

Article

Spatiotemporal Patterns and Influencing Factors of the “Three Modernizations” Integrated Development in China’s Oil and Gas Industry

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Abstract

Against the backdrop of China’s “carbon peaking” and “carbon neutrality” goals, as well as the advancement of new industrialization, the oil and gas industry is undergoing a critical transformation from resource-dependent growth toward innovation-driven, low-carbon, and high-quality development. The integrated advancement of high-end, intelligent, and green transformation—collectively referred to as the “Three Modernizations”—has become a vital pathway for promoting industrial upgrading and sustainable growth. Based on panel data from 30 Chinese provinces from 2009 to 2023, this study constructs a comprehensive evaluation index system covering 19 secondary indicators across three dimensions: high-end, intelligent, and green development. Using the entropy-weighted TOPSIS method, kernel density estimation, Dagum Gini coefficient decomposition, and σ – β convergence models, the study examines the spatiotemporal evolution, regional disparities, and convergence characteristics of HIG integration, and further explores its driving mechanisms through a two-way fixed effects model and mediation effect analysis. The results show that (1) the overall HIG integration index rose from 0.34 in 2009 to 0.46 in 2023, forming a spatial pattern of “high in the east, low in the west, stable in the center, and fluctuating in the northeast”; (2) regional disparities narrowed significantly, with the Gini coefficient declining from 0.093 to 0.058 and σ decreasing from 7.114 to 6.350; and (3) oil and gas resource endowment, policy support, technological innovation, and carbon emission constraints all positively promote integration, with regression coefficients of 0.152, 0.349, 0.263, and 0.118, respectively. Heterogeneity analysis reveals an increasing integration level from upstream to downstream, with eastern regions leading in innovation-driven development. Based on these findings, the study recommends strengthening policy and institutional support, accelerating technological innovation, improving intelligent infrastructure, deepening green and low-carbon transformation, promoting regional coordination, and establishing a long-term monitoring mechanism to advance the integrated high-quality development of China’s oil and gas industry. Overall, this study deepens the understanding of the internal logic and spatial dynamics of the “Three Modernizations” integration in China’s oil and gas industry, providing empirical evidence and policy insights for accelerating the construction of a low-carbon, secure, and efficient modern energy system.



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Keywords: oil and gas industry; high-end development; intelligent development; green development; spatial convergence; Gini coefficient

1. Introduction

Under the dual objectives of China's "carbon peaking" and "carbon neutrality" strategies, coupled with the ongoing advancement of new industrialization, the oil and gas industry is experiencing a fundamental transformation from resource-dependent expansion to innovation-driven, low-carbon, and high-quality development. As a critical pillar of national energy security and a significant source of carbon emissions, the industry faces the urgent challenge of ensuring energy supply while achieving sustainable, green, and intelligent transformation. The integrated advancement of high-end, intelligent, and green development—collectively termed the "Three Modernizations" (HIG)—has emerged as a key pathway for promoting industrial upgrading and sustainable growth.

Existing research largely examines single-dimensional transformations, such as technological innovation, intelligent manufacturing, or green production, but systematic studies on integrated HIG development, its spatiotemporal evolution, and regional disparities are scarce. Additionally, the mechanisms through which resource endowment, policy support, technological innovation, and carbon emission constraints jointly affect HIG integration remain underexplored.

To address these gaps, this study constructs a comprehensive HIG evaluation system and analyzes 30 Chinese provinces from 2009 to 2023. Employing the entropy-weighted TOPSIS method, kernel density estimation, Dagum Gini coefficient decomposition, and σ – β convergence models, the study examines the spatiotemporal dynamics and regional disparities of HIG integration. Further, a two-way fixed effects model with mediation effect analysis is applied to explore how resource endowment, policy support, technological innovation, and carbon constraints directly and indirectly drive integration.

The study makes three primary contributions:

1. **Methodological contribution:** It develops a unified, quantifiable framework for evaluating integrated HIG development, enriching analytical tools for industrial modernization research.
2. **Empirical evidence:** It documents spatial heterogeneity and convergence dynamics in China's oil and gas industry under the "dual carbon" agenda.
3. **Mechanism insights:** It identifies interactive pathways through which policy, innovation, and environmental constraints collectively facilitate integrated transformation.

These findings provide theoretical insights and practical policy guidance for accelerating the high-quality, intelligent, and low-carbon transformation of China's oil and gas sector.

The overall research framework is illustrated in Figure 1.

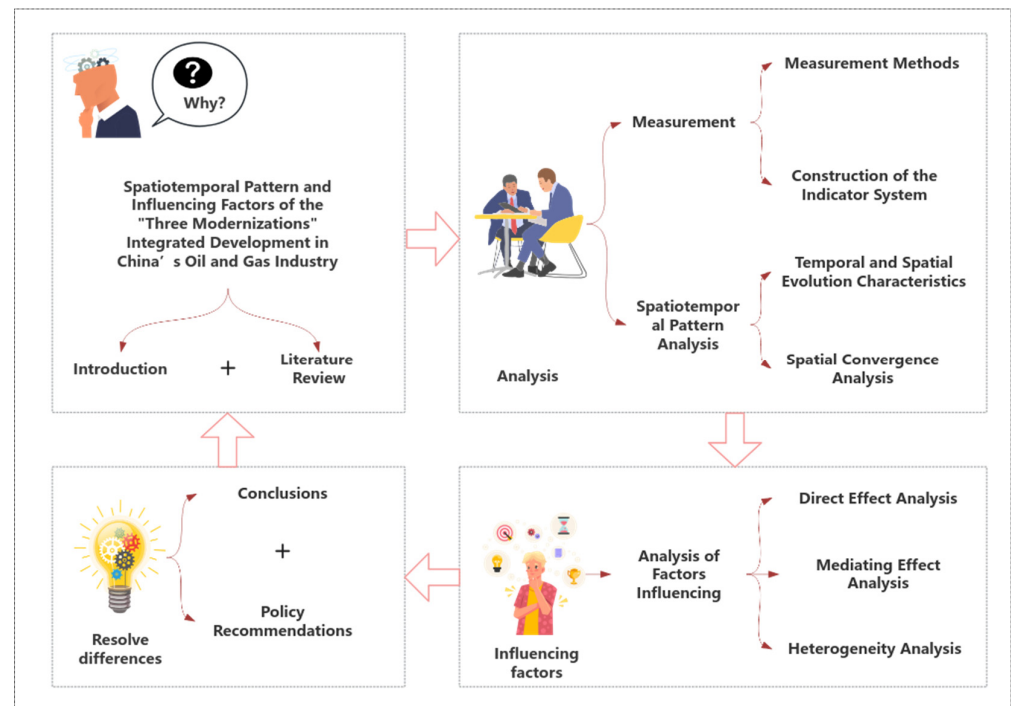


Figure 1. Research Framework of This Research.

2. Literature Review

The integrated development of “Three Modernizations” involves multiple dimensions such as structural upgrading, technological innovation, and ecological transition. Its theoretical basis can be traced to the literature on regional convergence, industrial modernization, and green development [1].

2.1. Spatial Inequality and Regional Convergence

Barro and Sala-i-Martin proposed the convergence theory, arguing that as capital accumulation and technological diffusion advance, interregional disparities tend to narrow over time [2]. Rey and Montouri further incorporated spatial econometric methods, emphasizing the role of geographical proximity and spillover effects in regional convergence [3]. Subsequent studies revealed that regional differences in factor endowment, industrial structure, and policy environment often lead to conditional rather than absolute convergence. In the energy sector, Chang et al. and Dong et al. demonstrated that China’s energy industry exhibits significant spatial heterogeneity, and regional coordination effects play a vital role in convergence speed [4,5]. These findings provide a theoretical foundation for examining the spatial distribution and convergence of the oil and gas industry’s HIG integration.

2.2. Industrial Modernization and Policy-Driven Mechanisms

The theory of industrial modernization posits that upgrading the industrial structure is central to achieving high-quality growth. Porter emphasized the dual driving roles of policy support and technological innovation in promoting competitiveness. Recent studies have extended this framework to manufacturing and energy industries [6]. For instance, Song et al. found that technological innovation significantly accelerates industrial high-end transformation [7], while Chang and Fu highlighted the importance of digital manufacturing and information technology in industrial modernization [8]. However, most existing studies focus on single dimensions—either high-end, intelligent, or green development—without constructing a unified measurement system to capture their integrated effects.

2.3. Green Transformation and the Energy Industry

Under the dual-carbon strategy, green development has become a research frontier. The Porter Hypothesis suggests that well-designed environmental regulations can stimulate innovation and enhance competitiveness through the “innovation compensation effect” [9]. Recent studies, such as Shen et al. and Li et al. confirmed that environmental policies and green technological innovation jointly promote sustainable transitions in energy-intensive sectors [10,11]. Meanwhile, digitalization and intelligent management are increasingly regarded as new drivers for improving energy efficiency and reducing emissions. Nevertheless, research specifically focusing on the integrated modernization of the oil and gas industry remains scarce, and the synergistic mechanisms among policy, technology, and environmental constraints have yet to be systematically explored [12].

3. Measurement of the Integrated Development Level of the “Three Modernizations” in China’s Oil and Gas Industry

3.1. Definition of the Connotation of “Three Modernizations” Integration

The high-end, intelligent, and green transformation of the oil and gas industry represents the core pathway for promoting its high-quality transformation and upgrading.

High-end development is primarily achieved by strengthening the industrial foundation, expanding industrial scale, and improving industrial efficiency. It emphasizes technological innovation, equipment upgrading, and management optimization to drive technological progress and breakthroughs in independent key technologies across exploration, processing, and equipment manufacturing, thereby enhancing industrial added value and international competitiveness.

Intelligent development relies on information technology and automation systems, focusing on strengthening intelligent infrastructure, increasing intelligent investment, and enhancing intelligent output. It promotes the digitalization, networking, and intelligentization of exploration, production, transportation, and management processes, thereby improving resource development efficiency, safety assurance, and scientific decision-making capacity.

Green development centers on advancing green production, controlling pollution emissions, and strengthening pollution management. Through energy conservation, clean production, green refining processes, and the application of carbon capture, utilization, and storage (CCUS) technologies, it reduces energy consumption and emissions, reinforces resource recycling, and promotes low-carbon, clean, and sustainable industrial development.

