steady improvements in resource security, product supply capacity, and price buffering capability from 2001 to 2022. Over the past 22 years, rapid economic growth has significantly increased demand for oil and gas resources, making resource shortages more acute. However, China's strategy of leveraging both domestic and international resources and markets to address domestic supply gaps has proven effective. Despite a consistently high level of dependence on foreign oil and gas, the overall supply of resources and products has been reliably maintained. Moreover, despite considerable fluctuations in international oil prices over the past two decades, the oil and gas industrial chain has demonstrated a strong ability to buffer these price shocks, thereby minimizing their impact on downstream industries.

The recovery index increased significantly, suggesting that from 2001 to 2022, China's oil and gas industry achieved notable progress in factor allocation, scale expansion, and structural adjustment. These improvements have enhanced the industry's capacity to maintain stable development in the face of complex and diverse shocks.

The innovation index showed a consistent upward trajectory, indicating substantial growth in innovation input and output across the upstream, midstream, and downstream sectors. This trend highlights innovation as a key endogenous driver for enhancing the overall resilience and competitiveness of the OGI chain.

The transformation index remained relatively stable during most of the period but demonstrated a marked increase after 2019. This shift is primarily attributed to the implementation of China's "dual carbon" policy, which has accelerated the industry's transition toward low-carbon development. The transformation includes not only reductions in carbon emissions but also the emergence of new business models in the OGI chain, with carbon capture, utilization, and storage (CCUS) technologies serving as a key example.

To clearly compare the characteristics across different stages, six representative years—2001, 2005, 2010, 2015, 2020, and 2022–were selected to construct a radar chart illustrating the resilience index of China's OGI chain across different dimensions, as shown in Figure 3.

