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PEAK PREDICTION OF NATURAL GAS CONSUMPTION IN CHINA UNDER MULTI SCENARIO SIMULATION

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Abstract: As a crucial energy source during the green and low-carbon transition period of the energy sector, understanding the evolution patterns of natural gas consumption is of paramount importance for constructing a modern energy system, safeguarding China's energy security, and achieving the "dual carbon" goals. This paper identifies population, affluence, technological advancement, industrial structure, and energy consumption structure as the primary factors influencing China's natural gas consumption. It employs the VIF test to examine multicollinearity among these factors and introduces the Ridge Regression method to mitigate the risks posed by multicollinearity. By solving the undetermined coefficients of the extended Stochastic Impacts by STIRPAT model, it overcomes the potential forecasting risks inherent in the model. The ADF test is utilized to assess the stationarity of variables, ensuring the reliability of the forecasting results from the extended STIRPAT model. Based on scenario analysis, this study explores the trends in China's natural gas consumption. The findings are as follows:(1) The extended STIRPAT model, constructed on the basis of factors such as population, affluence, technological advancement, industrial structure, and energy consumption structure, demonstrates high prediction accuracy and serves as an effective forecasting tool for analyzing the evolution trends of natural gas consumption.(2) Optimizing China's population growth rate, facilitating high-quality economic development, promoting the green and low-carbon development process, and driving high-quality development of the industrial structure are conducive to accelerating the peak of natural gas consumption in China and reducing its overall consumption volume.(3) By accelerating the comprehensive adoption of a green and low-carbon development model, China's natural gas consumption is projected to reach its peak around 2035, with a peak range of approximately $4620\times10^8 m^3 \sim 5160\times10^8 m^3$, an average annual growth rate dropping to below 0.3%, and a foreign dependency ratio ranging from 39% to 45%.(4) By expediting the implementation of pro-natality policies, appropriately regulating industrial development, and optimizing the energy mix, China's natural gas consumption is expected to plateau during the 2040-2045 period, with a peak consumption level between $6500\times10^8 m^3 \sim 7500\times10^8 m^3$, an average annual growth rate of natural gas consumption slowing down to 2.2%-2.9%, and a foreign dependency ratio reaching 55%. By 2050, China's natural gas consumption is anticipated to stabilize at around $6000\times10^8 m^3$.

Keywords: Natural gas consumption; Influencing factors; STIRPAT model; Scenario analysis; Peak prediction

1 INTRODUCTION

The report of the 20th National Congress pointed out that promoting green and low-carbon economic and social development is a key link to achieving high-quality development. Low-carbon high-quality development is a fundamental strategy for achieving the "dual carbon" goals in China's modernization. Natural gas, as a low-carbon, safe, and efficient fossil energy source, has become the optimal choice to support the restructuring and layout optimization of the energy system. The Energy Production and Consumption Revolution proposes that by 2030, the proportion of natural gas consumption will reach 15%, and the main body of energy increment will shift to clean energy. In 2023, China's natural gas consumption accounted for about 8.5%, which is still a significant gap compared to the world average of 24%. This signals that China's natural gas consumption still holds considerable growth potential in the future. Understanding the changing trends of China's natural gas consumption under different development scenarios is of critical importance for national energy transition planning and decision-making.

Current research by domestic and international scholars on natural gas consumption forecasting primarily focuses on two aspects: analysis of influencing factors and methodological studies for predictions. Relatively abundant research outcomes have been achieved in identifying influencing factors for natural gas consumption, with notable examples including: WANG Jianliang et al. [1] applied grey relational analysis to identify energy consumption structure, GDP, and urbanization rate as core determinants of natural gas demand in eastern and central China; LI Hongbing et al. [2] integrated grey relative correlation analysis with stepwise regression to pinpoint urbanization rate and economic development as effective explanatory variables for natural gas consumption in the Sichuan-Chongqing region in China. While grey relational analysis demonstrates strong quantitative identification capabilities for correlating multiple variables with observed values [3], its results may exhibit significant deviations when handling datasets containing anomalous values. Chai Jian et al. [4] established a structural model of natural gas consumption with factors such as economic behavior and supply capacity, and analyzed the differences in regional driving factors of natural gas consumption using the Bayesian methods. While Bayesian approaches effectively reduce subjectivity in factor selection, their computational complexity process and high data requirements pose challenges for practical implementation. Building on this, some scholars have introduced the LMDI (Logarithmic Mean Divisia Index) decomposition model into natural gas consumption studies for factor analysis. The LMDI method offers advantages such as robustness in handling zero values. GAO Jian et al. [5] decomposed natural gas consumption drivers into nine effects using the LMDI model: spatial expansion, pipeline network density, population density, residential gas penetration rate, energy consumption elasticity, natural gas substitution, economic growth, and pipeline scale; Raza et al. [6] employed the LMDI method to examine drivers of decoupling in natural gas consumption share, energy intensity, economic structure share, GDP per capita, and population; Liu et al. [7] identified economic, demographic, and production factors as key variables influencing long-term natural gas consumption forecasts. In summary, existing studies have identified five potential influencing factors for China's natural gas consumption: population size, affluence level, technological advancement, industrial structure, and energy consumption structure.