The integrated development of the “Three Modernizations” is not an isolated process but a mutually reinforcing and synergistic evolution. Through high-end development to consolidate the technological and industrial foundation, intelligent development to empower management and production processes, and green development to guide the direction of low-carbon and environmental protection, the integration achieves an organic combination of technological innovation, intelligent management, and green production. This ultimately promotes economic efficiency while ensuring efficient resource utilization and environmental friendliness in the oil and gas industry. To vividly illustrate the integration mechanism among the “high-end, intelligent, and green” dimensions of China’s oil and gas industry, this study constructs a conceptual diagram of the integration mechanism, as shown in Figure 2.

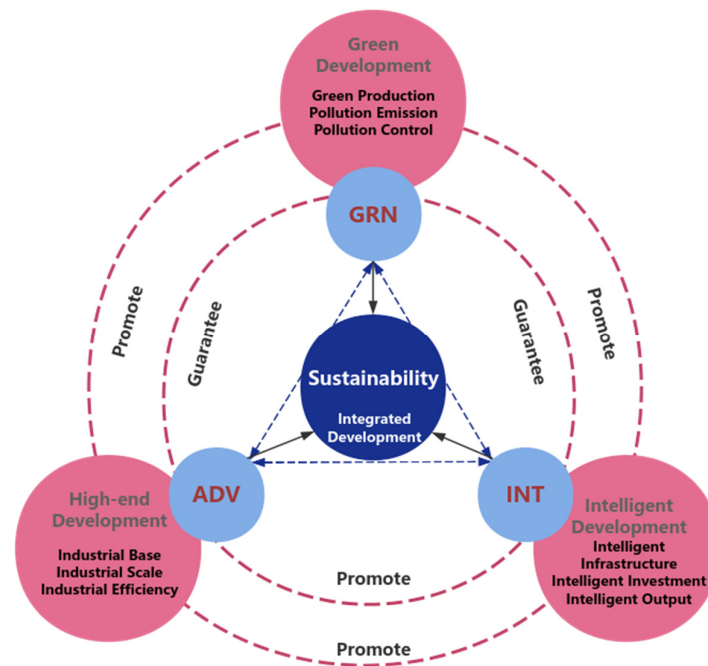


Figure 2. Mechanism of the “Three Modernizations” (HIG) Integrated Development in China’s Oil and Gas Industry.

3.2. Construction of the Indicator System for Measuring “Three Modernizations” Integration

To scientifically assess the level of integrated development of the “Three Modernizations” in China’s oil and gas industry, this study follows the principles of dynamism, quantifiability, and hierarchy. Based on the connotations of high-end, intelligent, and green development and drawing on the research of Wang Yi et al. [1], a comprehensive measurement system is constructed. The system includes three primary indicators—high-end, intelligent, and green development—and 19 secondary indicators. The specific indicators are shown in Table 1.

Table 1. Measurement Indicator System for the Integrated Development of the ‘Three Modernizations’ in China’s Oil and Gas Industry.

Primary Indicator	Secondary Indicator	Tertiary Indicator	Attribute
High-end Development (ADV)	Industrial Base (IND)	Regional Energy Reserves (RER)	Positive
		Oil and Gas Industry Investment (OGI)	Positive
	Industrial Scale (SCL)	Total Industry Profit (TPI)	Positive
		Industrial GDP (GIO)	Positive
		Average Employee Salary (ASE)	Positive
Intelligent Development (INT)	Industrial Efficiency (EFF)	Total Assets (TAI)	Positive
		Number of Employees (NEI)	Positive
	Intelligent Infrastructure (INF)	Share of R&D Personnel (RDP)	Positive
		Internet Penetration Rate (IPR)	Positive
	Intelligent Investment (INX)	R&D Expenditure (RDX)	Positive
		Patent Applications and Grants (NPG)	Positive
Green Development (GRN)	Intelligent Output (INP)	Technology Market Transaction Value (TMT)	Positive
		Coal Production (RCO)	Negative
	Green Production (GPR)	Crude Oil Production (COO)	Negative
		Natural Gas Production (NGO)	Positive
	Pollution Emission (PEM)	Total Carbon Emissions (TCE)	Negative
		Carbon Intensity (CEI)	Negative
	Pollution Control (PCO)	Industrial Solid Waste Utilization Rate (ISW)	Positive
		Pollution Control Investment as % of GDP (PCI)	Positive

3.3. Measurement Methods

To ensure the objectivity and scientific validity of evaluating the integrated development level of the “Three Modernizations” in China’s oil and gas industry, and to comprehensively reflect the differences and relative advantages among various regions, this study employs the entropy-weighted TOPSIS method for comprehensive measurement. the calculation steps are as follows [13]:

Step 1: Standardize all indicators:

$$\text{For positive indicators : } X'_{tij} = \frac{X_{tij} - \min X_{tj}}{\max X_{tj} - \min X_{tj}}, \quad (1)$$

$$\text{For negative indicators : } X'_{tij} = \frac{\max X_{tj} - X_{tij}}{\max X_{tj} - \min X_{tj}}. \quad (2)$$

In Formulas (1) and (2), X'_{tij} is the standardized value, X_{tij} is the value of the j -th evaluation indicator in the i -th province in year t ; $\max X_{tj}$ and $\min X_{tj}$ represent the maximum and minimum values, respectively, of the j -th indicator across all provinces in year t .

Step 2: Dimensionless normalization and calculation of proportion p_{tij} :

$$p_{tij} = X'_{tij} / \sum_{t=1}^{\theta} \sum_{i=1}^m X'_{tij}. \quad (3)$$

Step 3: Calculate information entropy e_j :

$$e_j = -\frac{1}{\ln m} \sum_{i=1}^m p_{tij} \ln p_{tij}. \quad (4)$$

Step 4: Calculate the coefficient of variation (degree of divergence) a_j :

$$a_j = 1 - e_j. \quad (5)$$

Step 5: Calculate the weight of each indicator W_j :

$$W_j = a_j / \sum_{j=1}^n a_j. \quad (6)$$

Step 6: Calculate the comprehensive score (TOPSIS method) s_{ti} :

$$s_{ti} = \sum_{j=1}^n W \times X'_{tij}. \quad (7)$$

3.4. Data Sources

This study uses panel data on China’s oil and gas industry covering 30 provinces from 2009 to 2023. Due to data continuity and availability, Tibet, Hong Kong, Macao, and Taiwan are excluded from the sample. The data are mainly sourced from the China Statistical Yearbook, China City Statistical Yearbook, China Ecological and Environmental Statistical Yearbook, China Environmental Statistical Yearbook, Compilation of Patent Statistics Yearbook, Statistical Bulletin on Science and Technology Investment, and China Energy Statistical Yearbook. For missing or incomplete observations, linear interpolation was applied to ensure data consistency and completeness. Based on these data, the integration level of the “three modernizations” in China’s oil and gas industry was calculated, as presented in Appendix A Table A1.

4. Spatiotemporal Pattern Analysis of the “Three Modernizations” Integration in China’s Oil and Gas Industry

Building on the dataset described above, the calculated integration levels of the “three modernizations” provide a foundation for analyzing both temporal and spatial dynamics of the oil and gas industry. Before exploring the influencing factors, it is essential to examine how the integration level has evolved over time, how it is distributed across regions, and how regional disparities emerge. The following section therefore presents a spatiotemporal pattern analysis, revealing the developmental trajectory and convergence characteristics of the “three modernizations” integration across China.

4.1. Temporal Evolution Characteristics

To examine the temporal variation in the “three modernizations” integration level in China’s oil and gas industry, the kernel density estimation (KDE) method is employed. KDE is a non-parametric statistical approach used to estimate the probability density function of a random variable. Its basic idea is to generate small probability density contributions around each data point using a series of kernel functions, and then aggregate these contributions to obtain the overall probability density estimate. This allows for the analysis of the distribution’s location, shape, dispersion, and polarization characteristics. In particular, if the kernel density curve exhibits bimodal or multimodal fluctuations, it indicates significant polarization of the integration level during that period; conversely, such polarization is weaker. The calculation formula is as follows [14]:

$$f(x) = \frac{1}{Nh} \sum_{i=1}^N K\left(\frac{X_i - x}{h}\right), \quad (8)$$

$$K(x) = \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{x^2}{2}\right). \quad (9)$$

In the above two formulas, $f(x)$ represents the probability density function, $K(x)$ is the kernel function, X_i denotes independent and identically distributed (i.i.d.) variables, x denotes independent, N is the number of variables (sample size), h is the smoothing parameter (bandwidth). In this study, the smoothing parameter is set to 0.04. A larger bandwidth produces a smoother density curve, but it also increases bias and reduces estimation accuracy.

Figure 3 presents the kernel density curves drawn using MATLAB R2017a based on the data calculated from the kernel density estimation formula. From the figure, it can be seen that Kernel density estimation (KDE) curves were plotted at the national level and for the eastern, central, northeastern, and western regions, revealing pronounced regional disparities and distinct spatiotemporal patterns. During the 11th Five-Year Plan, integration levels were generally low, with unimodal distributions. In later periods, the curves shifted rightward and became bimodal, indicating growing regional divergence and the rise in provinces reaching higher integration levels. The eastern region has consistently led, showing steady improvement but widening internal disparities. The central region exhibits moderate and balanced growth, while the northeastern region has stabilized after earlier fluctuations. The western region lags behind, with only gradual progress. Overall, the spatial pattern reflects a clear “high in the east, low in the west” trend. The bimodal distributions highlight increasing differentiation across and within regions, providing guidance for regional coordination and targeted policy measures to advance integrated HIG development in China’s oil and gas industry.

