Resilience Building of Natural Gas Trade Network Security under Dual Carbon Targets: A Study on Risk Identification and Multidimensional Strategies

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Abstract: With the transition of global energy structure to low-carbonisation, natural gas, as a key transitional energy source, and the security and resilience of its trade network are crucial to ensure the stability of energy supply. Based on the background of the 14th Five-Year Plan, this paper analyses the current status of the resilience of the international natural gas trade network and the risks it faces in terms of geopolitics, supply and demand imbalance, and cybersecurity, discusses China's challenges in terms of natural gas resource endowment, dependence on LNG imports, and contingency reserve capacity, etc., and puts forward proposals on diversifying gas supply, strengthening cybersecurity technology, deepening international cooperation, and enhancing system resilience, deepen international cooperation, enhance system resilience and other countermeasure suggestions. The study aims to provide theoretical references for China to build a more risk-resistant natural gas trading system, and to help achieve the goals of carbon peaking and carbon neutrality.

Keywords: Natural gas trade; Cybersecurity resilience; Energy security; Geopolitics; Contingency reserves.

1. Introduction

In the context of global energy transition, natural gas has become an important choice for optimising the energy structure due to its low-carbon and high-efficiency characteristics. "The 14th Five-Year Plan clearly states that China should focus on building a clean, low-carbon, safe and efficient energy system, promoting the transformation of energy consumption to electrification and low-carbonisation, while strengthening the regulation capacity of the energy system to ensure energy security and green development, with a focus on enhancing the capacity of natural gas reserves and supply, in order to realise the goal of reaching carbon peaks and carbon neutrality. Natural gas is the energy source with the lowest carbon emissions among fossil energy sources, with the advantages of low carbon, high efficiency and cleanliness, and is an important choice for building China's modern energy system. As a key transitional energy source in the energy transition process, the security of supply and demand of natural gas is a core component of energy security. The resilient strength of the natural gas trade network is the key to ensuring stable energy supply and reducing dependence on a single energy source. Strengthening the resilience of the natural gas trade network can ensure the stability of natural gas supply in the face of various internal and external shocks, effectively preventing the emergence of supply crises and thus safeguarding national and regional energy security.

Viewed from a global perspective, the international community's attitude towards fossil fuels is shifting as emission reduction targets under the Paris Agreement framework become more stringent. A few European countries have announced that they are abandoning coal in favour of greater investment in natural gas, which has led to stronger demand for cleaner, low-carbon fuels globally. The global oil and gas market is experiencing sharp price volatility due to a combination of factors, including the Russia-Ukraine conflict and slowing economic growth. Meanwhile, the global natural gas market continues to face the persistent impact of economic recovery and geopolitical conflicts, further accelerating the reconfiguration of the market landscape. Strengthening the security resilience of the natural gas trading network means strengthening the ability of the natural gas trading network to maintain its basic functions, quickly recover and adapt in the face of various internal and external risks and challenges. Under the role of internal demand and external influence, strengthening the security and resilience of natural gas trade network is of great significance to China's current efforts to ensure energy security, cope with geopolitical risks, adapt to climate change, promote economic development, enhance market competitiveness, safeguard people's livelihood, and push forward energy transformation. This paper combines international experience and domestic practice, systematically analyses the current situation and risks of natural gas trade network security resilience, and puts forward targeted recommendations, with a view to providing decision-making support for safeguarding national energy security.

2. Status and Challenges of Cybersecurity Resilience in Natural Gas Trade

As a clean energy source, natural gas is becoming increasingly important in the global energy mix. China is one of the world's largest energy consumers, and the demand for natural gas continues to grow. According to the latest research, the global energy distribution is mainly concentrated in the regions of Russia-Central Asia, West Asia, North Africa and the Americas, which leads to a typical centre-periphery pattern in the international energy trade network, generating an obvious stratified trade network pattern.

