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Review Paper

Review on the challenges and strategies in oil and gas industry's transition towards carbon neutrality in China



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ABSTRACT

In light of carbon-neutral pledge, the oil and gas industry has been facing several critical new challenges in China. The current status and new challenges in terms of market mechanism reform, supply-consumption balance and key technology innovation in China's oil and gas industry are reviewed in the present study, and new strategies and roadmaps are proposed to cope with the challenges. The study found that (i) the oil and gas market faces challenges such as incomplete pricing mechanisms, unclear subject rights, and the lack of recognition and trading of carbon assets. (ii) the trade-off between short-term supply security and long-term low-carbon supply is the most critical issue. (iii) in addition to typical challenges such as immature technology and lack of funding support, the unclear multiple technology coupling development mode also poses problems for the low-carbon transformation of the oil and gas industry. To address these new challenges, comprehensive strategies and roadmaps for China's oil and gas industry towards carbon neutrality are proposed and discussed in the aspects of participating in market transactions, restructuring production and consumption, deploying key technology innovations, and planning enterprise strategies. The present study is expected to provide a blueprint for the future development of China's oil and gas industry towards carbon neutrality.

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1. Introduction

The energy security strategy of "Four Revolutions and One Cooperation", focusing on developing a clean, low-carbon, safe and efficient energy system are proposed by China's President Xi Jinping (NEA, 2022a). Moreover, in September 2020, China's carbonneutral pledge was proposed to clarify the direction of low-carbon transition (Gov, 2021a). Oil and natural gas account for about 27.4% of China's total primary energy consumption in 2021, and about 24% of the total China's carbon emission of over 10.3 billion tons (CNPC, 2021a; NBS, 2022a). Therefore, the low-carbon transition of oil and gas industry is of great significance to realize energy security and carbon neutrality in China.

The carbon-neutral pledge brings new challenges for oil and gas

* Corresponding author. School of Business Administration, China University of Petroleum (Beijing) at Karamay, Karamay, 834000, Xinjiang, China. E-mail address: ZhangQi56@tsinghua.org.cn (Q. Zhang). industry. 1) In terms of market mechanisms, the revolution of low-carbon market mechanisms such as carbon trading market, green power trading mechanism and renewable portfolio standard (RPS), etc., are continuously grabbing the market share of oil and gas (Chen et al., 2020). 2) In terms of supply-consumption, the trade-off between carbon-neutral pledge and energy security accelerates the transition of supply and consumption structures of crude oil and natural gas (Zhang and Chen, 2022). 3) In terms of key technologies, zero-carbon and negative-carbon technologies with greater carbon reduction potential will become the hotspots of research & development (R&D), to accelerate the speed of low-carbon transition (Wang F. et al., 2021). 4) In terms of the oil and gas enterprises, the carbon-neutral pledge also urges enterprises to formulate more aggressive transition roadmap from oil and gas enterprise to comprehensive energy enterprise (Wang Z. et al., 2021).

In reponse to the major challenges bringing about by the carbon neutrality, a set of strategies and roadmaps need to be proposed for China's oil and gas industry. Chen et al. (2020) reviewed the historical evolution of China's petroleum market and proposed

strategies including deepening petroleum market reform, accelerating the elimination of inefficient refining capacity, diversifying oil supply sources, and so on. Sun et al. (2021) proposed the technology development direction for oil and gas industry from four aspects, improving energy use efficiency, optimizing energy consumption structure, adjusting the industrial structure, and cultivating negative-carbon industries. Hou et al. (2021) further clarified the functional positioning of oil and natural gas, arguing that oil is turning into a "raw material", and natural gas is entering its heyday. In addition, Huang et al. (2021) also argued that the oil and gas industry should be actively involved in renewable energy investments. Wang Z. et al. (2021), Wang and Yao (2021) focused on the strategic choices and main initiatives of oil and gas enterprises, and proposed suggestions, such as optimizing the layout of assets, laying out low-carbon businesses across borders, accelerating lowcarbon technology innovation, and deepening market mechanism reform.

In summary, the existing studies have been discussing the development pathway of China's oil and gas industry towards carbon neutrality. However, they mostly focus on single aspect (e.g., market mechanism revolution or technology innovation, etc.) and the proposed strategies are mostly general without detailed roadmap.

To bridge these gaps, responding to the new challenges for oil and gas industry towards carbon neutrality, the present study sorting out the current status of oil and gas industry in terms of market mechanisms, supply-consumption and key technologies. Then the new challenges towards carbon neutrality are refined, and a comprehensive and detailed roadmap for China's oil and gas industry towards carbon neutrality is proposed and analyzed finally.

2. Current status and new challenges for market mechanism reform in light of carbon neutrality

2.1. Deep marketization of the oil and gas industry

China has been gradually deregulating its oil and gas markets since the Reform and Opening, albeit slowly and with little progress (Chen et al., 2020; Li et al., 2018). To actively address challenges generated by carbon neutrality, deepening domestic oil and gas market reform must be accelerated by all stakeholders. Since the proposal of carbon-neutral pledge, China's central and local governments have enacted a series of policies for restructuring and liberalizing the domestic oil and gas industry, as summarized in Fig. 1. Notably, the government has continuously improved the tax system of the refined oil products and strengthened natural gas transmission price transparency.

To deepen and accelerate the reform of "simplification of administrative procedures, decentralization of powers, combination of decentralization with appropriate control, and optimization of services", there are three key challenges. Firstly, how to steadily reform oil and gas prospecting and exploitation administration and conduct the nationwide pilot program on competition-based assignments of oil and gas prospecting rights is the core for opening upstream of oil and gas industry. Secondly, how to open up gas pipelines to third parties in a fair and non-discriminatory way is regarded as one of the fundamental of China's oil and gas market reform (Boute and Fang, 2022; NDRC, 2019; NDRC, 2017; Xu et al., 2017; Zhu et al., 2017). At the same time, the gas transmission tariffs have been criticized as inefficient regulation although the central government has already created four pricing zones in the northwest, southwest, northeast and central-eastern regions to simplify the transmission tariff calculation (Fitchrating, 2021; NDRC, 2021).

Despite the establishment of China Oil and Gas Pipeline Network Corporation (PipeChina) in 2019, the challenges remain and can be clarified into following aspects. How to apply for thirdparty access to the pipeline network and how to calculate and allocate the spare capacity have not yet been solved. Moreover, the rights and obligations of various market entities have not been clarified, as well as their interrelationship (Andrews-Speed, 2020: Guo, 2021). In addition, the government has insufficient institutional capacity to maliciously hoard pipeline capacity by central state-owned enterprises (SOEs) (Chen et al., 2019). There are concerns that PipeChina and its provincial subsidiaries may favor central SOEs because its senior management is almost entirely made up of former executives from PetroChina, SINOPEC and CNOOC (Downs and Yan, 2020; Meidan, 2020). More importantly, the third-party access involved in the latest regulatory documents excludes users connected to urban gas distribution systems. As a result, China's oil and gas market reform remains at the national and provincial levels, with less depth and narrower scope comparing with the EU gas market reform (Boute and Fang, 2022).