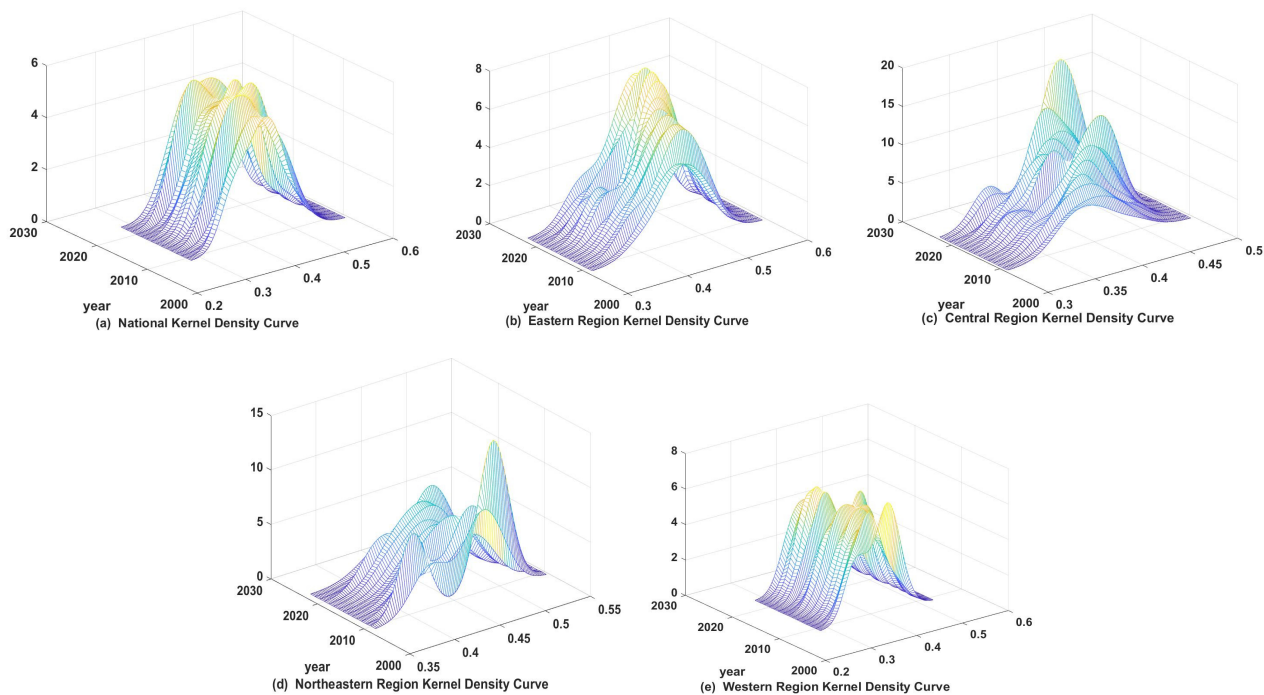


Figure 3. Kernel Density Curves of Integrated Development Levels in China's Oil and Gas Industry by Region.

4.2. Spatial Evolution Characteristics

To examine the spatial evolution of high-end, intelligent, and green (HIG) integration in China's oil and gas industry, ArcMap was used to plot the integration levels from 2009 to 2023 based on Appendix A Table A1 (Figure 4). Overall, most regions nationwide were at a medium integration level, with a concentration in the central region forming a relatively stable belt-like distribution.

During the 11th Five-Year Plan (2009–2010), eastern provinces such as Beijing (0.54, Stage IV), Tianjin (0.59, IV), and Shanghai (0.54, IV) exhibited high integration, while provinces like Hainan (0.32, II) and Fujian (0.39, II) lagged behind. Central regions such as Hubei (0.41, III) and Anhui (0.34, II) were generally at medium levels, whereas western provinces such as Inner Mongolia (0.31, II) and Guizhou (0.32, II) displayed relatively low integration.

From the 12th to 13th Five-Year Plans (2011–2020), the eastern and parts of the north-eastern regions demonstrated clear upward trends. For instance, Heilongjiang progressed from 0.48 (Stage III) in 2009 to 0.50 (IV) in 2016, while Shandong improved from 0.47 (III) to 0.52 (IV). Conversely, the western region, particularly resource-intensive areas like Inner Mongolia (0.30–0.30, Stage II) and Qinghai (0.40–0.39, III→II), experienced stagnation or slight declines, reflecting slower technological upgrading, weaker infrastructure, and ecological pressures. Central regions such as Anhui (0.36→0.39) and Hunan (0.37→0.39) showed gradual improvement, often advancing from Stage II to Stage III by the 14th Five-Year Plan.

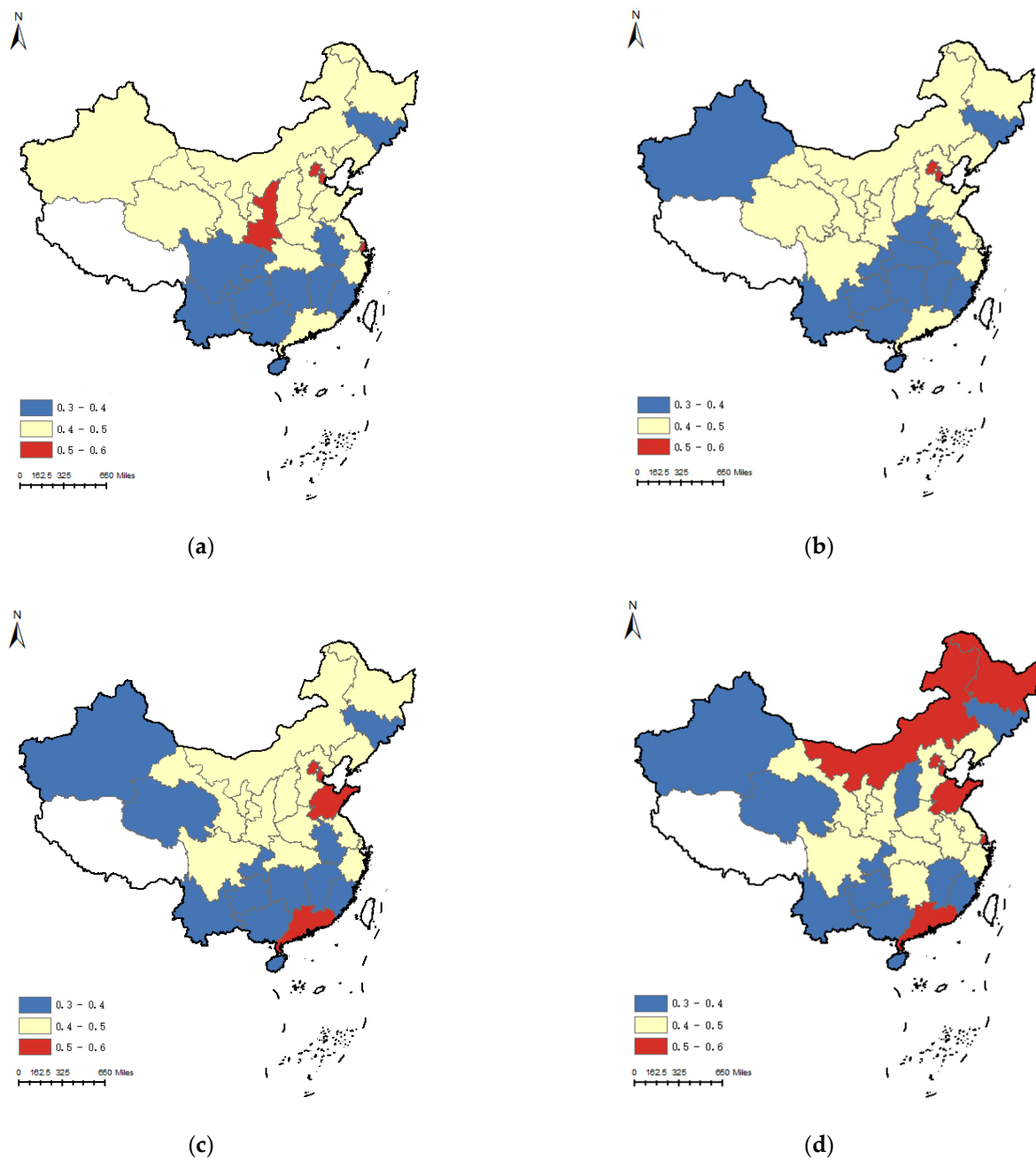


Figure 4. Spatial Evolution Trend of Integrated Development of the ‘Three Modernizations’ in China’s Oil and Gas Industry. (a) 11th Five-Year Plan period (2009–2010); (b) 12th Five-Year Plan period (2011–2015); (c) 13th Five-Year Plan period (2016–2020); (d) 14th Five-Year Plan period (2021–2023).

By the 14th Five-Year Plan (2021–2023), the spatial pattern formed a regional gradient: eastern provinces maintained strong integration (Beijing 0.52, IV; Guangdong 0.52, IV), the central region reached medium-high levels (Hubei 0.43, III; Anhui 0.40, III), the northeastern region showed mixed performance with Heilongjiang achieving Stage IV (0.52) while Jilin remained at Stage II (0.36), and the western region exhibited persistent heterogeneity, with Guangxi advancing to Stage IV (0.50) but Qinghai remaining low (0.37, II).

Overall, these spatial dynamics highlight that HIG integration is stronger in the east and weaker in the west, reflecting the combined influence of policy responsiveness, technological capacity, industrial structure, and resource endowment. The results underscore the need for region-specific strategies to promote balanced high-quality transformation across the full industrial chain.

