

## Article

# Integrated Assessment Modeling of China's Shale Gas Resource: Energy System Optimization, Environmental Cobenefits, and Methane Risk

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**Abstract:** Comprehensive evaluation of shale gas resource, which plays a role in energy system optimization, atmospheric environmental cobenefit, and methane risk, has long been ignored in China. This research aims to fill this gap and conduct a study based on the China-Multi-pollutant Abatement Planning and Long-term benefit Evaluation model to answer the research question, “When considering environmental and climate risks, does the shale gas resource in China exert a negative or positive effect?” Results show that shale gas plays an important role in replacing coal and optimizing the energy structure. Shale gas can also effectively help reduce the key local pollutant emissions. Approximately 84.85 thousand of deaths (persons) and 32.24 billion yuan of economic loss can be avoided in 2030 with the reduction of SO<sub>2</sub> and NO<sub>x</sub>. The methane risk, which has been disregarded in China when evaluating cobenefits, is also considered in this study. The economic loss due to methane leakage is estimated to reach approximately 2.76 billion yuan on average in 2030. Overall, the net atmospheric environmental cobenefit could reach 68.61 billion yuan on average in 2030, accounting for 0.04% of China's GDP. This study provides positive evidence for an integrated assessment of shale gas resource in coal-dominant developing countries.



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**Keywords:** shale gas in China; energy system optimization; environmental health cobenefit; methane risk; net benefit

## 1. Introduction

Shale gas resources are widely distributed globally, mainly in North America, Central Asia, the Middle East, North Africa, and Southern Africa [1]. However, the shale gas study in China is relatively limited [2], and study from the comprehensive assessment aspect is lacking. This paper contributes to the current literature via its integrated analysis on the shale gas development in China, including energy system optimization, environmental cobenefit, and climate risk. The study is designed to answer the questions “What are the main challenges in China's shale gas development? Is it worth promoting shale gas in China despite the comprehensive impacts?”

The reason why these questions are important to answer is that shale gas has drawn wide attention for its development in such countries as the United States, Canada, and United Kingdom. Especially regarding environmental impact and climate risk. The environmental impact [3–6] and climate risk [7] of shale gas are the focus of discussion. Westaway R. et al. and Stamford L. et al. [3–5] hold two extreme views on the potential impact of shale gas in the UK, and have conducted multiple rounds of debate. Turk J.K. et al. [7] showed that shale gas in the UK will increase the carbon budget overruns and may have an impact on the country's climate change goals. These issues are of vital importance both nationally and internationally. Nevertheless, such comprehensive studies in China remain lacking.

On the other hand, shale gas also plays an important role in energy substitution. But we noticed the proportion of gas varied in different countries, e.g., in 2018 approximately 19.63% in the United States, of which 58.69% is shale gas [8,9], and only 5.50% in China, of which 9.61% is shale gas [8,10]. In general, gas is an important realistic replacement for coal, considering the small proportion of gas used in China and its lack of research, the gap in comprehensive studies on shale gas should be filled. This study aims to answer the aforementioned questions.

First, studies in gas-dominant countries have provided answers to the questions for a comprehensive environmental impact analysis. For comprehensive research, Cooper J et al. [11, 12] conducted the first study and analysis of the overall sustainability of shale gas in the UK, they used 14 indicators for evaluation, and the conclusions are multifaceted. Therefore, the pros and cons of shale gas use are difficult to conclude based on a single level of research; this is one of the reasons why we hope to fill the gaps in China's research and conduct more comprehensive discussions. Moreover, as for the atmospheric environment and health benefits, earlier related studies were carried out by Jenner S. and Lamadrid A.J. [13] and Bunch A.G. et al. [14], they all came to a positive conclusion regarding shale gas. Of course, there are still some scholars arguing about this issue [3–5]. In terms of economic benefits, the research of Bilgili F [15] and Solarin S.A. et al. [16] proved the positive impact of shale gas on the U.S. economy. Research on shale gas about its economic benefits in European countries has produced some different opinions. Grecu E. et al. [17] used CBA (Cost Benefit Analysis) to evaluate shale gas production in Romania and showed that the shale gas exploitation has no real benefits in the long run in densely populated areas; Saussay A [18] and Cooper J [19] also believe that the economic success of American shale gas may not be replicated in European countries. It can be seen that a reasonable analysis angle of shale gas should be diverse and comprehensive, while such comprehensive discussion is lacking in China, so this paper aims to show the comprehensive impact of shale gas development in China to complete this worldwide story on shale gas.

Second, this paper contributes to studies on shale gas from the environmental impact on the consumption process. The research of the effect of shale gas consumption in China started late and has focused on energy substitution [20–22], carbon footprint and carbon reduction [20,22–25], and economic benefits [21,26]. Few quantitative studies on environmental impacts exist, and research focusing on health impacts is limited. Empirical studies (e.g., in Chongqing and Sichuan) are many, but few studies are from the perspective of the entire industry, including consumption processes, are available. International research on shale gas has mainly focused on the environmental impact [12,27], health problems [28,29], and sustainability studies considering social issues [11,12]; the United Kingdom, the United States, and Canada pay more attention to such issues, and showed strong concerns about the environment and health. To the best of our knowledge, the gas consumption research in China needs to be further expanded. The gas consumption in the electricity generation, industry, residential, and commercial sectors also has an unignorable impact on energy structure optimization and environmental benefits compared with coal consumption; Chen Y. et al. [20] and Chang Y. et al. [22] have mentioned these benefits. From the demand-driven aspect, this paper plans to answer the environmental impact question from the consumption side. Studies on the current gas consumption in China mainly focus on top-down analysis and the use of the computable general equilibrium (CGE) model to study the impact of natural gas consumption on the economy [30] and carbon emissions [31]. Nonetheless, the gas consumption description in CGE is at the sectoral level and could not reflect the influence of technology improvement. Therefore, this study plans to improve the gas consumption description further on the basis of the bottom-up model, with gas consumption calculated in consideration of residential heating and cooking, road transport, and industry material and combustion.

Third, the shale gas development will certainly lead to climate risk, such as methane leakage. The United States, the United Kingdom, and Canada mainly use baseline monitoring methods based on typical shale gas regions [32,33] combined with some predictive

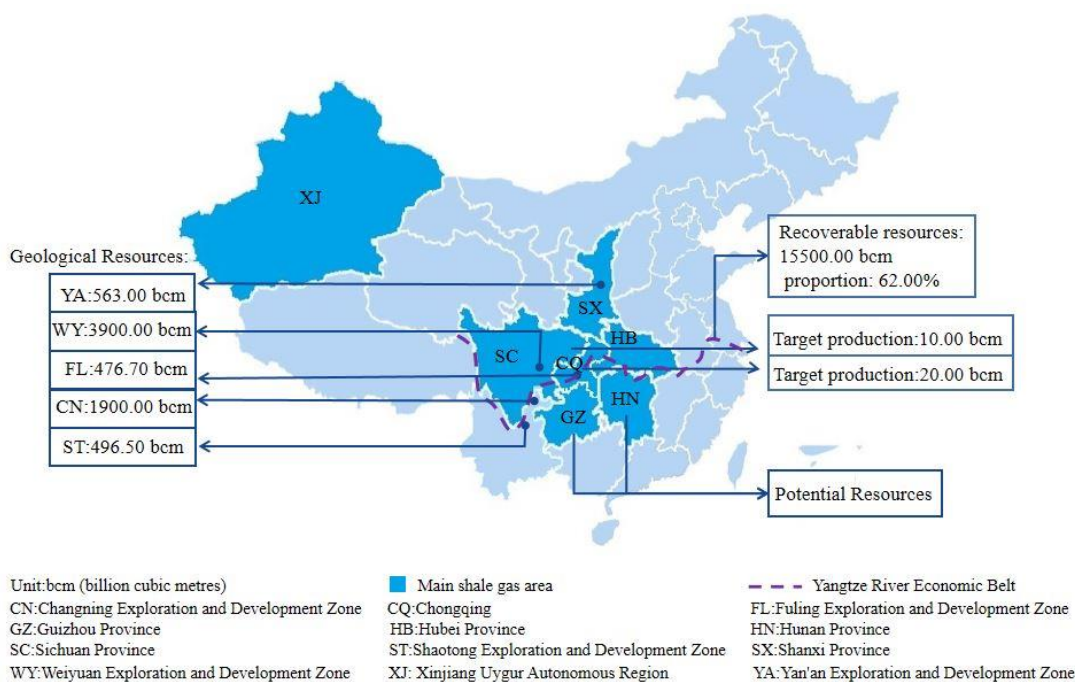
models [34] to conduct such studies, in addition, there are also studies on ozone [35] and hydrocarbons [36]. Based on these studies using actual observational data, methane emissions are indeed a climate risk worthy of attention. On the other hand, in China, some scholars have gained some enlightenment based on the US methane emission measures [37] but did not expand quantitative research based on specific data, in most environmental benefit studies [20,38], the consideration of methane leakage is limited, only mentioned in small amounts in research. Thus, considering the above two aspects, this study adds the methane leakage and climate risk of shale gas in China to the comprehensive environmental cobenefit analysis.

In addition, although shale gas may generate methane risks, some studies on different gas supply approaches can provide inspiration for methane treatment. For example, [39] used life cycle assessment methods to evaluate the carbon footprint of flue gas treatment, and proposed a new method for flue gas treatment; there are also some studies that have verified that wastewater treatment can synthesize natural gas [40], and introduced the use of carbon dioxide as a carbon source to produce energy storage media to solve solar energy-related problems [41]. The methane emitted from shale gas can also be recycled and utilized through related technologies to synthesize useful gases, etc.

