DOI 10.15302/J-SSCAE-2021.06.005

China's Natural Gas Development Strategy under the Constraints of Carbon Peak and Carbon Neutrality

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Abstract: Natural gas is a stable and flexible low-carbon fossil fuel. It has comparative advantages on both supply and consumption. It can be used as a transitional energy source for constructing a clean, low-carbon, safe, and efficient new energy system and for achieving carbon peak and carbon neutrality. Currently, China's energy transition involves many design schemes. There are considerable differences in the development prospects of natural gas. We analyzed the relationship, challenges, and principles of the carbon peak and carbon neutrality in this study. Based on these analyses, we studied the opportunities for natural gas development in China, explore the comparative advantages of natural gas in key areas such as power generation, transportation, city gas, and industry, and summarize the constraints in terms of terminal prices, infrastructure, pricing mechanism, and development speed. We also propose the development goals and key tasks for China's natural gas industry. Finally, five recommendations are proposed for China's natural gas development under carbon goals. The first is to strengthen top-level coordination and leadership to clarify the developmental positioning and ideas of natural gas. The second is to maximize the comparative advantages of promoting natural gas consumption. The third is to rationally use domestic and foreign resources to ensure sufficient and reliable supply. Fourth, infrastructure development should be promoted to improve supply efficiency. The fifth goal is to strengthen the policies and mechanisms of land, finance, and taxation.
Keywords: carbon peak; carbon neutrality; energy transition; natural gas; comparative advantages

1 Introduction

Peaking carbon emissions and achieving carbon neutrality are the major national strategies. The purpose is to promote high-quality economic and social development through the transition of the energy system and to facilitate the transformation of the energy system from fossil energy-based to renewable energy-based. China has a large-scale coal-based energy structure. The time required for energy transition is short, and the cost is high. Additionally, it has to explore a feasible pathway for the energy transition to tackle the energy security and stable supply issues brought about by the multiple scale, volatility, and uncertainty of renewable energy. Natural gas is a low-carbon fossil energy source with a strong development foundation and a huge development potential. It also has unique comparative advantages on both supply and demand. Natural gas plays an important role in the peak-shaving of power grids with massive access to renewable energy, low-carbon development in transportation, emission reduction in industries,

Received date: August 17, 2021**; Revised date:** November 10, 2021
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Funding program: China Basic Science Center Project of National Natural Science Foundation (72088101); CAE Advisory Project "Energy Strategy (2035)" (2019-ZD-20)
Chinese version: Strategic Study of CAE 2021, 23(6): 033–042
Cited item: Liu He et al. China's Natural Gas Development Strategy under the Constraints of Carbon Peak and Carbon Neutrality. *Strategic Study of CAE*, https://doi.org/10.15302/J-SSCAE-2021.06.005

and urban environmental pollution control. Moreover, natural gas can gain time for the smooth transition of energy systems and technological breakthroughs, such as energy storage, highly permeable green hydrogen, and carbon capture, utilization, and storage. Therefore, clarifying the role of natural gas at different stages of carbon peaking and carbon neutrality goals and giving full play to natural gas as a clean, low-carbon, and efficient energy resource is crucial for the high-quality development of China's natural gas industry and realization of carbon peak and carbon neutrality.

Domestic and international institutions have conducted many studies on China's roadmap to carbon neutrality and proposed predictions on the carbon-neutral path and future energy demand [1–9]. China's fossil energy consumption will account for 7% to 30% of the total primary energy consumption by 2060, based on the forecast results of these institutions. Natural gas consumption will reach 1.0×10^{11} m^3 to 4.9×10^{11} m^3, accounting for 3% to 16% of the total primary energy consumption. Significant differences exist in the forecast results for the future development of fossil energy, especially natural gas. This suggests a different understanding of the transition pathways for carbon peak and carbon neutrality and the role of natural gas in the energy transition. Thus, this research systematically studies the developmental basis of natural gas and its opportunities and advantages in both supply and demand, based on the scientific understanding of the development stages, challenges, and principles of carbon peak and carbon neutrality. This study also proposes goals and recommendations for natural gas development based on an analysis of its developmental constraints. This study aims to clarify the development status of natural gas and provide a basic reference for formulating pathways for carbon peak and carbon neutrality.

2 Scientific understanding of carbon peak and carbon neutral goals

2.1 Carbon peak and carbon neutrality are two stages of an organic whole

The overall development directions of the two stages are similar, but with certain divergences. (1) Different developmental stages: The carbon peak is a necessary stage and a prerequisite for carbon neutrality, whereas carbon neutrality is the ultimate goal and constraint for the carbon peak [10]. (2) Different development bases: The carbon peak is a process of gradual control of high-carbon fossil energy in the context of increasing energy consumption and the introduction of non-aqueous renewable energy, whereas carbon neutrality is under the background of reaching the energy consumption peak, gradual decommissioning of fossil energy facilities, and rapid growth of non-fossil energy consumption. (3) Different development priorities: The priority before 2030 is carbon control, to gain time for the mature growth of renewable energy. The priority after 2030 is to establish a renewable energy system to promote a revolutionary transformation of the energy structure. Overall, neither of the two stages can be separated to formulate a pathway for energy transition nor can they be weakened and merged into one. Peaking carbon emissions by 2030 is the focus of China's energy transition.