2.1. Resilience of International Energy Trade Networks

Analysed from the perspective of static structural stability assessment, the overall risk resistance of the international natural gas trading system is relatively weak, the robustness of the oil trading network is at a medium level, while the coal trading system shows optimal risk resistance. This difference suggests that the coal trade system is more stable when facing external shocks, and its topology has better self-healing properties [1]. The international trade pattern of natural gas shows significant core-periphery characteristics, with an overdependence on key node countries, and this structural vulnerability can easily amplify the negative effects of unexpected events, which may lead to the risk of disruption in the energy supply chain.

In the dimension of dynamic adaptive capacity, China has demonstrated a significant pivotal role in the global energy trade system. Based on the analysis of the node resilience stratification model, China's key indicators in the energy trade network have consistently ranked in the top two tiers, which reflects China's excellent resilience and dynamic adjustment mechanism in response to systemic risks. This advantage stems mainly from three dimensions: first, as the world's largest consumer of fossil energy, China has formed diversified import channels; second, through the construction of multilateral trade cooperation, it has formed an energy trade network that radiates around the globe; and third, by virtue of its position as the core hub in the trade network, it has constructed a unique risk buffer mechanism, which is a structural advantage that has effectively strengthened the resilience space of the energy supply chain.

2.2. Challenges to International Energy Trade Networks

In the global economic governance system, the international energy trade network not only carries fundamental strategic value, but also faces the serious challenge of complex risk superposition. Specifically manifested as: First, sudden black swan events (such as the new crown epidemic global pandemic) and geopolitical conflicts (such as the Russian-Ukrainian war) to form a composite impact, triggering cross-border energy supply chain persistent perturbations; Second, energy supply and demand structure of the spatial and temporal mismatch exacerbated the volatility of the market, typically characterised by the price of fossil fuels to present an irrational and violent oscillation, the state of this market disorder seriously weakened the global energy system stability; Third, energy security crises show a trend of normalised evolution, its duration and impact of the international energy trade network. Thirdly, energy security crises have shown a trend of normalised evolution, with significant uncertainties in their duration and scope of impact, and it is particularly noteworthy that the energy supply chain is undergoing structural reconfiguration, which is manifested in grey rhinoceros risks such as the strengthening of regional cooperation alliances and the diversification of trade routes [2].

2.3. Resource Endowment Is About Security of Supply

As the world's largest energy consumer, China's economic and social development has always been the primary issue of energy security. Resource endowment leads to China's natural gas in the supply and consumption derived from resource risk, transport risk, market risk, etc., in the face of higher uncertainty and uncontrollable factors, its impact on energy supply is more obvious. According to China Natural Gas Development Report (2024), China's natural gas market has achieved remarkable development in recent years. It has increased from 107.6 billion cubic metres (bcm) in 2010 to 394.5 bcm in 2023, with a CAGR of 9.7%. In 2023, natural gas accounted for 8.5% of total primary energy consumption, an increase of 0.1 percentage points from the previous year. Gas consumption in city gas, industrial fuel, natural gas power generation, chemical fertiliser and other fields are showing steady growth. It is expected that by 2024, China's apparent natural gas consumption could reach 425 billion cubic metres, 2.9 times that of 2012. This growth trend indicates that natural gas is playing an increasingly prominent role in China's energy structure.

2.4. China's LNG Trade Risk

China's increasing consumption of natural gas has led to a growing dependence on liquefied natural gas (LNG) imports. LNG trade faces a few risks that could have an impact on China's energy security and economic stability. Supply chain instability is a major risk to China's LNG trade. Factors such as political instability in LNG supplying countries, weather changes, and natural disasters such as earthquakes and tsunamis may have an impact on the LNG supply chain. International gas price volatility is also a key risk. the volatility and instability of international oil prices have an impact on LNG prices, which could lead to rising costs of LNG imports for China, which in turn could put pressure on its economy. the safety of LNG shipments is also a risk that needs to be looked at. lNG is a flammable and explosive chemical, and the risks of transporting it cannot be ignored. Global climate change and the environmental agenda are also creating some uncertainty for China's LNG trade. As the international community's focus on carbon emissions increases, the adoption of cleaner energy is becoming a global trend, and while LNG is cleaner than other fossil fuels, it still has carbon emissions.