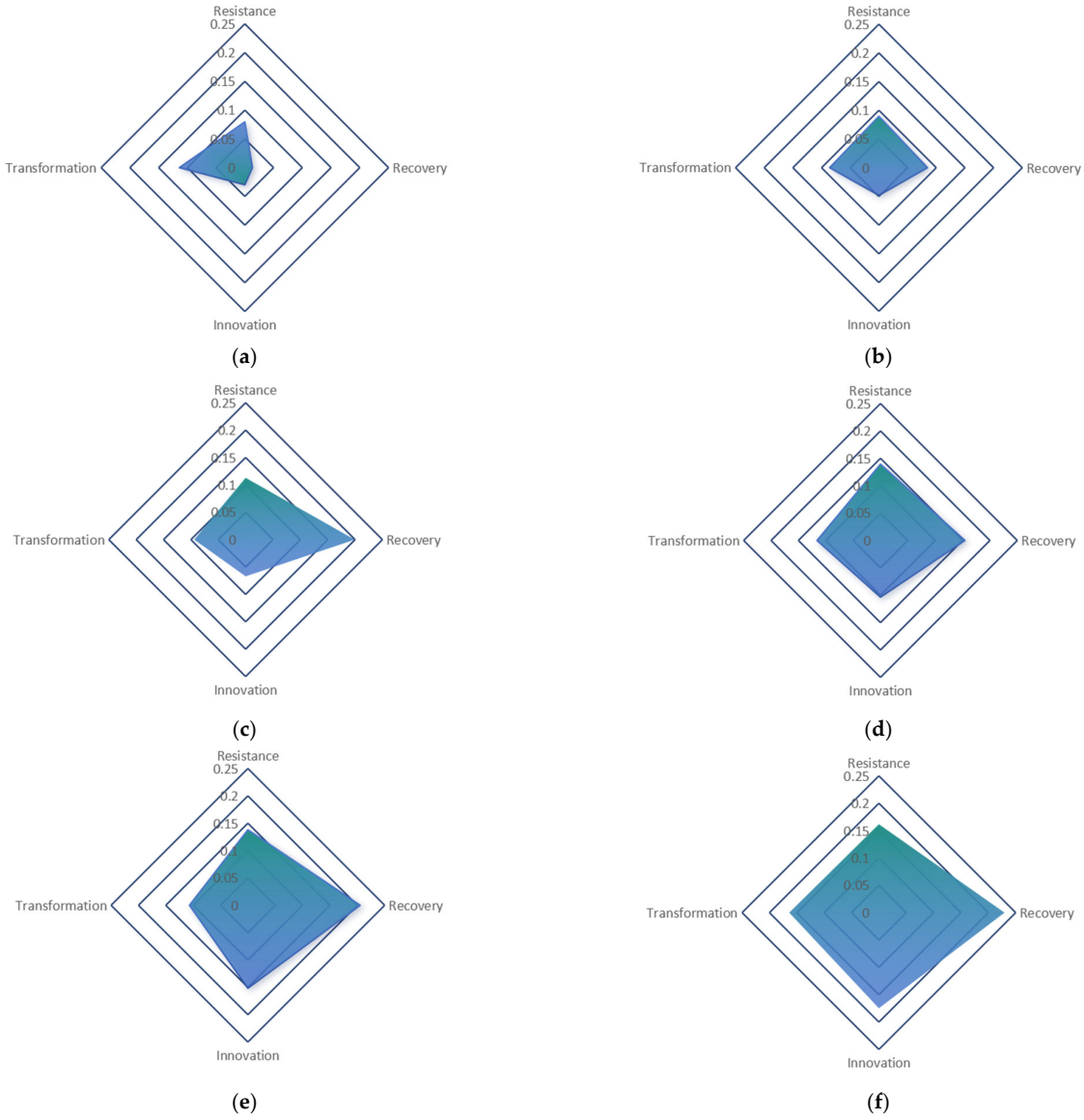


Figure 3. Radar Chart of the Resilience Index Evolution of China's OGI Chain. (**a**) Resilience Scores for Various Dimensions in 2001; (**b**) Resilience Scores for Various Dimensions in 2005; (**c**) Resilience Scores for Various Dimensions in 2010; (**d**) Resilience Scores for Various Dimensions in 2015; (**e**) Resilience Scores for Various Dimensions in 2020; (**f**) Resilience Scores for Various Dimensions in 2022.

As shown in Figure 3, the shape of the shaded area changes continuously, indicating that the functional performance of each dimension within the OGI chain's resilience system is constantly evolving and adapting. The expanding shaded area reflects a substantial enhancement in the overall resilience of the OGI chain, suggesting that its capacity to absorb and mitigate risk shocks has significantly improved over time.

3.2. Key Obstacle Factor Analysis

To identify the key obstacles hindering improvements in the resilience of China's OGI chain, Equations (13) and (14) were employed to calculate the obstacle degrees across different dimensions from 2001 to 2022. The results are presented in Figure 4.

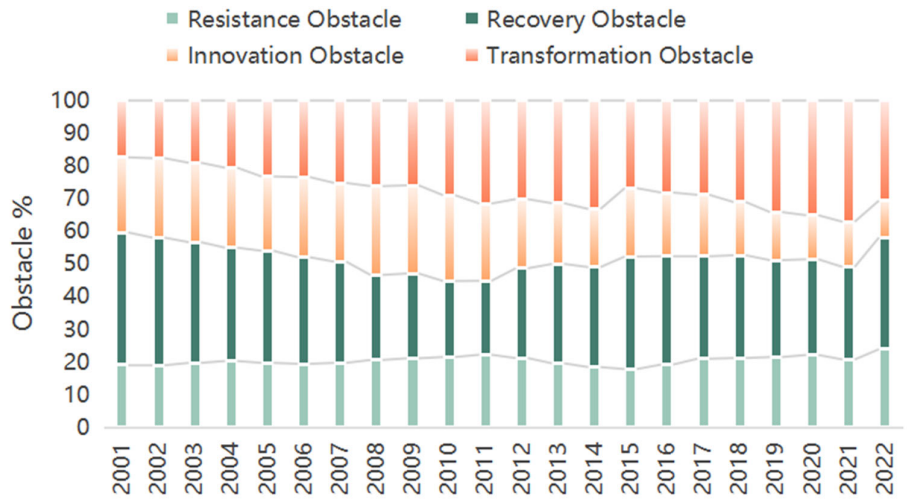


Figure 4. Trend of Obstacle Degree Changes in Various Dimensions of China's OGI.

