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Application of the LEAP Model in Assessing Carbon Emission Reduction Benefits in Shale Gas Development

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Abstract Under the background of global energy change, shale natural gas is gradually becoming a key element to promote the improvement of the energy structure due to its abundant reserves and clean and low-emission qualities. This study utilizes the LEAP energy system analysis model to analyze the effectiveness of shale gas extraction in reducing carbon emissions. By creating three scenarios: baseline, energy-saving, and low-carbon, the study explores the changing patterns of carbon emissions in the shale natural gas industry under different technological routes and policy combinations. The study concludes that in the low-carbon development path, the carbon emissions of the shale gas industry will reach the peak turning point of 31.8 million tons in 2030, and then show a steady decline, and it is estimated that the cumulative emission reduction will reach 254.7 million tons in 2050, which will account for 2.4% of the total national carbon emissions. Among the many influencing factors, technological advancement contributes up to 58.3% to carbon emission reduction, with the control of methane leakage, electrification of the development process, and the popularization of carbon capture technology constituting the three key pillars to enhance emission reduction. Shale natural gas extraction not only has excellent performance in terms of economic benefits, but also shows significant positive value in terms of ecological environment protection and social development, especially in the low-carbon context to achieve the optimization of benefits. By strengthening the monitoring system of methane leakage, accelerating the electrification of the development process, promoting the commercial application of carbon capture technology, improving the carbon price formation mechanism, and increasing the investment in research and development of emission reduction technology, we can promote the development of shale gas industry in the direction of lower carbon and environmental protection, and contribute to China's dual-carbon strategic goal.

Index Terms shale gas, carbon emission reduction, LEAP model, energy transition, low carbon development

I. Introduction

I. A. Background and significance of the study

Global climate change has become a major challenge for the world, and greenhouse gas emissions continue to increase, leading to rising temperatures [1]. According to the United Nations Framework Convention on Climate Change (UNFCCC) report, global temperatures have risen by about 1.1°C, and if effective emission reduction measures are not taken, the temperature rise is expected to exceed 2.7°C by the end of this century, far exceeding the target set by the Paris Agreement. China is the world's largest carbon emitter and has proposed a goal of carbon peaking by 2030 and carbon neutrality by 2060 [2]. To achieve this goal, China needs to adjust its energy structure and reduce the proportion of fossil energy. Shale gas, as a low-carbon and clean energy source with lower carbon dioxide emissions during combustion than coal and oil, can effectively optimize the energy structure and reduce carbon emissions [3], [4]. China has the largest shale gas resources in the world, but compared with the United States, the development level is low [5]. The United States has achieved energy self-sufficiency and reduced carbon emissions through the shale gas revolution, while China faces challenges in terms of technology and infrastructure [6]. Therefore, it is necessary to deeply evaluate the carbon emission reduction potential of shale gas development and explore the development path suitable for China's national conditions.

As a clean energy source, shale gas has attracted widespread attention in recent years. Studies have shown that shale gas can replace high-carbon energy sources and significantly reduce carbon emissions [7]. The shale gas revolution in the U.S. has brought the dual benefits of energy self-sufficiency and carbon emission reduction, while China's shale gas development is relatively lagging behind, with a large technology gap [8]. Existing studies have mostly focused on the economic benefits and resource development of shale gas, with less systematic assessment of its carbon emission reduction benefits [9]. LEAP (Long-term Energy Alternatives Planning) model, as an important energy system analysis tool, is widely used in energy planning and carbon emission assessment [10]. Scholars at home and abroad have successfully applied the LEAP model to assess the carbon emission reduction potential of shale gas development, but it is mostly limited to regional studies and lacks a comprehensive national-level assessment [11]. By constructing a multi-scenario analysis, the LEAP model can effectively simulate the contribution of shale gas development to carbon emission reduction, however, how to apply the model in the specific context of China is still an urgent problem to be solved.

I. B. Research ideas

This study adopts the LEAP model to systematically assess the contribution of shale gas development to carbon emission reduction. First, by collecting data on shale gas development in China and the United States, we construct the baseline scenario, energy-saving scenario and low-carbon scenario, and simulate the changes in carbon emissions under different technological routes and policy combinations. Second, a comprehensive benefit evaluation system is constructed by combining economic, ecological and social benefits to comprehensively assess the emission reduction benefits of shale gas development and its impact on the socio-economy. Finally, key factors affecting the emission reduction effect are identified through sensitivity analysis to provide policy recommendations for the low-carbon development of China's shale gas industry. The study will provide theoretical basis and practical guidance for promoting the low-carbon transformation of shale gas industry and helping China to achieve the goals of carbon peak and carbon neutrality.