In terms of forecasting methodologies for natural gas consumption, LI Hongbing et al. [8] applied the energy consumption elasticity coefficient to project China's natural gas demand at 1.18 – 1.25 billion tonnes of standard coal equivalent by 2030. However, the energy consumption elasticity coefficient method carries significant uncertainties in its predictions. Given this limitation, MU Xianzhong et al. [9] developed a system dynamics model to forecast natural gas consumption. The system dynamics model fails to adequately account for multicollinearity among factors. To address this limitation, LI Hongbing et al. [10] employed stepwise regression to analyze multicollinearity and developed a stepwise regression Cobb-Douglas (C-D) production function to forecast natural gas consumption. Subsequently, Li et al. [11] constructed a stepwise regression double-log demand function model to examine the evolving trends in China's natural gas consumption. Traditional models exhibit limited capability in handling uncertain information. To address this deficiency, scholars have integrated grey system theory into forecasting frameworks. The following notable advancements are included. WANG et al. [12] developed a fractional inverse cumulative grey model to forecast natural gas consumption in Commonwealth of Independent States (CIS) countries from 2022 to 2025. LI Hongbing et al. [13] established a GM(1,N) model based on validated influencing factors for predictive analysis. WU et al. [14] employed a Grey-Bernoulli model to predict natural gas demand in the US, Germany, UK, China, and Japan. MA et al. [15] proposed a wavelet kernel grey system model for consumption forecasting. ZHANG et al. [16] created an FPDGM(1,1) (Fractional Partial Differential Grey Model) to project China's natural gas consumption. LIU et al. [17] applied discretization techniques to develop a discrete fractional-order grey model with time power terms, predicting China's 2025 consumption will reach 439.14 billion cubic meters. ES Huseyin Avni [18] introduced a novel grey seasonal forecasting model for monthly natural gas consumption predictions in Turkey. Forecasting accuracy serves as a key criterion for evaluating model performance. To further enhance prediction precision, scholars have developed hybrid models for natural gas consumption forecasting. Some notable examples are as follows. HE Runming et al. [19] constructed an optimal combination model for consumption projections. Pala Zeydin[20] proposed a multi-hybrid modeling framework. WEI et al. [21] implemented a white-box hybrid model integrating Principal Component Analysis (PCA), Wavelet Packet Multiscale Analysis (WPMA), and Multiple Linear Regression (MLR). Manowska Anna et al. [22] established a hybrid model of ARIMA and LSTM artificial neural network to predict natural gas consumption. Hybrid models typically improve forecasting accuracy and reduce the sum of squared prediction errors. However, the aforementioned studies heavily rely on model accuracy, exhibiting limitations in addressing future uncertainties. To overcome this constraint, scholars have introduced scenario analysis into natural gas consumption forecasting. Scenario analysis, which considers the development trends of multiple situations, can effectively enhance the validity and credibility of the forecasting model when integrated into it. Representative studies are as follows. ZHENG Xiaoqiang et al. [23] utilized the LEAP (Low Emissions Analysis Platform) model under three substitution scenarios, projecting China's natural gas consumption to peak in 2041, 2045, and 2048 under respective assumptions. DUAN Hongbo et al. [24] explored the medium-to-long-term evolution trends of China's natural gas consumption across three defined policy scenarios.

In summary, while scholars have yielded substantial insights into both influencing factor analysis and predictive modeling of natural gas consumption, existing research exhibits notable gaps: ①Factor Analysis Limitations: Few studies conduct comprehensive and in-depth analysis of multicollinearity issues among influencing factors; ②Modeling Shortcomings: Rare efforts systematically perform stationarity testing on raw data or integrate factor decomposition with multi-scenario forecasting frameworks. Building upon these foundations, this study will select population size, affluence level, technological advancement, industrial structure, and energy consumption structure as potential determinants. It will employs ridge regression to assess data stationarity and address multicollinearity issues. Integrating with scenario analysis, it will develop an extended STIRPAT (Stochastic Impacts by Regression on Population, Affluence, and Technology) model to project China's natural gas consumption peak under differentiated pathways. These methodological innovations aim to provide actionable references for advancing China's Dual Carbon Goals (carbon peaking by 2030 and carbon neutrality by 2060).