In addition, current oil and gas pricing mechanisms remain semi-regulated and disordered. For example, domestic refined oil price is adjusted every 10 working days according to the international market instead of real-time changes with market fluctuations. Meanwhile, the cross-subsidy and price inversion problems for natural gas have not been effectively solved for years, which triggers the insufficient energy use and undermines the low-carbon transition (Boute and Fang, 2022; Lin and Li, 2021). Varying pricing regimes (market-based, government-guided, and government-set) and varying price levels (industrial and commercial, residential and power) coexist, followed by pricing disputations between gas buyers and sellers (Boute and Fang, 2022).

The contribution of three national oil and gas exchanges (Shanghai, Chongqing, and Shenzhen) to competitive pricing and risk mitigation falls short of our expectations. This can be attributed partly to the small variety of financial derivatives, small trading volume, and the absence of governmental regulation. To hedge against oil and gas price risks caused by complicated geopolitics and COVID-19, diversified oil and gas financial derivative instruments can help maintain domestic price stability and make China a price benchmark for the Asia-Pacific region (Chen et al., 2021).

2.2. National carbon emission trading scheme (ETS)

In July 2021, China's national carbon emission trading system (ETS) was launched in Shanghai with an opening carbon price of 48 CNY/ton. It covers more than 2,200 power enterprises and 4 billion tons of carbon dioxide emissions, which is known as the world's largest carbon market. By the end of 2021, the cumulative trading volume of carbon emission allowances reached 179 million tons, with a total trading value of approximately 7.7 billion CNY and the agreement fulfilment rate of 99.5% (PDOE, 2022). Currently, the national ETS market takes the power sector as its central task but will gradually expand its coverage to other industries with high emissions (NDRC, 2017). It is estimated that seven additional energyintensive industries, including petrochemical, chemical, building materials, steel and iron, nonferrous metals, paper making, and civil aviation, will be incorporated into the national ETS market during the 14th Five-Year Plan period. By then, the emissions covered are expected to reach 8 billion tons, accounting for 70%-80% of China's total carbon emissions. By 2030, the domestic cumulative carbon trading value will exceed 100 billion CNY (Pi, 2021).

How to formulate a strategic plan for carbon trading and reasonably managing corporate carbon assets will be an inevitable

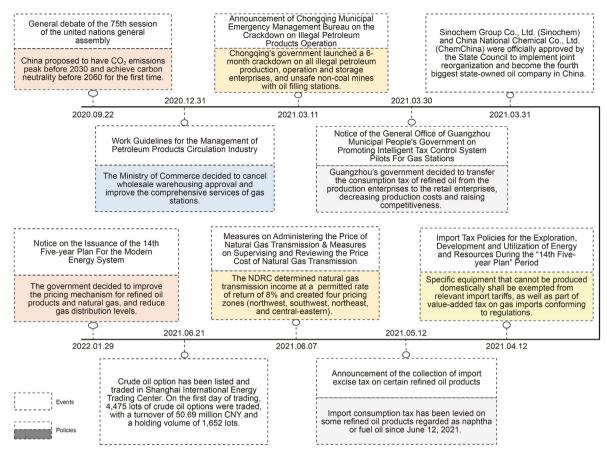


Fig. 1. Oil and gas industry development policies in light of carbon-neutral pledge.

challenge for domestic oil and gas enterprises. Since the launch of carbon trading market, the state-owned oil and gas enterprises have actively participated in carbon emission trading, especially SINOPEC, of which the cumulative carbon trading volume reached 17.5 million tons, and the transaction volume was 442 million CNY (SINOPEC, 2020). However, these attempts are still inappreciable in comparison with their actual carbon emissions, and more efforts need to be made by referring to the experiences of international oil and gas enterprises. For instance, BP, regarded as the most radical oil company in carbon mitigation and green development, began a pilot carbon trading scheme in 1998 and extended to the full company in 2020, involving approximately 150 individual business units (IBUs) worldwide in four categories, namely exploration and production, refining and marketing, chemicals, as well as gas, power and renewables. In this way, BP achieved its 10% mitigation goal, which was seven years ahead of schedule and created a value of \$650 million (Akhurst et al., 2003; Victor and House, 2006).

2.3. Energy use rights trading system

The establishment of a national energy use rights trading system is considered to be a powerful instrument to promote the realization of "double control" target for total energy consumption and intensity, which can further promote sustainable development (Yang et al., 2020). Since NDRC enacted the *Pilot Scheme for Paid Use and Transaction System of Energy Use Rights* in 2016 and selected four trial provinces including Zhejiang, Fujian, Henan, and Sichuan, China's energy use rights trading market has been promoted slowly (NDRC, 2016). However, with the proposal of the carbon-neutral pledge, developing an energy use rights trading market has

attracted concerns from China's government again. In September 2021, the State Council released the *Guidelines for Fully and Faithfully Implementing the New Development Philosophy in the Work on Achieving Peak Carbon and Carbon Neutrality* and clearly put forward to accelerate the construction of a national energy use right trading market (NCNA, 2021a). Taking Zhejiang as an example, there have been 43 transactions since 2021, with a total of 804.4 million tons of standard coal.

Towards the carbon neutrality, the oil and gas industry, as a typical industry with high energy consumption and high external dependency, has an urgent need to promote energy conservation and energy-efficient technology innovation. This requires intensive investment in R&D and equipment upgradation, which can be solved through trading energy use rights to an extent. In other words, the oil and gas enterprises with good performance in saving energy can make profits by selling their redundant energy use quotas to those enterprises who have poor performance. Therefore, the energy use rights trading system can transfer corporates' inner drivers for saving energy into market drivers. At this point, it's a kind of market-oriented policy similar to the carbon emission trading scheme.

3. Current status and new challenges for supply-consumption balance in light of carbon neutrality

3.1. Domestic supply and consumption

Recently, due to the increase of energy demand and the continuous expansion of refineries, China's oil and gas imports account for an increasing proportion. In 2021, the external

dependency of crude oil and natural gas has reached 71.9% and 44.1%, respectively, which seriously threatens energy security (NBS, 2022b). In addition, the dual-carbon target has been a critical external factor for the usage of China's fossil energy in the future (Fan et al., 2022; Lu and Chai, 2022). The country's commitment to carbon neutrality has introduced new requirements for the oil and gas industry to achieve low-carbon supply.