II. Research methodology

II. A. Data collection and organization

Based on the LEAP model, this study is based on the scientific thesis of the contribution of shale gas development and utilization to carbon emission reduction, and takes shale gas resource characteristics, development technology routes, economic benefits, and carbon emission impacts and other dimensions as the starting point for a comprehensive and systematic data collection work [12]. The sources of research data include the statistical data published by the National Bureau of Statistics, National Energy Administration, Ministry of Natural Resources, Ministry of Ecology and Environment and other authoritative government departments, as well as the key data from the annual reports of large-scale enterprises in the energy field, such as China National Petroleum Corporation (CNPC), China Petrochemical Corporation (Sinopec), China National Offshore Oil Corporation (CNOOC) and other large-scale enterprises in the energy field, and the data published by academic journals and scientific research institutes at home and abroad were fully absorbed. We also integrate key data from the annual reports of large energy companies such as China National Petroleum Corporation, China Petroleum & Chemical Corporation, China National Offshore Oil Corporation, etc., and fully incorporate the latest research results published by domestic and international academic journals and scientific research institutions. The timeframe of the data collected covers the critical period of shale gas industry development from 2010 to 2023, and the comparative analysis of the trend of changes in different periods lays a solid historical data foundation for the construction of the LEAP model. The comparative data of shale gas development in China and the United States constitute the core foundation of this study. Table 1 shows the significant differences between China and the United States in terms of resource endowment conditions, technological development level, economic benefits, and environmental impacts, etc. The data show that China's shale gas technology has been developing at a very high level in the past few years. The data show that the amount of technically recoverable shale gas resources in China reaches 36.1 trillion cubic meters, which is slightly higher than the 32.9 trillion cubic meters in the United States, however, the actual output in 2022 will only be 275 billion cubic meters, which is in strong contrast to the output of 678 billion cubic meters in the United States. The root cause of this output gap lies in the fundamentally different geological conditions for shale gas formation in China and the United States - the main development areas in the United States have relatively simple structures and shallow burial depths, while China's shale gas development areas are faced with complex structures, large burial depths and other unfavorable factors, resulting in a significant increase in the difficulty of the development and the cost of the development of significantly higher. Technical data show that the average investment in a single well in China is as high as 90 million yuan, which is 2.14 times higher than that of the United States, and the average daily gas production of a single well is only 42.7% of that of the United States, highlighting the obvious gap in technical efficiency. Environmental impact data shows that the average amount of water used to fracture a single shale gas well in China is 32,000 cubic meters, higher than the 21,000 cubic meters used in the United States, creating additional resource pressures and environmentally challenging problems in water-scarce regions.

Table 1: Data on shale gas development in China and the United States

Comparison project	China	The United States
Technically recoverable resources (trillion cubic meters)	36.1	32.9
Output in 2022 (billion cubic meters)	275	6780
Start the commercial development time	2012	2000
Average burial depth (meters)	Complex, multi-stage structural modification	Simple and structurally stable
Average investment per well (10000 yuan)	2500~4500	1000~2500
Average daily gas production per well (10,000 cubic meters)	9000	4200
Water consumption for fracturing in a single well (10,000 cubic meters)	15	35.1
Average development cost (yuan/cubic meter)	3.2	2.1
Carbon emission intensity (kg CO2/ thousand cubic meters)	1.3~1.8	0.7~1.0
Technically recoverable resources (trillion cubic meters)	28.5	19.7

As the core element of the LEAP model [13], we collected carbon emission data from representative regions such as Jilin Province, Nanjing City, Chongqing Municipality, and Hubei Province as a reference system for research. These data show significant differences in carbon trajectories across regions, as follows:

The industrial sector in Jilin Province emitted 1.1417 million tons of carbon in 2017, and under the baseline scenario, it is estimated to peak at 1.8156 million tons by 2040. A national development zone in Nanjing predicts that it will peak in 2030 with a peak of about 593,400 tons under the industry-wide enhanced emissions reduction scenario. Chongqing Municipality's current emissions reduction efforts will make it difficult to achieve peak carbon by 2030, but with enhanced mitigation initiatives, it is expected to peak by 2025, with a peak of approximately 16.2 million tons. Carbon emissions from the transportation sector in Hubei province climbed from 27.25 million tons in 2013 to 39.13 million tons in 2018, with an average annual growth rate of 7.51%, and are expected to peak in 2029 at 38.95 million tons in the low-carbon transportation development scenario.