2.2 Challenges for the energy transition to reach the goals of carbon peak and carbon neutrality

The essence of the energy transition is the upgrading and optimization of the energy consumption structure in different sectors, the upgrading and transformation of energy supply and demand systems and massive infrastructure. China is currently the largest energy consumer worldwide and its energy consumption is expected to continue growing. The share of fossil fuels in the energy consumption structure is high. The fossil energy infrastructure is numerous and new. Therefore, China's energy transition faces multiple challenges such as heavy tasks, short time, and high costs.

2.2.1 Large-scale energy systems with heavy tasks for carbon reduction

China has the largest energy production, conversion, transmission, distribution, and supply system globally. The total energy production in 2020 was 4.08×10^9 tce and the total energy consumption was 4.98×10^9 tce, accounting for approximately 25% of the total global energy consumption [11]. The installed capacities of thermal power, hydro power, wind power, and solar power rank first globally. China is still in its late stage of industrialization and its energy demand will continue to grow in the short term. According to the forecast results of multiple domestic and international institutions, China's total energy consumption will peak around 2035 (~ 5.7×10^9 tce) [1–9]. In terms of carbon emissions, the historical carbon peaks of the United States and the European Union (EU) are 5.7×10^9 t and 4.4×10^9 t, respectively. China's carbon emissions peak may exceed 1.04×10^{10} t by 2030. Thus, the task of adjusting and optimizing China's energy structure and reducing carbon emissions is arduous.

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2.2.2 Short energy transition time

EU countries achieved a carbon peak in the 1990s. Countries such as the United States, Japan, and South Korea also achieved a carbon peak in 2010. The time between carbon peak and carbon neutrality is normally 40–70 years, and the average time interval is approximately 50 years, according to the global net-zero emission target for 2050 [12]. The time interval in China is only 30 years. Under the circumstances of sustained economic development and continuous growth in energy consumption, China will face the dual pressure of development and emission reduction to achieve carbon peak and carbon-neutral goals. Given that less than 10 years are required to achieve the goal of a carbon peak, China needs to coordinate its short-, medium-, and long-term development plans and make full use of the 14th Five-Year Plan period as a critical window period [13] to build a solid foundation for achieving the short-term goal of carbon peak and medium- and long-term goals of carbon neutrality.

2.2.3 High energy transition cost

The total investment in achieving the goals of carbon peak and carbon neutrality in China is approximately 136–300 trillion CNY [14,15], accounting for one-third of the total global investment in achieving net-zero emissions by 2030. The cost of the energy transition is high. Consequently, it is vital to properly address the cost and waste issues caused by fossil energy infrastructure abandonment while fully introducing social capital and maximizing market regulation mechanisms to promote the development of renewables. For example, the average service life of coal-fired power units in Europe, the United States, Japan, and many other countries is approximately 40 years, and a majority of these units is currently in retirement. The coal development cycle was consistent with the low-carbon transition trend. Due to the late start of industrial development in China, the average operating life of coal-fired power units is only 12 years; the “one-size-fits-all” existing mechanism of coal-fired power units will cause a huge wastage of capital expenditure [16]. Therefore, in the process of achieving the goals of carbon peak and carbon neutrality, it is necessary to prevent the delay of the energy transition on the pretext of realistic issues and, more importantly, prevent the reckless advancement of the energy transition. The carbon peak and neutrality goals must be achieved systematically and orderly. The relationship between development and emission reduction and the relationship between short-term development and medium- and long-term development needs to be properly addressed. The development needs of different types of energy at different stages, sectors, and regions need to be considered as a whole to explore the optimal solution for the energy transition.

2.3 Principles of energy transition under the goals of carbon peak and carbon neutrality

2.3.1 Not at the expense of energy security

Fossil energy will continue to be the mainstay of China’s energy supply for a long time. Given the continuous growth in China’s energy consumption, high dependence on oil and gas imports, and insufficient development of renewables, hidden energy security issues in the process of the energy transition is gradually emerging. In terms of coal, due to global policy and investment restrictions, the sharp compression of production capacity and the rapid rise in energy prices has directly led to the power rationing crisis in multiple regions in China [17]. In terms of oil and gas dependence, China’s dependence rates were 70% and 40%, respectively. Moreover, China’s oil import quota has been continuously tightened in the context of carbon peak and carbon neutrality [18]. Additionally, international prices of oil and gas are undergoing intense fluctuations. These factors pose serious challenges to China’s oil and gas supply. Extreme weather events occur frequently worldwide, affecting renewable energy. Instability of wind and solar power supplies has gradually emerged. Therefore, energy transition in China needs to insist on construction before deconstruction and prioritize a stable fossil energy supply in the short term [19]. In the middle- to long-run, it is necessary to vigorously develop renewable energy and gradually reduce dependence on imported energy to support economic and social development with cleaner, low-carbon, safe, and independent energy [20].