To meet the needs of domestic demand while transitioning to low-carbon supply, China's Fourteenth Five Year Modern Energy System Plan calls for intensified oil and gas exploration and development efforts, with a focus on low- and negative-carbon technology and digital intelligent upgrading (NDRC, 2022). Therefore, most major enterprises have taken the initiative to make great progress in oil and gas supply. In 2021, the national oil and gas enterprises completed an investment of CNY 79.9 billion in exploration, achieving a year-on-year growth of 2.1% in crude oil and 7.8% in natural gas (MNR, 2022; NBS, 2022c). However, the process of oil and gas extraction not only supplies energy products but also causes huge amounts of CO₂ emission (Pang et al., 2022). Therefore, the trade-off between short-term supply security and long-term low-carbon supply is the most critical issue. It is expected to that the carbon reduction emission potential in oil and gas supply in 2050 can reach 16.71 million tons in the case of all low-carbon technology available (Sun et al., 2018). For this reason, there is an urgent need to develop efficient utilization and energysaving technologies for oil and gas supply.

The carbon-neutral pledge has also impacted the demand for oil and gas in China. The oil and gas market has been expected to maintain an expansion trend in the short term, with natural gas becoming a significant growth driver. In 2021, the demand of natural gas increased to 372.6 billion cubic meters, up 12.7% year on year (CEMRI, 2022). However, the growth rate of domestic natural gas production is slower than that of consumption, and the gap between supply and demand continues to expand. In 2021, the external dependency on natural gas rose to 44.1% (NBS, 2022b). External environmental risks have led to rapid fluctuations in oil and gas demand, with the Russia-Ukraine conflict putting pressure on China's energy security in early 2022. (Fang and Shao, 2022; Umar et al., 2022; Wen et al., 2021). China's crude oil imports fell by 14% in March 2022 compared to the same period in 2021, yet the spike in oil prices led to a 32.8% year-over-year increase in crude oil import transactions to \$33.2 billion (GAC, 2022; NBS, 2022b).

Overall, China's oil and gas market is facing varieties of challenges such as enhanced pressure for low-carbon transition, growing mismatch between supply and demand, and increased risks in the external environment. More importantly, there is an urgent need to accelerate the low-carbon transition while ensuring energy supply security, which is a dual requirement of quantity and quality.

3.2. Resource endowment

It is necessary to recognize the urgency of the dual-carbon target and reasonably control the consumption of fossil energy, while also recognizing the need to base on China's energy resource endowment and reasonably layout the development path of oil and gas energy. Currently, China's development and utilization of oil and gas resources do not align with the strategic position of achieving the dual-carbon goal and ensuring energy security. China's conventional oil and gas resources are limited, with low per capita reserves and storage. In 2020, China's per capita recoverable reserves of oil and gas are 2.48 tons and 6,000 cubic meters respectively, only 7.7% and

24.2% of the world average (Wang, 2020).

To address this challenge, China's National Energy Administration has formulated the "seven-year action plan" for the oil and gas industry to increase reserves and production, and the national investment in exploitation has increased steadily. By the end of 2021, the resource reserves of crude oil, natural gas, shale gas and coalbed methane were 3.69 billion tons, 6.34 trillion cubic meters, 365.97 billion cubic meters and 544.06 billion cubic meters respectively (MNR, 2022).

Globally, high-quality conventional oil and gas resources are facing depletion, and unconventional oil and gas have become a strategic replacement field. China has abundant unconventional oil and gas resources, accounting for over 70% and 90% of new proven reserves, respectively (Huang et al., 2022; Li et al., 2022). Drawing on the successful experience of unconventional oil and gas exploration and development in the United States, China has made significant breakthroughs in basic theory and technology. However, key development technologies such as deep shale gas and medium to high maturity shale oil still have a certain gap with the international developed level (Zou et al., 2015, 2021).

Overall, China has a significant resource base for developing unconventional oil and gas, and its high domestic demand necessitates a significant amount of imports to satisfy. As the world's largest oil importer and most promising natural gas market, China's efforts in exploration and development are vital for energy security. However, several key challenges hinder its development, including complex surface and underground geology, high costs of unconventional extraction, and increasingly prominent environmental and carbon emissions issues. In the future, policy support, technology development, and improvement of oil and gas reserve capacity are important guarantees to address these challenges.

3.3. Infrastructure facilities

The basic trend of oil and gas infrastructure construction in China is shifting towards structural adjustment and transition. By the end of 2021, the country had completed a total of 176,000 km of long-distance oil and gas pipelines, with natural gas pipelines accounting for about 115,000 km, crude oil pipelines accounting for 31,000 km, and refined oil pipelines accounting for 30,000 km (CEMRI, 2022). As China moves towards carbon neutrality, the growth rate of domestic oil consumption has slowed down, while natural gas demand is rapidly increasing. Therefore, the construction of natural gas infrastructure is accelerating. Currently, China has 347 underground gas storage depots, forming a gas storage and peaking capacity of over 17 billion cubic meters. Additionally, the country has built 22 LNG receiving stations, with a total receiving scale of 9,600 tons per year (NEA, 2022b).

However, the current infrastructure construction faces new challenges in the pursuit of carbon neutrality. Firstly, China's oil and gas infrastructure is still in the initial stage of physical connection, and lacks uniformity between national and regional layouts (Song et al., 2022). Secondly, China's natural gas emergency reserve capacity is relatively inefficient, and there is an urgent need to strengthen natural gas storage and peaking capacity (Wang et al., 2022). In terms of technology, the lack of financial investment in oil and gas storage and transportation has led to the backwardness of relevant technology applications (Wang et al., 2021b). It is necessary to strengthen the development and application of key technologies such as marine oil and gas storage and transportation technology, long-distance pipeline laying technology in the permafrost zone.

4. Current status and new challenges for key technologies in light of carbon neutrality

4.1. Digital technologies

Current status: International energy research institutes have estimated that the digital transition could potentially reduce carbon emissions from oil and gas industry by 15%–20%. This reduction could amount to 1.3×10^9 t of carbon emissions from 2016 to 2025 (Accenture, 2017; Ekholm and Rockstrom, 2021; SEG, 2019). Therefore, digital technologies play a crucial role in improving data asset utilization, reducing costs, and increasing efficiency (Maroufkhani et al., 2022; Wu et al., 2022). The low-carbon transition and carbon-neutral pledge are driving the adoption of various digital technologies in the oil and gas industry.