4.3. Regional Differences and Their Sources

To investigate the regional disparities in the “High-end, Intelligent, and Green” (HIG) integration level of China’s oil and gas industry and the sources of these disparities, this study adopts the Gini coefficient decomposition method [15]. First, the Gini coefficient is used to assess the degree of inequality in the HIG levels across regions. Then, the Gini coefficient is decomposed to analyze the contribution of different factors to overall inequality. In this study, the overall Gini coefficient G is decomposed into the contribution of within-region disparities G_w , the contribution of between-region disparities G_{nb} , and the hypervariable density G_l , which allows for a more detailed assessment of inter-regional inequality. The variables satisfy the following definition: $G = G_w + G_{nb} + G_l$ represents

$$G = \left(\sum_{i=1}^k \sum_{m=1}^k \sum_{j=1}^{h_i} \sum_{n=1}^{h_j} |y_{im} - y_{jn}| \right) / 2h^2\bar{y}. \quad (10)$$

Among them, y_{im} represents the high-end, intelligent, and green development level of the m -th province in region i , y_{jn} represents the high-end, intelligent, and green integrated development level of the n -th province in region j , $\bar{y}$ represents the average value of the high-end, intelligent, and green integrated development level, and h represents the number of provinces in the sample.

$$G_{ii} = \left(\frac{1}{2\bar{y}_i} \sum_{m=1}^{h_i} \sum_{n=1}^{h_i} |y_{im} - y_{in}| \right) / h^2 \quad (11)$$

$$G_w = \sum_{i=1}^k G_{ii} P_i S_i \quad (12)$$

$$G_{ij} = \left(\sum_{m=1}^{h_i} \sum_{n=1}^{h_j} |y_{im} - y_{jn}| \right) / h_i h_j (\bar{y}_i - \bar{y}_j) \quad (13)$$

$$G_{nb} = \sum_{i=2}^k \sum_{j=1}^{i-1} G_{ij} (P_i S_i) D_{ij} \quad (14)$$

$$G_l = \sum_{i=2}^k \sum_{j=1}^{i-1} G_{ij} (P_i S_i + P_j S_j) (1 - D_{ij}) \quad (15)$$

$$D_{ij} = (d_{ij} - P_{ij}) / (d_{ij} + P_{ij}) \quad (16)$$

$$d_{ij} = \int_0^\infty dF_i(y) \int_0^y (y-x) F_j(x) \quad (17)$$

$$P_{ij} = \int_0^\infty dF_j(y) \int_0^y (y-x) F_i(x) \quad (18)$$

In the above formula, i and j represent different regions, m and n represent different provinces, k and $h_i(h_j)$ represent the number of regions and the number of provinces in region $i(j)$, $\bar{y}$ represents the average value of high-end, intelligent and green development level, and d_{ij} as well as P_{ij} represent the mathematical expectations of the sum of all sample values that satisfy $y_{ij} - y_{mn} > 0$ and $y_{ij} - y_{mn} < 0$ in region i and region j . The Gini coefficients for each region and their decomposition, calculated based on the above formulas, are presented in Appendix B, Tables A2–A4.

(1) Intra-Regional Gini Coefficients

As shown in Appendix B Table A2, intra-regional disparities vary across regions. The eastern region maintains relatively balanced integration, with Gini values ranging from 0.058 to 0.093 (average 0.072) over 2009–2023. The central region shows notable improvements, with Gini declining from 0.082 in 2009 to 0.031 in 2023 (average 0.056), reflecting enhanced technological upgrading and green transformation. The western region exhibits persistent internal disparities, with Gini fluctuating between 0.072 and 0.087 (average 0.082), while the northeastern region shows volatility, with Gini ranging from 0.043 to 0.085 (average 0.058), indicating uneven development among provinces due to limited infrastructure and technological capacity [16].

(2) Interregional Gini Coefficients

Appendix B Table A3 reports interregional disparities. Gaps between the eastern–central regions decreased from 0.105 in 2009 to 0.069 in 2023, and central–western gaps declined from 0.083 to 0.072, indicating gradual diffusion of resources and technology. The eastern–western gap remained relatively high, fluctuating around 0.097 in 2009 and 0.088 in 2023, reflecting persistent structural imbalances. The northeastern region continues to show relatively large differences with other regions, e.g., northeast–central decreased modestly from 0.084 to 0.066, highlighting limited interregional synergy.

(3) Overall Gini Coefficients

The overall Gini coefficients in Appendix B Table A4 reveal persistent regional disparities in integrated HIG development. The total Gini ranged from 0.034 in 2022 to 0.051 in 2019, averaging 0.044 over the period. Contribution decomposition shows that within-region disparities account for approximately 49.7% of total variation, while between-region disparities contribute around 24.7%, and hyper-variability density around 25.7%. The eastern region consistently has the lowest Gini values, reflecting relatively balanced integration, whereas the western region remains comparatively high. The central region exhibits clear improvement since 2012, and the northeastern region shows fluctuations with occasional rebounds, reflecting ongoing challenges in achieving coordinated HIG integration across all regions.

Overall, the Gini analysis confirms that while disparities in China’s oil and gas industry have gradually narrowed, regional imbalances persist, emphasizing the need for targeted policies to promote balanced and coordinated HIG development.

4.4. Spatial Convergence Analysis

To further explore the regional development dynamics of the “three modernizations” integration, it is necessary to examine not only the dispersion of integration levels across regions (σ -convergence) but also the speed and direction of convergence over time. The following subsection introduces the σ -convergence analysis, which evaluates the extent to which regional disparities in the oil and gas industry’s HIG integration are narrowing, providing a foundation for subsequent β -convergence assessment.

4.4.1. σ -Convergence Analysis

The calculation formula of σ -convergence is as follows:

$$\sigma_k = \sqrt{\frac{\sum_i (\omega_i(k) - \bar{\omega}(k))^2}{N}}. \quad (19)$$

In the above formula, $\omega_i(k)$ refers to the integrated development level of the “three integrations” in the oil and gas industry of each region with k as the period, $\overline{\omega(k)}$ refers to the average value, and N refers to the number of regions in the sample. If the σ coefficient decreases over time, it indicates σ -convergence.

As shown in Table 2, the σ -convergence results indicate that from 2009 to 2023, the overall level of high-end, intelligent, and green (HIG) integration in China’s oil and gas industry exhibited a clear σ -convergence trend, suggesting that regional disparities in coordinated development gradually narrowed. This reflects an increasingly balanced and coordinated pattern of regional HIG development.

Table 2. Estimated Parameters of σ -Convergence in the Integrated Development of China’s Oil and Gas Industry.

Year	National σ	Eastern Region σ	Northeastern Region σ	Central Region σ	Western Region σ
2009	7.114	7.643	4.549	5.674	5.711
2010	7.100	7.290	4.876	4.877	5.996
2011	6.815	6.198	6.540	4.455	6.279
2012	6.326	5.445	4.991	4.973	6.601
2013	5.756	6.639	3.726	4.055	4.831
2014	6.779	5.304	4.573	3.057	5.210
2015	6.779	7.060	3.865	3.734	4.975
2016	6.159	5.966	4.521	3.272	5.550
2017	6.691	5.989	3.989	4.733	6.094
2018	6.666	5.766	4.056	5.013	6.184
2019	6.863	6.359	3.686	3.963	5.831
2020	6.752	6.161	4.392	3.650	5.969
2021	6.241	5.767	4.687	3.098	5.236
2022	6.074	5.211	6.968	2.918	5.911
2023	6.350	5.093	6.992	2.472	6.103

At the national level, the σ coefficient decreased from 7.114 in 2009 to 6.350 in 2023, indicating a moderate reduction in overall regional disparities. Regionally, the eastern region showed the fastest convergence, with σ declining from 7.643 in 2009 to 5.093 in 2023. This rapid convergence reflects the region’s advantages in technological innovation, intelligent manufacturing, and green development, supported by the concentration of advanced enterprises and favorable policy environments.

The central region experienced a modest convergence trend, with σ decreasing from 5.674 in 2009 to 2.472 in 2023, suggesting gradual improvements in technology diffusion and industrial coordination, though limitations in infrastructure and policy implementation remain. The western region exhibited a slower convergence pace, with σ fluctuating around 5.711 in 2009 to 6.103 in 2023, and occasional stagnation in some years, constrained by weak infrastructure and limited technological capacity. The northeastern region displayed relatively high volatility, with σ ranging from 4.549 in 2009 to 6.992 in 2023, reflecting structural bottlenecks and path dependence in transitioning from a resource-based economy, which continues to hinder HIG integration progress.

Overall, these results demonstrate that while regional disparities in HIG integration have narrowed, the convergence pace varies significantly across regions, highlighting the need for differentiated policy and development strategies tailored to regional conditions.

4.4.2. β -Convergence Analysis

The calculation formula for β -convergence is as follows:

$$\log\left(\frac{y_{i,t+1}}{y_{it}}\right) = \varphi - (1 - e^{-\beta}) \log(y_{it}) + \mu_{it}, \quad (20)$$

$$r_{t+1} = \varphi - (1 - e^{-\beta}) \log(Wy_t) + \mu_t, \quad (21)$$

$$(I - W)r_{t+1} = (I - W)\varphi - (1 - e^{-\beta})(I - W) \log(Wy_t) + (I - W)\mu_t. \quad (22)$$

In the above formulas, $i(i = 1, 2, \dots, n)$ is the sample region, y_{it} is the integrated development level of the “three integrations” in the oil and gas industry of the i -th region in period t , $\log\left(\frac{y_{i,t+1}}{y_{it}}\right)$ is the logarithmic growth rate of the integrated development level of the “three integrations” in the oil and gas industry from period t to period $t + 1$, β is the convergence rate, φ is a constant term, μ is the random error term of the model, W is the spatial weight matrix, and Wy_t is the sample average observation value based on the spatial weight matrix.

Based on the β -convergence parameter estimates in Table 3, China’s oil and gas industry shows a clear β -convergence pattern in integrated high-end, intelligent, and green (HIG) development. Across most regions and periods, the β coefficients are negative and statistically significant, indicating that provinces with lower initial HIG levels grow faster and gradually converge toward a balanced state, consistent with the β -convergence theory.

Table 3. Estimated Parameters of β -Convergence in the Integrated Development of China’s Oil and Gas Industry.