2 CONSTRUCTION OF THE EXTENDED STIRPAT MODEL

The STIRPAT prediction model considers factors such as economy, affluence level, and technological advancement, and adds random factors to effectively eliminate the impact of proportional changes in factors on the distortion of analysis results, making up for the shortcomings of the IPAT model. It has been widely applied in empirical studies[25]. The generalized model expression is:

$$I_t = aP_t^b A_t^c T_t^d u \tag{1}$$

In Equation (1): I_t represents environmental pressure data in the t -th year; a denotes the constant term; P_t、A_t、T_t correspond to population size, affluence level, and technological advancement in the t -th year, respectively; b、c、d are the elasticity exponents for each respective variable; u signifies the random error term.
There are numerous factors influencing natural gas consumption. In addition to population, affluence level, and technological advancement, industrial structure and energy consumption structures also significantly impact natural gas consumption. Based on this, we incorporate population, affluence level, technological level, industrial structure, and energy consumption structure into the predictive model, constructing an extended STIRPAT model. The factors in the extended STIRPAT model are defined as follows:
1) Population factor is represented by the total permanent population at year-end, denoted as variable P;
2) Affluence level factor is measured by per capita GDP, denoted as variable A;
3) Technological advancement factor is represented by energy consumption intensity, denoted as variable T;
4) Industrial structure factor is measured by the proportion of secondary industry composition [2], denoted as variable Y;
5) Energy consumption structure factor is measured by the share of natural gas in primary energy consumption [8], denoted as variable Z.
The general expression for establishing the extended STIRPAT model for natural gas consumption forecasting is as follows:

$$NGC_t = aP_t^b A_t^c T_t^d Y_t^f Z_t^g u \tag{2}$$

In it, NGC represents natural gas consumption; a is the constant term; P、A、T、Y、Z are the driving force coefficients of the variables b、c、d、f、g; u is the random error term; and t denotes the time in the t -th year.
From Equation (2), the extended STIRPAT model is nonlinear. To simplify the solving process, we apply a logarithmic transformation to Equation (2), converting it into a linear model:

$$\ln NGC_t = \ln a + b\ln P_t + c\ln A_t + d\ln T_t + f\ln Y_t + g\ln Z_t + \ln u \tag{3}$$

In it, b、c、d、f、g serve as the driving force coefficients of the variables b、c、d、f、g, reflecting the change in natural gas consumption caused by a variation in one variable while holding others constant.

3 PREDICTION AND ANALYSIS OF CHINA'S NATURAL GAS CONSUMPTION PEAK

3.1 Data Description

The data on China's natural gas consumption, population, affluence level, technological advancement, industrial structure, and energy consumption structure from 2000 to 2022, as selected in this study, are collated and calculated from publicly available sources including *China Statistical Yearbook*, *China Natural Gas Development Report (2022 Edition)*, and *China Natural Gas Development Report (2023 Edition)*. The relevant data are summarized in Table 1.

Table 1 Relevant Data on Natural Gas Consumption and Influencing Factors in China

Year	Natural Gas Consumption （$10^8 m^3$）	Population （10,000 persons）	Affluence Level (yuan/person）	Technological Advancement （ton/10,000yuan）	Industrial Structure（%）	Energy Consumption Structure （%）
2000	245.03	126743	7912.08	1.47	45.54	2.2
2001	274.30	127627	8686.49	1.40	44.79	2.4
2002	291.84	128453	9475.64	1.39	44.45	2.3
2003	339.08	129227	10634.16	1.43	45.62	2.3
2004	396.72	129988	12450.40	1.42	45.90	2.3
2005	466.08	130756	14325.84	1.40	47.02	2.4
2006	573.32	131448	16693.94	1.31	47.56	2.7
2007	705.23	132129	20441.56	1.15	46.88	3.0
2008	812.94	132802	24039.14	1.00	46.97	3.4
2009	895.20	133450	26115.98	0.96	45.96	3.5
2010	1080.24	134091	30734.30	0.88	46.50	4.0
2011	1341.07	134916	36166.22	0.79	46.53	4.6
2012	1497.00	135922	39624.20	0.75	45.42	4.8
2013	1705.37	136726	43368.72	0.70	44.18	5.3
2014	1870.63	137646	46754.94	0.67	43.09	5.6

2015	1931.75	138326	49799.62	0.63	40.84	5.8
2016	2078.06	139232	53608.01	0.59	39.58	6.1
2017	2393.69	140011	59426.47	0.55	39.85	6.9
2018	2817.09	140541	65410.17	0.51	39.69	7.6
2019	3059.68	141008	69961.65	0.49	38.59	8.0
2020	3339.89	141212	71776.27	0.49	37.84	8.4
2021	3772.96	141260	81356.15	0.46	39.29	8.8
2022	3746.95	141175	85723.90	0.45	39.92	8.4

3.2 Development of the Extended STIRPAT Model for China’s Natural Gas Consumption Forecasting

Simultaneously incorporating numerous influencing factors into the prediction model, the potential problem of multicollinearity between factors inevitably leads to the risk of distorted prediction results [8]. To diagnose collinearity issues among the influencing factors, a Variance Inflation Factor (VIF) test was applied. A VIF value exceeding 10 indicates significant multicollinearity for a given variable. The multicollinearity test results for China’s natural gas consumption influencing factors are presented in Table 2. According to Table 2, there is a potential multicollinearity relationship between various factors. Simply incorporating these influencing factors into the STIRPAT extended model at the same time can lead to overfitting of the STIRPAT extended model and a risk of distortion in the predicted results.