As shown in Figure 4, the obstacle values across the four dimensions fluctuated between 2001 and 2022. The obstacle degree in the resistance dimension remained relatively stable, with slight increases observed from 2006 to 2011 and again from 2015 to 2022. The recovery dimension exhibited the greatest fluctuation, with a continuous decline between 2001 and 2011, followed by a significant increase from 2012 to 2015. The obstacle degree in the innovation dimension showed an overall downward trend, whereas the transformation dimension experienced a fluctuating upward trend. These patterns delineate two stages: the first from 2001 to 2014, and the second from 2015 to 2021.

In summary, recovery-related obstacles have consistently been the primary factors hindering the improvement of resilience in China's OGI. Conversely, the overall innovation and development environment of China's OGI has remained relatively favorable over the past 22 years.

To clarify the key factors affecting resilience improvement in China's OGI, obstacle factors from 2001 to 2022 were ranked, and the top five key obstacle factors were identified, as presented in Table 2.

From 2001 to 2021, indicator D8 (CCUS) consistently ranked first among the obstacles. China began focusing on carbon dioxide-enhanced oil recovery technology as early as 2000, which can be considered the initial prototype of China's CCUS technology. However, it was not until the 12th Five-Year Plan period that CCUS was officially designated as a key research and development technology within the OGI. Large-scale and commercial exploration of CCUS technology only commenced after 2016.

Indicator C4 (innovation outcomes in the downstream segment of the industrial chain) ranked second in obstacle severity 15 times during the 16 years from 2001 to 2016. This period marked the golden expansion era for the downstream sector of China's OGI chain. Driven by rapid economic growth, refining capacity, and sales networks experienced significant growth spurts. However, the market during this period was primarily demand-driven, and the industry's scientific and technological research capabilities lagged behind the pace of market growth. From 2017 to 2021, indicator A4 (dependence on natural gas imports) surged to second place in the obstacle rankings. This shift is closely linked to the explosive growth of China's LNG imports after 2016. Whereas natural gas import dependence was less than 2% in 2006, it reached 45.4% by 2021. With continued urban and industrial gas demand growth and pressures from the "dual carbon" transition, this indicator remains a critical focus for long-term monitoring.

Table 2. Key obstacle factors and degree of obstacles affecting the resilience of China's OGI from 2001 to 2022.

Title 1	NO. 1		NO. 2		NO. 3		NO. 4		NO. 5	
	Index	Obstacle	Index	Obstacle	Index	Obstacle	Index	Obstacle	Index	Obstacle
2001	D8	9.41	C4	8.63	B3	6.20	C2	4.95	C3	4.85
2002	D8	9.27	C4	8.48	B3	6.09	C2	4.89	C3	4.72
2003	D8	9.24	C4	8.42	B3	6.02	C2	4.88	C3	4.65
2004	D8	10.17	C4	9.03	B11	6.32	D7	5.33	C3	5.05
2005	D8	10.39	C4	9.19	B11	6.49	D7	5.68	C3	4.85
2006	D8	10.44	C4	9.81	B11	6.59	D7	5.46	C2	4.85
2007	D8	10.97	C4	10.38	B11	6.77	D7	5.68	C3	4.78
2008	D8	12.16	C4	11.39	B11	6.81	D7	6.06	C3	5.25
2009	D8	12.34	C4	11.23	B11	6.77	C2	5.86	C7	5.22
2010	D8	13.30	C4	11.68	B11	7.11	D7	6.69	C2	6.06
2011	D8	11.46	C4	10.87	D7	8.89	B11	7.72	C2	5.49
2012	D8	10.86	C4	9.32	D7	8.36	B11	6.99	B10	5.23
2013	D8	10.39	C4	9.00	D7	8.35	B11	6.65	B5	5.40
2014	D8	10.80	D7	8.62	C4	8.08	B11	6.38	A4	5.56
2015	D8	10.93	C4	8.87	B11	6.30	B5	5.82	A4	5.80
2016	D8	10.14	C4	8.51	A4	6.07	B5	5.65	B11	5.60
2017	D8	11.06	A4	7.31	C4	6.82	B10	6.10	D5	5.87
2018	D8	11.18	A4	8.34	B10	6.56	D5	6.47	C4	6.37
2019	D8	11.98	A4	8.79	B10	6.83	D5	6.45	C5	6.13
2020	D8	13.24	A4	9.33	B10	7.21	C5	6.78	A3	6.75
2021	D8	12.53	A4	10.96	B4	7.78	B10	7.33	C5	7.19
2022	A4	13.22	B4	10.70	B10	9.43	C2	9.15	A3	8.87

