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Strengthening the Resilience of China's Natural Gas Trade Network Security

-- An Energy Security Perspective under the "Dual Carbon" Goal

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Abstract: Against the backdrop of the "dual-carbon" goal, the global energy transition and drastic changes in the geopolitical landscape, the strategic position of natural gas as a key low-carbon transition energy source has become increasingly prominent, and the security and resilience of its trade network has become a core issue in guaranteeing China's energy security. However, its trade network faces multiple challenges such as resource dependence, geopolitical conflicts, fluctuations in supply and demand, and network security, threatening energy security and supply chain stability. Based on the system resilience theory and the "14th Five-Year Plan" energy strategy framework, this paper combines the structural characteristics of the international energy trade network and the resilience theory, systematically analyses the current situation and problems of China's natural gas trade network in static and dynamic dimensions, and reveals the multiple challenges faced by China's natural gas trade network in the areas of resource endowment, geopolitics, market supply and demand, network security and emergency response capability. The study finds that the current natural gas trade network in China is facing multiple challenges. The study finds that China's current natural gas trade network has problems such as low overall resilience, dependence on core countries, and lagging infrastructure, which are prone to supply risks in case of extreme shocks. By building a four-dimensional resilience enhancement framework of "diversified supply-technical protection-international synergy-system optimisation", the study proposes comprehensive measures such as expanding the diversified supply layout of gas sources, strengthening the digital security protection system, deepening the global resource cooperation, perfecting the emergency reserve mechanism and scientific risk management, etc., which will provide theoretical support for the construction of a safe and efficient natural gas trade network for China in the complex international environment. The study provides theoretical support and practical path for China to build a safe and efficient natural gas trade network in the complex international environment. The study shows that by improving the efficiency of domestic shale gas development (targeting a 50% self-sufficiency rate), deploying quantum encryption technology (reducing the risk of data leakage by 90%), building a transnational supply chain alliance (reducing the impact of geopolitical conflicts by 35%) and expanding storage capacity (adding 20 billion cubic metres of new gas), we can effectively strengthen the security and resilience of the natural gas trading network, which is of great reference value for enhancing the risk-resistant capacity of the energy system and promoting low-carbon transformation. This is an important reference value for enhancing the risk-resistance of the energy system and promoting low-carbon transformation, and will provide a guarantee for China to achieve its "dual-carbon" goal and energy security.

Keywords: Natural gas trade; Cyber security resilience; Energy security; Geopolitics; Risk management.

1. Introduction

Energy security is an important cornerstone of national development, according to the International Energy Agency (IEA) predicts that by 2040, the proportion of natural gas in global energy consumption will increase to 25%, becoming a key transition energy source to achieve the goal of carbon neutrality [1]. As the world's largest energy consumer, China's natural gas consumption has been growing at an average annual rate of 10% [2], and the 14th Five-Year Plan clearly states that efforts should be made to build a clean, low-carbon, safe and efficient energy system, to promote the transformation of energy consumption to electrification and low-carbon, and at the same time, to strengthen the regulatory capacity of the energy system to ensure energy security and green development. At the same time, it will strengthen the regulation capacity of the energy system to ensure energy security and green development, and focus on enhancing the reserve and supply capacity of natural gas in order to achieve the goal of carbon peaking and carbon neutrality. As the energy source with the lowest carbon emission among fossil energy sources (carbon emission per unit calorific value is only 56% of that of coal), natural gas has the advantages of low carbon, high efficiency and cleanliness, which makes it an important choice for building China's modern energy system. The security of its supply and demand has become a core component of energy security, and China's natural gas consumption will reach 383 billion cubic metres in 2023, with its dependence on the outside world rising to 45%, far exceeding that of the United States (15%) and Japan (98% dependent on imports but with a perfect reserve system). The global energy market is undergoing profound changes: the Russian-Ukrainian conflict has led to the reconstruction of the European natural gas supply chain, and the TTF price fluctuation in 2022 will reach 210%; the U.S. liquefied natural gas (LNG) exports have jumped to the top of the world, reshaping the pattern of global trade; and the natural gas demand in the Asia-Pacific region has grown by an average annual growth rate of 3.2%, making the region the most energetic consumer market [3]. Against this backdrop, especially as the dependence of the natural gas trade network

on a small number of core countries exacerbates the risk of supply disruptions, the security resilience of the natural gas trade network - i.e., the ability of the network to maintain functionality and recover quickly in the face of internal and external shocks such as geopolitical conflicts, price volatility, and supply chain disruptions - has become the key to guaranteeing stable energy supply in China. - has become the key to guaranteeing China's stable energy supply. In this context, enhancing the security resilience of natural gas trade networks is not only an urgent need to guarantee energy security, but also a strategic choice to support high-quality economic development and low-carbon transformation. In this paper, we study the current situation assessment, problem diagnosis, and countermeasure construction in three dimensions, aiming to provide systematic solutions to enhance the resilience of China's natural gas trade network.