- 1) **Big data analytics:** Big data analytics plays a critical role in the oil and gas industry by providing insights to analyse and predict seismic reservoirs, improve reservoir simulations, reduce drilling time, enhance petrochemical asset management, and improve occupational safety (Bello et al., 2017; Plate and Moritz, 2016; Sang et al., 2021; Tarrahi and Shadravan, 2016; Zhao et al., 2021). In 2020, Daqing Oilfield launched the Intelligent Command Center, which uses big data analytics to monitor 70.8% of large stations and 95% of old area substations in a centralized manner (CNPC, 2022). The center utilizes a comprehensive system for data acquisition, transmission, and analysis, providing an effective tool for the industry to streamline operations and increase efficiency.
- 2) **Cloud computing:** As data collaboration deepens and scales up, the oil and gas industry is expected to widely adopt cloud computing technology, which has the advantages of efficient resource sharing and dynamic deployment. CNPC has developed the "Dream Cloud" platform system, which includes a unified data poll to manage exploration and development data. It realized the data cooperation for 16 oil and gas companies, more than 450,000 wells, more than 26,000 station libraries (Guo and Hu, 2019; Shi et al., 2020).
- 3) **Blockchain:** Blockchain technology has been shown to reduce transaction costs and improve data visibility, traceability, and sharing (Ahmad et al., 2022; Aslam et al., 2021). In April 2018, Sinochem Energy Technology Company completed a pilot transaction using blockchain for a gasoline export from Quanzhou, China to Singapore. This implementation resulted in a reduction of trading costs by over 30% (Cao et al., 2020).
- 4) **Internet of things (IoT):** The IoT typically comprises three components: a sensing layer for collecting data, a transmission layer for data transfer, and an application layer for oil and gas data analysis and processing (Cao et al., 2020; Rahmani et al., 2022; Wei and Wang, 2015; Zhang, 2016). CNPC has developed the "Oil and Gas Production Internet of Things System (A11)", which covers comprehensive sensing of production objects such as oil and gas wells, metering rooms, and related gathering and transmission pipeline networks. It can realize automatic collection and control of production data, monitoring and management for oil and gas field production and operation (CNPC, 2021b).
- 5) **Artificial intelligence (AI):** Al technology, through deep learning and interpretation of oil and gas data, has the potential to develop accurate geological models and intelligent production equipment, recognize language and images, and greatly improve production management and decision-making (Cao et al., 2020; Liu H. et al., 2022). In 2020, CNOOC developed an intelligent oil recovery system based on AI technology, which has enabled predictive maintenance of electric submersible

- pumps at the Caofeidian Operation, and reduced production downtime by about 30% and maintenance costs by 20% (CNOOC, 2020).
- 6) **Digital Twin:** The digital twin technology can enable various applications, such as visual management, remote guidance management, and offline production optimization, significantly enhancing the intelligence of the oil and gas industry (Bo et al., 2020; Chen et al., 2021; Xue et al., 2020). In 2020, CNOOC Ruifei developed the "Oil Brain" system, which implements oil and gas field exploration, field visualization operations, and off-site expert online guidance (Chen et al., 2021).

Challenges: 1) The applications for carbon footprint monitoring, carbon sink measurement, carbon reduction potential assessment and data management are insufficient (Mohammadpoor and Torabi, 2020); 2) Both the investment costs of hardware and software facilities such as sensors and IoT equipment and management costs for data recording, storage and analysis are relatively high (Cao et al., 2020; Okita et al., 2020); 3) There are insufficient skilled and professional human resources (Georgiou et al., 2021; Koroteev and Tekic, 2021); 4) There are only few overall planning and unified technical standards (Teng et al., 2021; Wanasinghe et al., 2020); 5) There are deviations in cognitive communication, behavioural patterns and management processes between traditional oil and gas business and digital technology applications, and a cultural concept and management model in line with the digital enterprise has not yet been formed (Yao et al., 2021).

4.2. Renewable energy power generation technologies

Current status: Currently, photovoltaic and wind power technology are widely used in the oil and gas industry (Zereshkian and Mansoury, 2021; Wu et al., 2022; Zhang Q. et al., 2021). The electricity generated from these sources is mainly used for oil and gas pipeline valve chamber power, cathodic protection power for oil and gas facilities, and electric heating for oil transmission pipelines, etc. In recent years, China's oil and gas industry has attempted to enter the photovoltaic and wind power industry. CNOOC has been involved in the photovoltaic industry since 2012, albeit with slow and limited progress; SINOPEC's photovoltaic power generation business started in 2016, and its 13th Five-Year Plan target installed capacity is 500 MW, but only 22% has been completed in practice. In the wind power industry, CNOOC firstly proposed to explore offshore wind power projects in 2019, followed by SINOPEC and PetroChina. However, compared to large international oil and gas companies with extensive experience, the China's oil and gas industry has lagged relatively behind in the layout of photovoltaic and wind power generation, and the installed capacity is generally

Over the past decade, the cost of photovoltaic and wind power has fallen significantly, with photovoltaic falling by more than 85% and onshore wind power costs falling by more than 56% (CNPC, 2021a). With stable growth expected, China's oil and gas industry can leverage its the large internal electricity market and good spatial resource endowment to quickly layout the photovoltaic and wind power fields, securing a place in future energy supply (Pinkse and Van den Buuse, 2012; Sun et al., 2022). On the one hand, as shown in Fig. 2, oil and gas resources are primarily located in the northwest and northeast regions, which have abundant wind and solar energy resources. Meanwhile, China's world-leading photovoltaic and wind power industries can provide technical support to the oil and gas industry. On the other hand, as reservoirs owned by oil and gas companies gradually enter the late stage of extraction or depletion (Zou et al., 2020), electricity consumption will increase as water content rises. The newly discovered and developed oil and

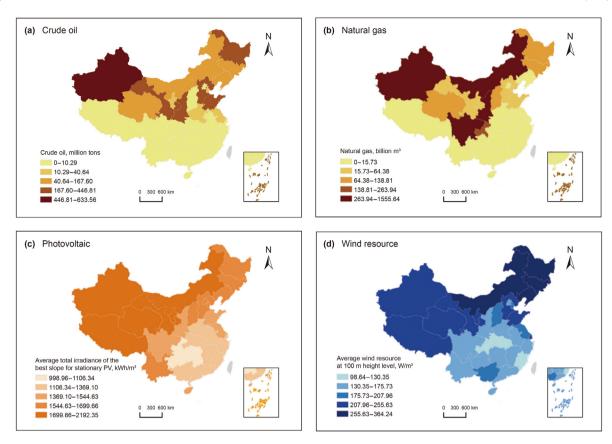


Fig. 2. Geographical distribution of oil and gas, wind, and solar energy resources.

gas reservoirs in recent years are mainly characterized by low permeability, low abundance or deeper layers (Zheng et al., 2019), resulting in higher energy demand for extraction. These factors highlight the necessity and significant advantages of China's oil and gas industry in deploying photovoltaic and wind power.