2.3.2 Not at the expense of significantly increasing energy costs

Cost reduction needs consideration as an internal driving force to promote the substitution of non-fossil energy for fossil energy in the process of the energy transition. The scale and pace of renewable energy development needs consideration from the perspective of the total cost of energy supply, and the comparative cost advantages of renewable and fossil energy also need to be integrated [21]. The simulation results showed that the cost of renewable energy consumption increases as the penetration rate increases. If the penetration ratio is 30%, the cost of consumption accounts for approximately 17% of the average electricity retail price in China, and the cost of consumption can be as high as 30% with a higher penetration rate [22]. Therefore, the development of renewable energy in China needs to fully consider the maturity and development scale of energy storage and peak regulation technologies to avoid a situation where the electricity price and terminal cost increase significantly.

2.3.3 Not at the expense of energy efficiency

According to research results from the International Energy Agency (IEA), the cumulative contribution of energy efficiency to carbon reduction from 2020 to 2070 is approximately 40% [23]. China's energy consumption per unit GDP in 2020 was approximately 0.49 tce/10 000 CNY, which is 1.4 times the world average and 2.1 times that of developed countries [11,24]. Improving energy efficiency will support and guide China in achieving its goals of carbon peak and carbon neutrality.

3 Development opportunities and advantages of natural gas in China

3.1 Solid resources and infrastructure bases

3.1.1 Abundant supply of natural gas worldwide

The world's natural gas resource reserves are rich, especially with the advent of the shale gas revolution, which has dramatically increased natural gas production. The world's natural gas resources, reserves, production, and reserve–production ratios are shown in Table 1. The global remaining recoverable conventional and unconventional natural gas resources in 2019 were 8.03 × 10^{14} m^3 in total, and the remaining proven recoverable reserves in 2020 were 1.881 × 10^{14} m^3. Based on the gas production in 2020 (3.85 × 10^{11} m^3), the global natural gas reserve–production ratio is 48.8, which is still at a relatively high level, providing a solid base for sustainable development [25]. In recent years, with the continuous development of liquefied natural gas (LNG) infrastructure, the number of LNG-exporting countries globally has exceeded 50. The volume of the LNG trade continues to increase rapidly. The average annual growth rate of LNG trade volume in the past 10 years has been 6.8%, which is much higher than the 1.8% growth rate of pipeline gas. In 2020, the LNG trade volume reached 4.879 × 10^{11} m^3, accounting for 51.9% of the world's total natural gas trade, surpassing pipeline gas for the first time [26]. In the future, global natural gas production will grow at an average annual rate of 1.4%, and the production will reach 5.4 × 10^{12} m^3 in 2040 [27]. Abundant reserves of global natural gas resources, continuous growth in production, and continuous improvement in natural gas infrastructure have laid a vital foundation for China to utilize natural gas resources worldwide.

Table 1. World natural gas resources, reserve, production, and reserve–production ratio. (Unit: × 10^{12} m^3)

Items		Central Aasia–Russia	Middle East	Africa	North America	Latin America	Europe	Asia Pacific	Total
Remaining recoverable resources	Conventional	133.00	102.00	51.00	50.00	28.00	19.00	44.00	427.00
	Unconventional	37.00	20.00	50.00	91.00	56.00	28.00	94.00	376.00
Remaining proven recoverable reserves in 2020		56.60	75.80	12.90	15.10	7.90	3.20	16.60	188.10
Production in 2020		0.80	0.69	0.23	1.11	0.15	0.22	0.65	3.85
Reserve–production ratio		70.50	110.40	55.70	13.70	51.70	14.50	25.40	48.80

Note: The remaining recoverable resources data were released by the IEA by the end of 2018 [25]; the remaining proven recoverable reserves and production data were released by BP p.l.c. by 2020 [26].

3.1.2 Rapid development of natural gas exploration and exploitation in China

China is rich in natural gas resources, with a relatively low degree of natural gas exploration and exploitation. China has great potential for gas development. The technically recoverable resources of conventional gas, shale gas, and coalbed methane in China are 3.33 × 10^{13} m^3, 1.285 × 10^{13} m^3, 1.25 × 10^{13} m^3, respectively, with a total of 5.865 × 10^{13} m^3. By the end of 2019, China's cumulative proven technically recoverable reserves of conventional gas, shale gas, and coalbed methane were 7.69 × 10^{12} m^3, 4.334 × 10^{11} m^3, and 3.285 × 10^{11} m^3, and the proven rates were 23%, 3.4%, and 2.6%, respectively, suggesting an early stage of exploration [28]. The Chinese natural gas industry has achieved significant development since 2000. Conventional and unconventional gases have been simultaneously developed. Twenty-eight large gas fields with geological reserves exceeding 100 billion cubic meters have been discovered successively, including Sulige, Anyue, Kelasu, Fuling, and Puguang. The newly added proven geological reserves exceeded 5 × 10^{11} m^3 over 18 consecutive years (Fig. 1). Four large gas blocks, Ordos, Sichuan, Tarim, and China South Sea, have been built, and natural gas production has increased from 2.44 × 10^{10} m^3 in 2000 to 1.888 × 10^{11} m^3 in 2020 (Fig. 2), with an average annual growth rate of 10.8%. Through comprehensive analysis of resources, exploration discoveries, and production, China's natural gas production is expected to reach 3.0 × 10^{11} m^3 by 2035