3. Outstanding Problems in China's Natural Gas Trading Network

The current comprehensive resilience of natural gas trade network security is low, relying mainly on a few core countries to support it, with a low level of network resilience. The natural gas international trade network has a greater destructive impact in the event of shocks, and the network structure is less stable. In addition, the number of edges in the natural gas trade network is much smaller compared to the international coal and oil trade network, which indicates that the trade links between countries in the network are not close, and they are also the most vulnerable to damage when subjected to external shocks.

3.1. Risks due to Resource Endowment

The characteristics of China's natural gas resource endowment have led to the derivation of resource risks, transport risks, market risks, etc., in terms of supply and consumption. In the face of high uncertainty and uncontrollable factors, the impact of these risks on energy supply is more obvious. For example, more than 80 per cent of China's geological resources of conventional natural gas to be proved belong to low-permeability, deep, deep-water and high-sulphur gas, making exploration and development difficult and risky.

3.2. Geopolitical Factors

In the geopolitical context, the transnational gas pipeline transport system is characterised by significant vulnerabilities. As a typical trans-regional energy infrastructure, its strategic interdependence exposes the system to multiple sources of risk: first, physical security risk, cross-border terrorist attacks, pipeline damage caused by extreme weather events and other emergencies directly threaten the integrity of the transport corridor; second, socio-political risk dimension, supply chain disruptions triggered by disputes over labour rights and interests, and policy changes caused by regime change in the resource countries and other systematic risks. Secondly, the socio-political risk dimension, the systemic risks such as supply chain disruptions caused by labour rights disputes and policy changes due to regime changes in resource countries have formed the transmission mechanism of energy supply disruption; thirdly, the strategic game risk dimension, the geopolitical crisis represented by the Russian-Ukrainian conflict not only reconfigured the Eurasian energy transport map, but also catalyzed the explicit development of the trend of weaponisation of energy [3]. This composite risk matrix leads to three major strategic consequences: firstly, the hidden costs of cross-border energy trade show an exponential growth, which is manifested in the surge of insurance costs, agreement implementation risk premiums, and other market-based manifestations; secondly, there is a dynamic downward shift of energy security thresholds, and special attention needs to be paid to the decline in supply chain resilience caused by insufficient redundancy in infrastructure; and lastly, the attributes of the strategic gaming tools of oil and gas resources are strengthened to form a Finally, the strategic gaming tool attribute of oil and gas resources has been strengthened, resulting in the Matthew effect of asymmetric expansion of the bargaining power of supply and demand sides, and this structural change is reshaping the power topology network of global energy trade.

3.3. Tight Market Supply and Demand Situation

China has long been one of the world's largest importers of LNG. According to customs data, 92.5 million tonnes of LNG were purchased in 2022, up 19 percent from the previous year. Among them, Australia, Qatar and Malaysia ranked in the top three, accounting for 27%, 17% and 10% respectively. In 2023, the country imported 165.6 billion cubic metres of natural gas, up 9.9% year-on-year. Although sea transport is convenient and fast, overseas gas sources are vulnerable to the international situation, such as trade disputes, shipping lane blockades and other uncertainties may interrupt supply routes at any time. China's proven natural gas reserves rank third in the world, with vast development potential. By the end of 2022, more than 130 large and medium-sized gas fields have been discovered in the country, mainly in the Tarim Basin, Ordos Basin and Sichuan Basin. However, the complex geological structure and high development costs have led to a slow growth rate of domestically produced gas [4]. According to statistics, domestic gas production will be about 232.4 billion cubic metres in 2023, still a big gap compared with the huge market demand. Coupled with the fact that commercial production of shale gas has just started, it will take time to increase production on a large scale.

The global gas market will gradually stabilise in 2024, but the overall supply and demand situation will remain challenging. Russia's pipeline gas supply to Europe may be further reduced, and the balance between global gas supply and demand will face a new test. Against this backdrop, China's natural gas market is facing the challenges of price volatility and supply uncertainty, but also new opportunities to promote the transformation of energy structure and enhance energy security. It is difficult to rely solely on a few major exporting countries to ensure adequate and sustainable supply, and once a country is hit by disasters, sanctions and other circumstances, it will directly affect the supply of the domestic market. Due to seasonal demand, the natural gas market is particularly vulnerable during the winter peak season. Relying solely on domestic storage and peaking capacity, there is no way to guarantee self-sufficiency and risk resistance in the face of high demand for natural gas.