Challenges: 1) In response to the substitution of electricity for oil and gas, there is an urgent need for the oil and gas industry to expand its business and decarbonize its production. However, on the one hand, oil and gas companies will face multiple challenges in terms of human capital, technology and financial support, as renewable energy generation is a less familiar business (Fan et al., 2021; Hartmann et al., 2021; Alova, 2022). On the other hand, there is a high degree of uncertainties about technological advances in photovoltaic and wind power. To prevent the economic and environmental effects of technology lock-in, clarifying the future direction of technology development will be an important prerequisite for oil and gas companies to make investment in construction and layout planning (Haelg et al., 2018; Seto et al., 2016; Pickl, 2019).

- 2) When the photovoltaic devices and wind turbine are manufactured or scrapped, their negative externalities on important environmental factors such as land use, water resources, and air cannot be ignored (Tawalbeh et al., 2021). Therefore, there is an urgent need to design and improve the recycling methods and policies for photovoltaic devices to mitigate their negative impacts (Deng et al., 2022; Li et al., 2019).
- 3) Unlike conventional energy sources, solar and wind energy are intermittent and unstable. As photovoltaic and wind power gain large-scale access to the grid, unprecedented security and stability issues arise (Pomerantseva et al., 2019; Wang N. et al., 2021; Yang et al., 2022). Therefore, various energy storage

technologies that have the ability to regulate the peak and frequency will become critical supporting technologies for renewable energy (Bullich-Massagué et al., 2020).

4.3. Carbon capture utilization and storage (CCUS)

Current status: Currently, the demonstration of major CCUS projects has been included in China's "14th Five-Year Plan" for the first time, becoming an indispensable and important component of China's carbon neutrality technology mix. CCUS has a wide range of applications in the oil and gas industry, providing multiple benefits such as reducing greenhouse gas emissions, and improving oil and gas recovery rates (Zhang X. et al., 2021). Although CCUS has many utilization ways, only CO₂-EOR has advantages of technology maturity (reaching TRL 11 internationally) and economic profitability at present (Liu J. et al., 2022; Yuan et al., 2022). In August 2022, China's first million-ton CCUS project, the "Qilu Petrochemical-Shengli Oilfield Million-ton CCUS Project," was officially launched and is expected to reduce annual CO₂ emissions by 1 million tons, with an anticipated increase in the recovery rate of over 12%.

The "Golden Age" of CCUS deployment lies from 2040 to 2060 in the world, while from 2030 to 2050 in China, which will reach about 1.4×10^9 t CO₂/a by 2060 (Chen et al., 2022). According to Annual report of carbon capture, utilization and storage (CCUS) in China (2021), 5.1×10^9 t CO₂/a through CO₂-EOR and about 9.0×10^9 t CO₂/a through CO₂ enhanced natural gas recovery (CO₂-EGR) can be stored in China (Cai et al., 2021; Liu S.Y. et al., 2022). It also reflects the necessity and huge advantages of China's oil and gas industry to deploy CCUS.

Challenges: 1) Most CCUS projects currently face the challenge

of high energy consumption and high costs, with an average net carbon reduction cost of 150–450 CNY/t CO₂ (Zhang X. et al., 2021). This has also led to the failure of most CCUS projects launched in the past three decades (Wang N. et al., 2021). Meanwhile, there are only a few large-scale CCUS integration projects at the million-ton level (GCCSI, 2021).

- 2) In terms of pipeline network planning, the optimization models have successfully been applied to CCUS sources-sink matching at the global, national, county or industry levels, and continue to expand and refine various influencing factors (Fan et al., 2020; Tang et al., 2021; Wei N. et al., 2021; Wei Y.M. et al., 2021). The previous studies have considered the impacts of technology competition, topography, policy, society, and other factors (Tang et al., 2021). However, the practicability of current models is still insufficient, especially for the CO2-EOR, where current models lack the consideration of complex variability of oil reservoir geological characteristics.
- 3) There are only few unified and comprehensive selection guidelines for China's oil reservoirs. Callas et al. (2022) developed a quantitative, criteria-driven methodology to assess the potential suitability of depleted oil reservoirs for carbon storage based on capacity and injectivity optimization, retention and geomechanical risk minimization, and economic constraints. It has been successfully applied to the selecting of 1317 fields in the Gulf of Mexico. However, compared with foreign marine oil reservoirs, China's oil reservoirs are mainly continental, characterized by high heterogeneity, small reserves and high water-cut. Therefore, there is an urgent need to develop a unified and comprehensive method for sequestration site selection which is applicable to China's oil reservoirs.

4.4. Hydrogen

Current status: The calorific value of hydrogen energy is three times that of gasoline, and its reaction products are clean and lowcarbon (Du et al., 2022). In addition, the discharge time of hydrogen energy storage can realize from hour to quarter, and its capacity can reach gigawatt level, which has obvious advantages over other energy storage technologies (Xu and Liu, 2022). In recent years, domestic energy giants have been actively deploying the entire hydrogen energy industry chain, including production, storage, transportation, and utilization. SINOPEC is planning to develop the hydrogen energy industry chain in two major areas: hydrogen transportation and hydrogen-based refining. The company plans to build 1,000 hydrogen refuelling stations or co-build stations with gas stations (SINOPEC, 2021). By the end of 2020, SINOPEC had carried out 27 pilot projects for hydrogen refuelling stations. PetroChina is focusing on diversified hydrogen production, as well as low-cost and efficient hydrogen storage and transportation. In November 2022, PetroChina's largest integrated refining project, a 3-million-ton/year hydrogenation unit for naphtha, was successfully put into trial production. CNOOC is planning to develop offshore wind power and electrolysis to produce hydrogen. Overall, hydrogen energy is an important part of China's new energy industry and a crucial step for energy transition in the oil and gas industry. Moreover, it is expected that the proportion of hydrogen energy in China's terminal energy consumption will reach about 20% in 2060 (CHA, 2021). Therefore, hydrogen energy has great development prospects.

Furthermore, the oil and gas industry has great advantages in deploying hydrogen energy: 1) In terms of technology advantage, the oil and gas industry has been a major producer and consumer of hydrogen for many years, and has rich technical base; 2) In terms of infrastructure advantage, by the end of 2020, the long-distance oil and gas pipeline in China reached 144,000 km, and hydrogen-

natural gas mixed transportation by using existing natural gas pipeline network is a feasible and cost-effective solution (PipeChina, 2022). In addition, the oil and gas industry have rich experience in transporting liquid fuels such as CNG, LNG and LPG by tankers and ships; 3) In terms of terminal sales, the oil and gas industry has a large number of gas station facilities and obvious location advantages, thus it can reduce construction costs and seize market demand by transforming into an integrated gas and hydrogen station.