Table 2 VIF Test Results

Influencing Factors	$\ln P$	$\ln A$	$\ln T$	$\ln Y$	$\ln Z$
VIF	36.113	63.186	285.746	5.194	364.987

To accurately estimate the coefficients of the extended STIRPAT model and avoid estimation distortion, this study introduces ridge regression, a method capable of addressing multicollinearity and reducing data overfitting. The ridge regression approach is applied to fit the extended STIRPAT model for natural gas consumption forecasting, enabling precise coefficient estimation and mitigating the risk of distorted prediction results. Ridge regression stabilizes coefficient estimation by shrinking the coefficients of the extended STIRPAT model. The ridge regression estimates of the coefficients are presented in Table 3.

Analysis of Table 3 reveals that the ridge regression method has improved the underlying multicollinearity issues among the factors. All factors passed the P-value test, confirming that the coefficient estimates of the extended STIRPAT model are statistically significant. The coefficient of determination (R^2) for the ridge regression estimates is 0.986, indicating that the extended STIRPAT model explains 98.6% of the variations in China’s natural gas consumption. This demonstrates a strong overall fit of the model and highlights the high reliability of its prediction results.

Table 3 Results of undetermined coefficients for ridge regression estimation

Variable	B	Std.Error	t	P	R^2	Adjusted R^2	F
$\ln a$	-89.979	6.957	-12.933	0.000***	0.986	0.982	239.184
$\ln P$	8.366	0.598	13.991	0.000***			
$\ln A$	0.102	0.011	8.945	0.000***			
$\ln T$	-0.526	0.031	-16.838	0.000***			
$\ln Y$	0.887	0.382	2.323	0.033**			
$\ln Z$	0.440	0.023	18.773	0.000***			

Note：***、**、*denote statistical significance at the1%, 5% and 10% level, respectively.

From the driving force coefficients of various factors, the coefficient for energy consumption intensity (representing technological level, T) is -0.526, indicating that energy consumption intensity has a negative effect on changes in natural gas consumption. Holding other factors constant, a 1% increase in energy consumption intensity leads to a 0.526% decrease in natural gas consumption. This demonstrates that advancements in technology effectively mitigate China’s natural gas demand. The driving force coefficients for population (P), affluence level (A), industrial structure (Y), and energy consumption structure (Z) are 8.366, 0.102, 0.887, and 0.440, respectively, signifying positive contributions to natural gas consumption. Specifically: A 1% increase in population corresponds to an 8.366% rise in natural gas consumption; A 1% increase in affluence level (per capita GDP) corresponds to a 0.102% rise in natural gas consumption; A 1% increase in industrial structure corresponds to a 0.887% rise in natural gas consumption; A 1% increase in energy consumption structure corresponds to a 0.440% rise in natural gas consumption, assuming other variables remain unchanged. The established linear form of the extended STIRPAT model for China’s natural gas consumption forecasting is expressed as follows:

$$\ln NGC_t = -89.979 + 8.366 \ln P_t + 0.102 \ln A_t - 0.562 \ln T_t + 0.877 \ln Y_t + 0.44 \ln Z_t \quad (4)$$

Convert equation (4) into a nonlinear form yields:

$$NGC_t = e^{-89.979} P_t^{8.366} A_t^{0.102} T_t^{-0.562} Y_t^{0.877} Z_t^{0.44} \tag{5}$$

In it, e is the natural constant, approximately equal to 2.718.

When non-stationary data series lack cointegration relationships, the linear form of the extended STIRPAT model for China's natural gas consumption forecasting may exhibit spurious regression, severely compromising the model's prediction accuracy. To address this, the Augmented Dickey-Fuller (ADF) test [26] is employed to assess the stationarity of the data series. If a unit root is detected in a data series, it indicates non-stationarity; conversely, the absence of a unit root confirms stationarity. To further validate the reliability of the extended STIRPAT model's predictions, ensure the robustness of parameter estimates, and avoid spurious regression, the ADF test is applied to evaluate the stationarity of all variable data series. The ADF test results are presented in Table 4.

According to Table 4, the data sequences of each variable have passed the P-value test, and the AIC values of each variable are relatively low, confirming the stationarity of variables in the extended STIRPAT model. These variables can thus be incorporated into the extended STIRPAT model for forecasting China's natural gas consumption.

Table 4 ADF Test Results

Variable	Order of Differencing	t	P	AIC	Critical Values			Stationarity
					1%	5%	10%	
$\ln NGC$	2	-6.232	0	-66.596	-4.223	-3.189	-2.73	Stationary
$\ln P$	2	-4.849	0	-122.021	-3.809	-3.022	-2.651	Stationary
$\ln A$	2	-4.987	0	-10.548	-3.833	-3.031	-2.656	Stationary
$\ln T$	2	-4.269	0.001	-51.158	-3.833	-3.031	-2.656	Stationary
$\ln Y$	0	-3.688	0.004	-85.692	-4.069	-3.127	-2.702	Stationary
$\ln Z$	0	-3.581	0.006	-65.946	-4.069	-3.127	-2.702	Stationary