Between 2001 and 2021, the third-ranked obstacle indices showed varied frequencies: B11 appeared eight times, B10 four times, and B3 three times. These results suggest that the overall economic efficiency of the OGI and competitive dynamics in the downstream segment constitute major constraints on improving the resilience of the OGI chain, often causing significant fluctuations in resilience.

From 2004 to 2013, indicator D7 appeared six times as the fourth-ranked obstacle and three times as the third-ranked obstacle. Sulfur dioxide (SO_2) emissions in China's OGI are primarily associated with the processing, refining, combustion, storage, and transportation of sour natural gas. This indicates that over the past decade, despite rapid industry growth, the application of low-sulfur technologies has been insufficient to offset emission increases driven by the industry's expansion.

Overall, the obstacle degree analysis results align well with the actual development trajectory of China's OGI, demonstrating the reliability of the evaluation.

3.3. Coupling Coordination Analysis

Using Formulas (15)–(17), we calculated the coupling and coordination relationships between the various subsystems of China's OGI chain resilience. The results are shown in Figure 5.

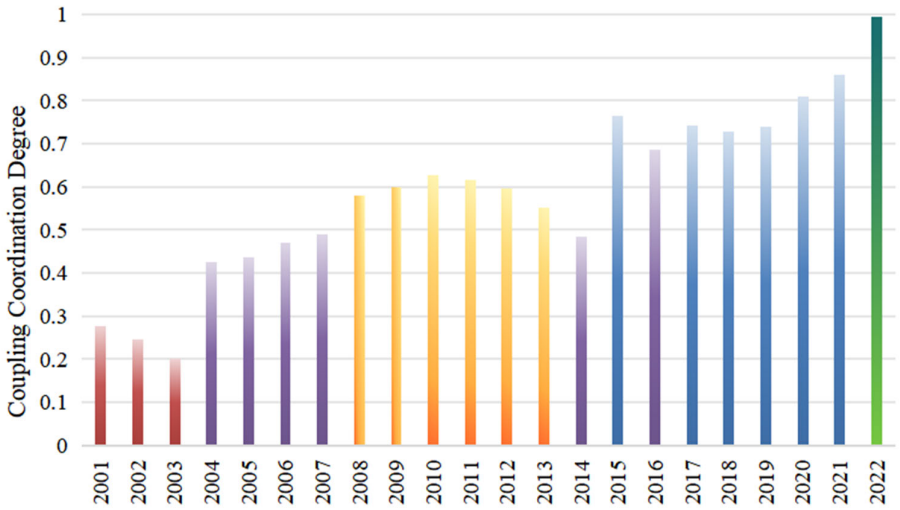


Figure 5. Resilience Coupling Coordination of Resilience Subsystems in China's OGI Chain.

In Figure 5, the overall coordination of the various subsystems of China's OGI chain resilience shows a volatile upward trend from 2001 to 2022. For phase-specific feature analysis, a hierarchical study of coupling coordination relationships was conducted.