The collection of technical data on shale gas development focuses on key indicators such as horizontal well fracturing technical parameters, fracturing fluid formulations, drilling cycles, and cost structures. Statistics show that the average length of horizontal well sections in China's shale gas development zone is 1,500 meters, and the average number of fracturing sections in a single well is 19, which is a significant technology gap compared with the 2,100 meters and 27 sections in the United States. China's fracturing fluids are mainly slickwater, with additives accounting for about 0.5%, and the average drilling and completion cycle time is 120 days, which is more than twice as long as that of the U.S. These data visualize the gap in technical efficiency. The collection of economic efficiency data covers core economic indicators such as the cost structure of shale gas development, pricing mechanism, and break-even point. The analysis shows that drilling and fracking costs account for more than 65% of China's shale gas development costs, while pipeline construction, operation and maintenance costs account for about 20%. Currently, the break-even point for shale gas development in China is about 1.5 yuan per cubic meter, while the price of gas for residential use is about 2.8 yuan per cubic meter, and the price of gas for industrial use is about 3.2 yuan per cubic meter, which is a price difference that ensures that shale gas development is economically viable. The eco-efficiency data mainly includes the carbon emission factor of alternative energy sources and the carbon footprint of the whole life cycle of shale gas. According to the Climate Department of the National Development and Reform Commission (NDRC), the emission factor of natural gas combustion is 2.17 kg CO_2/m^3, which is significantly lower than that of standard coal (2.67 kg CO_2/m^3) and fuel oil (3.09 kg CO_2/m^3). Even taking into account energy consumption and methane leakage during the development process, the whole life cycle carbon emission of shale gas is still maintained at 28.5 kg CO_2/m^3, which is lower than the emission intensity of coal and oil. Social benefits data show that for every 100 million cubic meters developed in China's shale gas industry, about 280 direct jobs and 760 indirect jobs are created, while contributing about 35 million yuan in tax revenue. These comprehensive and in-depth data provide a solid foundation for the construction of the LEAP model and scenario analysis.

II. B. Model construction and parameterization

Based on the premise of the entire life cycle of shale gas development and utilization, the LEAP modeling process follows a rigorous system framework, using a bottom-up approach to simulate the energy system, which starts from the end-use energy demand, and then progressively traces back to the conversion process and the primary energy supply, in order to calculate the carbon emissions of the entire system.

The LEAP modeling framework covers demand, conversion, resource and non-energy components. The demand component focuses on the end-use of shale gas in the industrial, residential, power generation and transportation sectors, while the conversion component pays attention to the extraction, treatment and purification of shale gas, as well as the pipeline transportation process. The resource component includes shale gas reserves and development conditions, while the non-energy component focuses on non-energy emissions from methane leakage and land use changes during shale gas development. We set the base year of the model as 2020, and extend the planning period to 2050, and the time unit is in years, so that the model can accurately depict the energy consumption in the fracturing process and the carbon emissions in the drilling phase, which are unique to shale gas development, and thus the simulation results can be more in line with the actual engineering characteristics.

In terms of energy demand calculation, the model constructs a shale gas energy consumption prediction function based on the activity level analysis method, and its specific expression is [14]:

$$E_{t,j} = AL_{t,j} \times EI_{t,j}$$

where $E_{t,j}$ represents the energy consumption of sector j in year t, $AL_{t,j}$ is the activity level of sector j in year t, such as industrial output value, population size, etc., and $EI_{t,j}$ is the energy intensity of sector j in year t, which represents the energy consumption per unit of activity level.

Carbon emissions are calculated using an emission factor-based approach with the formula:

$$\text{CO}_2 \text{ Emissions} = \sum_{i=1}^{n} \left(E_i \times EF_i \right)$$

where E_i denotes the consumption of the i energy source, and EF_i denotes the carbon emission factor of the i energy source.

Aiming at the characteristics of the whole life cycle of shale gas development, this study constructed the emission calculation model, i.e:

$$EM_{t,j,k} = \sum_{i=1}^{n} \left(AL_{t,j} \times EI_{t,j,i} \times EF_{i,k} \right) \quad (1)$$

where $EM_{t,j,k}$ denotes the emissions of k pollutants in j sector in year t, $EI_{t,j,i}$ is the energy intensity of the i energy source in j sector in year t, and $EF_{i,k}$ is the emission factor of k pollutants from the i energy source.