3.3 Scenario Parameter Settings

The future trend of China's natural gas consumption is influenced by multiple uncertainties, and the peak time and value of natural gas consumption may vary in different scenarios. scenarios. This study establishes two overarching scenarios —Baseline Mode and Low-Carbon Mode—by comprehensively considering trends in China's population dynamics, affluence level, technological advancement, industrial restructure, and energy consumption structure. These scenarios simulate the future development paths of influencing factors under distinct conditions, with their combinations yielding eight distinct development sub-scenarios (see Table 5). In Baseline Mode, the future growth rates of influencing factors are calibrated based on targets specified in relevant national policy documents. In the Low-Carbon Mode, to align with China's dual carbon goals, parameters are adjusted as follows compared to the Baseline Mode: accelerated optimization of the energy consumption structure; heightened technological advancement effects; moderated growth rates for population, affluence level, and industrial structure.

Table 5 Different Development Scenario Settings

Scenario	Population	Affluence Level	Technological advancement	Industrial Structure	Energy Consumption Structure
Baseline Scenario	Baseline	Baseline	Baseline	Baseline	Baseline
Scenario1	Low-Carbon	Low-Carbon	Baseline	Low-Carbon	Baseline
Scenario2	Low-Carbon	Baseline	Low-Carbon	Baseline	Low-Carbon
Scenario3	Baseline	Baseline	Baseline	Low-Carbon	Baseline
Scenario4	Baseline	Baseline	Low-Carbon	Low-Carbon	Baseline
Scenario5	Baseline	Baseline	Low-Carbon	Baseline	Baseline
Scenario6	Baseline	Baseline	Low-Carbon	Baseline	Low-Carbon
Scenario7	Baseline	Low-Carbon	Baseline	Low-Carbon	Baseline

Parameter Settings for Baseline and Low-Carbon Modes of Influencing Factors are as follows.

Population Factor: China's population grew from 1.267 billion in 2000 to 1.412 billion in 2021 (a 1.11-fold increase), exhibiting a fluctuating growth pattern. During the 14th Five-Year Plan period (2021 – 2025), China will undergo a critical demographic shift, entering its first phase of negative population growth [27]. The annual average growth rate is projected to decline to approximately 0.2%, with the population reaching a peak plateau of around 1.431 billion. Subsequently, the growth rate will gradually decrease, and China's population is expected to sustain negative growth from 2026 to 2050, with the annual average growth rate slowing to -0.2%. By 2050, the population is forecast to drop to approximately 1.368 billion (0.97 times the 2021 level), while the annual average growth rate declines from 1.79% (2000 – 2021) to -0.11% (2022 – 2050). Based on these projections: population growth rate in baseline mode can be set to -0.2‰ to 1.4‰. and population growth rate in low-carbon mode can be set to -4 ‰ to -0.25 ‰.

Affluence Level Factor: The affluence level, a critical indicator of socioeconomic development, is predominantly influenced by national economic performance. China's GDP growth rate declined from 8.5% in 2000 to 3% in 2022, before rebounding to 5.2% in 2023. The national economy has transitioned from a scale-and-speed-driven phase to a structural adjustment phase and is now entering a high-quality development phase[10]. Future economic growth is projected to moderate. Based on these trends: the per capita GDP growth rate in baseline mode can be set to 4.5%. and the per capita GDP growth rate in the low-carbon mode can be set to 3.5%.

Technological Level Factor: Technological advancement serves as a critical indicator reflecting China's energy utilization efficiency and ecological conditions. Since the introduction of the dual carbon goals, China's energy utilization technology has progressively improved, enhancing energy efficiency and further ameliorating the ecological environment. Drawing on the historical trajectory of energy consumption intensity in developed nations and aligned with t*he Guiding Opinions on Fully and Accurately Implementing the New Development Philosophy to Achieve Carbon Peaking and Carbon Neutrality*, energy consumption intensity is projected to decline significantly. However, further substantial reductions will become increasingly challenging once intensity reaches a certain threshold [10]. Based on these insights: the rate of decrease in energy consumption intensity for technological level in baseline mode can be set to -0.5% to 2%, and the rate of decrease in energy consumption intensity for the low-carbon mode can be set to -0.5% to 2.5%.

Industrial Structure Factor: In response to national policies such as energy conservation, emissions reduction, and the dual carbon goals, China's industrial sector has undergone continuous optimization and adjustment, maintaining a commitment to technological innovation, green development, and industrial upgrading. The proportion of energy-intensive industries has steadily declined. Based on these trends: the annual reduction rate of energy-intensive industries' share in baseline mode can be set to 1.65% and the annual reduction rate of energy-intensive industries' share in the low-carbon mode can be set to 1.7%.

Energy Consumption Structure Factor: The optimization of energy consumption structure is reflected by the share of natural gas consumption in primary energy. As a critical component in building China's modern energy system, natural gas's transitional role has become increasingly prominent in the short-to-medium term, though its long-term transitional significance is expected to gradually diminish. While China' s natural gas consumption has risen annually, its growth rate has shown a declining trend. According to *the 14th Five-Year Plan for a Modern Energy System* and *the Energy Production and Consumption Revolution Strategy (2016－2030)*, natural gas is projected to account for 15% of primary energy consumption by 2030, with its share continuing to grow. Based on these projections: the growth rate of natural gas consumption proportion in the baseline mode of energy consumption structure can be set to 2.5%, and the growth rate of natural gas consumption proportion in the low-carbon mode of energy consumption structure can be set to 3%.

