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Three-Dimensional Enhancement Measures for China's Natural Gas Pipeline Networks Driven by the "Dual Carbon" Goal

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Abstract

Under the guidance of "dual-carbon" goal, China's energy industry is accelerating its transformation, and natural gas, as a clean transitional energy, plays a key role in the energy consumption structure. Natural gas pipeline network, as the core infrastructure for natural gas transmission, has a direct bearing on the low-carbon transformation of the whole energy system in terms of its operational efficiency and the scale of clean energy transmission. Therefore, optimising the pipeline network is crucial to achieving the "double carbon" goal. Based on the background of "dual-carbon", this study reviews the development history of China's natural gas pipeline network, analyses the current situation and existing problems of natural gas pipeline network in the process of development, and further proposes specific enhancement measures for the high-quality development of natural gas pipeline network. The study concludes that although China's natural gas pipeline network has formed a "national network" pattern, there are still a lot of problems in the process of development, such as unbalanced regional layout, obstacles to the transformation of digital intelligence, and imperfections in the market mechanism and regulatory system, and other challenges are still prominent. In view of these challenges, this paper proposes to optimise the spatial layout, increase the promotion of pipeline network digital intelligence and improve the relevant regulatory system and other specific three-dimensional enhancement measures, in order to promote China's natural gas pipeline network to a more efficient, intelligent and green direction, and to provide a solid support for the "dual-carbon" goal.

Keywords

"Dual-Carbon" Goal; Energy Transition; Natural Gas Pipeline Network; Enhancement Measures.

1. Introduction

The proposal of "striving to peak carbon dioxide emissions by 2030 and striving to achieve carbon neutrality by 2060" (hereinafter referred to as the "dual-carbon" target) is based on the realistic needs of China's ecological civilisation construction and the inherent logic of sustainable development, and also highlights China's position as a major global power. It also demonstrates China's responsibility as a major global country in the process of building a community of human destiny. The proposal of the "dual-carbon" target has set a clear transformation direction for the energy industry, driving the industry to promote the low-carbon transformation of the economic system as a core priority in the new development stage.

As a core transitional energy source connecting traditional high-carbon fossil energy and renewable energy systems, the large-scale utilisation of natural gas is a key path to optimising the energy structure and reducing carbon emissions. The natural gas pipeline network, as an indispensable infrastructure in the process of large-scale transmission, distribution and

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utilisation of natural gas, is a key link connecting gas field production, storage and peak adjustment, and terminal consumption, and has an irreplaceable strategic position in ensuring stable supply of natural gas, giving full play to the value of its transitional energy source, and supporting the smooth transformation of the energy system, and is the core task of building modern energy under the goal of "dual carbon". "It is an irreplaceable strategic position for guaranteeing the stable supply of natural gas, giving full play to its transitional energy value and supporting the smooth transformation of the energy system. However, at present, there are still multiple challenges in China's natural gas pipeline network in terms of spatial layout, digital development and institutional reform. In view of this, this paper starts from the development history of natural gas pipeline network, by sorting out the current situation and problems faced by the construction of natural gas pipeline network, and then put forward targeted enhancement measures.

2. China's Natural Gas Pipeline Network Development History

2.1. Natural Gas Pipeline Network Early Foundation Stage (1950-1979)

In this period, China's natural gas pipeline construction shows a "lone start", "number of wisdom blank" and "system of initial construction" characteristics.

In terms of pipeline mileage and layout, the Sichuan Basin was the starting point for development, relying on local resources. 1963 saw the completion of the Bayu Pipeline, China's first specialised gas pipeline, but it was only an isolated point-to-point pipeline, without the concept of a "network", and its layout was focused on Sichuan and Chongqing, serving the local industry, with a lack of cross-regional transmission capacity. By the end of 1970s, the total mileage of pipelines in the country was small, and only a small regional gathering and transmission network was initially formed.

Pipeline network digital intelligence, technical conditions are limited, there is no concept of digital and intelligent. Pipeline operation and monitoring relied on manual on-site operation and simple instrumentation, backward communication, slow information transfer, no remote monitoring and automation system, and data records relied on paper ledgers.

In terms of policy and system, the Petroleum and Natural Gas Pipeline Bureau of the Ministry of Fuel and Chemical Industry was established in 1973 to centralise and unify the management of long-distance oil and gas pipelines and auxiliary facilities. The management system is government-enterprise integrated and highly planned, with construction and operation being the responsibility of government departments or subordinate units, lacking special regulations, relying on internal regulations and administrative orders for management, and pricing being set by the government, with no market-based factors.

2.2. Stage of Rapid Development of Natural Gas Pipeline Network (1980-2002)

During this period, China's natural gas pipeline construction was characterised by "trunk line shaping", "digital intelligence exploration" and "institutional exploration".