Challenges: 1) Most key technologies are immaturity. The hydrogen industry chain can be divided into hydrogen production, transportation and storage (T&S), and utilization. Among the production technologies, green hydrogen production from electrolytic water is widely considered to be the mainstream in the future (Xu and Yu, 2021). However, it hasn't realized commercialization and its TRL is mostly below 9 at present. In addition, no large-scale hydrogen T&S technology with obvious feasibility and cost-effective has been developed yet (Xu and Yu, 2021).

- 2) The costs are relatively high. In terms of production, the current costs of various green hydrogen production from electrolytic water technologies are much higher than that of grey and blue hydrogen, as shown in Fig. 3 (IEA, 2021; Xu and Yu, 2021). Therefore, the blue hydrogen made from fossil energy + CCS will become the main production technology in the early and medium stage. In terms of transportation, pipeline is still the best choice for largescale fixed-line hydrogen transportation. However, to avoid the "hydrogen embrittlement", hydrogen pipeline needs to be made of low carbon material, which is more than twice the cost of natural gas pipeline. Although the hydrogen blending in natural gas pipelines has become a cost-effective way, the proportion of hydrogen cannot exceed 20% currently (Xu and Yu, 2021). In addition, the single station investment cost of new hydrogen refuelling station is about 8-20 million CNY, which is much higher than that of gas station. Moreover, it is expected that it will take 10-15 years to realize positive cash flow due to the low market share of hydrogen fuel cell vehicles in the early stage (Du et al., 2022).
- 3) The industry standard and regulation system are not sound. In recent years, discussions and concerns about the safety of hydrogen fuel cell vehicles have also become a key factor limiting its development. In addition, there are many problems in the process of hydrogen refuelling station construction, such as the lack of clear approval and supervision department (He et al., 2020).

5. Strategies and roadmaps for oil and gas industry's transition towards carbon neutrality

In light of the new challenges considering carbon neutrality, this section attempts to present a far-reaching discussion from the following aspects and then provide a roadmap for China's oil and gas industry.

5.1. Strategy and roadmap of market mechanism reform

In addition to accelerating the marketization of oil and gas industry, encouraging oil and gas enterprises to participate in the carbon trading system will play a more important role in responding to the carbon-neutral pledge. It is regarded as an alternative for transferring external costs of the low-carbon transition to the internal. Referring to the international lessons, this study proposes several coping strategies for the deep involvement of oil and gas enterprises in carbon emission trading. Establishing a robust and reliable accounting and compilation system to measure and verify carbon emission data is the cornerstone of corporate carbon assets management. In particular, near-real-time carbon emission accounting technologies are urgently needed to help

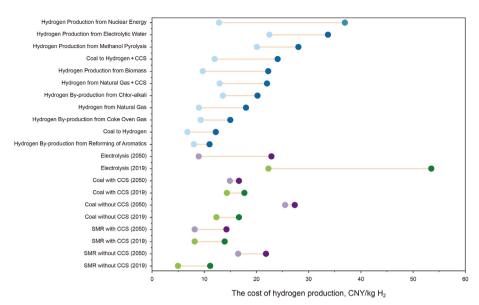


Fig. 3. Costs of different hydrogen production technologies (Notes: SMR refers to steam methane reforming to hydrogen; Blue points indicate the costs of hydrogen production technologies in China, statistics for 2021; green points indicate the costs of hydrogen production technologies in the world, statistics for 2021; purple points indicate the predicted value for 2050.).

achieve carbon neutrality (Liu Z. et al., 2022). Currently, many energy-intensive companies are required to disclose their greenhouse gases (GHGs) emissions, but the quality of GHG reports and their contribution to assessing companies' environmental performance are debatable. Multiple estimation methods and varying operational processes at the facility level could undermine the comparability and commensurability of corporate-level GHG emissions estimates (Wegener et al., 2019). Although China already issued Accounting Methods and Reporting Guidelines for Greenhouse Gas Emissions of China's Oil and Gas Producers (Trial) in 2014, which clarifies the accounting boundary in emission sources and types of gases and methods for examining activities level and emission factors, consolidating GHG emissions from different facilities at the corporate level could lose eco-efficiency information and obscure the poor performance of specific facilities (NDRC, 2014). Therefore, unpacking carbon emission accounting and improving granularity is expected to be a taste of what's to come.

To better engage in the energy use rights trading system, oil and gas enterprises are suggested to take a series of tactics and measures in advance. First of all, the oil and gas enterprises should establish a comprehensive monitoring framework for business units and facilities' energy consumption to fully explore their energy-saving potential, relying on emerging digital and internet technologies. Secondly, allocating energy use quota within the corporate should follow a principle of both equity and efficiency, but as a matter of fact, it's a really hard thing to do. Four different allocation schemes based on historical consumption/emissions, economical outputs, and energy-saving costs could provide a reference (Pan and Dong, 2022). To sum up, the preliminary roadmap for the opening of China's oil and gas industry and its participation in carbon emission and energy use rights trading is shown in Fig. 4.

5.2. Strategy and roadmap of supply-consumption balance security

Recently, the substitution effect of renewable energy for traditional energy has not been fully reflected, oil and gas will remain the mainstay of China's energy consumption in short-to-medium

term. Towards carbon neutrality, the government has issued energy development targets that call for 25% and 80% of non-fossil energy consumption by 2030 and 2060, respectively (GOV, 2021b; NCNA, 2021b; NDRC, 2022). Under this background, many scholars and institutions have predicted oil and gas development pathways, as shown in Fig. 5, the oil and gas consumption will reach its peak around 2025 and 2040 respectively (CNPC, 2021a; Kuang et al., 2022; Pan et al., 2020; Yang et al., 2016). Therefore, the oil and gas industry should maintain confident in promoting the development of crude oil and in particular natural gas in short-tomedium term. However, the high external dependence will still be a problem threatening energy security. To realize carbon-neutral pledge while ensuring energy security, the following development pathways for oil and gas supply and demand are proposed.

The oil and gas industry needs to concentrate its efforts on breakthroughs in key technologies, increasing unconventional oil and gas single well production and recovery factor, and accelerating the deployment of infrastructure and carbon-negative technology. This requires comprehensive efforts in technology innovation, national cooperation, and market reforms. Firstly, the investment in exploration and development needs to be continuously increased to break through the restrictions on exploration in restricted areas, and achieve large-scale development of unconventional oil and gas resources such as shale gas, coalbed methane, and tight oil and gas (Hu et al., 2021). At the same time, it is crucial to enhance the R&D of key technologies such as renewable energy, CCUS, and hydrogen energy, and infrastructure. Secondly, facing the constantly increasing external dependence, the international cooperation through the "Belt and Road" initiative need to be strengthened to achieve diversification of external suppliers. In addition, the industry should also increase the layout and construction of storage and transportation facilities, and construct a "national network" with interconnection and unified scheduling. Finally, green finance and policy innovation, such as carbon trading and carbon taxes, should be actively explored by the industry. Enterprises need to actively shoulder the responsibility of environmental protection and sustainable development.