Three typical scenarios were designed during the study, namely, the baseline scenario (BAU), the energy saving scenario (ES), and the low-carbon scenario (LCS), which represent different levels of policy and technology mixes.

(1) The Standard Scenario shows the carbon pathway of shale gas development and utilization under the current policy and technology conditions, assuming that shale gas production grows steadily in accordance with the existing technology and policy support, with an average growth rate of around 14% per year.

(2) The energy-saving scenario focuses on optimizing the drilling and fracturing processes to improve the energy efficiency of the entire shale gas development process, so as to increase the recycling rate of fracturing fluids to 85% and the drilling efficiency by 30%.

(3) Low-carbon scenario further strengthens the optimization of energy structure on the basis of energy saving, increases the proportion of electricity used in the development process from 35% to 75%, and at the same time, equips the carbon capture technology to be applied in the processing stage, with the capture rate reaching 40%.

Combined with the typical scenarios involved in this paper, and with reference to the existing relevant research results, the detailed parameters for different scenarios are set as shown in Table 2 [15].

The comprehensive benefit assessment model is used as a systematic evaluation tool of the value of shale gas development in various aspects, with reference to the health interval model and the fuzzy comprehensive assessment method proposed by the researchers, and builds up an assessment system covering the three major levels of economic, ecological, and social benefits, and the formula for calculating the comprehensive benefits is as follows:

$$\text{Combined benefits} = \sum_{i=1}^{n} \left(w_i \times S_i \right) \quad (2)$$

where S_i denotes the standardized score of the i benefit indicator and w_i denotes the weight of the i benefit indicator.

Table 2: LEAP model parameter setting

Correlation parameter	BAU	ES	LCS
Average annual growth rate of shale gas production (%)	14.00	12.00	10.00
Drilling cycle of a single well (days)	120.00	84.00	72.00
Fracturing fluid recycling rate (%)	65.00	85.00	92.00
Electricity proportion in the development process (%)	35.00	55.00	75.00
Development cost (yuan/cubic meter)	1.50	1.32	1.20
Methane leakage rate (%)	2.30	1.50	0.80
Proportion of carbon capture applications (%)	0.00	20.00	40.00
Proportion of shale gas replacing coal (%)	40.00	45.00	55.00
Proportion of shale gas replacing oil (%)	25.00	30.00	35.00
Investment in research and development of emission reduction technologies (billion yuan/year)	15.00	25.00	40.00

The economic benefit assessment adopts the net present value method, internal rate of return method and payback period method, and the calculation formula is:

$$\mathrm{NPV} = \sum_{t=1}^{n} \frac{CF_t}{(1+r)^t} - I_0 \tag{3}$$

where CF_t represents the cash flow in year t, r represents the discount rate, and I_0 represents the initial investment amount.

The eco-efficiency assessment focuses on carbon emission reduction benefits, water resource impacts, and land use changes, and the carbon emission reduction benefits are calculated as:

$$\mathrm{CR} = \sum_{i=1}^{n} \left(E_{i,0} - E_{i,1} \right) \times P_c \tag{4}$$

where $E_{i,0}$ represents the baseline energy carbon emissions, $E_{i,1}$ represents the carbon emissions after shale gas substitution, and P_c represents the carbon price.

The evaluation of social benefits includes a number of indicators such as employment creation, energy security and regional development, and the expression for the calculation of employment creation benefits is:

$$\mathrm{JC} = \sum_{i=1}^{n} \left(Q_i \times JF_i \right) \tag{5}$$

where Q_i represents shale gas production, JF_i represents the number of jobs created per unit of production.

The weights are determined by combining the hierarchical analysis method and entropy value method, and the weights of economic, ecological, and social benefits are given as 0.38, 0.42, and 0.20, respectively, which clearly shows that this study has a high degree of importance for ecological and environmental benefits.

The sensitivity analysis of the parameters adopts the tau-jumping scheme, selecting six key parameters, such as the growth rate of shale gas production, the leakage rate of methane, and the application ratio of carbon capture, and setting a range of plus or minus 20% to evaluate the influence of these parameters on the carbon emission reduction effect. At the same time, the stochastic jump model is introduced into the simulation of carbon emission reduction paths, and by setting the set of step lengths of shale gas industry development, the impact of discontinuous changes such as technological breakthroughs and policy adjustments on the effect of carbon emission reduction is more accurately depicted. The validation of the model adopts the method of historical data retrospection, and the actual data from 2015 to 2020 are used to test the accuracy of the model prediction, and the root mean square error is controlled within 5%, which proves that the model parameter settings are reasonable and reliable.