3.4. Network Security Risks

Pipeline cybersecurity in the digital age needs to be strengthened. For example, the largest U.S. fuel transporter Cronier suffered a cyberattack, resulting in 5,500 miles of pipeline was forced to shut down, the U.S. declared a state of emergency, which also sounded the alarm for our country. In addition, in the process of China's digital transformation, there are also cases such as the "intelligent refinery based on the whole process of the business of the industrial control system network security protection programme", showing the importance of network security protection. In the mining sector, network security is essential to ensure the normal operation of mining equipment. In the event of a cyber attack, the extraction equipment may malfunction, affecting the production of natural gas. In the transport segment, especially when transported through pipelines, the same cybersecurity risks similar to those of oil pipelines exist, as hackers may invade the pipeline control system and change the transport parameters, leading to dangerous situations such as abnormal pipeline pressure. In the storage segment, cybersecurity issues may affect the safety monitoring system of storage facilities, making it impossible to accurately judge the storage status, which may lead to leakage and other security risks. In the distribution chain, cyberattacks may disrupt the distribution plan, leaving some areas undersupplied with natural gas and others oversupplied.

3.5. Emergency Supply Capacity

Short-term natural gas emergency supply and demand compression play an important role in upgrading natural gas energy systemicity and ensuring national energy security. China should enhance its emergency supply capacity mainly and demand compression capacity as a supplementary enhancement path. On the supply side, a multi-support emergency system should be built with underground storage as the main part, LNG and PNG as the supplementary part, and interconnection of pipeline networks. In addition, China's gas storage capacity accounts for only 6% of total gas consumption, far lower than one-third of Europe, and it should accelerate the use of salt caverns to build underground storage, and improve the level of market-oriented operation. In recent years, the pace of construction of gas storage complexes in China has accelerated significantly. As of early 2023, there were more than 40 large underground gas storage wells with an effective working capacity of about 13 billion cubic metres. However, they are still unbalanced in terms of geographical distribution, with most of them concentrated in the vicinity of several large producing areas in Northeast, North China and Northwest China. The number of small storage and distribution sites within cities is high, and the overall storage ratio is far below the level of developed countries, making it difficult to cope with sudden seasonal peak load requirements.

While prioritising residential demand, alternative flexibility is an effective way to enhance resilience on the demand side. Although the total mileage of long-distance natural gas pipelines in China has reached 87,000 km, and the total receiving and unloading capacity of LNG receiving terminals has reached 116 million tonnes/year, the infrastructure development is still insufficient compared to the fast-growing consumption demand. Especially in remote and rural areas, the coverage of natural gas supply network is low, which affects the popularity and utilisation efficiency of natural gas. At this stage, China's LNG receiving terminals are small in size and unevenly distributed, some of them are already operating at capacity when gas consumption peaks, while others have not yet been utilised to their full potential, which is still insufficient compared to countries with a large number of LNG receiving terminals.

4. Recommendations for Countermeasures to Strengthen the Resilience of Natural Gas Trade Cybersecurity

4.1. Diversified Gas Supply

Diversification of gas supply channels through international cooperation will reduce dependence on a single market. Cooperation with countries rich in natural gas resources should be actively expanded to increase the sources of imports, while the exploration and development of domestic natural gas resources should be stepped up to improve domestic self-sufficiency. Encourage and support technological innovation in the natural gas sector to improve supply efficiency and security. Investment in technological research and development in natural gas exploration, extraction, storage and transportation should be increased, and the application of new technologies and processes should be promoted to improve the efficiency and security of the entire supply chain. Expanding the overseas import map, in-depth cooperation with emerging gas sources such as Southeast Asia, Africa, South America, etc., and setting up multinational corporations responsible for procurement; exploring the option of a natural gas pipeline from Siberia to North China, and borrowing Mongolia or the Korean Peninsula to lay pipelines, to circumvent geopolitical strife zones and provide another alternative path; introducing third-party mediation agencies to supervise the implementation of contracts, and carrying out regular credit assessments to Avoiding disputes arising from transaction defaults.