2. Status of Cybersecurity Resilience in The Natural Gas Trade

2.1. Characteristics of Network Resilience in International Gas Trade

2.1.1. Hierarchical network pattern

The global natural gas trade network shows "center-periphery" distribution characteristics: Russia - Central Asia (accounting for 30% of global natural gas reserves), West Asia (35%), North Africa (8%), and the Americas (22%) as the main gas source centres, forming a trade network with the core exporting countries as the hub and peripheral consuming countries as the nodes [4]. trade network [4]. According to the analysis of complex network theory, the node concentration of natural gas trade network HHI index (Herfindahl-Hirschman index) is as high as 0.38, which is significantly higher than that of oil (0.25) and coal (0.18), indicating its lower level of resilience, as shown in table 1.

Table 1. Comparison of the resilience of major global energy trade networks

Type of energy	HHI index	Number of key nodes	Recovery time (months)
petroleum	0.38	5	6-12
petroleum	0.25	10	3-6
coals	0.18	15	1-3

For example, the 2022 Nord Stream pipeline explosion directly caused European gas prices to soar to €340/MWh, a 300% increase from the pre-conflict period, highlighting the knock-on risk of core node disruptions [4]. From the static resilience indicator, the density of the international natural gas trade network is only 0.12 (coal network 0.25), and the top 5 countries in terms of node degree centrality (Qatar, Australia, the United States, Russia, and Norway) control 68% of the global export volume, presenting a fragile structure of "dominated by a small number of core countries" (Liu Xiaoli, 2022). In terms of dynamic resilience, China is ranked 7th globally in terms of meso-centrality in the energy trade network, with some potential as a transit hub, but the node's resilience is prone to drop to the third tier under extreme shocks (e.g., disruption of a single gas source).

2.1.2. International Comparison of Resilience Levels

The entropy weight method is used to construct a comprehensive resilience index that includes network density, node importance, and resilience, and it is found that the resilience of the natural gas trade network (0.42) is significantly lower than that of the coal (0.68) and oil (0.55) networks. The key reasons are: natural gas trade relies on two dedicated infrastructures, pipeline and LNG shipping, with high asset specificity and weak substitutability; long contract duration (mostly more than 10 years), with insufficient flexibility in market adjustment; core exporting countries are concentrated in politically sensitive regions (e.g., the Middle East, Russia), with large geoexposure to risk [4].

2.2. Status of China's Natural Gas Trading Network

2.2.1. Rapid demand growth and rising external dependence

China's natural gas consumption has been growing at an average annual rate of 7.8% in the past decade, reaching 383 billion cubic metres in 2023, surpassing Japan to become the world's second largest consumer. Restricted by resource endowment, domestic production is only 239 billion cubic metres, and imports are 144 billion cubic metres (of which LNG accounts for 62%), mainly relying on Australia, Qatar and the United States, with external dependence rising from 32% in 2015 to 45% in 2023. Domestic storage capacity accounts for only 6% of consumption, well below the international average of 15% [5]. Pipeline import transport is highly dependent on Australia (35%), Qatar (18%) and Russia (12%), accounting for 65% of total imports, and the China-Russia Eastern natural gas pipeline accounts for 30% of total imports, with geopolitical fluctuations directly affecting the stability of supply, and the risk of disruption from a single source is prominent.

2.2.2. LNG Trade Risk Mapping

Supply chain risks are highly volatile. In 2021, a gas workers' strike in Australia led to a 22% weekly decline in China's imports, with spot prices in South China soaring to US$35/MMBtu; in 2022, Typhoon Huan Lanuo delayed LNG shipments in Southeast Asia, and emergency reserves in the Yangtze River Delta region were utilised at a rate of 40%. LNG price instability: international LNG prices are linked to crude oil (60% of pricing weight); in 2022, Brent crude oil prices will fluctuate by 120%, increasing China's import costs by US$23 billion. Transport security: 70% of global LNG shipments need to go through the Strait of Malacca, and pirate attacks and shipping lane congestion (e.g., blockage of the Suez Canal in 2021) directly threaten supply chain security [6].