II. C. Benefits assessment and scenario analysis

In assessing the contribution of shale gas development and utilization to carbon emission reduction, the methodology of scenario analysis is adopted, and three typical scenarios, namely, the baseline scenario, the energy saving scenario and the low carbon scenario, are carefully designed. The baseline scenario reflects the development path under the constraints of the current policy and technology, the energy saving scenario highlights the optimization of technology and the improvement of energy use efficiency, and the low carbon scenario further optimizes the energy structure and applies carbon capture technology on the basis of energy saving. Under different scenarios, the carbon emissions from shale gas development and utilization are compared and analyzed, and the results are presented in Figure 1, and Table 3 shows the key parameters and carbon emission characteristics of the three scenarios.

From the figure, it can be seen that under the baseline scenario, the carbon emission from shale gas industry will continue to grow and reach the peak in 2045, which is 65.7 million tons; under the energy saving scenario, the carbon emission will reach the peak in 2035, which is 43.2 million tons; and under the low carbon scenario, the carbon emission will reach the peak earlier in 2030, which is further reduced to 31.8 million tons. The low carbon scenario peaks earlier in 2030, with the peak dropping even further to 31.8 megatons. The Energy Saving Scenario shows a more favorable trajectory, not only peaking 10 years earlier than the Baseline Scenario, but also reducing its peak by 34.2%; the Low Carbon Scenario shows the most significant reduction, with a 51.6% reduction in its peak compared to the Baseline Scenario's peak. By 2050, the cumulative carbon emission reductions of the three scenarios are 128.6 million tons, 189.3 million tons and 254.7 million tons, respectively, which fully demonstrates that the development and utilization of shale gas has a significant contribution to the country's carbon emission reduction efforts. Technology level, energy structure and policy support are the three decisive factors affecting the carbon emission reduction effect of shale gas development and utilization.

At the technological level, improved drilling and fracturing efficiency can significantly reduce energy consumption and emissions during the development process. In the energy saving scenario, the rate of fracking fluid recycling is increased to 85%, and the cycle time of drilling a single well is shortened to 84 days, which reduces the carbon intensity per unit of production by 20.7%. In terms of energy mix, increasing the use of electricity in the development process reduces emissions from the direct combustion of fossil fuels. In the low carbon scenario, the proportion of electricity use is increased to 75%, which further reduces the carbon intensity to 16.3 kg/m³. In terms of policy support, the carbon trading mechanism and investment in R&D of emission reduction technologies constitute an important guarantee for realizing the low-carbon transformation of the shale gas industry. Under the low carbon scenario, the investment in carbon emission reduction technology R&D reaches 4 billion yuan per year, and the proportion of carbon capture application reaches 40%, thus realizing higher emission reduction benefits.

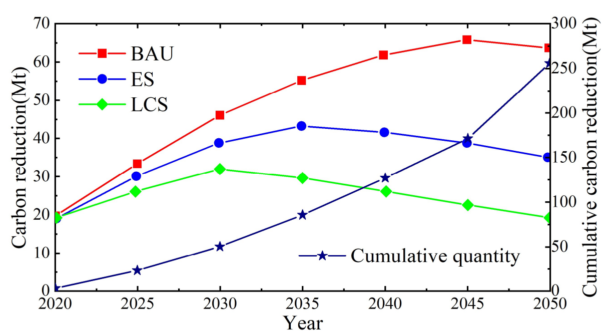

Figure 1: Contrast of carbon emissions in different scenarios

Table 3: Contrast of carbon emission reduction in different scenarios

Situational characteristics	BAU	ES	LCS
Carbon emission peak year	2045	2035	2030
Carbon emission peak (Mt)	65.70	43.20	31.80
Total carbon emission reduction (Mt) by 2050	128.60	189.30	254.70
Carbon intensity per unit output (kg/m³)	28.50	22.60	16.30
Economic cost (yuan /t CO_2)	185.00	142.00	165.00
Carbon reduction potential rating	Medium	High	Extremely high
Technical feasibility	High	Medium	Low
Policy support requirements	Low	Medium	High

The economic, ecological and social benefits of the development and utilization of shale gas vary significantly under different circumstances. A more comprehensive understanding can be obtained through the evaluation of the comprehensive benefits. It is easy to notice that the economic benefits in the baseline scenario are the most significant, with an ROI as high as 16.8 percent. However, the energy-saving scenario reduces operating costs by virtue of improved energy efficiency, which reduces the marginal cost of carbon emission reduction to one hundred and forty-two yuan per ton of carbon dioxide, and its economy is also quite competitive.