Year		2009–2010 (11th FYP)		2011–2015 (12th FYP)		2016–2020 (13th FYP)		2021–2023 (14th FYP)	
Parameter		Intercept	β	Intercept	β	Intercept	β	Intercept	β
General	Estimated Value	−0.604 ***	−0.703 ***	−0.694 ***	−0.786 ***	−0.624 ***	−0.744 ***	−0.735 ***	−0.859 ***
	t-value	−5.09	−5.24	−9.54	−9.69	−9.05	−9.21	−8.00	−8.00
	R ²		0.337		0.388		0.364		0.426
	N		60		150		150		90
Eastern	Estimated Value	−0.869 ***	−1.128 ***	−0.747 ***	−0.959 ***	−0.866 ***	−1.124 ***	−0.764 ***	−1.012 ***
	t-value	−4.56	−4.68	−6.74	−6.93	−11.96	−12.12	−5.36	−5.47
	R ²		0.563		0.500		0.557		0.517
	N		20		50		50		30
Central	Estimated Value	−1.176 *	−1.421 *	−0.945 ***	−1.145 ***	−1.180 ***	−1.452 ***	−1.239 ***	−1.495 ***
	t-value	−2.25	−2.16	−4.24	−4.36	−9.05	−9.15	−4.01	−4.10
	R ²		0.608		0.593		0.717		0.706
	N		6		15		15		9
Northeast	Estimated Value	−1.198 ***	−1.275 ***	−0.807 ***	−0.832 ***	−0.960 ***	−1.019 ***	−0.990 ***	−1.080 ***
	t-value	−4.04	−4.08	−4.27	−4.28	−8.41	−8.51	−4.41	−4.42
	R ²		0.649		0.395		0.512		0.550
	N		12		30		30		18
Western	Estimated Value	−1.038 ***	−1.123 ***	−0.924 ***	−0.977 ***	−0.956 ***	−1.011 ***	−1.179 ***	−1.282 ***
	t-value	−4.85	−4.87	−6.94	−7.06	−11.28	−11.39	−7.67	−7.72
	R ²		0.555		0.485		0.501		0.658
	N		22		55		55		33

Note: Superscripts *** and * indicate statistical significance at the 1% and 10% levels, respectively.

From 2009 to 2010 (11th FYP), the general β coefficient is -0.703 ($t = -5.24$, $R^2 = 0.388$), reflecting a slow convergence pace at the early stage of policy implementation. During 2011–2015 (12th FYP) and 2016–2020 (13th FYP), the absolute values increased to -0.786 ($t = -9.69$, $R^2 = 0.426$) and -0.744 ($t = -9.21$, $R^2 = 0.364$), respectively, indicating strengthened driving mechanisms and accelerated regional alignment. In 2021–2023 (14th FYP), the β coefficient slightly decreased to -0.859 ($t = -8.00$, $R^2 = 0.426$), suggesting that many provinces are approaching a near-equilibrium state.

Regionally, the eastern provinces exhibit large and stable absolute β values throughout the periods: -1.128 ($t = -4.68$) in 2009–2010, -0.959 ($t = -6.93$) in 2011–2015, -1.124 ($t = -12.12$) in 2016–2020, and -1.012 ($t = -5.47$) in 2021–2023, reflecting pronounced convergence due to strong economic foundations and comprehensive policy support. In the central region, β values fluctuate from -1.421 ($t = -2.16$) to -1.495 ($t = -4.10$), showing a slower and more volatile convergence trend constrained by weaker infrastructure. The northeastern region maintains moderate convergence with β values ranging from -1.275 ($t = -4.08$) to -1.080 ($t = -4.42$). The western region demonstrates steady convergence, with β values between -1.123 ($t = -4.87$) and -1.282 ($t = -7.72$), reflecting ongoing alignment despite structural limitations.

Overall, these results indicate that provinces with lower initial HIG levels are catching up, but the convergence pace varies by region and period, emphasizing the importance of differentiated regional strategies to promote high-quality integration across China's oil and gas industry [17].

5. Analysis of Factors Influencing the “Three Modernizations” Integration in China's Oil and Gas Industry

Based on the spatiotemporal pattern and convergence analysis presented in the previous chapter, it is evident that regional disparities and temporal trends play a significant role in the development of the “three modernizations” integration in China's oil and gas industry. To better understand the underlying drivers of these patterns, the following chapter investigates the factors influencing the integration level, formulating research hypotheses and constructing appropriate models to quantify their effects.

5.1. Research Hypotheses

The high-quality transformation of China's oil and gas industry urgently requires a deep integration of high-end, intelligent, and green development. The driving mechanisms for promoting this “Three Modernizations” (HIG) integration involve both key intermediary variables and fundamental direct factors, forming a composite advancement system. Accordingly, this study constructs the following mechanism of influence model, as shown in Figure 5, and proposes the following hypotheses:

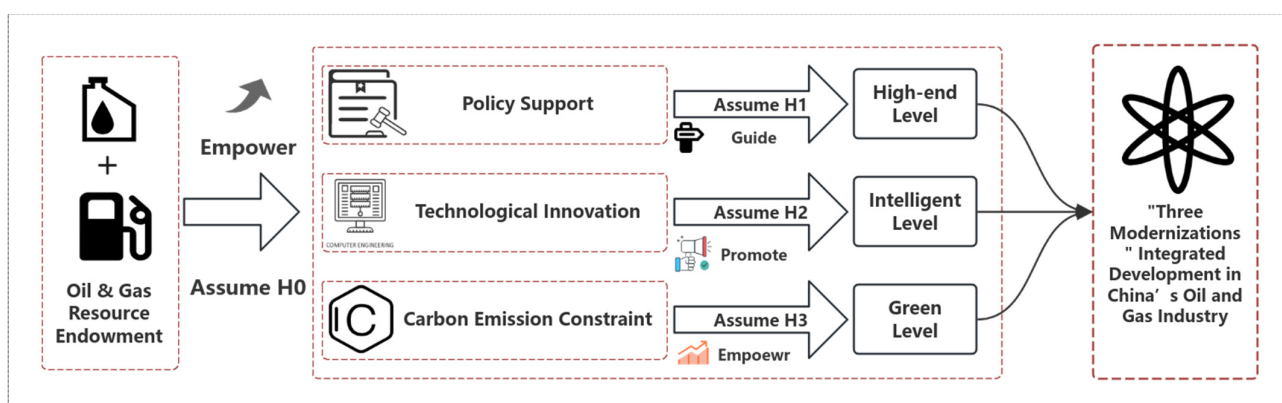


Figure 5. Mechanism of Influence for the “Three Modernizations” (HIG) Integrated Development in China's Oil and Gas Industry.

Hypothesis 0: Oil and gas resource endowments have a significant positive direct effect on the integrated development of HIG in the oil and gas industry.

Hypothesis 1: Policy support positively influences the level of HIG integration by promoting high-end development in the oil and gas industry, serving as a mediating factor.

Hypothesis 2: Technological innovation positively affects HIG integration by advancing intelligent development in the oil and gas industry, acting as a mediating factor.

Hypothesis 3: Carbon emission constraints positively impact HIG integration by facilitating green development in the oil and gas industry, functioning as a mediating factor.

5.2. Model Construction

5.2.1. Direct Effect Model

To examine the influencing mechanism of the integrated development of the “three integrations” in China’s oil and gas industry, this paper constructs a provincial-time two-way fixed effects model:

$$HIG_{it} = \alpha + \beta OGE_{it} + \gamma CV_{it} + CityFE + YearFE + \varepsilon_{it}. \quad (23)$$

In the above formula, HIG , β , OGE , CV , $CityFE$, $YearFE$ are, respectively, the integrated development level of the “three integrations” in the oil and gas industry of province i in year t , the regression coefficient, the oil and gas resource endowment value of each region, the set of control variables, the provincial regional fixed effect, the year fixed effect.

5.2.2. Mediating Effect Model

To further explore the impact mechanisms of policy support level, technological innovation level, and carbon emission constraints on the integrated development of the “three integrations” in China’s oil and gas industry, this paper draws on the research of Wang Yi [1] and constructs the following mechanism effect models:

$$ADV_{it} = \beta_0 + \beta_1 PSP_{it} + \beta_i CV_{it} + CityFE + YearFE + \varepsilon_{it}, \quad (24)$$

$$INT_{it} = \beta_0 + \beta_1 TIS_{it} + \beta_i CV_{it} + CityFE + YearFE + \varepsilon_{it}, \quad (25)$$

$$GRN_{it} = \beta_0 + \beta_1 CEC_{it} + \beta_i CV_{it} + CityFE + YearFE + \varepsilon_{it} \quad (26)$$

In the above formula, ADV , PSP , INT , TIS , GRN and CEC are, respectively, represent the high-end development level of the oil and gas industry, policy support degree, intelligent development level of the oil and gas industry, technological innovation level, green development level of the oil and gas industry, and carbon emission constraint degree of province i in year t .

5.3. Variable Selection

5.3.1. Independent Variables

This study selects the overall integration level of the “three modernizations” in China’s oil and gas industry and its constituent dimensions as the dependent variables to comprehensively reflect the industry’s development in high-end, intelligent, and green aspects. Specifically, the HIG level represents the comprehensive index of the “three modernizations” integration, capturing the overall high-quality development of the industry. The high-end level (ADV), intelligent level (INT), and green level (GRN) are used to measure the industry’s performance in technological advancement, intelligent application, and green low-carbon development, respectively, allowing for a more detailed analysis of different development dimensions.

5.3.2. Dependent Variables

The explanatory variables mainly include oil and gas resource endowment (OGE), policy support (PSP), technological innovation (TIS), and carbon emission constraints (CEC), which are considered key factors influencing the integration of the “three modernizations”

in the oil and gas industry. Specifically, *OGE* is measured by the standardized oil and gas output of each region, reflecting the fundamental role of resource conditions in industry development. *PSP* is measured by government expenditure on oil and gas exploration (log-transformed), indicating the effect of policy guidance and financial support on industrial innovation and green transformation. *TIS* represents the proportion of new technologies, equipment, and processes applied in the industry, capturing the level of technological progress. *CEC* is measured by the carbon market price (log-transformed), reflecting the impact of low-carbon policies and market mechanisms on green development.

5.3.3. Control Variables

Control variables include economic development level (*FDL*), oil and gas resource consumption (*OGC*), industrial structure (*MAR*), government regulation (*GAC*), and environmental regulation (*ENV*), which are used to account for external factors potentially affecting the relationship between dependent and explanatory variables. *FDL* is measured by per capita GDP (log-transformed), representing the influence of regional economic foundation. *OGC* is measured by the oil and gas consumption of each region (log-transformed), controlling for resource consumption pressure. *MAR* reflects the ratio of the oil and gas industry output to regional GDP, capturing differences in regional industrial structure. *GAC* is measured by the ratio of local fiscal expenditure to GDP, while *ENV* is measured by industrial pollution control intensity, controlling for the potential effects of policy and regulatory factors on the “three modernizations” integration.

5.3.4. Descriptive Statistics of Variables

The relevant variables selected in this study and the results of descriptive statistics are shown in Table 4:

Table 4. Descriptive Statistics of Variables.