2.3. External Shocks and Systemic Vulnerability Exposure

2.3.1. Cybersecurity Challenges in Digital Transformation

With the application of technologies such as smart pipeline monitoring and blockchain trading platforms, cybersecurity threats are becoming increasingly prominent. the ransomware attack on the Coronel Pipeline in the US in 2021 demonstrated that digital vulnerabilities in critical infrastructure can paralyse supply chains. 70% of pipeline monitoring systems in China still use traditional firewalls, and only 30% deploy intrusion detection systems (IDS). 2022, a provincial pipeline network was out of service for 48 hours due to a ransomware attack, resulting in a direct economic loss of 120 million yuan [9]. China's technical reserves in the field of industrial control system protection, data encryption and other areas are still

insufficient, and there is an urgent need to build a full chain security system.

2.3.2. Ripple effects of geopolitical shock

The Russian-Ukrainian conflict triggered a reconfiguration of the global gas trade landscape, with Russia's pipeline gas supply to Europe falling by 45 per cent in 2022, driving a 28 per cent increase in European LNG imports. The United States took the opportunity to expand its exports, with a 37% increase in LNG exports to China, but the contract price included a 15% "geopolitical premium", a move that severely squeezed China's purchasing space. 120 million tonnes of Chinese LNG imports in 2023, 80% of which were transported via the Strait of Malacca, with an average annual loss of more than $500 million due to pirate attacks. China-Myanmar natural gas pipeline due to the unrest in Myanmar, 2021-2023 cumulative shutdown 12 times, resulting in a gas supply gap of 5 billion cubic metres in the southwest [7].

2.3.3. Systemic tests of climate extremes

In 2021, the winter cold wave caused China's daily natural gas consumption to exceed 1.2 billion cubic metres, and the utilization rate of gas storage reservoirs reached 85%, resulting in the phenomenon of "suppressing non-gas to protect the people" in some areas; in 2023, the summer high temperature spawned a surge in gas consumption for power generation, and the load rate of LNG receiving stations in East China exceeded 95%, exposing the problem of insufficient seasonal peaking capacity. The impact of meteorological disasters on overseas supply synchronisation. The impact of meteorological disasters on overseas supply is simultaneously amplified. In 2022, the cold wave in Texas, the United States, led to a 60% drop in LNG production capacity, and the spot price in the global market rose by 40% in a single day [8].

3. Issues Facing the Resilience of Natural Gas Trade Networks in Terms of Security

3.1. Structural Dependencies Leading to Network Vulnerability

3.1.1. Gas concentration risk

The characteristics of China's natural gas resource endowment lead to the derivation of resource risk, transport risk, market risk, etc., in terms of supply and consumption. The top three import source countries account for 65% of the total (the IEA suggests a safety threshold of below 40%), with a single country, Australia, accounting for 35%, far exceeding the US (22% dependence on Canadian gas) and the EU (35% dependence on Russia's all-time high), and if the relationship between China and Australia deteriorates and leads to supply disruptions, there will be a gap of 12bn m3 of gas in the winter months in North China.2023 After the "Nord Stream" pipeline explosion, the European Union ( ) reduced its single-source dependence to less than 25% through diversification strategies, while China's interest in the Australian LNG project accounts for only 18%, most of which is purchased from spot, with weak bargaining power [4]. Meanwhile, more than 80% of China's conventional natural gas geological resources to be proved belong to low-permeability, deep, deep-water and high sulphur gas, which is difficult to explore and develop with high risk.

3.1.2. Infrastructure network deficiencies

The number of global natural gas trade network edges (trade relations) is 127, which is only 41% of that of coal network (312), and the number of trade edges between China and emerging gas sources (e.g. Africa and South America) is less than 20. The domestic pipeline network is "strong in the south and weak in the north", with the storage capacity in North China accounting for 45% of the country's total, but the storage capacity in Southwest China is only 3% of the consumption; the LNG receiving stations are concentrated in the Southeast coast (accounting for 78% of the country's total), and the peaking in the inland areas of Northwest China relies on the pipeline interconnection, with a 48-hour response time for emergencies. Meanwhile, 82% of China's natural gas resources to be developed are low-permeability fields, and the cost of a single well is as high as 320 million yuan, which is 2.5 times higher than that of the United States.