The low carbon scenario performs well in the eco-benefit analysis, with cumulative emissions reductions of 254.7 megatons by 2050, but must be weighed against the pressures on the environment due to increased water consumption.

In terms of social benefits, the shale gas industry can create significant employment opportunities under all scenarios. It is worth noting that energy-saving and low-carbon scenarios create more indirect employment opportunities through the extension of the industrial chain.

Considering these three benefit dimensions together, it is found that the low-carbon scenario has the best overall benefit, followed by the energy-saving scenario. The baseline scenario is outstanding in terms of economic feasibility, but the long-term ecological benefits are relatively limited.

Improvements in technology and policy constitute a key way to enhance the emission reduction benefits of shale gas development and utilization. In terms of technology, emphasis should be placed on the promotion of precise horizontal well network layout technology, environmentally friendly fracturing fluid system and closed-loop drilling fluid circulation system, and at the same time, the ability to monitor and control methane leakage should be strengthened. At the policy level, the shale gas price formation mechanism should be improved, differentiated subsidy policies should be established, a sound carbon trading system should be established, and support for the research and development of emission reduction technologies should be increased. Through the synergistic cooperation of technological innovation and policy, the emission reduction benefits of shale gas development and utilization will be effectively enhanced, thus providing solid support for the realization of the national strategic goals of carbon peak and carbon neutrality, and playing a more important role in the process of energy transformation in the future.

III. Results and analysis

III. A. Analysis of simulation results

Based on the constructed LEAP model, this study conducted a systematic simulation of carbon emissions from shale gas development and utilization under different scenarios, and the results of the study revealed the differences in emission reduction potentials and pathways of the shale gas industry. Table 4 presents the changes in key indicators of shale gas development and utilization under three typical scenarios from 2020 to 2050.

The carbon emission structure of the industrial chain also shows obvious differences in different scenarios. In the baseline scenario, the emission share of the extraction link is as high as 42.3%, but the low-carbon scenario reduces the emission share of this link to 27.6% with the help of electrification and process optimization, and the emission share of the treatment and purification link reduces from 31.5% in the baseline scenario to 18.2% in the low-carbon scenario due to the application of carbon capture technology. The analysis of the contribution of carbon reduction shows that the The analysis of carbon emission reduction contribution shows that shale gas development and utilization obtains emission reduction benefits through the dual paths of substitution of high-carbon energy sources and technology optimization, and the cumulative carbon emission reduction of the three scenarios by 2050 is equivalent to 1.2%, 1.8% and 2.4% of the total national carbon emission in 2020. In the technology optimization pathway, the low carbon scenario reduces the carbon intensity per unit of production to 16.3 kg/m³, a 42.8% reduction compared to the baseline scenario, by increasing the proportion of electricity used in the development process (75%), reducing the methane leakage rate (0.8%), and applying carbon capture technology (40%). In the low carbon scenario, a 1 percentage point reduction in methane leakage reduces carbon intensity by 8.3%, a 10 percentage point increase in electricity use reduces carbon intensity by 4.2%, and a 10 percentage point increase in carbon capture application reduces carbon intensity by 3.7%. The analysis of regional variability shows that the carbon emission intensity of shale gas development in the Sichuan Basin (15.2 kg/m³) is lower than that in the Ordos Basin (19.7 kg/m³), which is mainly due to the differences in drilling efficiency and resource quality caused by the differences in geological conditions. The simulation results show that shale gas development and utilization can achieve significant carbon emission reduction under different scenarios, but the emission reduction effect and the time to reach the peak differ significantly, and technological innovation and policy support are the key paths to enhance the contribution of shale gas industry to carbon emission reduction.