	Variable	Definition	Max	Min	Mean	Std. Dev.	Expected Sign
Dependent Variables	Oil and Gas Industry HIG Level (<i>HIG</i>)	China oil and gas industry high-end, intelligent, and green development index	0.593	0.281	0.425	0.067	+
	High-end Level (<i>ADV</i>)	China oil and gas industry high-end development index	0.870	0.203	0.458	0.125	+
	Intelligent Level (<i>INT</i>)	China oil and gas industry intelligent development index	0.866	0.119	0.493	0.178	+
	Green Level (<i>GRN</i>)	China oil and gas industry green development index	0.924	0.060	0.270	0.197	+
Explanatory Variables	Oil and Gas Resource Endowment (<i>OGE</i>)	Standardized oil and gas resource output of each region	1	0	0.144	0.172	+
	Policy Support (<i>PSP</i>)	Government expenditure in oil and gas exploration, log-transformed	6.911	2.449	4.786	0.778	+
	Technological Innovation (<i>TIS</i>)	Proportion of new technologies, equipment, and processes applied in oil and gas industry	0.531	0.004	0.159	0.110	+
	Carbon Emission Constraint (<i>CEC</i>)	Carbon market price, log-transformed	4.549	4.247	4.384	0.064	+

Table 4. Cont.

	Variable	Definition	Max	Min	Mean	Std. Dev.	Expected Sign
Control Variables	Economic Development Level (FDL)	Per capita GDP, log-transformed	9.820	5.072	7.543	0.896	
	Oil and Gas Resource Consumption (OGC)	Oil and gas consumption of each region, log-transformed	13.204	9.085	10.878	0.721	
	Industrial Structure (MAR)	Ratio of oil and gas industry output to regional GDP	0.615	0.158	0.438	0.088	
	Government Regulation (GAC)	Ratio of local fiscal expenditure to GDP	0.695	0.087	0.247	0.105	
	Environmental Regulation (ENV)	Industrial pollution control intensity	0.992	0.001	0.111	0.113	

5.4. Mechanism Analysis

5.4.1. Direct Effect Analysis

Table 5 presents the results of a fixed-effects regression analysis conducted in STATA 16 using provincial panel data for China. The findings indicate that oil and gas resource endowments have a significant positive effect on the integrated HIG development of the industry. The baseline regression coefficient is 0.194, which decreases slightly to 0.152 after including control variables, yet remains statistically significant. This demonstrates that resource endowments play a crucial role in enhancing high-end, intelligent, and green development.

Table 5. Direct Effect Test Results.

	(1)	(2)	(3)
	HIG	HIG	HIG-1
OGE	0.194 *** (12.18)	0.152 *** (10.70)	0.114 * (8.83)
Control Variables	NO	YES	YES
Province Fixed Effects	YES	YES	YES
Year Fixed Effects	YES	YES	YES
Intercept	0.397 *** (111.47)	0.137 *** (2.49)	0.253 ** (1.87)
N	450	450	450
Adj-R ²	0.247	0.449	0.275

Note: Superscripts ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively.

After controlling for province and year fixed effects, the results remain robust, indicating that regional heterogeneity and temporal trends do not materially affect the estimates. Overall, the resource advantage in oil and gas significantly promotes the industry's HIG integration, providing a foundational guarantee for resource-rich regions to accelerate high-quality development.

For robustness testing, some relatively less important indicators in the indicator system of the “Three Modernizations” integrated development in China’s oil and gas industry were removed, and only the core indicators were retained to recalculate the integrated development level, denoted as HIG-1. The regression results using this new variable are presented in Column (3) of Table 5. The coefficient remains positive, indicating that oil and gas resource endowment still exerts a positive promoting effect on the integrated development level.

Table 6. Cont.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	<i>HIG</i>			<i>HIG-1</i>			<i>ADV</i>	<i>INT</i>	<i>GRN</i>
Intercept	0.181 *** (4.22)	0.227 *** (4.01)	0.154 *** (2.61)	0.399 ** (2.19)	0.238 *** (4.54)	0.263 * (2.88)	−0.020 (−0.18)	0.399 *** (5.69)	−0.982 *** (−1.76)
N	450	450	450	450	450	450	450	450	450
Adj-R ²	0.655	0.400	0.348	0.487	0.411	0.452	0.354	0.369	0.383

Note: Superscripts ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively.

5.4.3. Heterogeneity Analysis

To further investigate whether the driving mechanisms of HIG integration in China's oil and gas industry exhibit structural heterogeneity, this study conducts multidimensional heterogeneity analyses based on the main regression results. Considering the significant differences in spatial layout, resource endowments, and industrial chain structure across the industry, heterogeneity tests are performed from three perspectives: Industrial Chain Segment Heterogeneity: Based on the functional division of the oil and gas industry, the sample is categorized into upstream (exploration and production), midstream (transportation and storage), and downstream (refining and sales) segments to examine the applicability and performance differences in the HIG integration pathway across different chain segments. Regional Heterogeneity: Considering the uneven regional development in China, the sample is analyzed according to eastern, central, and western regions to identify the heterogeneous impacts of policy implementation, technological conditions, and governance capacity on HIG integration. Resource Endowment Heterogeneity at the City Level: The sample is further divided into resource-based and non-resource-based cities to assess whether resource endowments provide a structural advantage or create path dependence for integration development.

(1) Industrial Chain Segment Heterogeneity Analysis

Considering differences in industrial chain roles, resource endowments, technological capacities, and policy environments across China, the driving mechanisms of HIG integration vary significantly. To reflect these disparities, this analysis examines upstream, midstream, and downstream segments across the country's regions, highlighting segment-specific pathways for promoting high-quality transformation.

Table 7 presents the industrial chain segment heterogeneity analysis, revealing an increasing HIG integration trend from upstream → midstream → downstream, with downstream firms achieving the highest coordination. In the upstream segment (exploration and production), oil and gas resource endowment (*OGE*) strongly promotes HIG integration (coefficient = 0.512, $t = 9.27$, $p < 0.01$), while carbon emission constraints (*CEC*) hinder it (−0.609, $t = -1.95$); policy support (*PSP*) enhances industrial upgrading (*ADV*, 0.043, $p < 0.01$), and technological innovation (*TIS*) boosts intelligentization (*INT*, 0.582, $p < 0.01$). In the midstream segment (transportation and storage), all factors are positive—*OGE* = 0.079 ($t = 4.04$, $p < 0.01$), *PSP* = 0.009 ($t = 0.47$), *TIS* = 0.635 ($t = 9.73$, $p < 0.01$), and *CEC* = 0.345 ($t = 1.79$)—with carbon constraints serving as external drivers that encourage efficiency and emission reduction (adjusted $R^2 = 0.657$ –0.834). In the downstream segment (refining and sales), all variables significantly promote HIG integration—*OGE* = 0.155 ($t = 5.26$, $p < 0.01$), *PSP* = 0.027 ($t = 3.45$, $p < 0.01$), *TIS* = 0.651 ($t = 8.32$, $p < 0.01$), and *CEC* = 0.436 ($t = 1.93$, $p < 0.05$), with adjusted $R^2 = 0.582$ –0.808—reflecting the firms' market proximity, flexible technologies, and responsiveness to policy that allow environmental pressure to be internalized as innovation incentives. Overall, the results indicate a structural gradient: upstream is resource-driven but carbon-sensitive, midstream is technology-driven and

carbon-responsive, and downstream is market-driven with integrated HIG synergy. Achieving full-chain high-quality transformation therefore requires segment-specific strategies, focusing on clean extraction and efficiency innovation upstream, smart logistics midstream, and green refining with intelligent marketing downstream [20].

Table 7. Heterogeneity Analysis Results by Industrial Chain Segment.

	Upstream (Exploration and Production)			
	HIG	ADV	INT	GRN
OGE	0.512 *** (9.27)	-	-	-
PSP	-	0.043 *** (2.73)	-	-
TIS	-	-	0.582 *** (6.66)	-
CEC	-	-	-	−0.609 ** (−1.95)
Control Variables	YES	YES	YES	YES
Province Fixed Effects	YES	YES	YES	YES
Year Fixed Effects	YES	YES	YES	YES
Intercept	0.274 *** (4.31)	−0.116 (−0.49)	0.486 *** (2.51)	2.993 *** (2.18)
N	135	135	135	135
Adj-R ²	0.818	0.671	0.796	0.552
	Midstream (Transportation and Storage)			
	HIG	ADV	INT	GRN
OGE	0.079 *** (4.04)	-	-	-
PSP	-	0.009 *** (0.47)	-	-
TIS	-	-	0.635 *** (9.73)	-
CEC	-	-	-	0.345 * (1.79)
Control Variables	YES	YES	YES	YES
Province Fixed Effects	YES	YES	YES	YES
Year Fixed Effects	YES	YES	YES	YES
Intercept	−0.070 *** (−0.62)	0.429 *** (2.12)	0.237 *** (1.69)	−1.198 * (−1.59)
N	105	105	105	105
Adj-R ²	0.657	0.506	0.834	0.744
	Downstream (Refining and Marketing/Sales)			
	HIG	ADV	INT	GRN
OGE	0.155 *** (5.26)	-	-	-
PSP	-	0.027 *** (3.45)	-	-
TIS	-	-	0.651 *** (8.32)	-
CEC	-	-	-	0.436 ** (1.93)
Control Variables	YES	YES	YES	YES
Province Fixed Effects	YES	YES	YES	YES
Year Fixed Effects	YES	YES	YES	YES
Intercept	0.273 *** (3.79)	0.340 *** (4.78)	0.467 *** (3.28)	−1.981 *** (−2.17)
N	210	210	210	210
Adj-R ²	0.582	0.654	0.808	0.517

Note: Superscripts ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively.

(2) Regional Heterogeneity Analysis

Considering the differences in industrial chain division, resource endowments, technological capacity, and policy environments across China, the driving mechanisms of HIG integration in the oil and gas industry exhibit significant heterogeneity. Based on the geographical division standard of the National Bureau of Statistics, the 30 provinces (and municipalities) are categorized into eastern, central, and western regions to reflect regional development disparities.