3.2. The Twin Threats of Geopolitics and Transport Security

3.2.1. Geo-sensitivity of pipeline transport

Natural gas pipeline transport covers a wide geographical area and is highly susceptible to international geopolitical changes. There are seven cross-border natural gas pipelines in China, of which the Central Asia pipeline (accounting for 30% of imports) passes through politically sensitive areas such as Kazakhstan and Uzbekistan, and the unrest in Kazakhstan in 2022 led to the disruption of the pipeline's gas supply for three days. In 2023, 17 terrorist attacks on gas pipelines in Central Asia resulted in an 8 per cent reduction in gas deliveries to China. European sanctions against Russia have led to increased volatility in global LNG prices, with Asian LNG spot prices peaking at $70/MMBtu in 2022, a 400 per cent increase year-on-year. Geopolitical conflicts not only lead to supply disruptions, but also push up insurance costs, with pipeline transport insurance rates in the Middle East rising by 300% compared to 2019, and LNG shipments passing through the Red Sea needing additional security personnel, increasing the cost of single-vessel shipments by $150,000 [5].

3.2.2. "Weaponisation of resources" Escalation of risk

Russia's use of gas as a geopolitical tool, with price discrimination against "unfriendly countries" in 2022 and a 100 per cent premium to European spot prices over long-term contracts; and Qatar's use of 12 per cent of global LNG capacity to leverage its export plans during the 2022 World Cup, leading to short-term supply constraints in the Asia-Pacific region. China's role in the "One Belt, One Road" initiative has been significant. China's energy cooperation in the "One Belt, One Road" is facing tightened project scrutiny: in 2023, the European Union will restrict Chinese companies' participation in gas infrastructure investment in Central and Eastern Europe on the grounds of "energy sovereignty", affecting the LNG terminal expansion project in Croatia.

3.3. Shortcomings in Market Mechanisms and Emergency Response Capacity

3.3.1. Inadequate price formation mechanisms

Domestic natural gas prices still implement the "benchmark price + floating" control, and the international market linkage lagging behind (spot price conduction time of about 45 days), in 2022, when the international LNG price surge, the domestic city fuel companies have large losses (losses of up to 20 billion yuan). Futures market development is lagging behind, Shanghai Oil & Gas Trading Centre LNG futures turnover is only 5% of ICE Europe futures, lack of effective price discovery and risk hedging tools [10].

3.3.2. Emergency stockpile system gaps

China's gas storage capacity is only 22 billion cubic metres (accounting for 6% of consumption), much lower than the EU (18%) and the United States (15%), and the structure is unreasonable: underground storage accounts for 60% (90% in the United States), most of which is the renovation of depleted fields (slow peaking), and salt cavern storage accounts for only 20% (70% in Europe). Emergency response mechanism is the existence of a "triple short board", demand-side load regulation capacity is insufficient (industrial users can interrupt the load of only 10%), the regional reserve synergy is inefficient (inter-regional transfer needs to be coordinated with eight provincial pipeline network), reserve mobilisation decision-making process is long (from warning to start up to 48 hours) [6]. 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 sufficient and continuous supply, and once a country is hit by a disaster, sanctions, etc., it will have a direct impact on 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 capacity and peaking capacity, there is no way to guarantee self-sufficiency and anti-risk ability in the face of high demand for natural gas. China should enhance its emergency supply capacity, supplemented by demand compression capacity. In remote and rural areas, the coverage of natural gas supply network is low, which affects the popularity and efficiency of natural gas utilisation. At this stage, China's LNG receiving terminals are small in size and unevenly distributed, with some LNG receiving terminals already operating at capacity during peak gas consumption, while others have yet to fulfil their role, and China still has an insufficient number of LNG receiving terminals compared to countries with more LNG receiving terminals. Short-term natural gas emergency supply and demand compression play an important role in enhancing the systemic nature of natural gas energy and ensuring national energy security.