What's more, we noticed that the use of shale gas will be challenged in other ways [42]. Including the social influence and public attitude [11,43,44], shale gas extraction, recovery and reuse technology [45–50], government subsidy pressure [51,52], and so on. At the social impact level, the study of Cooper J et al. [11] in the United Kingdom shows that the use of shale gas can bring employment opportunities and financial benefits to local communities, but it needs to overcome social barriers such as low public support. Actually, public opposition is a worldwide problem [42], and shale gas extraction in densely populated areas (such as northern England) and more remote “primitive” environments (such as Poland and Bolivia) is prone to cause public opposition; Leaders and residents in the southern United States [43] maintain somewhat paradoxical perceptions with respect to shale energy development. While in Weiyuan County, China [44], nearly half of the people were found to support relevant policies, a very small number completely oppose it. In terms of shale gas extraction, recovery and reuse technology, the problem that has always been explored is how to determine the potential and limitations of shale gas [46–48] through various technologies, and improve shale gas recovery rate by carbon dioxide injection technology [49] and heating treatment [50]. In addition, there are concerns about government subsidies for shale gas use in China; Liu J. et al. [51] and Bai Y. et al. [52] showed that shale gas development needs subsidies in the early stages, and fiscal subsidies are effective incentives for shale gas investment. So, while shale gas brings benefits, it will also face challenges. On the whole, there are more positive effects, and the negative impacts can be solved through technological advancement and policy norms with the passage of time. These international research conclusions can provide references for the promotion and use of shale gas in China.

Lastly, given that there are few comprehensive studies on China's shale gas development, does that mean the shale gas in China is not a good research object? The answer is “No.” The future use of shale gas in China has great potential [53–57], many scholars have conducted research on shale gas potential areas such as Sichuan and Chongqing. In the long run, shale gas will perform well and there is more room for improvement [21,58]. Some studies believe that the shale gas industry in Chongqing is more sustainable than that in Sichuan [59]. A study has also predicted that shale gas, even under the reference (REF) scenario, will start to play a role in the power system after 2025, and the main application areas in the technical breakthrough scenario will be East and North China [23]. Based on the reality in China, according to relevant policy information [60–63], the distribution of China's shale gas resources is shown in Figure 1. China's shale gas resources are unevenly distributed, mainly distributed in Sichuan Province, Xinjiang Wuer Autonomous Region, Chongqing City, Guizhou Province, Hubei Province, Hunan Province, and Shaanxi Province; Guizhou Province and Yunnan Province are potential areas of shale gas resources;

and the recoverable shale gas resources in the Yangtze River Economic Zone account for more than 60% [63]. Compared with North America and other regions with rich shale gas resources, although China has relatively small resources, the potential for future development cannot be ignored. Shale gas is widely distributed in various geological periods in China [64]. Its reserves continue to increase, and the proven rate is low [65]. The 3500 m shale gas exploration technology will be improved and surpassed [66]. From the 14th Five-Year Plan, the Chinese government will vigorously promote the development of shale gas and strive to increase shale gas production in 2030. By 2035, the proportion of shale gas in China’s natural gas production will increase from less than 1/10 to about 1/3 [67]; natural gas dependence on foreign countries exceeded 40% in 2019 [68], so the development of shale gas can undoubtedly help reduce external dependence and ensure energy security. Further, it can be seen from Figure 1 that the distribution of shale gas is relatively concentrated, which is convenient for mining and quantitative production, but this will also make the regional air pollution and methane impact more prominent. Therefore, this article needs to conduct a comprehensive analysis of China’s shale gas topics that lack comprehensive research around these issues.



**Figure 1.** Shale gas resource reserves/development goals.

The remainder of this paper is organized as follows. Section 2 is the methodology design of this article, including model description and scenario setting. Section 3 discusses the impact of shale gas development on the improvement of energy structure. Section 4 evaluates the positive environmental cobenefit for local pollutant reduction and the negative impacts of methane leakage and climate risk. In Section 5, the main conclusions and discussions are provided.

## 2. Methodology

### 2.1. Model Description

Most of China’s research focuses on greenhouse gas emissions throughout the life cycle [20,22–25], comparison of energy substitution [20–22], and economic benefits [21,26]. Most of these studies have shown the advantages of shale gas from the perspective of energy substitution; at the same time, they also show that the economic benefits of shale gas are not optimistic, and there are still different opinions on its environmental emission

reduction effects. So, we will discuss these issues further. At the same time, we found that the existing studies lack air quality models for atmospheric research and pollutant emission coefficients based on technology for nationwide studies. Thus, this paper aims to focus on the atmospheric environmental cobenefit based on emission coefficient linked at the technological level.

The analysis is based on the China-Multi-pollutant Abatement Planning and Long-term benefit Evaluation (China-MAPLE) model. It is a technology-rich model based on the Reference Energy System. The MAPLE model elucidates the full processes, including mining, processing, energy conversion and distribution, and final energy consumption, in the energy system. The model also describes technological improvement, the complex internal relations among processes, and the external constraints of the energy system.

The main frame structure of the model is shown in Figure 2. The core modules of the model are energy system analysis and pollutant emission modules. The resource supply module provides a resource supply curve based on the distribution, import, and export of major resources in the energy system analysis module. The final energy demand prediction module predicts the future energy service demand with exogenous economic parameters and assumptions. The resource supply module is composed of resource supply curve, resource reverse limit, and production costs. The demand module establishes the main influencing factors by departments and inputs the demand of final energy consumption into the energy system optimization module. Then, the system cost is provided for the energy system optimization module through the calibration of major pollutant emissions and technology composition in the local pollutant module. The cobenefit module is based on the pollutant module, adding the cost of emission reduction to determine the total system cost of pollutants. Meanwhile, the climate risk evaluation module is added to calculate the methane leakage and its damage to human health and economic development during the development of shale gas. The model output is determined collectively with the climate risk evaluation and energy system optimization modules. In accordance with the scenario design or emission constraints, the model calculates and selects the optimal technology combination and fuel consumption in the future in medium and long term to determine the specific role of shale gas development in energy system optimization and structure adjustment. The model also comprehensively considers the positive environmental cobenefit and negative climate risk and eventually obtains the net benefit of shale gas development for the environment.

The objective function is to minimize the total cost of the energy system under the conditions of meeting the given demand and constraints. The costs include investment and dismantling costs, the fixed and variable costs of operation and maintenance, the costs of energy extraction and import, export earnings, distribution costs, taxes, and subsidies. The objective function of the model also includes the residual value of assets and the welfare loss caused by demand reduction. Formulas (1) and (2) are the objective functions of the model.

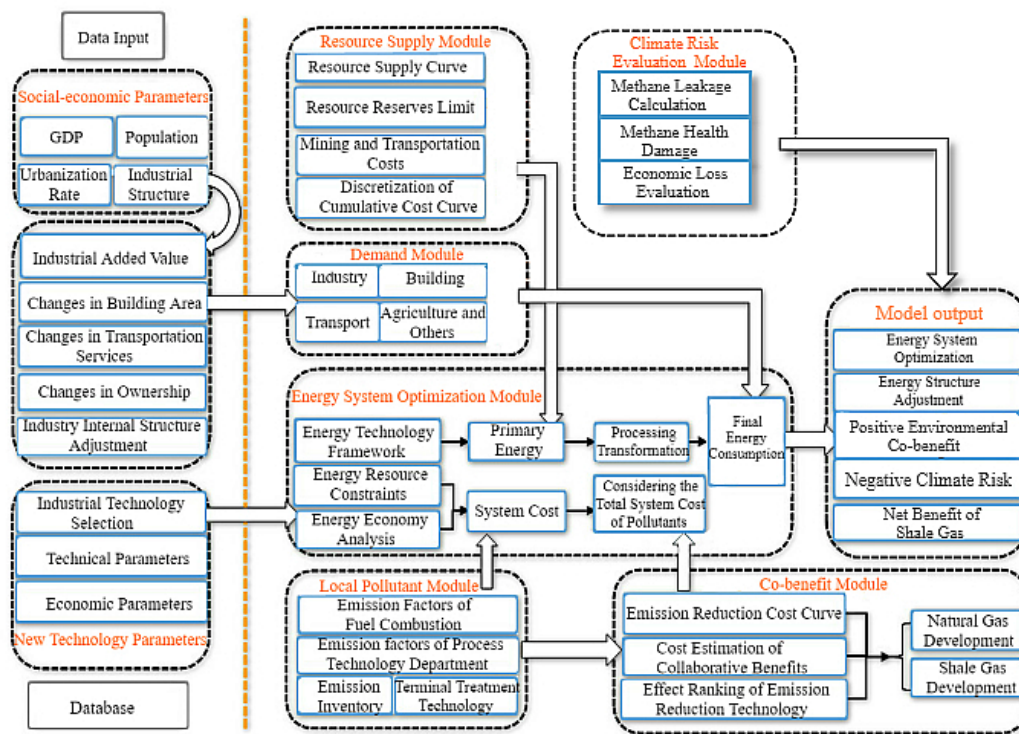
$$VAR\_OBJ(z) = \sum_{r \in REG} REG\_OBJ(z, r) \quad (1)$$

$$REG\_OBJ(z, r) = \sum_{y \in Y} (1 + d_{r,y})^{TY-y} \times AC(r, y) - RVA(z, r) \quad (2)$$

where  $NPV$  represents the net present value of the system, and  $d_{r,y}$  is the discount rate.  $TY$  represents the target year of discount,  $Y$  represents the time period,  $R$  refers to regions,  $AC(r,y)$  is the annual operation cost of region  $r$  in year  $y$ , and  $RVA$  is the residual value of assets.