DOI 10.15302/J-SSCAE-2021.06.005

through measures such as the simultaneous development of conventional and unconventional resources and marine and nonmarine resources. There is still great potential for the development of natural gas in China.

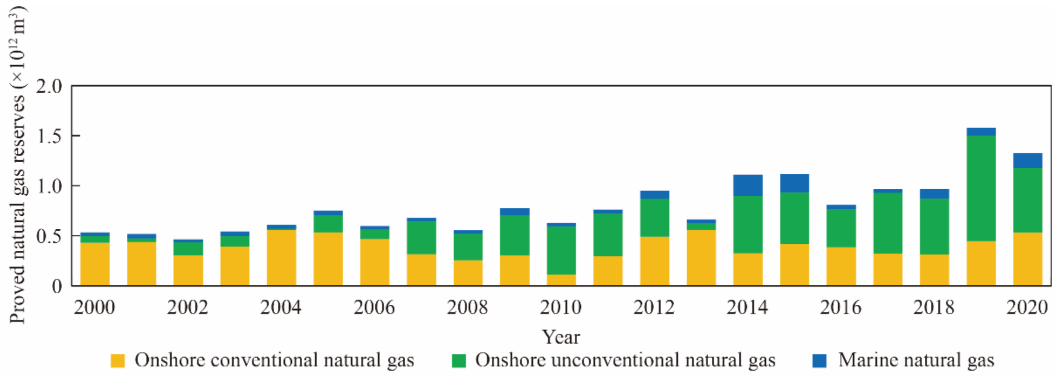

Fig. 1. China's newly added proven natural gas reserves (2000–2020).

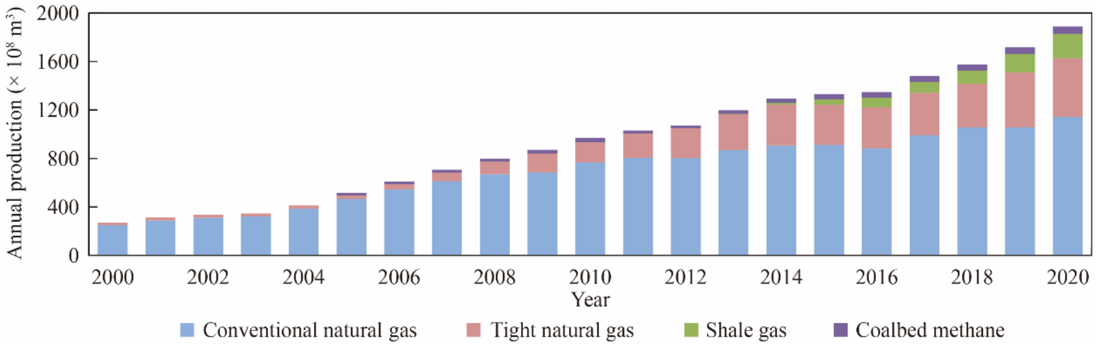

Fig. 2. China's Natural gas production (2000–2020).

3.1.3 Natural gas infrastructure progressively improved

The natural gas infrastructure is an essential foundation for the rapid development of natural gas. Since the initiation of the West-to-East Gas Transmission Project in 2000, China has built an infrastructure network that traverses east–west, north–south, and inside–outside. China has constructed both domestic pipeline systems (e.g., West-to-East, Sichuan-to-East, and Shaanxi–Beijing gas pipelines) and international transnational pipelines (e.g., Central Asia, China–Russia, and China–Myanmar pipelines). Four major natural gas import pathways and three horizontal and three vertical domestic natural gas pipeline network are developed. The four import pathways include the West-to-East gas pipeline, North-to-South gas pipeline, China-Myanmar gas pipeline, and LNG imports from the sea. By the end of 2020, the total mileage of domestic long-distance natural gas pipelines and urban gas pipeline networks are 1.1×10^4 km [29] and 7.0×10^4 km, respectively. Twenty-two coastal LNG receiving terminals have been constructed with a total receiving capacity of 8.8×10^7 t/a [30]. Twenty-seven gas storages were constructed, with a storage capacity of 1.61×10^{10} m^3 and a peak shaving capacity of 1.02×10^{10} m^3. In general, the development of the natural gas infrastructure has supported China's natural gas imports, exceeding 1.4×10^{11} m^3, and natural gas consumption reaching 3.28×10^{11} m^3 [29].