In terms of pipeline mileage and layout, under the guidance of national strategy, pipeline construction entered a new phase of cross-regional and long-distance. 1997 saw the completion of the first line of the Shaanxi-Beijing pipeline, which transported resources from the west to the east on a large scale, thus laying the foundation for the prototype of the "West-to-East Natural Gas Transportation"; in 2002, the first line of the West-to-East Natural Gas Transportation started, which marked the beginning of the construction of the east-west axial corridor of national trunk pipeline network. In addition, Shibu Ninglan Pipeline, Zhongwu Line, Shaanjing Second Line, etc. are also planned and constructed at this stage. The layout was concentrated from the Sichuan Basin and developed into a point-axis pattern with Northwest, Southwest and the sea as the starting point of resources, and North China, East China and South

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China as the main consumer markets, initially constructing the skeleton of the national backbone pipeline network. By the end of 2002, the total mileage of natural gas pipelines nationwide reached about 14,800 kilometres.

As for the digitalisation of pipeline network, digital technology was introduced. PetroChina gave priority to applying digital technology to the West-East Natural Gas Pipeline Jining Line, and made use of satellite remote sensing technology, etc. in the construction of the Second West-East Natural Gas Pipeline and the China-Myanmar Oil and Gas Pipeline in 2008 . communication technology upgrades, began to establish a production information system, and some of the key data are recorded electronically. However, the system coverage is insufficient, the level of data application is shallow, each system is independent, "data silos" are emerging, and the application of intelligent equipment is rare.

In terms of policies and institutions, the management system has begun to explore the separation of government and enterprises, and the three major national oil companies have been established, but there is still an administrative monopoly, and the Regulations on the Protection of Oil and Natural Gas Pipelines were promulgated in 1989 to provide legal protection for pipeline safety, but there is a lack of systematic regulations. The pricing mechanism was dominated by government pricing, with a low degree of market openness. However, with the establishment of the market economy system and the accession to the WTO, the discussion of breaking the monopoly and introducing competition appeared, laying the groundwork for subsequent reforms.

2.3. Stage of Deepening and Improving the Natural Gas Pipeline Network (2003-2017)

During this period, China's natural gas pipeline construction was characterised by "network expansion", "intelligent upgrading" and "reform brewing".

In terms of pipeline mileage and layout, the mileage grew explosively. Led by the "West-to-East Gas Pipeline" strategy, the peak of trunk pipeline construction, West-to-East Gas Pipeline Line 1, Line 2, Line 3, etc. constitutes an east-west energy artery, and Sichuan gas will be sent east to the Yangtze River Delta Sichuan resources. Diversification of import channels, the completion of the Central Asia gas pipeline A/B/C line, etc., China-Myanmar oil and gas pipeline to open up the Southwest import channel. The regional pipeline network has been encrypted, the coastal LNG receiving terminal is equipped with an external pipeline, the third and fourth lines of Shaanxi-Beijing have strengthened the capacity of gas supply to North China, and the Zhonggui line has become a liaison line between the North and the South. The total mileage of natural gas pipelines nationwide increased from about 14,800 kilometres at the end of 2002 to about 74,000 kilometres at the end of 2017, with an optimised layout, the emergence of a "national network" and a significant expansion of coverage.

In terms of pipeline network intelligence, the pipeline network has advanced from automation to informationisation and networking, SCADA system has been popularised and deepened, production information system has been widely used, and fibre optic communication and network coverage have become standard. Key intelligent technologies such as GIS integration, intelligent pipe cleaning and internal detection, fibre optic sensing technology pilot, mobile inspection and management system have been explored and applied, but the problem of "data silos" has been highlighted, and the in-depth application is in its infancy.

Policy and institutional aspects, market-oriented reform exploration but encountered difficulties. "Control the middle, release the two ends" reform direction proposed, the pipeline network of third-party access difficult to start, the revision of laws and regulations to improve the price mechanism reform continued to promote but did not touch the core of the pipeline and transmission links and sales link bundled, the national pipeline network company has not been established, constraints on the process of marketisation.

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3. China's Natural Gas Pipeline Network Development Status and Existing Problems

3.1. Development Status of Natural Gas Pipeline Network

(1) Accelerated expansion of pipeline network scale, the basic formation of the backbone network

In recent years, China's natural gas trunk pipeline network construction has achieved remarkable results. The construction of natural gas pipelines has shown strong momentum. Calculated, the average annual growth rate of natural gas pipeline construction during the decade of 2014-2023 reached 8.82%, which is significantly higher than the construction growth rate of crude oil pipeline during the same period, showing a continuous acceleration trend. In terms of interconnection, pipeline network construction has been effective, and provincial natural gas pipeline network companies have been continuously integrated into the national pipeline network system, which has greatly enhanced the flexibility and efficiency of natural gas deployment. By the end of 2023, the total length of newly built natural gas pipelines will reach about 124,000 kilometres, with the "national network" basically taking shape, and the construction of long-distance pipelines such as the West-to-East pipeline, the Sichuan-to-East pipeline and the Shaanxi-to-Beijing pipeline will be used to supply gas to the eastern region, thus constructing a relatively complete natural gas transmission network.