3.4 Scenario-Based Forecast and Analysis of China' s Natural Gas Consumption Peak

By incorporating the development trends of influencing factors under different scenarios into the extended STIRPAT model for China's natural gas consumption forecasting, the prediction results across scenarios are illustrated in Figure 1 and Table 6. Analysis of Figure 1 and Table 7 reveals distinct evolution patterns of China's natural gas consumption under various development scenarios, with specific details as follows:

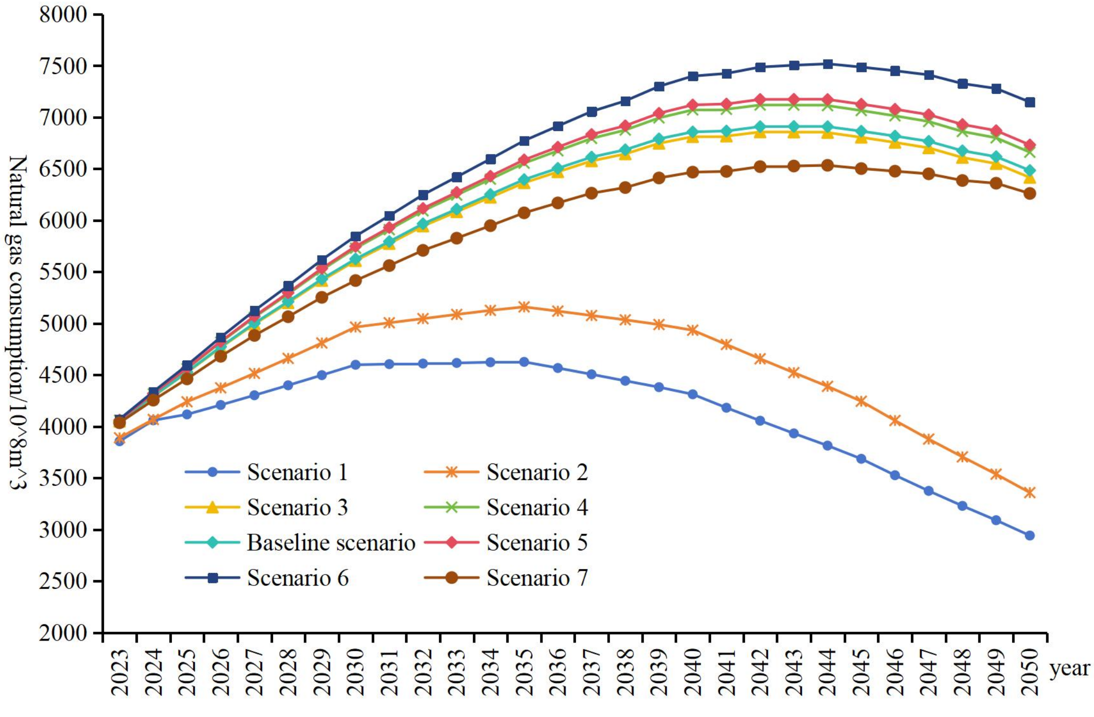

Figure 1 Future Natural Gas Consumption Trends in China under Different Scenarios

Table 6 Peak Time and Peak Value of Natural Gas Consumption in China

Scenario	Peak Year	Peak/10^8m^3	Scenario	Peak Year	Peak/10^8m^3
Baseline Scenario	2043	6910.61	Scenario1	2035	4626.32
Scenario2	2035	5159.83	Scenario3	2042	6856.86
Scenario4	2042	7118.79	Scenario5	2043	7174.59
Scenario6	2044	7518.39	Scenario7	2044	6533.55

Under the Baseline Mode, where population, affluence level, technological advancement, industrial structure, and energy consumption structure follow their baseline development trends, China’s natural gas consumption is projected to peak in 2043 at approximately 6,910.61 $\times$ 10^8 m^3. Between 2040 and 2045, natural gas consumption will remain in a plateau phase, with the annual growth rate declining from 12.46% (2000 – 2022) to 2.58% (2023 – 2043). Subsequently, from 2044 to 2050, consumption is expected to decrease at an annual negative growth rate of -0.71%, dropping to $6483.93\times10^8 m^3$ by 2050.

In scenario 1, the technological advancement and energy consumption structure follow the baseline development trend, while the population, affluence level, and industrial structure follow the low-carbon development trend. China's natural gas consumption will reach its peak in 2035, with a peak of approximately $4626.32\times10^8 m^3$. The average annual growth rate of natural gas consumption will decrease from 12.46% from 2000 to 2022 to 0.16% from 2023 to 2035. From 2036 to 2050, China's natural gas consumption will decline at an average annual growth rate of -2.79%, and by 2050, natural gas consumption will decrease to $2941.36\times10^8 m^3$.