3.2 Natural gas in China has the resources and infrastructure for leapfrog development

China's natural gas consumption has rapidly increased. The natural gas consumption increased from 2.45×10^{10} m^3 in 2000 to 3.28×10^{11} m^3 in 2020. The proportion of natural gas in the energy consumption structure increased from 2.2% to 8.4%. Industry, residents, electricity, and transportation are the four critical gas-consuming sectors, accounting for 38%, 17%, 16%, and 7% of China's natural gas consumption in 2019, respectively. The world has a sufficient natural gas supply. Under the constraints of carbon peak and neutrality, natural gas has comparative advantages in terms of consumption and utilization in critical sectors, such as power generation, transportation, city gas, and industry.

3.2.1 Power generation sector

Compared to coal-fired power generation (abbreviated as coal power), gas-fired power generation (abbreviated as gas power) is clean, low-carbon, flexible, and efficient. (1) Compared to coal power, gas power has obvious environmental advantages. The emissions of CO_2 and nitrogen oxide during natural gas combustion are 44% and 50% lower than those of coal, respectively, and there are no dust particles or SO_2 emissions [31]. (2) The peak-regulating gas power plant has the advantages of a fast start and stop, a fast ramp rate, and good regulation performance. The cold start of coal power plants requires five hours, while the peak-regulating gas power plant only requires 9–10 min to start at full load [32]. Peak-regulating gas power plants can not only improve the grid security problems caused by the large-scale access of intermittent and random renewable energy but also solve the problems of reduced energy efficiency and increased emissions during the deep peak-shaving process of large coal power plants. (3) Gas-fired power generation is highly efficient. The energy utilization rate of heat and power cogeneration plants can reach 80%, far exceeding that of conventional generating plants (approximately 30%) [31]. By the end of October 2020, China’s gas power plants were mainly of two types: peak-regulating and cogeneration. The installed capacity and geographical distribution are shown in Fig. 3. The total installed capacity is 97 GW, including 39.5 GW of peak-regulating plants (41%) [33]. The annual natural gas used for power generation reached 5.71×10^{10} m^3. The demand for peak regulation is increasing with the continuously increasing demand for air pollution prevention and large-scale intervention in renewable energy. Peak-regulating gas power plants are expected to have promising prospects.

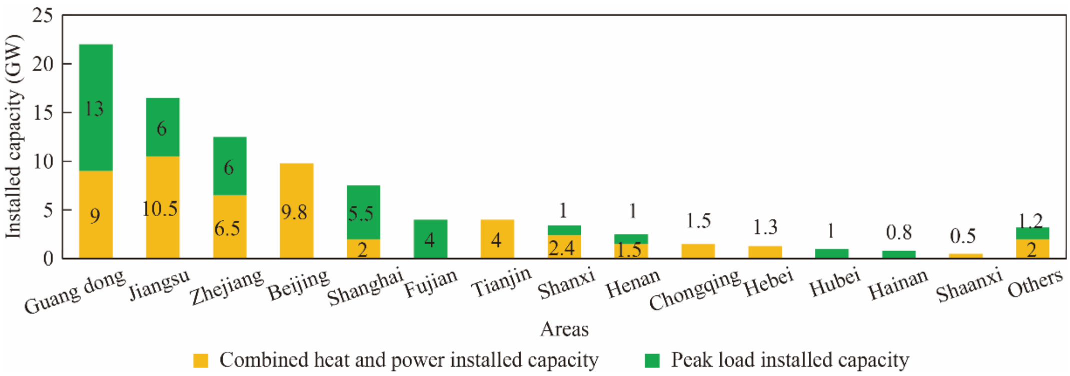

Fig. 3. The installed capacity of gas-fired power plants by geography and type.

3.2.2 Transportation sector

Natural gas offers prominent economic and environmental advantages in the transportation sector. The heat produced by 1 L of gasoline is similar to that of 1 m^3 of natural gas. When the international oil price is 60 USD/barrel, the domestic gasoline retail price is approximately 7 CNY/L. The gas fuel price is only 3.5–5.0 CNY/m^3, signifying that the fuel cost of natural gas vehicles is only 50%–70% of that of oil vehicles. Compared to gasoline vehicles, natural gas vehicles can significantly reduce the emissions of CO, CO_2, and nitrogen oxides in the exhaust and zero emissions of suspended particulates, lead oxide, and other harmful substances (Table 2). In addition, natural gas vehicles have incomparable advantages over electric vehicles in long-distance and freight transportation, particularly in cold regions. Natural gas vehicles can work with electric vehicles to promote the energy revolution in the transportation sector. By the end of 2019, the number of natural gas vehicles in China exceeded 7.6 million, including more than 7 million compressed natural gas (CNG) taxis, city buses and 600 000 LNG heavy trucks. There are approximately 6000 CNG stations and 3900 LNG stations [34]. The world’s largest natural gas transportation market has been developed. The annual natural gas consumption in the transportation sector is 3.63×10^{10} m^3, which is equivalent to approximately 2.96×10^7 t of refined oil. Currently, natural gas vehicles account for less than 3% of China’s total vehicle ownership. With the improvement in natural gas infrastructure, natural gas vehicles will significantly contribute to the low-carbon transformation of the transportation sector through the motivation of economic and environmental factors.