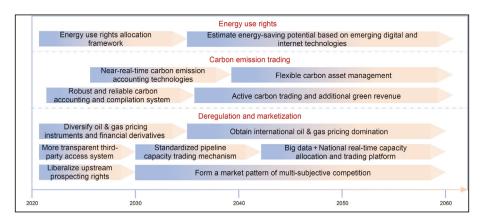


Fig. 4. The roadmap of market mechanism reform.

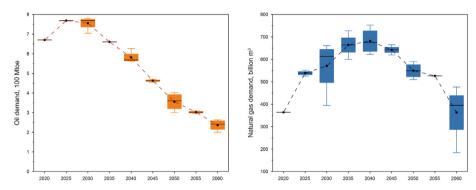


Fig. 5. The supply-consumption balance roadmap of crude oil and natural gas.

5.3. Strategy and roadmap of technology innovations

Technology innovation and application are the key solutions to improve quality and efficiency in the oil and gas industry, and are the main drivers to achieve the dual-carbon goal. This section discusses the key technology development strategies and roadmap in China's oil and gas industry from digitalization, photovoltaic, wind power, CCUS, hydrogen and multiple technology synergy development, respectively, as shown in Fig. 6.

- 1) Facilitating the digital intelligence of the oil and gas industry. Towards carbon neutrality, digital technologies should be used in carbon-neutral related business, such as building a carbon emission monitoring and data management system for the oil and gas industry. On the other hand, the application pathway of different technologies needs to be reasonably planned: 1) Big data analysis has been applied widely and enabled the oil and gas industry to realize digitalization basically; 2) Cloud computing, blockchain and IoT technologies will be widely used by 2025, 2030 and 2030 respectively to promote the comprehensive efficiency of oil and gas industry; 3) Artificial intelligence and digital twin technologies will play a major role after 2030 to facilitate the digital intelligence of the oil and gas industry.
- 2) Accelerating the deployment of renewable energy generation technologies. Although the oil and gas industry has some experience in carrying out photovoltaic and wind power projects, the existing installed capacity is clearly insufficient in the face of large-scale clean power demand for energy transition and decarbonized production. Firstly, oil and gas companies need to invest in photovoltaic and wind power technologies in

line with the direction of technology development. The development trend of key technology components for photovoltaic and wind power is shown in the Fig. 6. In term of photovoltaic. high conversion efficiency cells are the critical component. Thinfilm solar cells will be widely used by around 2030. In term of wind power, large-scale and light-weight is the future trend of wind power. The high-modulus and high-strength glass fiber will become the mainstream of blade technology in the early stage. Moreover, with the cost reduction of carbon fiber, it will gradually replace glass fiber to become the mainstream. Meanwhile, energy storage technology can ensure the stability and safety of photovoltaic and wind power generation. Therefore, oil and gas companies combine with self-production characteristics as well as technology innovation to layout wind-photovoltaic-storage hybrid power system. Finally, in order to reduce the negative environmental externalities of photovoltaic and wind power end-of-life, an improved recycling mechanism is also necessary.

Developing multiple oil flooding and storage centers based on CCUS.

Towards carbon neutrality, the oil and gas industry needs to develop multiple oil flooding and storage centers based on CCUS, for which it should focus on the following aspects. Developing a methodological process for sequestration site selection, which needs to consider: ① The characteristics of China's oil &gas reservoirs; ② Capacity and injectivity optimization; ③ Geological and ecological risks minimization; ④ Economic cost constraints; ⑤ The negative externality of the environment and human health.

Establishing a specific source-sink matching system for deploying CCUS-EOR. Based on the existing source-sink matching

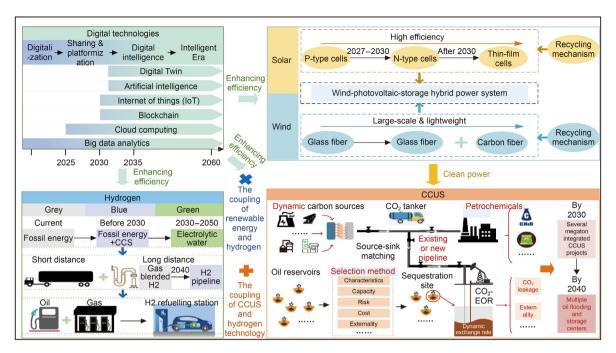


Fig. 6. The roadmap of key technologies for oil and gas industry toward carbon neutrality.

model, the following improvements are needed: ① More comprehensive, broader, and dynamical carbon sources (Zhang et al., 2022); ② Considering the existing and new pipelines; ③ Considering the dynamic effects of geological characteristic changes on the CO_2 exchange rate and storage potential; ④ Considering petrochemical utilization of CO_2 , such as methanol, to improve the economics of CCUS; ⑤ Quantifying the externality of environment and human health as the economic cost for sourcesink matching. ⑥ It is necessary to consider the variation of CO_2 leakage rate in different reservoirs and the construction of related monitoring facilities.

Finally, the oil and gas industry need to focus on large-scale integrated CCUS projects, prioritize developing oil flooding and CO₂ storage technologies, and strive to build several megaton integrated CCUS-EOR projects by 2030. Subsequently, developing multiple oil flooding and storage centers in oil and gas basins by 2040.

4) Breakthrough the bottleneck of hydrogen production and Transportation & Storage (T&S) technologies. Although the oil and gas industry has rich experience in hydrogen production, T&S, and utilization, its current capacity is already stretched in the face of the large-scale demand for low-carbon hydrogen towards carbon neutrality. The key factors limiting its development is the high uncertainties of technology innovation. The cost of electrolytic water to green hydrogen technology remains high currently, and by 2030, it can be cost-competitive with blue or grey hydrogen in areas with high resource endowment. Subsequently, it will become the main technology for hydrogen production by 2050. However, what's worse is that hydrogen T&S technologies have encountered a bottleneck. In order to reduce cost, natural gas blended hydrogen transportation seems to be an economic-feasible way, however, the allowed ratio of hydrogen blending is low and difficult to enhance. Moreover, the costs of constructing new hydrogen pipelines or refuelling stations remain high. Therefore, in the future, the oil and gas industry should pay more attention to the R&D of hydrogen T&S technology.