4.2. Securing Trade Networks

Technical level: Enhance the application of encryption technology. Encrypt data transmission in the natural gas trading network, whether in terms of pipeline monitoring data, transaction data or storage data, to ensure that the data is not stolen or tampered with during transmission. For example, encryption algorithms such as Advanced Encryption Standard (AES) can be used. Intrusion detection system improvement. The establishment of an advanced intrusion detection system can monitor network activities in real time and detect and stop suspicious network intrusions in a timely manner. For industrial control systems in natural gas trading networks, such intrusion detection systems should be able to identify unusual access patterns to specific devices and processes.

Personnel and management level: Improve the awareness of network security among relevant personnel. Conduct network security training for staff related to the natural gas trade network, including technicians and managers, so that they can understand the importance of network security and common means of network attacks, such as phishing emails and malware. Establish a perfect network security management system. Clarify the responsibility for network security, standardise the network operation process, for example, stipulate that only authorised personnel can access key network systems, and conduct regular network security audits to find management loopholes and improve them in a timely manner.

4.3. Strengthening International Co-Operation

Strengthening international cooperation is conducive to the convergence of natural gas prices in the international and Chinese markets. In the international natural gas market, prices are affected by a variety of factors, such as supply and demand, geopolitics and financial markets. Through in-depth cooperation with the international market, China can better integrate into the international natural gas price system. For example, participation in international natural gas futures market trading enables domestic natural gas prices to reflect the changing trends in the international market, and at the same time allows the international market to better understand China's demand. This helps to reduce the impact of price fluctuations on China's natural gas market and improve market stability and predictability.

In the development and utilisation of international natural gas resources, international cooperation offers vast scope. China can cooperate with energy enterprises in other countries to jointly invest in the development of overseas natural gas resources. For example, in the Middle East and Africa, it can carry out exploration and exploitation projects through cooperation with local enterprises and international energy giants. Such cooperation can not only increase the total supply of global natural gas resources, but also obtain a stable share of natural gas resources for China. In terms of trade cybersecurity resilience, co-development projects can prompt all parties to jointly invest resources to safeguard the project's cybersecurity, from data security in the resource exploration phase to pipeline network security in the transport phase, and other aspects, so as to jointly deal with possible cybersecurity threats, and to ensure that the natural gas resources can be securely and stably supplied to the Chinese market.

4.4. Enhancing Energy System Resilience

Increase investment in energy reserve infrastructure. For natural gas reserves, it is necessary to build more and more advanced underground storage tanks, liquefied natural gas (LNG) receiving stations and other facilities. Underground gas storage can make use of geological formations such as depleted oil and gas fields and salt caverns, and has the advantages of large storage capacity and relatively low cost.

Increasing the number and scale of LNG receiving stations can improve China's ability to receive overseas LNG resources and further enrich the form of natural gas reserves. Meanwhile, in terms of new energy storage, it is necessary to encourage the construction of more large-scale energy storage power stations and optimise the layout of energy storage power stations, so that they can be better coordinated with natural gas power stations, power grids and other energy facilities, and realise the efficient conversion and storage of energy.

Promoting innovation in energy reserve technologies is key to enhancing the resilience of the energy system. In terms of natural gas storage technologies, more efficient storage technologies should be developed, such as improving the storage efficiency of underground storage reservoirs and improving LNG storage and regasification technologies. For new energy storage, it is necessary to increase R&D investment in new energy storage materials and technologies to reduce energy storage costs and improve the safety and reliability of energy storage. For example, research and development of high-performance lithium-ion battery materials, improve the energy density and cycle life of the battery; explore more suitable for large-scale energy storage liquid current battery technology, to solve its current technical bottlenecks.