Table 2. Pollutant emissions of fuels by type. (Unit: %)

Fuel type	CO	Hydrocarbon	Nitrogen oxides	Suspended particulates	Lead oxide	Other harmful substance
Gasoline	100	100	100	100	100	100
Diesel fuel	20–40	10–20	45–60	>1000	—	50
CNG	1–5	10–20	30–40	—	—	—
LNG	1–3	8–15	20–35	—	—	—

DOI 10.15302/J-SSCAE-2021.06.005

3.3.3 City gas sector

In recent years, with the acceleration of urbanization and implementation of air pollution prevention and control policies in China, the demand for city gas has continued to grow. The government intensively announced policies in recent years, such as the *Air Pollution Prevention and Control Action Plan*, *13th Five-Year Plan for Energy Development*, *Three-Year Action Plan for Winning the Blue-Sky War*, *Air Pollution Prevention and Control Work Plan in Beijing, Tianjin, Hebei, and Surrounding Areas in 2017*, *Clean Heating Plan in Northern Region (2017–2021)*, and *Opinions on Accelerating the Use of Natural Gas*, resulting in the rapid growth of city gas consumption from 3.6 × 10^{10} m^3 in 2010 to 6.41 × 10^{10} m^3 in 2020 (excluding gas used in the transportation sector). By the end of 2019, China's urbanization rate had reached 60.6%. There are 390 million natural gas users, accounting for 28% of the Chinese population and 43% of the urban population [35]. It is estimated that by 2035, China's degree of urbanization will reach 72% [36]. If more than 70% of the urban population uses natural gas, a city's natural gas consumption is expected to double.

3.3.4 Industrial sector

Natural gas is widely used in the industrial sector. China encourages "shifting from coal to gas" in the industrial sector and restricts the development of the natural gas chemical industry. Natural gas is primarily used in kilns in metallurgy, ceramics, glass processing, food processing, textile printing, papermaking, and industrial boilers that produce steam or hot water to replace coal, coal gas, or petroleum products. Natural gas is pure, containing few impurities. It is easy to control the temperature and ensure product quality. Natural gas is also convenient to store and transport without desulfurization or waste treatment processes, which greatly reduces the costs related to equipment maintenance, personnel, vehicles, and environmental protection. Natural gas consumption in the industrial sector has grown rapidly in recent years, from 1.95 × 10^{10} m^3 in 2010 to 1.29 × 10^{11} m^3 in 2020 [37]. With the continuous advancement of the "shifting from coal to gas" policy and the implementation of stricter environmental protection policies, natural gas consumption in the industrial sector will gradually increase. In the chemical industry, natural gas is mainly used to produce nitrogen fertilizer (synthetic ammonia) and methanol, followed by the production of acetylene, hydrocyanic acid, formaldehyde, methylene chloride, carbon tetrachloride, carbon disulfide, nitromethane, carbon black, and helium extraction [38]. To date, the natural gas chemical industry does not have a competitive advantage, owing to the policy of restricting chemical gas usage. Therefore, the amount of gas consumed by the chemical industry remained stable. In 2020, natural gas consumption was approximately 3.0 × 10^{10} m^3 [29].

4 Challenges faced by China's natural gas development under the constraints of carbon peak and carbon neutrality

4.1 High gas terminal price and limited price advantage

Natural gas has limited comparative advantages in the power generation and chemical industries, which is a critical factor restricting natural gas development. The competitiveness of natural gas in conventional power-generation systems is weak. More than 70% of the power generation costs of gas power plants are fuel costs. Thus, the price of natural gas is a decisive factor in the economic benefits of gas power plants. In 2019, the average natural gas purchase cost for gas power plants in the coastal provinces and the Beijing-Tianjin area was approximately 2–2.5 CNY/m^3, and the cost was as high as 3 CNY/m^3 in the peak seasons. The average cost of gas power in China is 0.5–0.6 CNY/kW·h, which is higher than the average cost of coal power (0.23–0.31 CNY/kW·h) [39]. Global gas prices dropped in 2020 affected by COVID-19 and the oversupply of the natural gas market. Consequently, the cost of gas power also dropped to 0.3–0.5 CNY/kW·h. However, it is still higher than the cost of coal power plants [39]. As an industrial fuel, natural gas has obvious environmental advantages but is less economical as a substitute fuel for producing glass, ceramics, and steam from industrial boilers. As a chemical raw material for synthetic ammonia and methanol, natural gas does not have outstanding economic benefits compared to coal. For example, the cost per ton of ammonia synthesized from natural gas is 35% higher than ammonia synthesized from anthracite. The cost per ton of methanol produced from natural gas was 66% higher than that of methanol produced from anthracite [40].