3.4. New Challenges to Cybersecurity in The Digital Age

3.4.1. Vulnerability of industrial control systems

China's natural gas extraction and pipeline transport has achieved 80% automation control, but 90% of the pipeline SCADA systems in China use old operating systems, such as Windows XP, and the vulnerability repair rate is less than 40%.2023 a North China gas storage reservoir was attacked by malicious code, resulting in a gas injection compressor shutdown for 6 hours. The Colonial Pipeline incident in the United States warned us that cyberattacks on energy infrastructure can trigger regional supply crises, and China has not yet established a unified industry standard for cybersecurity protection of pipeline SCADA systems and control systems of LNG receiving stations [7]. In the process of China's digital transformation, there are also cases such as the "intelligent refinery based on the whole process business of the industrial control system network security protection programme", which shows 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, with 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.

3.4.2. Data security and supply chain risk

Only 15% of China's cross-border trade data uses quantum encryption technology, and 12 incidents of trade data leakage tampering with operational prices occurred in 2022.2022 A company's bidding information was leaked, and international suppliers collectively raised their prices, resulting in an 8% increase in China's LNG import costs. Blockchain technology application lags behind, the world's major energy trading platforms (such as Vitol, Trafigura) has achieved 70% of the trade documents digitisation, while China's natural gas trade still relies on paper contracts, data tampering risk is high [10].

4. Countermeasure System to Enhance the Resilience of Natural Gas Trade Network Security

4.1. Building a Diversified Gas Supply System: Reducing the Risk of Single Dependency

4.1.1. "Three-dimensional expansion" of the international gas supply layout

Geographic dimension: Deepen cooperation with Southeast Asia (Malaysia, Indonesia), Africa (Nigeria, Mozambique) and South America, and increase the proportion of imports from emerging markets to 30% by 2025. Invest and build an LNG processing plant in Nigeria (equity capacity of 5 million tonnes/year) to avoid the risk of exporting from a single port; participate in the development of Vaca Muerta shale gas in Argentina, and build a trans-Andean pipeline directly to Chile to form a pivot point of gas source in the southern America. Signed long-term LNG purchase agreements with Mozambique and Tanzania, aiming to increase the share of African imports to 20% by 2030.

Transportation dimension: Promote the expansion of the Power of Siberia 2 pipeline (via Mongolia) and the Sakhalin-2 LNG project, so as to form a dual-track supply of "piped gas + LNG"; Planning the LNG transport route along the Arctic shipping lane, which will shorten the transport time by 15 days in summer compared with the traditional route, and reduce the dependence on the Strait of Malacca .

Dimension of cooperation mode: Set up a national-level multinational procurement company (e.g. "China Gas International Group"), coordinate LTA contracts (70%) and spot procurement (30%), establish a price mechanism of "benchmark price + floating + options"; introduce the International Chamber of Commerce (ICC) as a third-party regulator, and carry out credit rating of suppliers, with the proportion of procurement from countries with high default risk limited to 10%. (ICC) as a third-party regulator, carry out supplier credit rating, and limit the proportion of procurement from countries with high risk of default to 10%.

4.1.2. "Two-Wheel Drive" of Domestic Supply Capacity

Exploration and development breakthroughs: Through the

optimisation of horizontal wells and hydraulic fracturing technology to increase the development of deep shale gas in the Sichuan Basin (burial depth of more than 4,000 metres) and ultra-deep gas fields in the Tarim Basin (Keshen 20 gas field), with new proven reserves of 1.2 trillion cubic metres in 2025, the cost of a single well of shale gas in the Sichuan Basin reduced to 180 million yuan, the production increased to 30 billion cubic metres per year, and the share of unconventional natural gas production increased to 35%. to 35%. Promote "geology-engineering" integration technology, and reduce the development cost of deep gas fields from RMB 6 yuan/cubic metre to less than RMB 4 yuan/cubic metre.

Reserve peak strengthening: In Jiangsu Jintan, Henan Pingdingshan construction of salt cave gas storage reservoir (single reservoir capacity of more than 5 billion cubic metres), gas storage capacity of 150 billion cubic metres in 2030 (accounting for 12% of the consumption); in the coastal area layout of five 200,000-tonne LNG receiving station (such as Hainan Dongfang, Hebei Caofeidian), the formation of the "coastal 100-kilometre emergency reserve belt It will form a "100-kilometre emergency reserve belt along the coast", ensuring that 10 billion cubic metres of emergency resources can be called up within 72 hours.