Table 8 reports the regional heterogeneity analysis of HIG integration in China's oil and gas industry, based on eastern, central, and western regions. In the eastern region,

development is primarily technology-driven: *OGE* significantly promotes high-end development ($0.104, t = 5.20$), *TIS* strongly enhances intelligentization ($0.680, t = 9.45$), *PSP* contributes moderately to overall HIG integration ($0.023, t = 1.84$), and the effect of *CEC* is negligible ($0.002, t = 0.01$), with adjusted R^2 ranging 0.228–0.760. In the central region, *OGE* remains the key driver ($0.284, t = 10.94$), *TIS* has a positive but smaller effect on intelligentization ($0.372, t = 5.36$), *PSP* negatively affects advanced development ($-0.114, t = -3.80$), and *CEC* significantly promotes green development ($1.028, t = 1.87$), with adjusted R^2 0.398–0.695. In the western region, resource endowments continue to support high-end development ($0.104, t = 3.81$), while technological innovation ($0.177, t = 1.44$) and policy support ($0.024, t = 1.32$) show limited influence, and *CEC* negatively affects green development ($-0.736, t = -1.81$), with adjusted R^2 0.292–0.648. Overall, a spatial gradient emerges—strongest in the east, moderate in the central, and relatively lagging in the west—reflecting differences in industrial development stages, technological capacity, policy environments, and resource endowments. These findings indicate that achieving high-quality HIG integration requires region-specific strategies: promoting technology and green leadership in the east, optimizing policy and resource allocation in the central region, and enhancing green transformation capacity and technological support in the west, to foster coordinated regional development of the “Three Modernizations” [21].

(3) City-Type Heterogeneity Analysis

In the development of China’s oil and gas industry, the HIG integration pathways differ significantly between resource-based and non-resource-based cities. Resource-based cities, which rely on petroleum, natural gas, and other energy resources, primarily follow a “resource-driven + policy-guided” development model.

Table 9 presents the city-type heterogeneity analysis of HIG integration in China’s oil and gas industry, distinguishing resource-based and non-resource-based cities. In resource-based cities, which rely on petroleum, natural gas, and other energy resources, development follows a “resource-driven + policy-guided” model: *OGE* significantly promotes high-end development ($0.107, t = 7.11$), *PSP* positively affects intelligent development ($0.038, t = 2.89$), and *TIS* strongly enhances intelligentization ($0.422, t = 5.59$), while *CEC* has no significant effect on green development ($0.149, t = 0.53$), suggesting that the endogenous drive for green transformation remains insufficient (adjusted R^2 0.264–0.698). In non-resource-based cities, which follow an “innovation-driven + market-oriented” path, *OGE* has a stronger impact on high-end development ($0.349, t = 9.27$), *TIS* strongly promotes intelligent development ($0.704, t = 8.36$), *PSP* is not significant ($0.007, t = 0.73$), and *CEC* positively affects green development ($0.083, t = 0.88$), with adjusted R^2 0.186–0.764. Overall, high-end and intelligent development in resource-based cities relies on resources and policy support, whereas green development requires increased investment in technologies and environmental governance. Non-resource-based cities benefit from innovation and market mechanisms, highlighting the importance of an innovation-centered, green-guided HIG integration pathway [1].

Table 8. Regional Heterogeneity Analysis Results.

	East			
	<i>HIG</i>	<i>ADV</i>	<i>INT</i>	<i>GRN</i>
<i>OGE</i>	0.104 *** (5.20)	-	-	-
<i>PSP</i>	-	0.023 * (1.84)	-	-
<i>TIS</i>	-	-	0.680 *** (9.45)	-
<i>CEC</i>	-	-	-	0.002 (0.01)
Control Variables	YES	YES	YES	YES
Province Fixed Effects	YES	YES	YES	YES
Year Fixed Effects	YES	YES	YES	YES
Intercept	0.343 *** (3.64)	0.177 (0.96)	0.710 *** (4.06)	−0.022 (−0.03)
N	165	165	165	165
Adj-R ²	0.402	0.645	0.760	0.228
	Middle			
	<i>HIG</i>	<i>ADV</i>	<i>INT</i>	<i>GRN</i>
<i>OGE</i>	0.284 *** (10.94)	-	-	-
<i>PSP</i>	-	−0.114 *** (−3.80)	-	-
<i>TIS</i>	-	-	0.372 *** (5.36)	-
<i>CEC</i>	-	-	-	1.028 *** (1.87)
Control Variables	YES	YES	YES	YES
Province Fixed Effects	YES	YES	YES	YES
Year Fixed Effects	YES	YES	YES	YES
Intercept	0.130 ** (1.91)	0.803 *** (2.90)	0.313 *** (2.62)	−3.999 *** (−3.26)
N	120	120	120	120
Adj-R ²	0.695	0.398	0.669	0.540
	West			
	<i>HIG</i>	<i>ADV</i>	<i>INT</i>	<i>GRN</i>
<i>OGE</i>	0.104 *** (3.81)	-	-	-
<i>PSP</i>	-	0.024 (1.32)	-	-
<i>TIS</i>	-	-	0.177 * (1.44)	-
<i>CEC</i>	-	-	-	−0.736 ** (−1.81)
Control Variables	YES	YES	YES	YES
Province Fixed Effects	YES	YES	YES	YES
Year Fixed Effects	YES	YES	YES	YES
Intercept	0.086 (0.90)	−0.203 (−0.94)	0.250 * (1.48)	2.983 * (1.77)
N	165	165	165	165
Adj-R ²	0.326	0.648	0.552	0.292

Note: Superscripts ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively.

Table 9. Heterogeneity Analysis Results by City Type.

	Resource-Based Cities			
	<i>HIG</i>	<i>ADV</i>	<i>INT</i>	<i>GRN</i>
<i>OGE</i>	0.107 *** (7.11)	-	-	-
<i>PSP</i>	-	0.038 *** (2.89)	-	-
<i>TIS</i>	-	-	0.422 *** (5.59)	-
<i>CEC</i>	-	-	-	0.149 (0.53)
Control Variables	YES	YES	YES	YES
Province Fixed Effects	YES	YES	YES	YES
Year Fixed Effects	YES	YES	YES	YES
Intercept	0.279 *** (3.65)	0.334 *** (3.43)	0.713 *** (5.45)	−1.083 (−0.92)
N	240	240	240	240
Adj-R ²	0.428	0.264	0.698	0.377

Table 9. Cont.

	Non-Resource-Based Cities			
	HIG	ADV	INT	GRN
OGE	0.349 *** (9.27)	-	-	-
PSP	-	0.007 (0.73)	-	-
TIS	-	-	0.704 *** (8.36)	-
CEC	-	-	-	0.083 * (0.88)
Control Variables	YES	YES	YES	YES
Province Fixed Effects	YES	YES	YES	YES
Year Fixed Effects	YES	YES	YES	YES
Intercept	0.102 (1.33)	−0.388 *** (−3.02)	−0.081 (−0.53)	−0.229 ** (−0.52)
N	210	210	210	210
Adj-R ²	0.574	0.193	0.764	0.186

Note: Superscripts ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively.

6. Conclusions and Policy Recommendations

6.1. Conclusions

This study uses panel data from 30 provinces (2009–2023) to measure integrated HIG development in China’s oil and gas industry. The main findings are as follows:

(1) Steady improvement with persistent regional disparities

The national average HIG index rose from 0.34 in 2009 to 0.46 in 2023, reflecting coordination across high-end, intelligent, and green dimensions. Spatially, a pattern of “high in the east, low in the west, stable in the center, fluctuating in the northeast” emerged. Beijing (0.54), Tianjin (0.59), and Guangdong (0.52) lead, whereas Inner Mongolia (0.31) and Qinghai (0.37) lag behind, highlighting uneven technological and industrial foundations.

(2) Narrowing regional gaps with convergence trends

Kernel density estimation shows rightward shifts in HIG distribution with emergent bimodality, suggesting internal differentiation within regions. The Gini coefficient decreased from 0.093 to 0.058, σ coefficient declined from 7.114 to 6.350, and β -convergence tests indicate catch-up effects, particularly in the eastern region ($\beta = -1.128$).

(3) Multiple factors jointly drive integration

Two-way fixed effects regression indicates that resource endowment (0.152), policy support (0.349), technological innovation (0.263), and carbon constraints (0.118) significantly promote HIG integration. Policy primarily supports high-end upgrading, innovation drives intelligent and green transformation, and carbon constraints facilitate structural optimization, consistent with the Porter Hypothesis.

(4) Path dependence and regional heterogeneity remain significant

Industrial chain analysis shows a gradient from upstream (0.512) to midstream (0.635) and downstream (0.651). Regionally, the eastern region (0.680) is innovation-driven, the central region (0.284) relies on policy/resource support, and the western region (0.177) is constrained by low innovation capacity. Resource-based cities rely on resources and policy (0.107, 0.038), while non-resource-based cities achieve higher integration via innovation and market mechanisms (0.349, 0.704).

6.2. Policy Recommendations

(1) Strengthen Policy Guidance and Institutional Support Based on Regional Characteristics

The government should establish a comprehensive, multi-tier HIG policy framework that integrates high-end manufacturing, digital transformation, and green low-carbon

objectives into national and provincial energy strategies. A “HIG Integration Promotion Act” could be introduced to define strategic priorities, legal frameworks, and evaluation mechanisms. Fiscal and tax incentives should be expanded, including R&D subsidies, tax credits for intelligent equipment, and preferential green loans. Eastern provinces, which show higher innovation capacity, should emphasize innovation-driven policy support, such as increased R&D tax deductions and the establishment of national demonstration zones for digital and green transformation. Central and western provinces, with lower initial HIG levels, should receive targeted transfer payments and industrial upgrading subsidies to ease financial burdens, particularly for digital infrastructure construction and environmental retrofitting. These measures address observed regional disparities and convergence trends.

(2) Accelerate Technological Innovation and Domestic Equipment Development

Oil and gas enterprises should increase R&D investment, focusing on high-end drilling and extraction equipment, intelligent sensing and control systems, and carbon capture, utilization, and storage (CCUS) technologies. Governments should support joint innovation mechanisms integrating enterprises, universities, and research institutes, forming enterprise-led and research-supported innovation systems. National HIG Demonstration Laboratories in resource-rich provinces such as Shaanxi, Sichuan, and Heilongjiang can enhance technological self-reliance and accelerate commercialization. Fiscal incentives, including R&D expense deductions, patent transformation funds, and technology application subsidies, should be strengthened to promote technological diffusion, consistent with our findings that technological innovation significantly drives HIG integration.