The decision variables of the model are the variables that need to be solved by the model. These variables can refer to the parameters of energy extraction, conversion, and utilization processes in the energy system, as well as the activity levels of energy carriers and emissions. They are the basis for calculating the objective function and constraint conditions. Table 1 lists the main decision variables and explanations. The decision variables of this article are  $OBJ(y_0)$ ,  $D(r, t, d)$ ,  $NCAP(r, v, p)$ ,  $CAP(r, v, t, p)$ ,  $CAPT(r, v, t, p, s)$ ,  $ACT(r, v, t, p, s)$ ,

$FLOW(r, v, t, p, c, s)$ ,  $SIN(r, v, t, p, c, s)/SOUT(r, v, t, p, c, s)$ ,  $TRADE(r, t, p, c, s, imp)$ ,  $TRADE(r, t, p, c, s, exp)$ . These decision variables are directly related to  $y_0$ ,  $r$ ,  $t$ ,  $d$ ,  $v$ ,  $p$ ,  $s$ ,  $c$ ,  $imp$ ,  $exp$ , and other parameters, where  $y_0$  is the beginning of the period,  $r$  is region,  $t$  is period,  $d$  is demand,  $v$  is period,  $p$  is new technology,  $s$  is stage,  $c$  is commodities,  $imp$  denotes import,  $exp$  denotes export. These variables and parameters have been described in detail in the model, including not only the total system, but also the description at the sectoral level, and the description at the sub-sectoral level. The sector takes into account all sectors and technologies that consume natural gas, such as industrial heat consumption, road traffic and residential heating, and so on.



**MAPLE Integrated Assessment Framework**

**Figure 2.** Multi-pollutant Abatement Planning and Long-term benefit Evaluation (MAPLE) integrated assessment framework.

**Table 1.** Decision variables and descriptions.

Variable code	Description
$Obj(y_0)$	The total system cost discounted to $y_0$
$D(r, t, d)$	Energy service demand $d$ in region $r$ , period $t$
$NCAP(r, v, p)$	Capacity of new technology $p$ in period $v$ , region $r$
$CAP(r, v, t, p)$	Capacity of installed technology $p$ in period $t$ , region $r$
$CAPT(r, v, t, p, s)$	Total capacity of installed technology $p$ in period $t$ , region $r$
$ACT(r, v, t, p, s)$	Activity level of technology $p$ in period $t$ , region $r$
$FLOW(r, v, t, p, c, s)$	Amount of product $c$ produced or consumed by technology $p$ in period $t$ , region $r$
$SIN(r, v, t, p, c, s)/SOUT(r, v, t, p, c, s)$	The amount of commodities $c$ stored or released by technology $p$ in period $t$ , stage $s$ , region $r$
$TRADE(r, t, p, c, s, imp)$	The amount of commodities $c$ imported and exported by technology $p$ in period $t$ , region $r$ by technology $p$
$TRADE(r, t, p, c, s, exp)$	

## 2.2. Supply Curve

This study introduces a resource supply curve. The main resources contain non-renewable resources, such as coal, oil, and natural gas, and renewable resources, such as hydropower, wind power, and solar power resources. The research considers different sources of resources (domestic production and import and export sources), diverse production areas based on domestic production resources (such as North, East, Northeast, Central South, Southeast, and West China), and the supply of resources under different production capacities and costs. For the bottom-up energy optimization model, the price gradient of resource supply will directly affect the technology selection and then make the optimized technology structure of the energy system more reasonable than before.

The following are the basic principles for the endogenous price of resource supply: (1) the order of use of resources is strictly in accordance with the level of cost; (2) if the price exceeds the cost, then the resource will be completely exhausted. That is, from the exploitation of resources, the deposit will be exploited until it is exhausted. Exceptions include adequately large storage. Therefore, Formulas (3)–(5) are used in this study.

$$Z_t = \sum_i^{t-1} q_i \quad (3)$$

$$C(q, z) = \min_{x_i} \sum_{i=1}^J c_i \times x_i \quad (4)$$

and

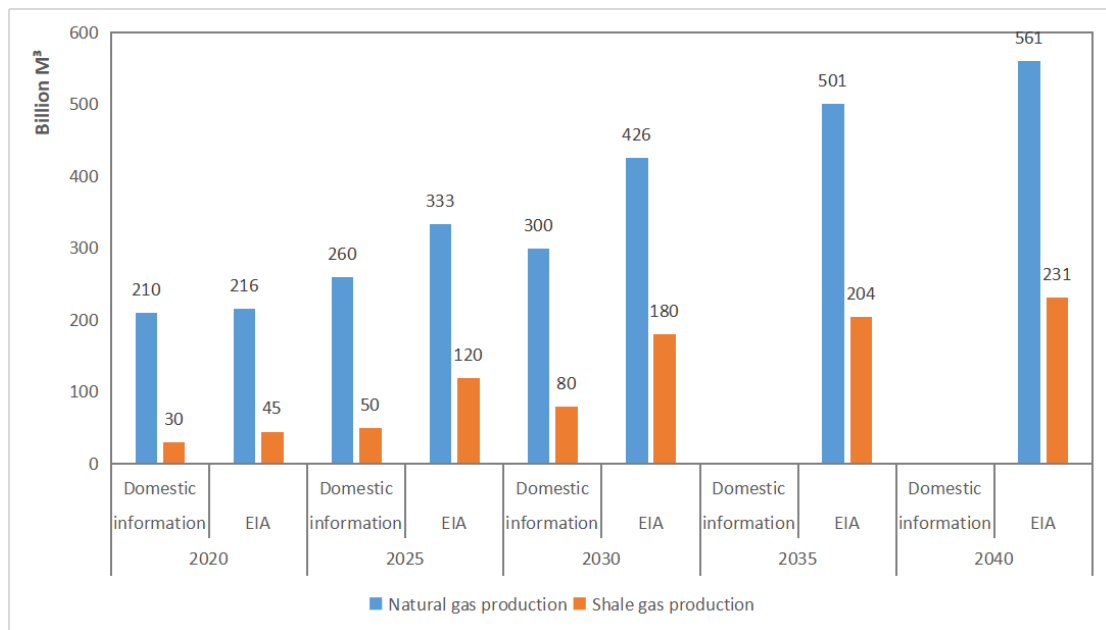
$$x_i \leq R_i, \forall i \text{ there is } q = \sum_{i=1}^J x_i \quad (5)$$

where  $Z_t$  is the cumulative mining amount based on time,  $q_i$  is the total mining amount of mineral storage  $i$ ,  $C(q, z)$  is the cost function,  $x_i$  is the currently mined amount of mineral storage  $i$ ,  $c_i$  is the unit mining cost of mineral storage  $i$ , and  $R_i$  is the total remaining volume of mineral storage  $i$ .

The short-term cumulative cost curve will show an upward trend with the increase in the extraction volume, i.e., the extraction cost will gradually increase, the intercept of the cost function will increase, and the unit extraction cost of the remaining reserves will continue to increase with the extraction process. High-quality mineral deposits with low mining costs per unit of reserves are often preferentially mined. With the development of the mining process, other reserves are gradually used. In consideration of the increase in the amount of new investment, the slope of the unit mining cost curve will decrease. In the long run, with the reduction in remaining mineral reserves, the difficulty and cost of mining will increase. Hence, when the mining reaches a certain degree, the unit mining cost will increase rapidly.

## 2.3. Scenario Design of Shale Gas Development

The medium- and long-term development goals of shale gas development and utilization in China are that during “the 14th Five-Year Plan” and “the 15th Five-Year Plan” periods, China’s shale gas industry will accelerate its development. The scenario considers the potential of marine development and shale gas breakthroughs within continental and marine–land transitional facies, with a number of large-scale shale gas fields newly discovered. We assume that an effective scale development will be achieved, and the shale gas production will reach 80–100 billion cubic meters by 2030. Detailed information on the production forecast of China’s natural gas and shale gas is indicated in Figure 3.



**Figure 3.** China's future production of conventional natural gas and shale gas.

BP Energy Outlook (2035) [69] predicts that China's shale gas production will maintain an average annual growth rate of 33% from 2025 to 2035 and will account for 13% of the global shale gas increase by 2035. Therefore, from the preceding analysis, three scenarios based on the current situation (Table 2), namely, reference (REF), shale gas moderate development (SGMD), and shale gas ambitious development (SGAD), are selected for analysis. Under the SGMD scenario, shale gas production is expected to reach 10.833 million cubic meters in 2030, with 40% share. In the SGAD scenario, shale gas production will reach 130 million cubic meters in 2030, accounting for 43%.

**Table 2.** Shale gas production and proportion in different scenarios; Unit: billion cubic meter.

	The SGMD Scenario		The SGAD Scenario	
	2025	2030	2025	2030
Natural gas production	249	274	260	300
Shale gas production	72.86	108.33	85	130
Shale gas production ratio	29%	40%	33%	43%

### 3. Results on Energy System Optimization

#### 3.1. Final Energy Demands

Figures 4 and 5, respectively, show the final energy consumption and the final energy consumption structure in the main years in the three cases. The unit of the ordinate in Figure 4 is million ton of standard coal equivalent (tce). For the final energy consumption, coal consumption will continue to account for the largest share under the baseline scenario, that is, at 42% in 2025 and 38% in 2030, followed by oil and electricity consumption. In 2030, natural gas (excluding shale gas) consumption will continue to rise, reaching 25 million tons of standard coal, accounting for 4% of the final energy consumption; the shale gas consumption will increase to 57 million tons, with 1% share.