4.2. Building a Strong Digital Security Defence: Building A Dual Protection System of "Technology + Management"

4.2.1. Technology layer: building an active defence

Upgrading data encryption: Deploying a quantum confidential communication system in the cross-border monitoring system of the West-East Natural Gas Pipeline, adopting the AES-256 encryption algorithm for key transaction data, and implementing a blockchain depository for pipeline monitoring data to ensure that data tampering can be traced back and the risk of data leakage can be reduced by 90 per cent. Pilot "Beidou + 5G" positioning technology, real-time trajectory monitoring of LNG carriers, with alarms triggered automatically for abnormal deviations.

Industrial control system protection: Formulate the "Natural Gas Industrial Control System Security Standards", make it mandatory to adopt domestic cryptographic algorithms (SM4), and establish a "whitelisting" mechanism (only authorised devices are allowed to access); pilot industrial Internet security platforms in Changqing Oilfield and Central Asia Pipeline, etc., and realise real-time vulnerability scanning (response time & lt; 10 seconds) for 100,000 + devices. lt; 10 seconds). In cooperation with countries along the "Belt and Road", a threat intelligence sharing platform has been set up to exchange APT attack feature libraries in real time, and the response time for defence against has been shortened to 30 minutes.

4.2.2. Management: establishment of a full-cycle security mechanism

Personnel capacity building: Implement the "Energy Network Security Talent Plan", set up additional "Energy Industrial Control Security" majors in colleges and universities, the coverage rate of annual network security training for enterprises reaches 100%, and the frequency of simulated phishing attack drills is no less than 2 times/year. Provide network security training to natural gas trade network-related staff, 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 of 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 identify management loopholes and improve them in a timely manner.

System process optimisation: The establishment of a "three-tier emergency response mechanism" (yellow / orange / red warning), the red warning can automatically cut off non-critical system network connections; the introduction of international third-party agencies (such as SGS) to conduct annual security audits, the implementation of key positions "two-factor authentication + biometrics " access.

4.3. Deepening International Cooperation: Building Resilience-Enhancing Trade Networks

4.3.1. Co-construction of market rules

Docking of price system: Promote data interoperability between Shanghai Oil & Gas Trading Centre and ICE, CME Group, and launch "China LNG CIF Index" (CLI) as a pricing reference for the Asia-Pacific region (with a weighting of no less than 30%), with the goal of increasing the influence of the Asia-Pacific benchmark price to 40% by 2030. Participate in international natural gas futures and options trading, and use financial instruments to hedge the risk of price fluctuations (hedging ratio of no less than 40% of imports).

Mutual recognition of standards system: Leading the development of "LNG shipping safety management international standards" "underground gas storage tank monitoring technical specifications", to promote China's standards into the ISO system to reduce technical barriers to trade.

Build a cross-border supply chain alliance: Establish the Asian Gas Security Initiative (AGSI) to develop unified cybersecurity standards and emergency response protocols.

4.3.2. Resource development synergies

Equity cooperation mode: Set up Sino-foreign joint ventures (with the Chinese side holding no less than 30%) in Qatar's northern gas field and UAE's offshore gas field to lock in a share of long-term supply (with an equity volume of 50 billion cubic metres/year by 2030); co-develop the Arctic LNG-2 project with Russia, and build a gas treatment plant in the Arctic Circle to shorten the transport radius.

Risk-sharing mechanism: Establish a "Belt and Road" energy security alliance, with member countries sharing geopolitical risk warnings (covering 50+ countries), emergency reserves (up to 20 billion cubic metres), and set up a $10 billion energy security fund for scenarios such as pipeline security and disaster response.

4.4. Optimising Energy System Resilience: Building A Three-Dimensional Emergency Response Network

4.4.1. "Hardware upgrades" to reserve facilities

Structural optimisation: Increase the proportion of underground gas storage to 70% (of which salt cavern storage accounts for 40%), utilise the salt mine resources in Jiangsu and Henan to build large salt cavern storage with a single storage capacity of more than 3 billion cubic metres, and increase the speed of gas injection by 50%. Using salt caverns and depleted gas fields, the capacity of new gas storage

reservoirs will be 20 billion cubic metres, and the proportion of gas storage capacity will be increased to 12%.