(3) Promote Intelligent Infrastructure Construction According to Regional Needs

Intelligent infrastructure is fundamental for digital transformation across the oil and gas value chain. In the eastern region (e.g., Shandong, Guangdong), AI-based operation systems, big data monitoring centers, and digital twin technologies should be prioritized to leverage innovation-led advantages. Central provinces (e.g., Henan, Hubei) should adopt public–private partnerships (PPP) to build regional energy data hubs and smart scheduling systems, supporting moderate innovation and policy-driven integration. In the western region (e.g., Xinjiang, Gansu), targeted fiscal support and network investment should expand 5G coverage and intelligent monitoring in remote extraction zones, mitigating constraints from weak innovation capacity. These measures are tailored to observed spatial heterogeneity and industrial chain gradients.

(4) Deepen Green and Low-Carbon Transformation

Green transformation should be the strategic priority for upgrading the oil and gas sector. Regional carbon quotas and differentiated carbon tax mechanisms should be implemented, with stricter standards in the east and more flexible policies in the west, reflecting observed regional disparities. CCUS demonstration bases in Shaanxi, Sichuan, and Heilongjiang should be expanded to promote large-scale industrial applications. Green supply chain certification and environmental performance disclosure systems should be introduced to enhance transparency and enterprise accountability. Financial institutions should be guided to develop green credit, green bonds, and carbon finance instruments to channel capital into low-carbon innovation projects, directly linking policy measures to the drivers identified in our study.

(5) Promote Regional Coordination and Differentiated Development

Differentiated strategies should be implemented to achieve complementary advantages and coordinated development. Eastern regions should leverage technology and innovation leadership to guide national standards and international cooperation. Central

regions should focus on industrial chain upgrading and policy synergy, forming green and intelligent manufacturing clusters supported by shared digital service platforms. Western regions should pursue resource-based green transformation strategies, supported by ecological compensation funds and renewable energy expansion, to reduce fossil dependency. Cross-regional cooperation, including technology transfer, carbon trading, and joint HIG industrial parks, should be strengthened, promoting nationwide integration consistent with observed convergence trends.

(6) Establish a Long-Term Monitoring and Evaluation Mechanism

A National HIG Integration Monitoring Platform should be established to track industrial, technological, and environmental indicators across provinces in real time. A “measurement–evaluation–feedback–optimization” closed-loop process should provide scientific evidence for policy improvement. A multi-level evaluation system linking central and local governments, enterprises, and research institutes should ensure dynamic supervision. Annual Regional HIG Integration Reports should be published to enhance transparency, promote public participation, and improve policy accountability, supporting sustained, high-quality development of China’s oil and gas industry.

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Appendix A

To assess the evolution of the “three modernizations” integration in China’s oil and gas industry, this study calculates the integration index for 30 provinces from 2009 to 2023. Based on the index distribution and following Wang Yi, the integration level is classified into four stages: Stage I (0–0.3, low), Stage II (0.3–0.4, relatively low), Stage III (0.4–0.5, relatively high), and Stage IV (0.5–0.6, high), facilitating the identification of regional and temporal development patterns [22]. The study period is further divided according to China’s Five-Year Plans: 11th (2006–2010), 12th (2011–2015), 13th (2016–2020), and early 14th (2021–2023) Plan periods, aligning the analysis with national policy cycles and allowing evaluation of policy impacts on industry integration.

Table A1. Level of Integrated Development of the ‘Three Modernizations’ in China’s Oil and Gas Industry.

Region	Province/City	11th FYP	Stage	12th FYP	Stage	13th FYP	Stage	14th FYP	Stage
Eastern	Beijing	0.54	IV	0.55	IV	0.55	IV	0.52	IV
	Tianjin	0.59	IV	0.54	IV	0.53	IV	0.53	IV
	Hebei	0.42	III	0.44	III	0.46	III	0.45	III
	Shanghai	0.54	IV	0.47	III	0.49	III	0.50	IV
	Jiangsu	0.46	III	0.47	III	0.48	III	0.47	III
	Zhejiang	0.45	III	0.44	III	0.46	III	0.46	III
	Fujian	0.39	II	0.39	II	0.38	II	0.40	III
	Shandong	0.47	III	0.49	III	0.52	IV	0.51	IV
	Guangdong	0.5	IV	0.50	IV	0.50	IV	0.52	IV
Central	Hainan	0.32	II	0.35	II	0.35	II	0.37	II
	Hubei	0.41	III	0.4	III	0.42	III	0.43	III
	Anhui	0.34	II	0.36	II	0.39	II	0.40	III
	Hunan	0.37	II	0.37	II	0.39	II	0.40	III
	Jiangxi	0.32	II	0.31	II	0.34	II	0.35	II
	Shanxi	0.48	III	0.44	III	0.47	III	0.4	III
	Henan	0.42	III	0.4	III	0.42	III	0.43	III
	Liaoning	0.46	III	0.46	III	0.46	III	0.45	III
	Jilin	0.38	II	0.38	II	0.40	III	0.36	II
Northeast	Heilongjiang	0.48	III	0.49	III	0.50	IV	0.52	IV
	Guangxi	0.44	III	0.45	III	0.46	III	0.50	IV
	Inner Mongolia	0.31	II	0.30	II	0.30	II	0.33	II
	Chongqing	0.38	II	0.35	II	0.37	II	0.38	II
	Sichuan	0.4	III	0.42	III	0.47	III	0.47	III
	Guizhou	0.32	II	0.33	II	0.31	II	0.32	II
	Yunnan	0.34	II	0.35	II	0.34	II	0.35	II
	Shaanxi	0.51	IV	0.48	III	0.48	III	0.46	III
	Gansu	0.46	III	0.44	III	0.42	III	0.41	III
Western	Qinghai	0.42	III	0.40	III	0.39	II	0.37	II
	Ningxia	0.43	III	0.42	III	0.41	III	0.44	III
	Xinjiang	0.41	III	0.37	II	0.36	II	0.39	II

Appendix B

Tables A2–A4 present the Gini coefficients and their decomposition for the “three modernizations” integration in China’s oil and gas industry. Table A2 shows the overall Gini coefficients. Table A3 shows the decomposition of intra-regional Gini coefficients. Table A4 shows the interregional Gini coefficients.

Table A2. Intra-regional Gini Coefficients of Integrated Development in China’s Oil and Gas Industry.

Year	Eastern Region	Northeast Region	Central Region	Western Region
2009	0.093	0.054	0.082	0.080
2010	0.087	0.055	0.071	0.082
2011	0.074	0.072	0.063	0.090
2012	0.067	0.057	0.071	0.097
2013	0.081	0.048	0.060	0.071
2014	0.066	0.055	0.045	0.075
2015	0.082	0.050	0.053	0.072
2016	0.074	0.056	0.044	0.080
2017	0.070	0.048	0.064	0.089
2018	0.066	0.048	0.067	0.089
2019	0.070	0.043	0.053	0.084
2020	0.067	0.050	0.048	0.084
2021	0.068	0.061	0.044	0.074
2022	0.059	0.085	0.038	0.082
2023	0.058	0.081	0.031	0.087
Average	0.072	0.058	0.056	0.082

Table A3. Inter-regional Gini Coefficients of Integrated Development in China’s Oil and Gas Industry.

Year	East—Northeast	East—Central	East—West	Northeast—Central	Northeast—West	Central—West
2009	0.087	0.105	0.097	0.084	0.080	0.083
2010	0.084	0.099	0.097	0.076	0.082	0.080
2011	0.075	0.088	0.096	0.087	0.099	0.082
2012	0.066	0.085	0.096	0.083	0.098	0.089
2013	0.080	0.095	0.091	0.063	0.069	0.069
2014	0.065	0.079	0.080	0.068	0.078	0.069
2015	0.084	0.098	0.095	0.058	0.069	0.067
2016	0.072	0.083	0.090	0.063	0.083	0.072
2017	0.067	0.083	0.097	0.069	0.090	0.082
2018	0.064	0.081	0.095	0.069	0.088	0.083
2019	0.068	0.081	0.101	0.058	0.086	0.076
2020	0.067	0.078	0.097	0.056	0.085	0.075
2021	0.074	0.084	0.089	0.056	0.074	0.067
2022	0.067	0.068	0.083	0.063	0.086	0.069
2023	0.066	0.069	0.088	0.066	0.094	0.072
Average	0.072	0.085	0.093	0.068	0.084	0.076

Table A4. Overall Gini Coefficient Trends of Integrated Development Levels in China’s Oil and Gas Industry.

Year	Gini Coefficient				Contribution Rate (%)		
	Indicator	Hyper-Variability Density	Between Regions	Overall	Within Regions	Between Regions	Hyper-Variability Density
2009	0.041	0.029	0.025	0.096	26.106	43.162	30.732
2010	0.044	0.026	0.024	0.094	25.865	46.887	27.248
2011	0.045	0.027	0.023	0.095	24.649	47.392	27.959
2012	0.044	0.026	0.023	0.093	25.138	47.198	27.664
2013	0.045	0.020	0.022	0.087	25.078	51.592	23.330
2014	0.040	0.020	0.020	0.080	24.808	50.606	24.587
2015	0.050	0.019	0.022	0.090	24.225	55.165	20.610
2016	0.041	0.024	0.021	0.086	24.949	47.539	27.512
2017	0.045	0.023	0.022	0.090	24.870	49.717	25.413
2018	0.044	0.023	0.022	0.089	24.979	49.677	25.344
2019	0.051	0.018	0.021	0.091	23.579	56.092	20.329
2020	0.048	0.019	0.021	0.088	23.738	54.565	21.697
2021	0.046	0.019	0.020	0.085	23.627	53.866	22.507
2022	0.034	0.026	0.020	0.080	24.788	42.906	32.306
2023	0.041	0.024	0.020	0.084	23.661	48.427	27.911
Average	0.044	0.023	0.022	0.089	24.671	49.653	25.677

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