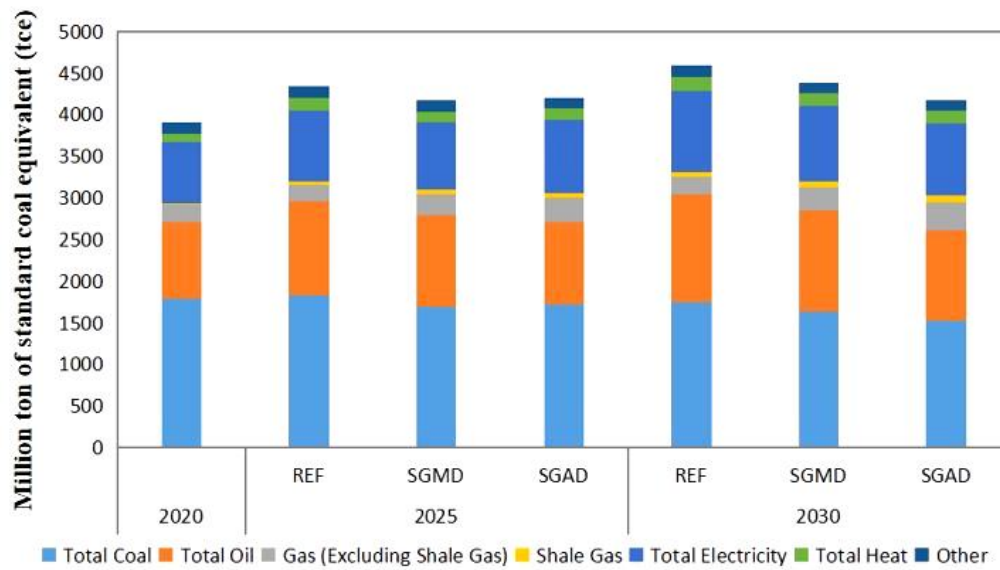


Figure 4. Final energy consumption.

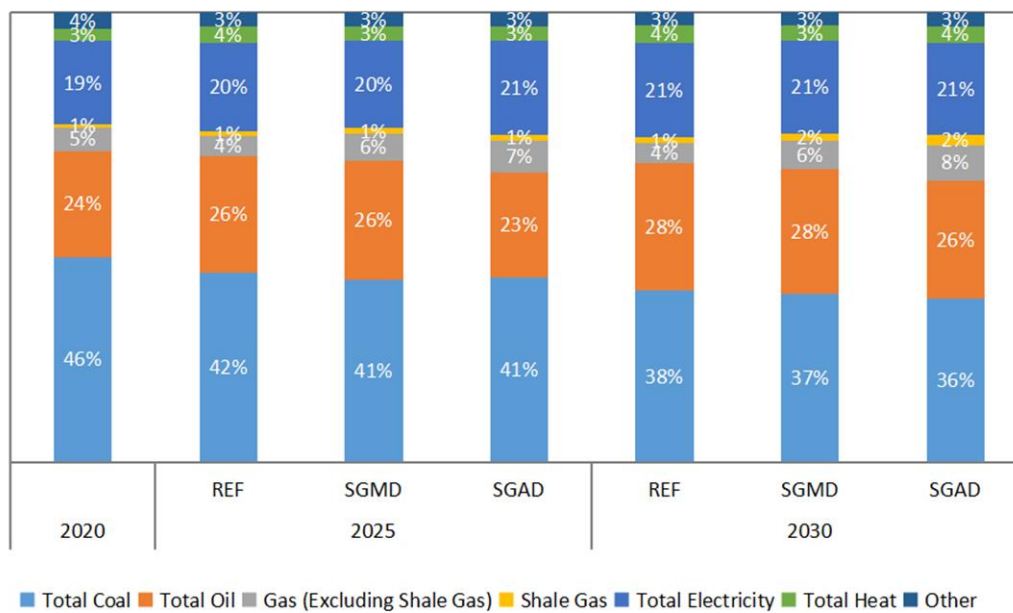


Figure 5. Final energy consumption structure.

Under the SGMD scenario, coal, oil products, and electricity will remain the three largest parts of the final energy consumption structure for a long period of time in the future, and coal, oil, and electricity will account for 37%, 28%, and 21%, respectively, in 2030. The consumption of natural gas (excluding shale gas) will show an upward trend in total and proportion, reaching 274 million tons of standard coal by 2030, with 6% share. Shale gas consumption is forecast to reach 51 million tons of standard coal in 2025 and 76 million tons of standard coal in 2030, accounting for 1% and 2% of the final energy consumption, respectively.

In the SGAD scenario, coal consumption will still be the largest by 2025 and 2030, but the proportion of final energy consumption will drop to 41% and 36%, respectively, followed by the consumption of oil products and electricity. Natural gas (excluding shale gas) consumption will achieve a large increase in this scenario; it is expected to reach

329 million tons of standard coal in 2030, accounting for 8%. Shale gas consumption will also reach 91 million tons of standard coal by 2030, with 2% share.

### 3.2. Primary Energy Demand

In the baseline scenario, the total consumption of primary energy can reach 5.67 and 5.90 billion tons of standard coal in 2025 and 2030, respectively. Among them, coal and conventional natural gas will be the two largest parts of primary energy consumption, accounting for 46.34% and 22.48% in 2030, respectively. They are followed by the consumption of nonfossil energy and oil. Shale gas will also become an important part of the primary energy consumption structure, with the consumption expected to reach 253 and 367 million tons of standard coal in 2025 and 2030, accounting for 4.47% and 6.22%, respectively.

The total primary energy depletion in SGMD is 2.23 billion tons of standard coal less than that in 2025 in the REF scenario. In 2030, coal will still account for the largest share of primary energy consumption at 41.19%; conventional natural gas is second only to coal at 20.80%; nonfossil energy and oil consumption are expected to account for 24.41% and 7.85%, respectively. Shale gas consumption could come up to 344 million tons of standard coal with a share achieving 5.75%.

Under the SGAD scenario, 5.52 and 5.77 billion tons of primary energy of standard coal will be consumed in 2025 and 2030, respectively. Coal still accounts for the largest proportion of primary energy consumption, but the proportion will drop to 36.33% by 2030. Conventional natural gas and nonfossil energy will occupy a more important position. In 2030, the consumption of conventional natural gas is expected to reach 1.46 billion tons of standard coal, with 25.35% share; nonfossil energy consumption is forecast to reach 1.421 billion tons of standard coal, accounting for 24.63%. Petroleum will account for 6.45% and 6.68% of primary energy consumption in 2025 and 2030, respectively. Shale gas consumption is going to exceed oil in 2030, accounting for 7.01% of primary energy consumption. Details of the primary energy consumption and consumption structure under the three scenarios are presented in Figures 6 and 7, respectively.

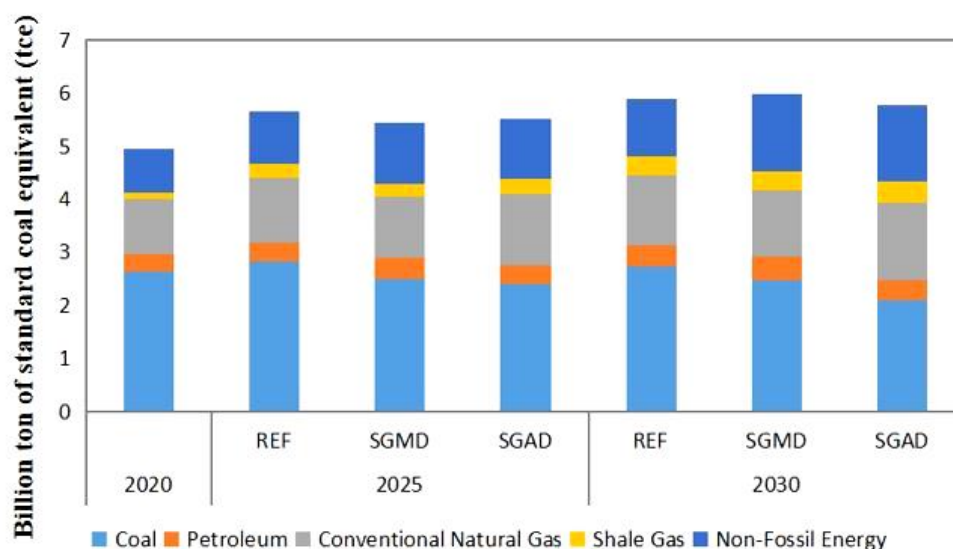


Figure 6. Primary energy consumption.

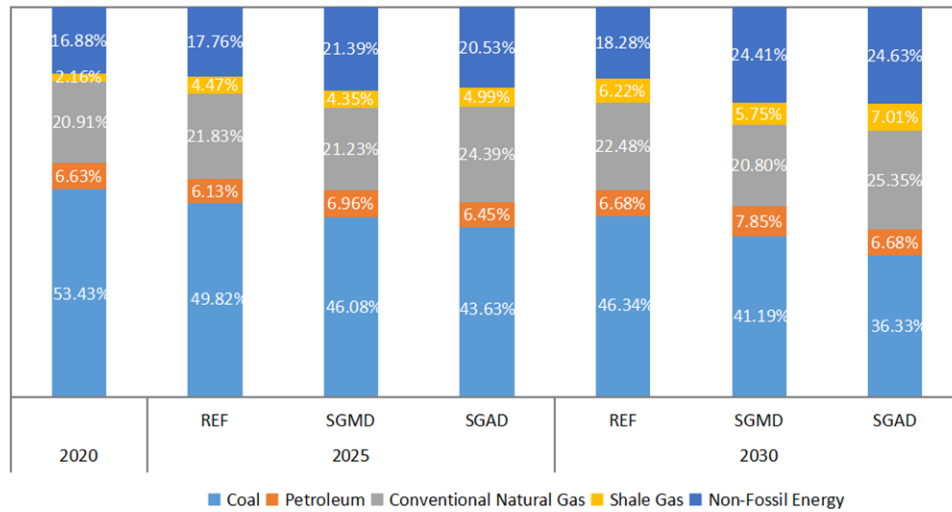


Figure 7. Primary energy consumption structure.