Sound policies support the construction of energy reserve systems. For example, enterprises should be encouraged to participate in the construction and operation of energy reserve facilities through policies such as financial subsidies and tax incentives. In terms of management, it is necessary to establish a sound regulatory mechanism for energy reserves to ensure the safe and rational use of reserve resources. For natural gas reserves, it is necessary to standardise the procedures for the use of reserves, clarify under what circumstances reserve resources can be used, and how to carry out scientific deployment. For new types of energy storage, it is necessary to formulate unified technical standards and safety norms, strengthen the safety supervision of energy storage facilities, and prevent the overall resilience of the energy system from being affected by the safety problems of the energy storage facilities themselves.

4.5. Science-Based Risk Resilience

Scientific forecasting of market demand. Firstly, a three-dimensional data governance system is established: the environmental variables dimension integrates data on the evolution of meteorological patterns, the macroeconomic dimension incorporates structural indicators such as the industrial sentiment index and the GDP growth rate, and the industrial operations dimension collects fluctuating curves of capacity utilisation in key industries. Using big data mining technology stack (including distributed computing framework, feature engineering tool chain) and computational economics methods (such as dynamic stochastic general equilibrium model) for the collaborative analysis of heterogeneous data from multiple sources, it is especially necessary to build a causal inference engine to identify the conduction paths between potential variables. On this basis, a multimodal prediction architecture is constructed, incorporating ARIMA time-series analysis, random forest regression integration, and deep learning networks based on the attention mechanism. The model performance is tuned by Bayesian hyperparameter optimisation algorithm and adversarial validation mechanism is applied to ensure the robustness of the prediction system. At the model explanatory level, SHAP value analysis technique is used to deconstruct the marginal contribution of each feature variable. Particular emphasis needs to be placed on the construction of the dynamic environmental adaptation mechanism, which requires the establishment of a market disturbance response function that dynamically couples exogenous variables such as seasonal fluctuation patterns (extracted by Fourier transform), macroeconomic policy shocks (quantified by using event analysis), and competitive game dynamics (constructed by constructing a Nash equilibrium simulation model). With this systematic approach, the root-mean-square error of demand forecasts can be reduced to within the 65 per cent confidence interval of the industry benchmark value.

Establish a big data analysis system for natural gas digital technology. Establish a comprehensive data collection system: collect data from all links in the natural gas industry chain, including upstream natural gas extraction data (e.g., production from various gas fields, extraction costs, etc.), midstream transport data (e.g., pipeline transport flow rate, inventory changes in storage facilities, etc.), and downstream consumption data (data on residential and industrial gas use, etc.). By analysing the big data, risk factors in the natural gas trading network are identified. So that early warnings can be issued so that relevant enterprises and departments can take measures, such as increasing supply sources or adjusting transport routes. In addition, big data is used to analyse factors such as the trend of market price fluctuations, the supply capacity and costs of different suppliers, so as to optimise trade decisions, such as in which regions to build storage facilities and how to plan transport routes, in order to improve the security and resilience of the natural gas trade network.

Formulate an emergency plan for natural gas supply, establish an emergency reserve system and improve the ability to respond to emergencies. Establishing a joint mechanism for maintaining natural gas supply in extreme weather: With its professional meteorological monitoring and forecasting capabilities, the meteorological department is able to provide timely early warning information on extreme weather, such as forecasts of cold tides, torrential rains, typhoons and other weather. Based on such early warning information, natural gas production, transport and supply plans are adjusted in advance. Ensure the safe and smooth supply of natural gas across the country under extreme weather conditions and maintain national energy security. National-level emergency reserves of natural gas should also be established to ensure a quick response in case of supply disruptions and to safeguard people's livelihoods and the gas needs of important industries. Promote market-oriented reform of natural gas prices, establish a flexible price adjustment mechanism, and adjust the relationship between supply and demand in a market-oriented manner. The improvement of the price mechanism will help stabilise market expectations and promote stability and sustainability of supply.

5. Conclusion

The resilience of natural gas trade network security is the core element of energy security. By analysing the global pattern and domestic shortcomings, this paper proposes that a resilience system should be constructed from multiple dimensions, including diversified supply, network security and international cooperation. In the future, China needs to accelerate technological research and policy innovation, balance short-term emergency and long-term transformation needs, and contribute Chinese solutions to global energy governance.

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