4.2 Incomplete gas infrastructure development

Although China's natural gas infrastructure is rapidly developing, there are still some structural contradictions. These can be reflected in the lagging of peak-shaving facilities, insufficient peak-shaving capacity, insufficient interconnection of pipelines, and lack of construction of the "last one thousand meters" city gas pipeline, restricting the scaled development of natural gas. Currently, China's total natural gas peak-shaving capacity accounts for only 7.2% of its total natural gas consumption [29]. This rate is far below the international level (15%–20%), resulting in a gas shortage in winter for some northern areas. Unstable gas sources increase gas prices in non-priority supply areas, restricting the large-scale application of natural gas. For example, due to gas shortages and increased gas prices, the sales volume of natural gas heavy trucks dropped significantly in the first half of 2018 [39]. The Pipe China Co., provincial natural gas companies, and city gas companies are responsible for the construction and operation of cross-regional, provincial long-distance, and city pipelines. Diversified market entities, insufficient interconnectivity, and indirect gas supply for large industrial consumers in cities may directly affect the safety of natural gas supply and the consumer market.

4.3 Unclear price mechanism and difficulty in benefit development

In recent years, China's natural gas market has successively integrated the prices of stock, incremental, residential, and industrial gas. Additionally, a pricing mechanism combining government control and market regulation was established. Thus, the scope of market-based pricing has gradually increased. However, the pricing mechanism must be further improved. For example, the lack of competitive peak-shaving electricity prices has led to the slow development of gas-peak-regulating power plants. According to the *Notice on Natural Gas Price* issued by the National Development and Reform Commission in 2013, the price of natural gas electricity can vary with different types of generators (cogeneration or peak-regulating). However, it must not exceed the benchmark coal price of over 0.35 CNY/kW·h. The advantages of gas peak-regulating power plants cannot be fully utilized owing to the inflexible price mechanism. The current overall utilization rate of gas peak-regulating power plants is lower than 40%, and some parts are lower than 20% [33], which increases the cost of gas peak-regulating power plants and restricts their large-scale development.

4.4 Acceleration required for natural gas development under the constraints of carbon peak and carbon neutrality

After 200 years of development, the natural gas market in the United States has entered a stage of full retail competition. It is characterized by a highly open market, complete legal and regulatory systems, transparent market information, a complete market pricing mechanism, and fair third-party access, showing prominent market competitive advantages [41]. Initially, the development of the U.S. natural gas terminal market relied on consumption through power generation and city gas. Finally, the replacement of industrial coal and transportation diesel and the growth of the gas power generation proportion lead to the large-scale consumption of natural gas [42]. In comparison, China's natural gas market remains in a non-competitive state. The Chinese natural gas industry is characterized by a late start of development, limited resources and reserves, complex geological conditions, insufficient market vitality and competitiveness, and incomplete legal and regulatory systems. Therefore, under the constraints of carbon peak and neutrality, the role of natural gas as a "cornerstone" for energy security and a "stabilizer" for power security should be fully utilized [29]. The opportunity of "stabilizing oil, increasing gas, and developing new energy" needs to be seized to deepen the reform of the natural gas industry, rationally deploy the natural gas industry, and enhance reliable and flexible supply.

5 Suggestions on China's natural gas development

China's natural gas industry needs to meet the demand for clean energy for economic and social development and promote the substitution of traditional high-carbon fossil energy. Moreover, it is necessary to encourage the integrated development of fossil fuels and renewable energy. Given the current supply and demand situation of natural gas in China and abroad, the comparative advantages of natural gas in key areas, its role in carbon peak and carbon neutrality, and resources, environmental, economic, and national security factors, it is expected that China's natural gas demand will double to reach its peak (over 6×10^{11} m^3) [3,42,43], and domestic natural gas production will exceed 3×10^{11} m^3 by 2040 [29]. In such a case, sufficient supply can be guaranteed with domestic production and reliable imports from pipelines in the northeast, northwest, and southwest, and LNG overseas. Natural gas is networked and continuously supplied. Future development needs to clarify top-level design and continue to promote the coordinated development of production, supply, storage, and marketing. China needs to work on these four aspects that effectively play the role of gas as transitional energy to pave the foundation for a clean, low-carbon, safe, and efficient energy system and achievement of carbon goals: expand consumption, ensure sufficient supply, strengthen infrastructure, and optimize mechanisms.