5) Focusing on the coupled development of multiple technologies. It is important to focus on the economic benefits or technical efficiency enhance from the coupling of multiple technologies: ① The coupling technology of renewable energy and hydrogen. On the one hand, renewable energy power can be used to produce green hydrogen; on the other hand, hydrogen energy storage has the advantages of large discharge timespan and high capacity, which is important to promote the high proportion penetration of renewable energy; ② The coupling technology of CCUS and hydrogen. On the one hand, fossil energy to hydrogen projects can be utilised as carbon sources for CCUS; on the other hand, low-carbon hydrogen can be produced based on CCUS, and it is also considered to be the dominant hydrogen production technology by 2030.

5.4. Strategy and roadmap of oil and gas enterprises' reform

Carbon-neutral pledge has increased the urgency of green transition for China's oil and gas enterprises. They are facing challenges such as heavier emission abatement obligation, less demand for their products, and more stringent investment environment. However, at the same time, multiple opportunities such as digital transition, renewable energy deployment, and CCUS have also emerged. Therefore, oil and gas enterprises should catch up the opportunity to take the lead in green transition. At the same time, major oil and gas enterprises should also increase the publicity of their own social obligation to fulfil the green transition, and guide smaller enterprises to join the low-carbon transition, so as to achieve the carbon-neutral pledge for whole industry.

In recent years, major oil and gas enterprises have committed to realizing carbon neutrality and announced milestones or strategies. Carbon-neutral pathways of six major oil and gas enterprises were investigated, and detailed pathways are shown in Table 1.

To respond to the carbon neutrality commitments, oil and gas companies are striving to achieve three main goals: decarbonizing traditional energy businesses, developing new energy businesses, and exploring multi-technology coupled management models. The

Table 1Carbon-neutral pathways of major oil and gas enterprises.

Company target			Relative millstones	
			Volume/Structure	Intensity
BP	Become a net zero company by 2050 or sooner	 Net zero across BP's operations on an absolute basis by 2050 or sooner. Net zero on carbon in BP's oil and gas production on an absolute basis by 2050 or sooner. 		 50% cut in the carbon intensity of products BP sells by 2050 or sooner. Reduce methane intensity of operations by 50%.
Shell	Become a net-zero company business by 2050		(Scope 1 and Scope 2) by 50% by 2030, compared to 2016 levels	s > Carbon intensity reduction target: Short-term: 2024 (by 9%–12%) Medium and long term: 2030 (by 20%), 2035 (by 45%), 2050 (by 100%) The Seep the methane emissions intensity below 0.2% by 2025.
Aramco	Achieve net-zero Scope 1 and Scope 2 greenhouse gas emissions across operated assets by 2050	Reduce net Scope 1 and Scope 2 GHG emissions from the Upstream and Downstream businesses by 52 MMtCO ₂ e from business-as-usual 2035 forecast emissions.		➤ Reduce upstream carbon intensity by at least 15% by 2035;
CNPC	Achieve near-zero emission by 2050	Chilistons.	 ➤ The proportion of nevenergy capacity reaches 7% by 2025; ➤ Achieve the balance among renewable business, oil business, and gas businesse in energy structure by 2035 	g s
Total	Achieve carbon neutrality (Scope 1+2+3) by 2050	➤ Net Zero across Total's worldwide operations by 2050 or sooner (Scope 1+2) ➤ Net Zero across all its production and energy products used by its customers in Europe by 2050 or sooner (Scope 1+2+3)		> 60% or more reduction in the average carbon intensity of energy products used worldwide by 2050 (less than 27.5 g CO₂/MJ), with intermediate steps of 15% by 2030 and 35% by 2040 (Scope 1 + 2 + 3)
CNOOC	Achieve carbon neutrality by 2050		➤ 2021-2030: The carbon peak goal will be achieved; ➤ 2041-2050: The carbon neutrality goal will be achieved.	n ➤ 2021–2030: carbon intensity will be decreased.

following is the formulated carbon neutrality development strategy for oil and gas companies: 1) China's demand for natural gas is expected to peak around 2040, thus companies need to adjust their business focus while ensuring the dominant position of natural gas. At the same time, digital technologies, such as digital twin, cloud computing, and big data analysis, can be used to optimize operations and management as well as improve production efficiency. 2) the oil and gas companies need to ultimately transform into comprehensive energy companies. Before 2030, enterprises should focus on developing wind and photovoltaic power generation technologies, while conducting research on energy storage technologies such as hydrogen storage and sodium-ion batteries to prepare for the next technological upgrade. Before 2040, hydrogen fuel cell technology and hydrogen storage technology should be gradually promoted, combined with wind and photovoltaic power generation technologies, to build a renewable energy power grid. Before 2050, large-scale renewable energy technologies should be promoted, and traditional fossil fuels should be gradually phased out, achieving comprehensive carbon neutrality. 3) Oil and gas companies can rely on the advantages of oil and gas fields to carry out CCUS demonstration projects, explore breakthrough CO2 resource utilization and storage technologies, such as CO2 mineralization and deep saline formation storage technology, and lay out CCUS pipeline construction. After 2030, with the cost of CCUS technology decreasing, enterprises can actively promote the scale application of CCUS. Meanwhile, the companies actively include carbon emissions into their business considerations to improve their economic benefits and sense of social responsibility. 4) In the process of achieving carbon neutrality, oil and gas companies need to consider adopting multiple technology coupling solutions. This requires enterprises to collaborate with universities, governments, and other relevant institutions to integrate resources and professional knowledge from all parties and achieve more efficient and sustainable management and operation solutions.

6. Conclusions

The oil and gas industry plays a vital role to realize China's carbon-neutral pledge and energy security because of its huge carbon reduction potential. However, most previous studies failed to present detailed strategies and pathways. To bridge these gaps, this study reviews the current status and new challenges in terms of market mechanisms, oil and natural gas consumption and key technologies. To address the new challenges, this study presents a detailed and comprehensive roadmap for China's oil and gas industry towards carbon neutrality. Several corresponding countermeasures are highlighted in the roadmap.

(1) In terms of market mechanism reform, encouraging participation in market transactions through establishing a robust and reliable accounting and compilation system, improving the granularity of carbon emission accounting, monitoring business units and facilities' energy consumption, allocating energy use quota with the principle of both equity and efficiency.

- (2) In terms of crude oil and natural gas supply-consumption balance, promoting the development of oil and gas, particularly unconventional resources, in short-to-medium term, and increase the R&D and deployment of key technologies to realize carbon-neutral pledge while ensuring energy security.
- (3) In terms of key technology innovation, the oil and gas industry should deploy key technologies based on the industry's advantages, accelerate breakthroughs in key technology innovation, and focus on the coupled development of multiple critical technologies.
- (4) In terms of enterprises' carbon-neutral plans, oil and gas companies in China should prioritize developing renewable energy, hydrogen and CCUS technologies, while maintaining the role of natural gas as a transitional energy source. Collaboration with academic and government institutions is necessary for the implementation of efficient and sustainable management strategies.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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