### 3.3. Power Generation Structure

The power generation and power generation structure in the main years in the three cases are shown in Figures 8 and 9, respectively. Total power generation will reach 7758.11 TWh by 2025 under the REF scenario, with coal power accounting for the largest share of the power generation structure at 50.37%, followed by hydropower and wind power, which account for 18.31% and 15.74%, respectively. Nuclear power, gas power, and solar power will account for 8.52%, 5.25%, and 1.75%, respectively, and the remainder will be oil power, biomass power, tidal power, and other energy power, each reaching less than 1% of total power generation. By 2030, the total amount of coal-fired power will increase to 9027.86 TWh, but its share in the power generation structure will drop to 48.36%; hydropower will also decrease to 16.95%, whereas wind power is forecast to increase to 17.43%. The proportions of nuclear power, gas power, and solar power in the power generation structure will increase by 9.32%, 6.13%, and 1.80%, respectively.

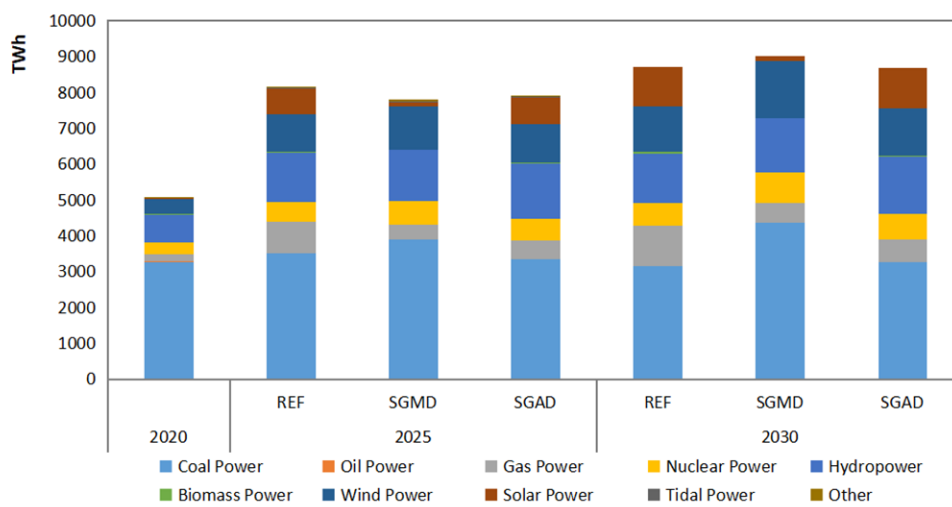


Figure 8. Power generation.

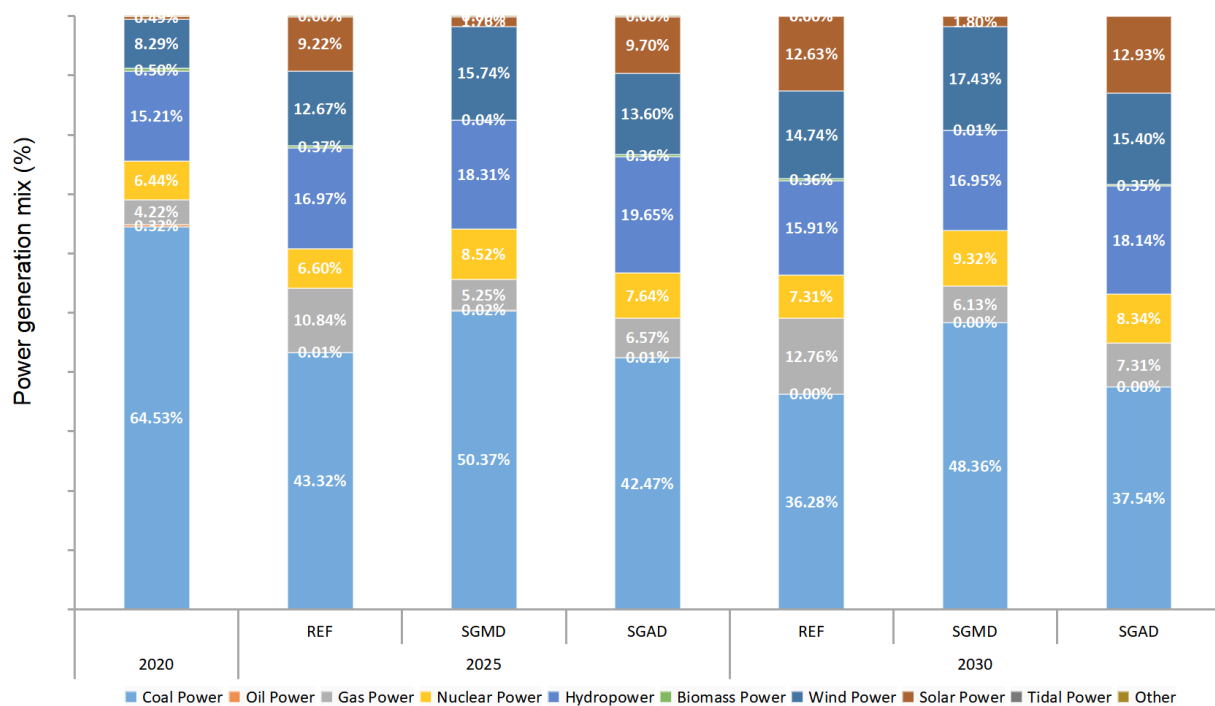


Figure 9. Power generation structure.

In the SGMD scenario, the total power generation is expected to be 7890.56 and 8690.53 TWh in 2025 and 2030, respectively. Coal power, which is the largest source for power generation, is expected to reach 42.47% and 37.54% of the power generation structure in 2025 and 2030, respectively. It is followed by hydropower and wind power, which will account for 18.14% and 15.40% of the power generation structure, respectively, in 2030. Next is nuclear power, which will account for 8.34% of the total power generation in 2030. Gas power will be less than solar power, with a value of 635.65 TWh in 2030, accounting for 7.31%. Solar power is expected to account for 12.93% in 2030. The generation of biomass, oil, tidal, and other energy power will account for less than 1% of the power generation structure.

The total power generation in SGAD will have an increase of 4.07% and 0.31% compared with that in SGMD in 2025 and 2030, respectively. Coal power is going to account for the largest proportion of the power generation structure in 2030 at 36.28%, a remarkable drop from the 43.32% share in 2025. It is followed by hydropower and wind power. Hydropower is forecast to account for 18.14% in 2025 and will decline to 15.91% in 2030. Wind power is going to attain 12.67% in 2025 and rise to 14.74% in 2030. Gas and solar power generation will have great development, with anticipated portions of 12.76% and 12.63% of the power generation structure, respectively. Nuclear power is estimated to be 7.31% in 2030. The generation of other types of energy will still have a very small share.

### 3.4. Carbon Emissions

Under the REF scenario, carbon emissions will continue to rise, reaching 11.22 billion tons in 2025 and 11.184 billion tons in 2030. In the SGMD scenario, the margin of carbon emission increase is predicted to be small, achieving 10.54 and 10.58 billion tons in 2025 and 2030, respectively. Under the SGAD scenario, carbon emissions will first increase and then decrease and are expected to account for 10.34 and 9.94 billion tons in 2025 and 2030, respectively. The peak will be reached before 2030.

#### 4. Key Local Pollutant Emissions and Environmental Health Impacts

##### 4.1. Emissions of SO<sub>2</sub> and NO<sub>x</sub>

The details of SO<sub>2</sub> and NO<sub>x</sub> emissions in major years are shown in Figure 10 (the unit of the vertical axis in the figure is kiloton (kt)). Less SO<sub>2</sub> in the SGMD scenario will be discharged compared with that in the REF scenario. The emissions will be reduced by 3.49 and 5.77 million tons in 2025 and 2030, respectively, with the extent of 12.20% and 18.10%, respectively. Of them, 26.13 million tons will be discharged in 2030. The SGAD scenario has a higher emission reduction effect than the two other scenarios. The emission reduction will be increased by 5.38 and 6.91 million tons in 2025 and 2030, respectively. Compared with the general situation, the emission will be decreased by 21.50% and 26.40%. The emission will be 19.22 million tons in 2030. In terms of sectoral emission reduction, the SO<sub>2</sub> emission reduction effect of the industrial sector is more significant than that of the residential sector. The transportation sector is not the main emission sector of SO<sub>2</sub>. Compared with the REF scenario, the SGMD scenario indicates that the SO<sub>2</sub> emission reduction of the industrial sector will be 3.39 million tons in 2025 and 5.52 million tons in 2030. Under the SGAD scenario, the SO<sub>2</sub> emission reduction of the industrial sector will be 5.30 million tons more than that in the general scenario in 2025 and 6.81 million tons in 2030. Given that the industrial sector emits more SO<sub>2</sub> than the transportation and residential sectors, the effect of shale gas development on SO<sub>2</sub> emission reduction is the best in the industrial sector. Therefore, we conclude that the more radical the shale gas development is, the more obvious the effect of SO<sub>2</sub> emission reduction will be. The SO<sub>2</sub> emission reduction effect of shale gas development varies for different departments.