Under Scenario 2, where affluence level and industrial structure develop according to baseline trends while population, technological advancement, and energy consumption structure follow low-carbon development trajectories, China's natural gas consumption is projected to peak in 2035 with a peak volume of approximately $5159.83\times10^8 m^3$. The annual growth rate of natural gas consumption will decline from 12.46% during 2000-2022 to 0.25% during 2023-2035. Subsequently, from 2036 to 2050, China's natural gas consumption is expected to decrease at an average annual rate of -2.65%, ultimately declining to $3358.09\times10^8 m^3$ by 2050.

Under Scenario 3, where population, technological advancement, energy consumption structure, and affluence level according to baseline trends while industrial structure follows a low-carbon development trajectory, China's natural gas consumption is projected to peak in 2042 with a peak volume of approximately $6856.86\times10^8 m^3$. The annual growth rate of natural gas consumption will decline from 12.46% during 2000-2022 to 2.67% during 2023-2042. Subsequently, natural gas consumption will enter a plateau phase from 2043 to 2045. From 2043 to 2050, China's natural gas consumption is expected to decrease at an average annual rate of -0.66%, ultimately declining to $6415.36\times10^8 m^3$ by 2050.

Under Scenario 4, where population, energy consumption structure, and affluence level according to baseline trends while technological advancement and industrial structure follow low-carbon development trajectories, China's natural gas consumption is projected to peak in 2042 with a peak volume of approximately $7118.79\times10^8 m^3$. The annual growth rate of natural gas consumption will decline from 12.46% during 2000-2022 to 2.85% during 2023-2042. Subsequently, natural gas consumption will enter a plateau phase from 2043 to 2046. From 2043 to 2050, China's natural gas consumption is expected to decrease at an average annual rate of -0.66%, ultimately declining to $6660.42\times10^8 m^3$ by 2050.

Under Scenario 5, where population, industrial structure, energy consumption structure, and affluence level according to baseline trends while technological levels follow a low-carbon development trajectory, China's natural gas consumption is projected to peak in 2043 with a peak volume of approximately $7118.79\times10^8 m^3$. The annual growth rate will decline from 12.46% during 2000-2022 to 2.75% during 2023-2043, with natural gas consumption remaining in a plateau phase from 2040 to 2045. Subsequently, from 2044 to 2050, China's natural gas consumption is expected to decrease at an average annual rate of -0.71%, ultimately declining to $6731.62\times10^8 m^3$ by 2050.

Under Scenario 6, where population, industrial structure, and affluence level according to baseline trends while technological advancement and energy consumption structure follow low-carbon development trajectories, China's natural gas consumption is projected to peak in 2044 with a peak volume of approximately $7518.39\times10^8 m^3$. The annual growth rate will decline from 12.46% during 2000-2022 to 2.83% during 2023-2044. Subsequently, from 2045 to 2050, China's natural gas consumption is expected to decrease at an average annual rate of -0.72%, ultimately declining to $7147.53\times10^8 m^3$ by 2050.

Under Scenario 7, where population, technological advancement, and energy consumption structure develop according to baseline trends while industrial structure and affluence level follow low-carbon development trajectories, China's natural gas consumption is projected to peak in 2044 with a peak volume of approximately $6533.56\times10^8 m^3$. The annual growth rate will decline from 12.46% during 2000-2022 to 2.21% during 2023-2044. Subsequently, from 2045 to 2050, China's natural gas consumption is expected to decrease at an average annual rate of -0.61%, ultimately declining to $6260.56\times10^8 m^3$ by 2050.

It is not difficult to observe that the peak time and amount of China's natural gas consumption peak vary across different scenarios. It can be predicted that with China's accelerating population decline, the rapid rise of renewable energy replacing fossil fuels, and the comprehensive implementation of green low-carbon development, China's natural gas consumption is likely to peak around 2035, with the peak volume estimated between $4600\times10^{8}m^{3}\sim5200\times10^{8}m^{3}$ [28].If China's negative population growth is alleviated, energy efficiency is improved, energy structure transformation is continuously promoted, industrial structure is constantly optimized and adjusted, and natural gas has a long-term role as a transitional energy, it is predicted that China's natural gas consumption will peak in 2040-2045 [23], with the volume ranging between $6500\times10^{8}m^{3}\sim7500\times10^{8}m^{3}$. This aligns broadly with the findings of *the World and China Energy Outlook* report by CNPC Economics & Technology Research Institute and the consensus among scholars regarding China's natural gas consumption peaking [29-30].