Layout balancing: New regional gas storage centres in the northwest (Xinjiang), southwest (Sichuan), to solve the "south to the north" "west to east" of the peak bottleneck, to shorten the regional emergency response time to less than 24 hours.

"Weather-supply-demand" linkage model: Integration of meteorological big data (e.g., cold wave warnings) with consumption forecasts to increase the efficiency of winter peaking by 25 per cent.

4.4.2. "Flexible regulation" of demand-side response

Load management system: Establish an interruptible load bank for industrial users (with a scale of 50 billion cubic metres/year), guide the use of gas in a staggered manner by means of stepped gas pricing (20% premium during peak hours) and capacity compensation (300 yuan/cubic metre), and focus on the promotion of the "gas-electricity hybrid" production mode in the chemical industry, building materials industry and other industries to enhance the elasticity of load regulation. The focus is on promoting "gas-electricity hybrid" production mode in chemical and building materials industries to enhance load regulation flexibility.

Multi-energy complementary mechanism: In Beijing, Tianjin, Hebei and the Yangtze River Delta to build "natural gas peaking power station + lithium battery storage" joint system (installed capacity of 10 million kilowatts), to achieve from no-load to full-load operation within 30 minutes, to replace some of the coal-fired units, and to improve the system's shock resistance.

4.5. Strengthening Risk Governance: Building A Data-Driven Decision-Making System

4.5.1. Intelligent Forecasting and Early Warning

Demand prediction model: Integrate meteorological data (resolution up to 1km), economic indicators (GDP, industrial added value) and user behaviour data to build a machine learning-based demand prediction model ($R^2 \geq 0.92$), with the error rate of prediction 7 days in advance controlled within 5%.

Risk mapping: Develop a "natural gas trade network risk visualisation platform" to monitor in real time the political stability of gas source countries (with reference to the Global Risk Index), the degree of congestion of transport routes (AIS vessel data), and the threshold of price fluctuations (over 50% triggers an orange warning), forming a "red - orange - green" four-colour risk mapping. Yellow - Green" four-colour risk map.

4.5.2. Contingency planning and institutional safeguards

Special plan system: formulate the Emergency Plan for Disruption of Natural Gas Supply and the Special Plan for Guaranteeing Supply in Extreme Weather, clearly define the priorities of gas consumption for people's livelihoods (60%), key industries (30%), and emergency reserves (10%), and set up an inter-departmental linkage mechanism (48-hour joint watch by the Development and Reform Commission, the Bureau of Energy, and the Bureau of Meteorology).

Market-oriented reform package: promote natural gas price convergence, residential gas with "benchmark price + step gas price", non-residential gas completely market-oriented; the establishment of the reserve use compensation mechanism, the government gave 0.5 yuan / cubic metre of financial subsidies to the enterprise emergency reserves to mobilise social capital to participate in the enthusiasm.

5. Conclusion

Structural deficiencies are the core challenge: China's natural gas trading network is characterised by "high dependence and low resilience", with the core problems being high concentration of gas sources, insufficient infrastructure network connectivity and a large gap in emergency reserves.

Multidimensional countermeasures form a systematic programme: The resilience of trade networks can be effectively enhanced by diversifying gas sources to reduce single dependency, digital technology to strengthen security, international cooperation to enhance network compatibility, and an emergency response system to strengthen resilience to shocks.

Policy and market synergy is the key: It is necessary to establish a long-term mechanism of "government guidance + enterprise main body + social participation", and activate market vitality and form endogenous power of resilience enhancement through policy tools such as financial subsidies, price reforms, and standard setting.

6. Future Prospects

Driven by technological innovation: Exploring the "hydrogen-natural gas" hybrid delivery technology (with 15% hydrogen mixing), using the existing pipeline network to build a zero-carbon energy corridor; developing an intelligent inspection robot for underground gas storage (with a 30% increase in inspection efficiency), reducing the risk of manual intervention.

Institutional innovation breakthroughs: Piloting a "capacity market" for natural gas reserves, allowing companies to trade storage capacity indicators; establishing an "energy security resilience index" appraisal system, and incorporating the resilience of trade networks into the performance evaluation of local governments.

Global Governance Participation: Promote the establishment of the BRICS Gas Alliance to build non-Western-led trade rules; Initiate the establishment of the Asia-Pacific Energy Security Early Warning Centre under the framework of APEC to enhance the regional synergistic response capacity.

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