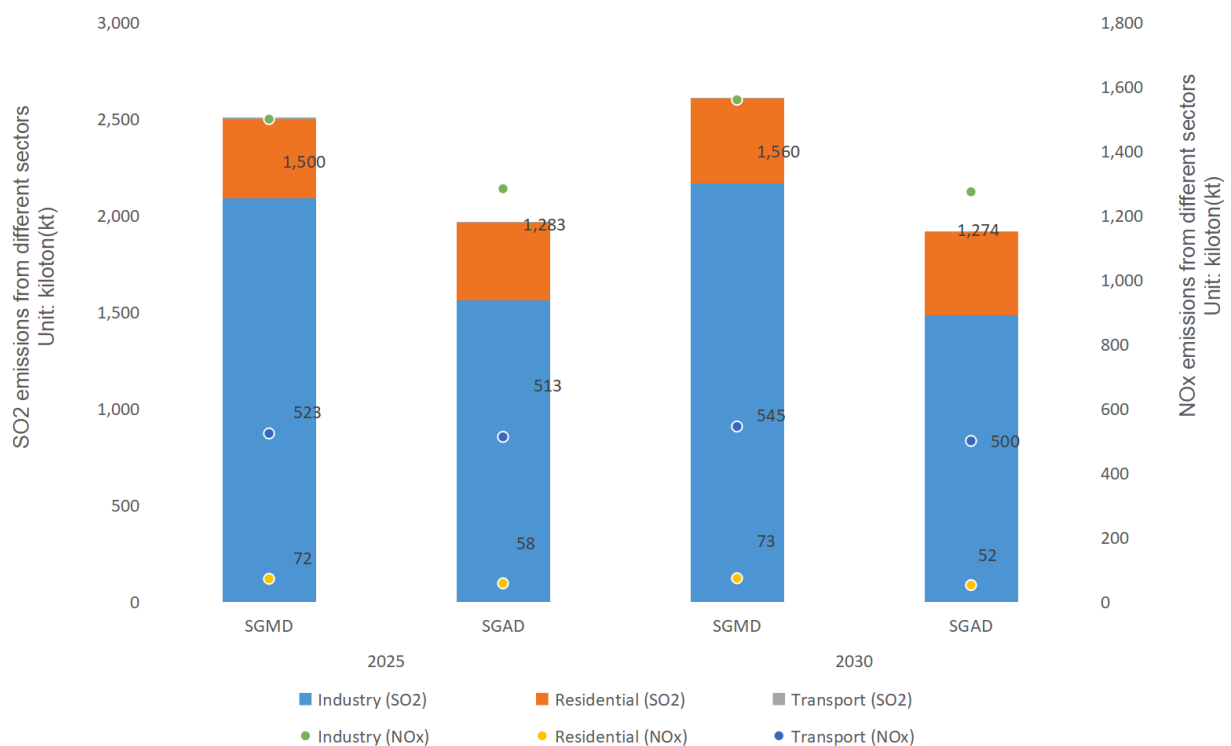


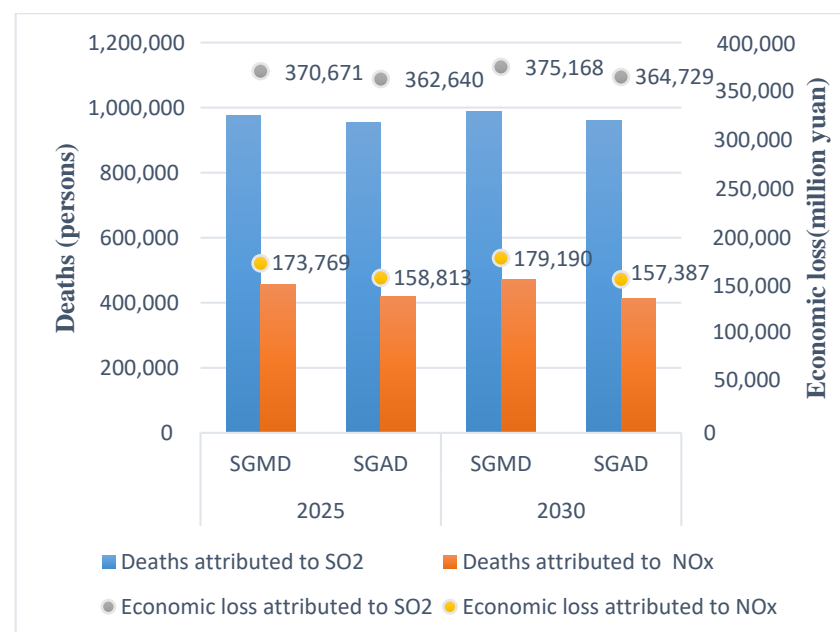
Figure 10. Emissions of SO<sub>2</sub> and NO<sub>x</sub> from different sectors.

At all levels, the SGMD scenario emits less NO<sub>x</sub> than the REF scenario; the emissions will be reduced by 4.26 and 6.78 million tons in 2025 and 2030, respectively, accounting for 16.9% and 23.7%, respectively. In 2030, the emission will be 21.78 million tons. A higher emission reduction effect will be shown in the SGAD scenario. On the basis of the SGMD scenario, emissions in the SGAD scenario will be reduced by 2.41 and 3.52 million tons in 2025 and 2030, respectively, with decreases of 11.50% and 16.20%, respectively. The emis-

sion will be 18.26 million tons in 2030. From the point of view of sector, the industrial sector will make a more remarkable  $\text{NO}_x$  emission reduction effect compared with the transport and residential sectors. Compared with the REF scenario, the SGMD scenario will induce a reduction in the  $\text{NO}_x$  emission of the industrial sector by 1.90 million tons in 2025 and 3.07 million tons in 2030. Under the SGAD scenario, the industrial sector will emit 2.16 million tons of  $\text{NO}_x$  less than that of the SGMD scenario in 2025 and 2.85 million tons in 2030.

#### 4.2. Environmental Health Impacts of $\text{SO}_2$ and $\text{NO}_x$

The development of shale gas can reduce the number of deaths due to  $\text{NO}_x$  and  $\text{SO}_2$  (Figure 11). In the context of the radical development of shale gas, the coal replacement effect of shale gas is prominently reflected. Compared with the general scenario, it produces less  $\text{SO}_2$  and  $\text{NO}_x$ , resulting in reductions of 27,472 and 57,377 deaths in 2030, respectively.



**Figure 11.** Deaths and economic losses attributed to  $\text{SO}_2$  and  $\text{NO}_x$ .

Simultaneously, as the shale gas development reduces the number of deaths attributed to  $\text{SO}_2$  and  $\text{NO}_x$ , the economic losses caused by  $\text{SO}_2$  and  $\text{NO}_x$  will also decrease, and economic losses will be avoided in SGAD. The economic losses caused by  $\text{SO}_2$  and  $\text{NO}_x$  in SGAD will be reduced by 3.00% and 12.00%, respectively, in 2030, compared with those in SGMD. The calculation of the main parameters of  $\text{SO}_2$  and  $\text{NO}_x$  and the exposure response coefficient are from the research results of Holnicki P. et al. (2018), Chen D. et al. (2014), and Cao et al. (2011).

#### 4.3. Methane Leakage

Regardless of the calculation method, the aggressive development of shale gas results in an increase of approximately 20% in methane emissions compared with the SGMD scenario (Table 3). The calculated methane emissions under the calculation methods adopted by Zhu S. [70], NDRC/UNDP [71], and IPCC 2006 guidelines (small) [72] are relatively close. The SGAD methane emissions in 2030 will be in the range of 400–700 kt, and their respective gaps will be nearly 100 kt. The methane emissions calculated in accordance with the IPCC 2006 guidelines (middle) and IPCC 2006 guidelines (large) [72] are much higher than those based on the aforementioned three methods. The emissions under SGAD in 2030 will be 2387.70 and 4084.75 kt.

**Table 3.** Total methane emissions (kt).

Accounting Method	2025		2030	
	SGMD	SGAD	SGMD	SGAD
Zhu S. [70]	243.71	284.32	362.36	434.84
NDRC/UNDP [71]	292.97	341.79	435.6	522.74
IPCC 2006 guidelines (small) [72]	387.09	451.59	575.53	690.66
IPCC 2006 guidelines (middle) [72]	1338.22	1561.19	1989.69	2387.7
IPCC 2006 guidelines (large) [72]	2289.34	2670.79	3403.85	4084.74

Different emissions of methane occur at various links in the shale gas development process under diverse accounting methods (Table 4). From the accounting methods of Zhu S. [70] and NDRC/UNDP [71], similar amounts of methane are emitted from the natural gas extraction and transmission links. Most methane emissions are from the natural gas consumption link under the accounting methods of Zhu S. [70] and NDRC/UNDP [71]. In the calculation method of IPCC 2006 [72], the methane emission of natural gas exploitation is much higher than that of other links.

**Table 4.** Methane emission in each link (kt).

Link	The SGMD Scenario		The SGAD Scenario		Accounting Method
	2025	2030	2025	2030	
Natural gas extraction	72.60	107.94	84.69	129.53	Zhu S. [70]
Natural gas processing	36.30	53.97	42.35	64.76	
Natural gas transmission	46.67	69.39	54.44	83.27	
Natural gas consumption	88.15	131.07	102.84	157.28	
Total	243.71	362.36	284.32	434.84	
Natural gas extraction	75.19	111.79	87.72	134.15	NDRC/UNDP [71]
Natural gas processing	36.30	53.97	42.35	64.76	
Natural gas transmission	93.34	138.78	108.89	166.54	
Natural gas consumption	88.15	131.07	102.84	157.28	
Total	292.97	435.6	341.79	522.74	
Natural gas extraction	285.20	424.04	332.72	508.86	IPCC 2006 guidelines (small) [72]
Natural gas processing	0	0	0	0	
Natural gas transmission	16.33	24.29	19.06	29.14	
Natural gas consumption	85.56	127.21	99.81	152.66	
Total	387.09	575.53	451.59	690.66	
Natural gas extraction	1075.96	1599.77	1255.24	1919.78	IPCC 2006 guidelines (middle) [72]
Natural gas processing	42.78	63.61	49.91	76.33	
Natural gas transmission	79.47	118.15	92.71	141.79	
Natural gas consumption	140.01	208.16	163.33	249.8	
Total	1338.22	1989.69	1561.19	2387.70	
Natural gas extraction	1866.73	2775.51	2177.77	3330.71	IPCC 2006 guidelines (large) [72]
Natural gas processing	85.56	127.21	99.81	152.66	
Natural gas transmission	142.6	212.02	166.36	254.43	
Natural gas consumption	194.45	289.12	226.85	346.95	
Total	2289.34	3403.85	2670.79	4084.74	

#### 4.4. Environmental Health Impact of Methane

Based on the IPCC [73] fifth assessment report, the obtained GWP (Global Warming Potential) value of methane emission is shown in Table 5.