The natural breakpoint method was applied to classify the resilience coupling coordination degree (CCD) of China's OGI into five levels, as shown in Table 3: Level I Extremely Incoordination ($0 < R < 0.3$), Level II Mild Incoordination ($0.3 \leq R < 0.5$), Level III Primary Coordination ($0.5 \leq R < 0.7$), Level IV Mild Coordination ($0.7 \leq R < 0.9$), and Level V High-Quality Coordination ($0.9 \leq R \leq 1.0$).

Table 3. Types and Grades of Coupling Coordination Degree (CCD).

Grade	Extremely Incoordination	Mild Incoordination	Primary Coordination	Mild Coordination	High-Quality Coordination
CCD	[0.0, 0.3)	[0.3, 0.5)	[0.5, 0.7)	[0.7, 0.9)	[0.9, 1.0)

From 2001 to 2003, the system was in Level I Extremely Incoordination, with CCD values showing a declining trend. From 2004 to 2007, it entered a state of Level II Mild Incoordination but, compared to the previous phase, CCD values overall maintained an upward trend, indicating that the coupling and coordination between subsystems were continuously improving. From 2008 to 2013, the system reached Level III Primary Coordination, but the CCD value showed a declining trend from 2010 to 2013. From 2014 to 2016, the CCD value exhibited significant fluctuations. Due to the declining trend in the CCD value from 2010 to 2013 in the previous cycle, the CCD value in 2014 reverted to Level II. Although the CCD value briefly returned to Level III in 2015, but in 2016, it returned to Level II. From 2017 to 2021, the CCD value rose to Level IV Mild Coordination, with significantly improved coupling coordination among subsystems, indicating that the overall coordination of the OGI chain has improved when facing complex environments and challenges. In 2022, the CCD value exceeded 0.9, with coupling coordination among subsystems reaching Level V High-Quality Coordination.

4. Discussion

This study conducted a comprehensive assessment of the resilience of China's OGI chain and produced a series of insightful results. Compared with existing research on OGI chain resilience, this study presents both similarities and differences.

The similarities include the use of an objective weighting method to construct a comprehensive evaluation model; integration across different dimensions and time periods; and the observation that, from an overall resilience perspective, China's OGI chain exhibited a fluctuating upward trend with clear phased characteristics. This indicates that the current OGI chain possesses certain buffering, adaptability, and recovery capabilities when facing various internal and external shocks.

The differences lie in the conceptual interpretation of industrial chain resilience. Unlike Wu Wenjie (2024), who regard indicators such as GDP, per capita GDP, and industrial added value as key factors shaping OGI resilience [14], this paper constructs a comprehensive evaluation index system based primarily on endogenous factors (as shown in Table 1), while considering macroeconomic variables like GDP fluctuations as exogenous shocks. Moreover, this study treats the OGI as an integrated whole, due to the natural coexistence of oil and gas resources, their substitutability in consumption and use, and the shared nature of development, processing, and transportation units. Additionally, national energy industry policies and oil and gas companies' strategic layouts are generally considered holistically. Studying the OGI as a whole allows for a more accurate reflection of the complementary development between China's natural gas and oil industries since 2006, fully and comprehensively capturing their resource supply capabilities.

Despite its contributions, this study is not without limitations. The absence of publicly available data on national emergency oil and gas reserves limited the precision of the resilience assessment. Although proxy indicators (e.g., price buffering capacity) were employed, they may not fully capture the dynamic response mechanisms. Furthermore, the study period ends in 2022 due to the unavailability of updated data for 2023–2024, potentially omitting recent developments such as geopolitical shifts or CCUS adoption.