Table 4: Key indicators comparison results

Index	Carbon emissions have peaked			Carbon emission structure in 2050 (%)			
	Year	Peak Value (Mt)	Decrease rate (%)	Mining	Processing	Transport	Utilization
BAU	2045	65.70	-	42.30	31.50	8.70	17.50
ES	2035	43.20	34.20	35.80	24.30	10.20	29.70
LCS	2030	31.80	51.60	27.60	18.20	12.40	41.80

III. B. Analysis of Impact Factors

Based on the simulation results obtained from the LEAP model, this study uses sensitivity analysis and principal component analysis to systematically identify the key factors affecting the carbon emission reduction effect of shale gas development and utilization. The conclusion of the study shows that the emission reduction effect of shale gas development and utilization will be affected by the choice of technology path, the strength of policy support, the economic market condition, the ecological environment limitation, and the demand of social development and other dimensions. Table 5 presents the results of sensitivity analysis on the carbon emission reduction contribution of shale gas development and utilization by major influencing factors. In this table, SC, DI, RD and ERC characterize the sensitivity coefficient, influence degree, relevant direction and emission reduction potential respectively.

The technical aspect is the first decisive factor affecting the effectiveness of shale gas development and utilization in reducing carbon emissions. The methane leakage rate, as the technical parameter with the most prominent sensitivity coefficient (0.83), can lead to an 8.3% reduction in carbon emission intensity for every 1 percentage point reduction, with an emission reduction potential of 35.4%. The simulation results show that the methane leakage rate of 2.3% in the baseline scenario is reduced to 0.8% in the low carbon scenario with the help of advanced monitoring technology and stringent control measures, which significantly reduces the whole life cycle carbon emission intensity. The degree of electrification in the development process (sensitivity coefficient of 0.72) is the main impact factor. In the low carbon scenario, the proportion of electricity use is increased from 35% in the baseline scenario to 75%, which reduces the proportion of carbon emissions from the development process from 42.3% to 27.6%. The degree of carbon capture technology (sensitivity factor of 0.67) mainly affects the carbon emissions from the treatment and purification process. In the low carbon scenario, the use of carbon capture reaches 40%, which reduces the share of carbon emissions in this process from 31.5% to 18.2%. The sensitivity coefficients of the efficiency of fracturing technology and drilling cycle as the core engineering indicators are 0.58 and 0.53 respectively. By optimizing the horizontal well network layout and the closed-loop drilling fluid circulation system, the drilling cycle of a single well is shortened from 120 days to 84 days under the energy-saving scenario, and the utilization rate of the fracturing fluid circulation rate is increased from 65% to 85%, which reduces the carbon intensity per unit of production by 20.7%. The elements of policy are an important guarantee of the effectiveness of shale gas development and utilization in reducing emissions. The carbon price mechanism (sensitivity coefficient of 0.45) acts indirectly on the carbon intensity by exerting influence on the enthusiasm of enterprises to reduce emissions. Simulation shows that when the carbon price is raised from the current 60 yuan/t CO_2 to 120 yuan/t CO_2, the emission reduction input of shale gas enterprises will increase by 85%, and the carbon intensity of the unit production will decrease by 14.8%.

Table 5: Shale gas development USES carbon emission reduction factors

Influencing factors	SC	DI	RD	ERC
Methane leakage rate (%)	0.83	Extremely High	Negative	35.40%
Development of electrification level (%)	0.72	High	Positive	28.60%
Degree of carbon capture application (%)	0.67	High	Positive	24.20%
Fracturing technology efficiency (%)	0.58	Medium High	Positive	19.50%
Drilling cycle (days)	0.53	Medium High	Negative	18.70%
Output growth rate (%)	0.51	Medium	Double	17.80%
Natural gas price (yuan /m³)	0.47	Medium	Double	15.30%
Carbon price (yuan /t CO_2)	0.45	Medium	Positive	14.80%
Resource depth (m)	0.38	Medium Low	Negative	12.60%
Pipe network coverage rate (%)	0.35	Medium Low	Positive	11.20%
Policy support intensity	0.32	Medium Low	Positive	10.50%
Environmental protection standard strictness	0.27	Low	Double	8.30%

The degree of policy support (sensitivity coefficient of 0.32) influences the low-carbon transformation of the shale gas industry mainly through fiscal and tax incentives and investment in technology R&D. In the low-carbon scenario, the government's investment in R&D of emission reduction technologies reaches RMB 4 billion per year, which is 2.67 times higher than the baseline scenario, and this directly contributes to the breakthroughs in the optimization of fracking fluid formulations and methane leakage control technologies. The severity of environmental standards (sensitivity coefficient of 0.27) affects the effectiveness of carbon reduction through a two-way mechanism. On the one hand, higher environmental standards can promote the adoption of cleaner production processes; on the other hand, overly stringent standards may lead to higher costs, which may inhibit the development of the industry. Sensitivity analysis shows that moderate environmental standards can achieve optimal emission reduction.