**Table 5.** The GWP (Global Warming Potential) of methane leakage.

Acronym, Common Name or Chemical Name	Chemical Formula	Lifetime (Years)	GWP (20-Year)	GWP (100-Year)
Carbon dioxide	CO <sub>2</sub>	No single lifetime can be given. The impulse response function for CO <sub>2</sub> from Joos et al. (2013) has been used. 12.4	1	1
Methane	CH <sub>4</sub>	(Perturbation lifetime is used in calculation of metrics, not the lifetime of the atmospheric burden)	84	28

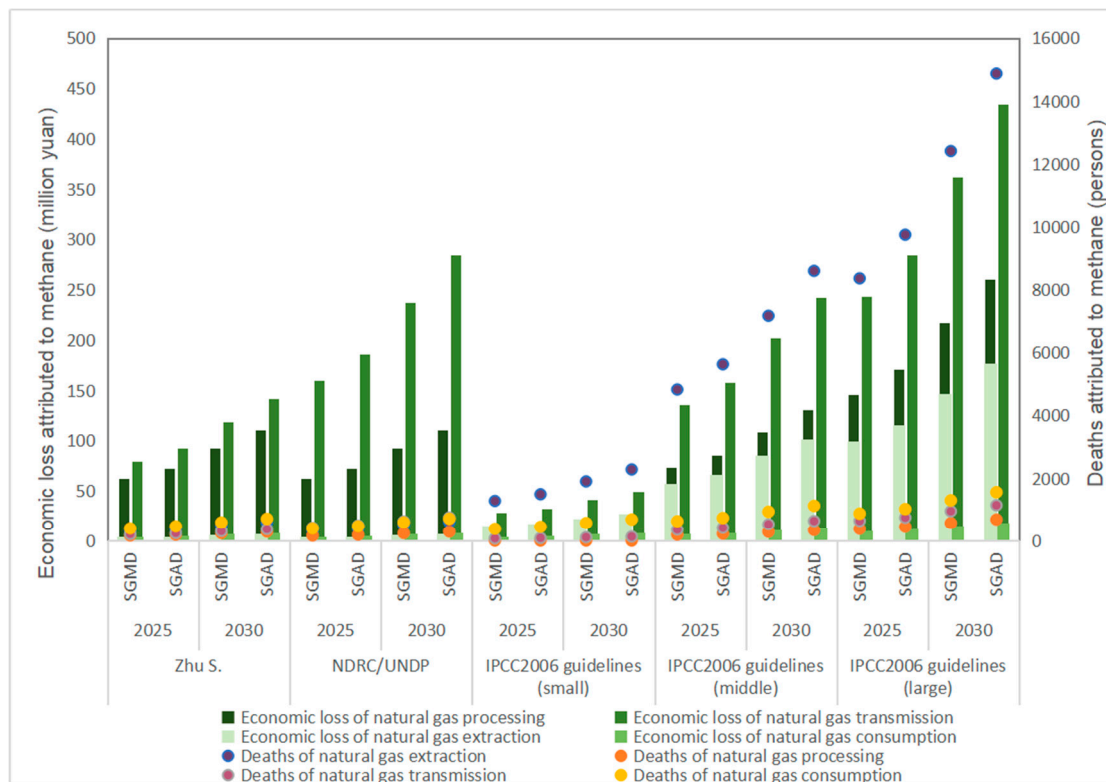
It can be seen that methane is a powerful greenhouse gas. In 100 years, its global warming potential will be about 28 times that of carbon dioxide. If calculated in 20 years, the warming potential of methane will be more than 80 times that of carbon dioxide. Therefore, under such a high global warming potential, based on the calculation data of shale gas methane leakage in Section 4.3, it can be seen that the environmental impact of shale gas methane leakage is indeed a concern.

The death toll and economic loss caused by methane under different scenarios are shown in Figure 12. Different accounting methods have significantly diverse calculation results for the total number of deaths due to methane emissions. The total number of deaths will be far more than other accounting methods by adopting the IPCC 2006 guidelines (middle) and IPCC 2006 guidelines (large) [72]. For all accounting methods, the number of deaths caused by methane emission in SGAD will be higher than that in SGMD. When the accounting method in the IPCC 2006 guideline [72] is adopted, the death toll in the natural gas exploitation stage is much higher than that in other stages, and the proportion of total deaths is over 73%. Under the accounting method of Zhu S. [70] and NDRC [71], a minimal difference in the distribution of deaths in each stage exists. The methane leakage in the natural gas consumption link accounts for the highest proportion of total deaths under the accounting method of Zhu S. [70], and the methane leakage in the natural gas transmission link accounts for the highest proportion of total deaths under the accounting method of NDRC [71].

The economic losses of methane leakage vary greatly under different accounting methods. The economic losses caused by methane emissions calculated using the IPCC 2006 guidelines (middle) and IPCC 2006 guidelines (large) [72] are much higher than the calculation results of Zhu S. [70], NDRC/UNDP [71], and IPCC 2006 guidelines (small) [72]. Different accounting methods have diverse distributions of economic losses in each natural gas stage. Under the accounting method of IPCC 2006 guidelines [72], the economic loss induced by the natural gas exploitation stage accounts for 80% of the total loss in the entire process, followed by the consumption stage, and, finally, the processing stage. Under the accounting methods of Zhu S. [70] and NDRC/UNDP [71], the proportion of economic losses caused by the four stages is approximately the same, with a small total amount.

The economic losses caused by the development of shale gas in SGAD are more than those in SGMD. Under the accounting methods of Zhu S. [70] and NDRC/UNDP [71], the economic loss in SGAD will be 123.68 and 148.62 million yuan more than that in SGMD in 2030, respectively. Under the accounting methods of IPCC 2006 guidelines (small), IPCC 2006 guidelines (middle), and IPCC 2006 guidelines (large) [72], the economic loss in SGAD will be 196.23, 673.67, and 1144.44 million yuan more than that in SGMD in 2030, respectively.





**Figure 12.** Number of deaths and economic loss attributed to methane.

#### 4.5. Economic Loss Avoided

The net environmental health cobenefit of shale gas development under diverse accounting methods in different scenarios is shown in Figure 13, the unit of the vertical axis in the figure is million Renminbi (RMB). The net environmental health cobenefit is composed of the economic losses avoided due to the reduction of  $\text{SO}_2$  and  $\text{NO}_x$  and the economic losses caused by the increase in methane on average, which shows the overall impact of shale gas development on human health. Regardless of which accounting method it is based on, the net environmental health cobenefit of shale gas development is always positive, which indicates that developing shale gas can help reduce the economic loss caused by air pollutants and has a positive effect on environmental protection and human health. The net environmental health cobenefit is high when the shale gas is developed aggressively and the period of shale gas development is long. The difference in the net environmental health cobenefit of shale gas development under various accounting methods is insignificant. In 2025, the average net environmental health cobenefit in SGAD will be 47.55 billion yuan, accounting for 0.04% of China's GDP that year, which is 22.73 billion yuan more than that in SGMD. In 2030, the average net environmental health cobenefit in SGAD will reach 68.61 billion yuan, occupying 0.04% of China's GDP that year, which is 31.79 billion yuan more than that in SGMD.

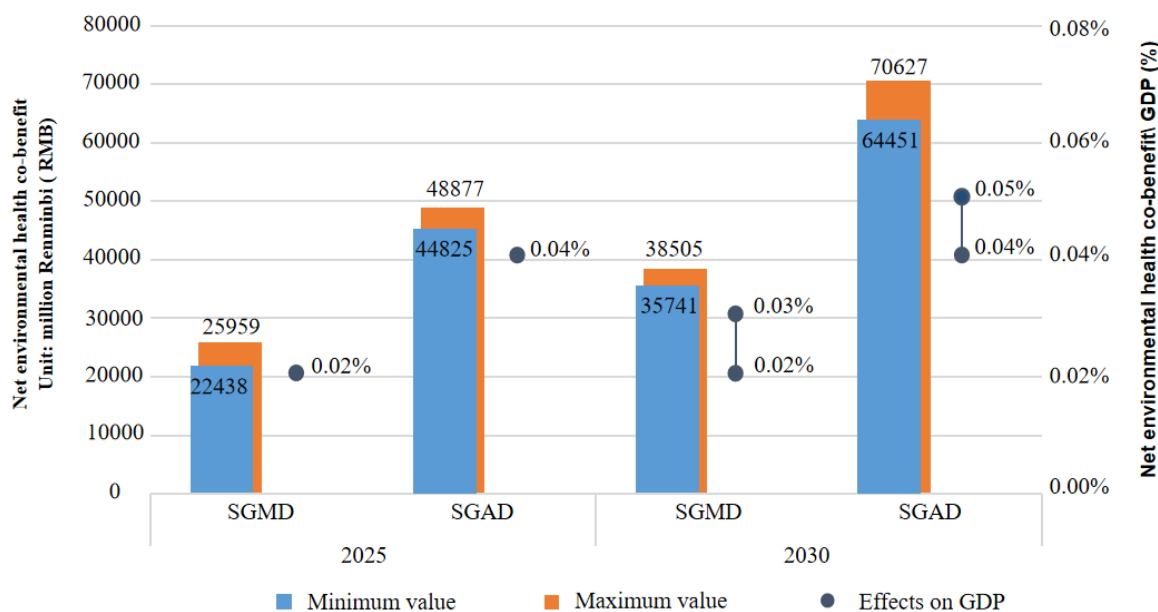


Figure 13. Net environmental health cobenefit of pollutants.