From the baseline scenario and Scenario 5, both project a peak year of 2043 for China's natural gas consumption. However, Scenario 5 yields a higher peak volume about $263.98\times10^{8}m^{3}$ than that of the baseline, indicating that low-carbon technological advancements effectively stimulate natural gas consumption growth, underscoring technology as a critical driver. Comparing Scenario 1 and Scenario 2, both scenarios predict a peak in 2035, yet Scenario 2 exhibits a peak volume approximately $533.51\times10^{8}m^{3}$ higher than that of Scenario 1. Similarly, in Scenarios 6 and 7, the peak occurs in 2044, with Scenario 6's peak volume exceeding Scenario 7's by around $984.84\times10^{8}m^{3}$. This suggests that the combined low-carbon development of technological levels and energy consumption structure exerts a stronger driving effect on natural gas consumption growth than the joint influence of affluence and industrial restructuring. Analyzing Scenario 1 versus Scenario 7 and Scenario 2 versus Scenario 6, it is clear that low-carbon population development effectively reduces natural gas consumption growth, advancing the peak by nearly a decade. This highlights the significant impact of demographic factors on China's natural gas consumption trends. Between Scenarios 3 and 4, both project a peak in 2042, but Scenario 4's peak volume surpasses Scenario 3's, demonstrating that the synergistic low-carbon development of technology and industrial structure drives natural gas consumption more effectively than industrial restructuring alone. Comparing Scenarios 4 and 5, low-carbon industrial restructuring reduces consumption growth and accelerates peak timing. Conversely, between Scenario 5 and 6, low-carbon energy consumption structure development delays the peak period and promotes consumption growth.

3.5 Further Discussion

To further validate the reliability of the results, a comparative analysis was conducted between the natural gas consumption data for 2023 and 2024 released by China's National Bureau of Statistics and the predictions derived from this study. In 2023 and 2024, China's natural gas market maintained stable growth, with consumption reaching 394.53 billion cubic meters and 426.05 billion cubic meters, respectively. As shown in Table 7, the absolute errors between the predicted values under all eight scenarios and the actual observed values for 2023 and 2024 remain below 5%. This demonstrates that the scenario assumptions in this study are reasonable and that the predictions exhibit high accuracy. The constructed extended STIRPAT model is therefore validated as a robust tool for forecasting trends in China's natural gas consumption.

Table 7 Analysis of Predicted and Actual Natural Gas Consumption in China from January to September 2024 and 2023

	Actual	Scenario 1	Scenario 2	Scenario 3	Scenario4	Baseline Mode	Scenario 5	Scenario6	Scenario7
2023 Natural Gas Consumption/10^8m^3	3945.30	3856.29	3889.83	4049.61	4060.52	4051.15	4062.06	4070.77	4035.67
Mean Absolute Percentage Error/%		2.25	1.42	2.64	2.92	2.68	2.95	3.18	2.29
2024 Natural Gas Consumption/10^8m^3	4260.5	4058.99	4067.84	4291.88	4315.04	4295.14	4318.32	4336.85	4254.87
Mean Absolute Percentage Error/%		4.72	4.52	0.74	1.28	0.81	1.36	1.79	0.13

With the high-quality and rapid development of China's economy and the continuous advancement of carbon peaking policies, China's natural gas consumption and imports have grown rapidly, leading to a persistent expansion of the supply-demand gap and a year-on-year increase in external dependence[31]. The future natural gas supply-demand relationship in China is expected to remain tight. Scholars predict that China's natural gas production will peak between 2035 and 2045, with peak production levels within this range[32]. Under optimistic scenarios, China's external dependence on natural gas is projected to reach 39%, while pessimistic estimates suggest it could rise to 55%. To ensure national energy security, it is imperative to vigorously implement the Seven-Year Action Plan for oil and gas reserve expansion and production enhancement, establish a diversified natural gas import system, and improve a multi-level natural gas storage mechanism [33].

4 CONCLUSION

This study identifies population, affluence level, technological advancement, industrial structure, and energy consumption structure as key factors influencing China's natural gas consumption. By employing the VIF test to address multicollinearity among variables and introducing the ridge regression method to eliminate its effects, the parameters of the extended STIRPAT model were determined. Scenario analysis was further applied to explore peak natural gas consumption trends in China. The main conclusions are as follows:

(1) The extended STIRPAT model, incorporating factors such as population, affluence level, technological advancement, industrial structure, and energy consumption structure, demonstrates high predictive accuracy and reliability. This model can serve as an effective tool for analyzing the evolution of natural gas consumption in other regions.

(2) As China transitions into a high-quality development stage, characterized by continuous improvements in energy efficiency and industrial restructuring, natural gas will retain its critical role as a transitional energy. China's natural gas consumption is projected to enter a peak plateau phase between 2040 and 2045, with consumption levels ranging from $6500\times10^8 m^3 \sim 7500\times10^8 m^3$.

(3) To facilitate the peaking of natural gas consumption, China must optimize population growth, strengthen measures aligned with the "dual carbon" goals, prioritize breakthroughs in core renewable energy technologies, accelerate the commercialization and adoption of renewable energy innovations, and advance the green and low-carbon transformation of its energy system. Concurrently, efforts should focus on increasing natural gas reserves and production, boosting R&D investments and technological innovation in critical sectors, establishing diversified natural gas import and storage mechanisms, cultivating new quality productive forces in the energy sector, and constructing a modern energy system to safeguard national energy security.

COMPETING INTERESTS

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

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