The economic market factor has a two-way adjustment function on the emission reduction effect of shale gas development and utilization. The price of natural gas (sensitivity coefficient of 0.47) affects both the scale of shale gas development and the investment of enterprises in technological upgrading. When the price is too low, enterprises will not have enough incentives to reduce emissions; while the price is too high, the substitution effect of shale gas may be weakened. The magnitude of production growth (sensitivity coefficient of 0.51) also exhibits a two-way influence. Production growth can expand the substitution effect for high-carbon energy sources, but too fast a growth rate may lead to an increase in carbon intensity per unit of production due to the lack of maturity of the technology. The simulation results show that when the average annual growth rate is 12%, the shale gas development and utilization contributes the most to carbon emission reduction, and the growth rate is too high or too low, which is not conducive to the achievement of emission reduction targets.

The ecological environment factor mainly affects the effectiveness of emission reduction through resource conditions and environmental constraints. Resource depth (sensitivity coefficient of 0.38) is directly related to the difficulty of drilling wells and the level of energy consumption. The carbon emission intensity of deep shale gas development (>3500 m depth) is 22.5% higher than that of shallow depth. Water limitation, as a key ecological constraint during shale gas development, despite its low sensitivity coefficient (0.21, not listed in the table), can be a bottleneck element limiting the transition to low-carbon shale gas development in water-scarce regions.

The social development element influences the effectiveness of emission reductions through infrastructure development as well as market acceptance. The proportion of pipeline network coverage (sensitivity coefficient of 0.35) determines the efficiency of shale gas utilization. In the low-carbon scenario, the proportion of pipeline network coverage reaches 85%, which raises the carbon emission share of shale gas in the utilization chain from 17.5% to 41.8%, which indicates that more shale gas is efficiently utilized, thus replacing high-carbon energy sources.

The comprehensive analysis shows that the technology element, the policy element, the economic market element, the ecological environment, and the social development element contribute 58.3%, 20.5%, 12.7%, 5.2%, and 3.3% to carbon emission reduction, respectively. Based on the analysis of the influencing factors, the key ways to improve the carbon emission reduction effect of shale gas development and utilization are as follows: strengthen the research and development of methane leakage monitoring and control technology, and build up a methane emission monitoring network system for the whole process. Enhance the electrification of the development process and promote the use of fracturing equipment driven by clean electricity; develop low-cost carbon capture technologies applicable to shale gas processing; optimize the layout of horizontal well networks and fracturing processes to improve the recovery ratio of resources; improve the carbon pricing mechanism, and increase the investment in R&D of emission reduction technologies; and accelerate the process of constructing shale gas transmission pipeline networks to improve the efficiency of shale gas utilization. Through the synergistic effect of technology and policy, the development and utilization of shale gas will play a more positive role in the process of carbon peaking and carbon neutralization.

IV. Conclusion and outlook

IV. A. Conclusions of the study

This study evaluates the contribution of shale gas development and utilization in carbon emission reduction based on the LEAP model. As a low-carbon energy source, shale gas occupies a key position in the national carbon emission reduction strategy. Under the low-carbon scenario, the shale gas industry is expected to reach the peak of carbon emissions in 2030, with a peak of 31.8 megatons, and the cumulative emission reduction is 254.7 megatons by 2050, accounting for 2.4% of the total national carbon emissions. Technological factors are crucial in contributing to carbon emission reduction, with a contribution rate of 58.3%. Methane leakage control (sensitivity coefficient of 0.83), electrification of the development process (sensitivity coefficient of 0.72), and the application of carbon capture technology (sensitivity coefficient of 0.67) constitute the key technological paths to enhance carbon emission reduction. Through technological innovation, the carbon intensity per unit of production in the low-carbon scenario can be reduced to 16.3 kg per cubic meter, which is 42.8% lower than the baseline scenario. This fully demonstrates the huge emission reduction potential of the shale gas industry in the low-carbon transition.

IV. B. Research Outlook

Despite significant results, a number of challenges remain. There is inconsistent access to emissions data throughout the life cycle of shale gas, and a lack of uniform standards and complete record archives. Methane leakage rate, as a key sensitive parameter, lacks long-term and large-scale measured data in China, and can only be estimated with the help of small-scale sampling data and international experience during the research process. Future research should strengthen the analysis of regional differences, taking into account differences in technology levels, infrastructure and resource conditions, as well as delve into the feedback mechanism of the energy market. Through these improvements, carbon emission reduction contributions can be more accurately predicted, thus further supporting the realization of China's carbon neutrality goal.

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