## 5. Conclusions and Discussion

China's domestic shale gas research mainly focuses on four themes: first, the potential of shale gas resources [53–57]; second, shale gas development in consideration of the current technical difficulties and mining costs [46–48], focusing on technological innovation; third, the positive influence of shale gas, which focuses on its energy substitution [20–22] and carbon reduction [20,22–25] effects; fourth, the negative impact of shale gas [24,25]. The position of our study in the literature is that we consider all the four aspects and the positive and negative effects, and highlight the atmospheric environmental impact. The main contribution is its comprehensive assessment and further improvement of the methodology for emission reduction evaluation during the consumption process. In addition, the economic loss is evaluated for determining the environmental cobenefit and the climate risk of methane leakage. Water and soil impacts are not in the research scope.

This study provides a clear answer to the question on the net economic cost of shale gas development. It conducts an integrated assessment of shale gas development in China. On the basis of the developed China-MAPLE model, this article explores the impact of shale gas on the improvement of energy structure, the major atmospheric pollutant emission reduction, and its negative climate risk. Shale gas will help reduce the coal proportion to 36.33% in the primary energy consumption in China. This finding is consistent with those of other studies [74]. In consideration of the final energy consumption in residential heating, transport, and industries, coal will be reduced by 36.00% in the total final energy consumption and 36.28% in electricity mix by 2030 in the SGAD scenario. Although shale gas is in a relatively backward position in the proportion of energy consumption, it is still in stable growth and has great potential. Especially in the context of radical development, shale gas will account for 7.01% of the primary energy consumption by 2030.

The utilization of shale gas not only improves the energy structure but also helps promote environmental health. Shale gas development mainly has two types of impacts on environmental health. On the one hand, the coal substitution effect of shale gas development is conducive to reducing the emissions of  $\text{SO}_2$  and  $\text{NO}_x$ . The total number of deaths in the SGAD scenario decreases by 970,000 persons, and the number of deaths per unit avoided is 0.70 persons/kt of standard coal shale gas. The reduction in deaths due to  $\text{SO}_2$  and  $\text{NO}_x$  leads to economic loss being avoided, which will be 32.24 billion yuan in SGAD

in total less than that in SGMD in 2030. These results provide additional information on economic loss avoided via shale gas development to the current literature.

On the other hand, shale gas development will cause methane leakage and endanger human health. Compared with the SGMD scenario, an increase of 27.07 million tons of methane on average in 2030 is estimated, which would cause 1.20 thousands of deaths (persons) and 457.33 million yuan of economic losses added if shale gas is promoted aggressively. In consideration of the two types of effects of shale gas development on environmental health, the net environmental health cobenefit of pollutants is always positive, demonstrating the positive impact of shale gas utilization on environmental health.

Overall, shale gas development has a positive atmospheric environmental impact in China and will help avoid 0.04% GDP loss in 2030 if promoted aggressively. Combined with China's abundant shale gas resources, technological innovation, and institutional guarantees, shale gas is expected to have great potential in China and become an important fuel for coal replacement. This article provides the following policy recommendations to promote the development of shale gas in China. On the one hand, a long-term and stable financial subsidy policy should be issued to improve the enthusiasm of shale gas enterprises in exploration and development and increase the national support for the shale gas industry. On the other hand, the management system of shale gas development in China should be improved, and a comprehensive supervision system of shale gas green development should be established. This study is only a rough assessment of the full picture. We should pay close attention to the formulation of relevant emission standards, technical specifications, and other relevant management specifications for the key risk points and regulatory elements of shale gas development.

Furthermore, some developing countries, which have high coal consumption and rich shale gas resources, are trying to use shale gas instead of coal policies for energy transformation. In accordance with the BP Statistical Review of World Energy [75], the coal consumption of India, South Africa, and Poland in 2018 accounted for 55.88%, 70.78%, and 48.00% of total energy consumption, respectively. These countries have formulated a policy for the replacement of coal with shale gas to alleviate the pressure on the environment caused by the energy structure dominated by coal and consider the shale gas resources of their own countries [76–78]. As a developing country, China's shale gas development experience will help these countries improve their encouragement policies for shale gas development and formulate comprehensive and detailed assistance policies for the shale gas industry in terms of tax relief, subsidies, and public calls. This study provides a reference as an integrated assessment in consideration of the positive environmental cobenefits and negative climate risks of the use of shale gas in developing countries. The argument for shale gas is not only based on global arguments on whether the shale gas fuel is clean. Developing countries, especially coal-dominant countries with rich gas resources, should consider the two sides of a coin and focus on the net environmental and economic benefits for their own countries.

To sum up, this research is based on the China-Multi-pollutant Abatement Planning and Long-term benefit Evaluation, a comprehensive evaluation of shale gas resources in terms of energy system optimization, mutual benefit of the atmosphere and methane risk, etc., and it aims to clarify and analyze the challenges and role played by China's shale gas resources when considering positive cobenefit and negative methane risk. The research gaps and innovations identified in this study are mainly in the following aspects. First, in terms of research ideas, a comprehensive shale gas evaluation study that China currently lacks was carried out. As for the method, we further improved the evaluation method based on the bottom-up model. In terms of conclusions, this study considers all the positive and negative effects of the use of shale gas in China, highlights the atmospheric environmental impact, and finally draws its comprehensive positive impact.

This research filled the gap in shale gas research in China on positive cobenefit and negative methane risk, and answered the three questions raised by the title. First, regarding energy system optimization, in our conclusion, although coal still accounts for the largest

share of energy consumption, the use of shale gas can help adjust the energy structure and reduce the future share of coal. Second, in terms of environmental co-benefits, the use of shale gas helps reduce emissions of SO<sub>2</sub> and NO<sub>x</sub>, the number of deaths due to SO<sub>2</sub> and NO<sub>x</sub>, and could help reduce the economic loss by 32.24 billion yuan. Third, we considered the risk of methane; the use of shale gas will increase methane emissions, cause environmental and health concerns, and increase climate risk losses, reaching 457.33 million yuan in 2030. Finally, a comprehensive conclusion can be drawn that the net environmental health cobenefit of shale gas development is positive, estimated to be 0.04% of China's GDP in 2030. These are the main contributions of our research.

The contribution of our research conclusions can be reflected in many aspects. At present, other related studies in China mainly focus on other air pollutants rather than methane [24,38], a few studies that have evaluated methane indicate that shale gas emits a great amount of greenhouse gases, and the conclusions are still uncertain [25]. In general, there is a lack of comprehensive evaluation of shale gas, and our conclusions are based on a comprehensive analysis of the use of China's shale gas, which is more reasonable. In China, we have set a goal of carbon neutrality by 2060. Although renewable energy will dominate the entire energy system in 2050, the phasing out of coal in the short term still needs the strong support of natural gas, and then natural gas will be replaced by renewable energy. Therefore, a comprehensive assessment of China's natural gas, especially shale gas development before 2030, will help clarify China's energy development path and provide an important reference for the 14th Five-Year Plan. At the same time, it also provides reference for energy transition in other developing countries, as some developing countries are still facing the problem of natural gas development [79,80], and relevant studies in these countries still lack a comprehensive analysis of air quality and methane emissions in addition to CO<sub>2</sub>. Especially in India [81] and Africa [80,82], there are high carbon emissions, and the use of natural gas will play an important role in the future energy structure and emission reduction. Finally, this comprehensive assessment also helps to provide a method reference for comprehensive analysis of the impact of shale gas. Of course, our research also has some limitations. This study did not discuss in detail the water and soil problems caused by shale gas. Other issues related to shale gas extraction and use in various countries, such as social issues, mining and recycling technologies, and pressure on government subsidies, were only briefly discussed. These questions will be investigated in future research.

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## Abbreviations

bcm	billion cubic meters
China-MAPLE	China-Multi-pollutant Abatement Planning and Long-term benefit Evaluation
CN	Changing Exploration and Development Zone
CO <sub>2</sub>	Carbon dioxide
CQ	Chongqing
EIA	U.S. Energy Information Administration
FL	Fuling Exploration and Development Zone
GZ	Guizhou Province
HB	Hubei Province
HN	Hunan Province
kt	Kiloton
Mtce	Million tons of coal equivalents
NDRC	National Development and Reform Commission
NO <sub>x</sub>	Nitrogen oxide
REF	Reference
RMB	Renminbi
SC	Sichuan Province
ST	Shaotong Exploration and Development Zone
SGMD	Shale gas moderate development
SGAD	Shale gas ambitious development
SO <sub>2</sub>	Sulfur dioxide
SX	Shanxi Province
tce	ton of standard coal equivalent
Twh	Tera Watt Hour(s)
UNDP	United Nations Development Programme
WY	Weiyuan Exploration and Development Zone
XJ	Xinjiang Uygur Autonomous Region
YA	Yan'an Exploration and Development Zone
YN	Yunnan Province

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