5. Conclusions and Implications

5.1. Research Conclusions

Based on Martin's "4R" resilience theoretical framework, this study constructs a comprehensive evaluation model using the entropy weight method, obstacle factor analysis, and the coupling coordination degree (CCD) model to assess the resilience of China's oil and gas industry (OGI) chain from 2001 to 2022. The main conclusions are as follows:

(1) The overall resilience of China's OGI chain exhibited a sustained upward trend during the study period, rising from 0.23652 in 2001 to 0.72977 in 2022, with an average annual growth rate of 5.51%. Despite experiencing multiple internal adjustments and external shocks, the system's capacity to absorb and adapt to risks has significantly improved.

(2) Distinct stage-based patterns emerged in alignment with China's Five-Year Plan cycles. A "V-shaped" resilience trajectory was observed during the 10th Plan, while the 11th and 12th Plans saw steady gains. Although setbacks occurred in the early years of the 13th and 14th Plans, long-term growth momentum was maintained. These variations highlight the system's adaptability amid oil price fluctuations, economic transitions, and global crises such as the COVID-19 pandemic.

(3) Significant differences in resilience performance were observed across dimensions. Recovery showed the greatest improvement, innovation followed a steady growth path, resistance remained relatively stable, and transformation accelerated after 2019 due to low-carbon development policies. These results reflect advances in technological and structural adjustment, though the capacity to withstand external shocks requires further reinforcement.

(4) Key obstacles constraining resilience improvement were identified. Recovery capacity remains the most critical bottleneck, particularly in relation to the underdevelopment

of CCUS technologies and insufficient innovation in the downstream sector. In addition, rising dependence on natural gas imports and inadequate economic returns across the value chain continue to impede overall resilience enhancement.

(5) The coupling coordination among resilience subsystems has progressively improved. From 2001 to 2022, the CCD between resistance, recovery, innovation, and transformation evolved from mild imbalance to moderate coordination, indicating enhanced internal synergy and an improved capacity for integrated response to complex and evolving risks.

These findings contribute to the understanding of industrial resilience evolution in the context of energy security and transition, offering valuable insights for policy formulation and strategic planning aimed at strengthening the resilience of critical energy infrastructure.

5.2. Research Implications

Based on the above findings, it is evident that enhancing the resilience of China's oil and gas industry chain primarily depends on technological innovation and low-carbon transformation. Moreover, government policy support plays a critical role in strengthening industrial resilience. Accordingly, the resilience of the oil and gas industry chain can be improved through the following three pathways:

(1) Technology-driven upgrading: Foster an integrated upstream and downstream R&D ecosystem, with a particular focus on carbon capture, utilization, and storage (CCUS), digital oilfield technologies, and the development of low-carbon materials.

(2) Diversification of supply sources: Strategically reduce dependence on imports by expanding domestic reserves and diversifying international procurement channels.

(3) Governance and policy optimization: Incorporate resilience assessment mechanisms into national energy planning and implement early warning systems for supply chain risks.

5.3. Future Research Directions

Despite the comprehensive assessment of resilience in China's oil and gas industry chain, several areas remain underexplored and warrant future investigation:

(1) The Advancement of Resilience Measurement Methods: The current study primarily uses entropy weight-based composite evaluation. However, given the complex networked nature of the OGI chain, future research could incorporate network analysis tools such as network density, centrality, and robustness indicators. The dynamic trade network model proposed by Liu et al. (2025) in the context of agricultural trade offers methodological inspiration [36].

(2) The Identification of Core Resilience Drivers: Current models focus on multidimensional indicators but lack a statistical identification of causality. Future studies may consider applying the Temporal Exponential Random Graph Model (TERGM) or panel structural equation modeling to identify key internal and external factors influencing resilience [37].

(3) The Exploration of Differentiated Resilience Enhancement Paths: The OGI chain's resilience performance varies across different economic cycles. Thus, exploring targeted policy and industrial responses under different scenarios—e.g., demand surges, supply disruptions, or geopolitical shocks—could yield tailored strategies. Comparative case studies or scenario simulations would be valuable.

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Abbreviations

The following abbreviations are used in this manuscript:

OGI	Oil and Gas Industry
CCD	Coupling Coordination Degree

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