DOI 10.15302/J-SSCAE-2021.06.005

5.1 Strengthening top-level design to clarify the role of natural gas in energy transition

It is recommended that natural gas needs to be clarified in the national roadmap as the main energy source for carbon peak and the transitional energy for carbon neutrality. Five development directions are proposed: strengthening domestic supply, expanding diversified gas supply, encouraging the development of gas peaking plants and gas vehicles, promoting gas storage and pipeline infrastructure, and improving fiscal and price mechanisms. The purpose is to give full play to the comparative advantages of natural gas, accelerate the development of the natural gas industry, contribute to the achievement of the carbon peak by 2030, gain more time for the maturation of key renewable technologies and the growth of renewable industries, and provide the most favorable support for the ultimate realization of the carbon neutrality goal by 2060.

5.2 Maximizing comparative advantages of natural gas to promote the natural gas consumption

Differences were present in the comparative advantages of natural gas in different energy consumption sectors. There is a real need for the leap-forward development of natural gas. To maximize the green and low-carbon advantages of natural gas, it is recommended to implement the concept of green development, continuously control air pollution, promote the coal-to-gas project in city gas and industrial sectors, and assist the sustainable development of cities and regional environments. To maximize the clean, low-carbon, and price advantages, it is recommended to deploy LNG and CNG stations with the focus on long-distance freight transportation and urban traffic in cold regions, accelerate the pace of oil-to-gas shift, and promote rapid carbon reduction in the transportation sector. To maximize the low-carbon and flexible advantages of natural gas, it is recommended to accelerate the planning and layout of gas peak-regulating power with a focus on renewable energy production bases and power demand load centers, to promote the large-scale development of renewable energy and the safety of power transmission. To fully exploit the low-carbon and high-efficiency advantages of natural gas, it is recommended to build cogeneration power plants following local conditions to promote efficient energy usage.

5.3 Utilizing domestic and international gas resources to ensure sufficient and reliable supply of natural gas

It is necessary to build a solid foundation for domestic natural gas supply, introduce diverse overseas gas resources, and meet sufficient internal and external supplies by adhering to the concept of independent and controllable energy security. The degree of domestic gas exploration and exploitation needs to be enhanced with equal emphasis on both conventional and unconventional gas, and marine-derived and nonmarine-derived gases. It is also necessary to strengthen the major scientific and technological breakthroughs in deep-buried reservoirs, deep oceans, and unconventional oil and gas exploration and development. Four major production bases in the Sichuan-Chongqing area, Ordos Basin, Xinjiang Province, and marine basins need to be enlarged to increase domestic production to 3×10^{11} m^3. For the acquisition of international natural gas resources, it is suggested that the concept of diversification is adhered to, concentrate on both investment and trade, import resources via both land and sea through both long-term contracts and spots, strengthen the supply from Central Asia and Russia, expand import channels in the Middle East and East Africa, and consolidate four major gas import channels in the northeast, northwest, and southwest, and LNG overseas. China is very likely to achieve a sufficient and reliable supply of natural gas through diversified import channels, resources, and trading methods.

5.4 Promoting infrastructure construction to improve the efficiency and level of energy security

Considering the seasonal imbalance and continuous supply, it is suggested to optimize the layout of the gas pipeline network and enhance its transmission and distribution capacity following the idea of networked infrastructure and redundant adjustment facilities, forming a national gas pipeline network that connects the inside and outside of the ocean and land. The layout of LNG receiving terminals needs to be planned as a whole and constructed under the principles of demand-oriented and moderately advanced to avoid the inefficient and scattered patterns brought by local investment impulses. It is also suggested that the capacity building of gas storage for peak-shaving be increased by actively promoting the construction of gas storage in the northeast, north, and southwest regions. The peak-shaving capacity must match the gas consumption following a moderate redundancy standard. It is recommended to continuously promote the construction of the production, supply, storage, and marketing system to realize the efficient and safe operation of the system through multi-link linkage. Since the "greenhouse effect" caused by the largest component of natural gas—CH_4— is still 21–28 times that of CO_2 after a hundred years [44], it is necessary to actively innovate technology, equipment, and management, clarify standards and responsibilities, and strictly control emissions and leakage of natural gas in the production, transportation, and application to ensure the maximum efficiency of natural gas.

5.5 Strengthening policy formulation to drive the rapid development of the natural gas industry

To fully guide and promote policies and mechanisms, it is critical to establish land use, sea use, safety, and environmental protection policies that are compatible with domestic natural gas exploration and development and to continue unconventional gas financial subsidies and preferential tax policies. The cost of peak-shaving needs to be considered by establishing the price mechanism of peak-shaving gas price and peak-shaving electricity price, reflecting the real cost of peak regulation. The promotion of the construction of gas storage and gas peaking power plants through two-way policy and market efforts is suggested. In the transportation sector, the oil-to-gas policy is recommended. In the industrial and fuel sectors, the coal-to-gas policy is recommended. The gas price mechanism also needs to be optimized by encouraging a direct supply policy for industrial parks and users, and significantly reducing the gas price used in industry and power generation. Multiple efforts at the policy level would promote gas industry development and safe gas supply and provide a solid guarantee for achieving carbon peak and carbon neutrality.

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