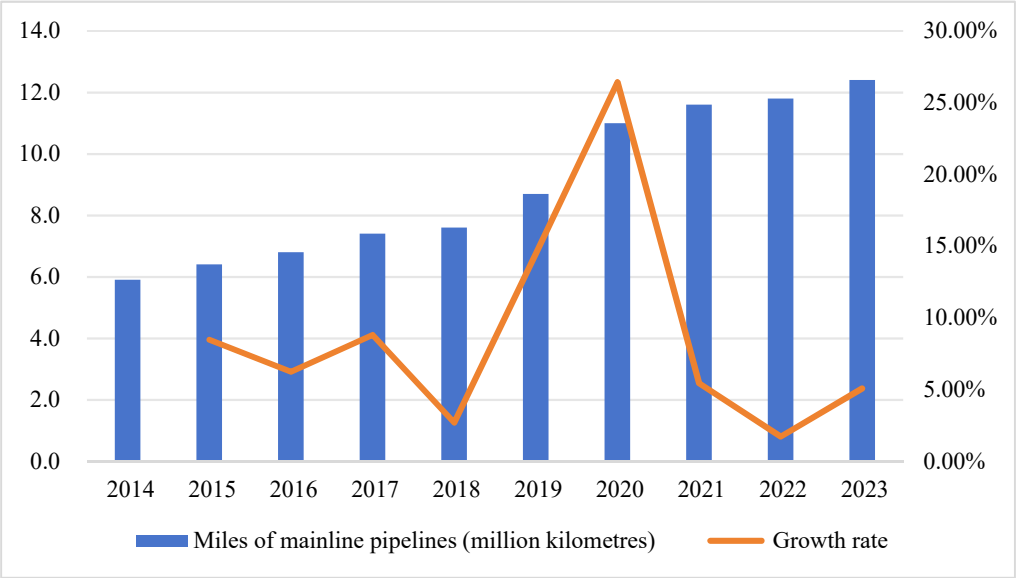

Fig.1 Mileage and Growth Rate of Natural Gas Pipelines in China, 2014-2023
Data source: China Natural Gas Development Report

(2) Numerical and Intelligent Transformation is Effective, Government Support Boosts Development

China's natural gas pipeline network digital and intelligent transformation has been very effective, which has become a key driving force to accelerate the transformation and upgrading of the natural gas industry [1]. At the 2019 Asia-Pacific International Pipeline Conference, Weihe Huang, an academician of the Chinese Academy of Engineering, depicted a development blueprint for the smart pipeline network: with the formation of an overall architecture of five levels of perception, data, knowledge, application and decision-making as the core, the construction of a smart integrated database and a specialised knowledge base, and through the construction of pipeline digital twins, support for the all-around perception of pipeline

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networks, comprehensive prediction, adaptive optimisation, and integration of management and control [2]. Nowadays, China's natural gas pipeline network is deeply integrated with the Internet, walking in the forefront of the development of "Internet +" traditional industries, and has built a production information system, SCADA system, and a variety of business management and optimisation systems, realising the monitoring and integrated optimisation of the whole industry chain [3]. The policy level has continued to make efforts, with the State-owned Assets Supervision and Administration Commission (SASAC) requiring the promotion of production and operation intelligence and the integrated application of advanced technologies such as 5G and the Internet of Things (IoT). PetroChina and other large enterprises have responded positively to promote the construction of "intelligent pipeline network". 2022, the General Office of the State Council issued the "Implementation Plan for the Renewal and Improvement of City Gas Pipelines and Other Aging Pipelines (2022-2025)", which emphasises the simultaneous promotion of the digital construction of the pipeline network, and the Internet of Things (IoT) and other technologies have been widely used. Intelligent pipe network system developed by National Pipe Network Group Zhejiang Province with the help of big data and other technologies, fibre-optic vibration early warning system to achieve all-weather supervision of the pipeline, the reduction of manpower for patrolling, and a significant increase in the rate of detection of the incident.2023, the National Energy Administration issued the "Opinions on Accelerating the Development of Energy Digitization and Intelligent Development", which further promotes the development of energy digitization and intelligent development, and assists the natural gas industry to improve its performance, ensure supply through the pipeline network through the digital transformation to enhance efficiency, safeguard supply, and promote energy conservation and emission reduction.

(3) Institutional Reform Advances Deeply, Rule of Law Guarantees Dual-Carbon Upgrade

In March 2019, the Opinions on the Implementation of the Reform of the Operation Mechanism of Oil and Natural Gas Pipeline Networks passed the deliberation, making clear the direction of reforms such as the formation of diversified oil and natural gas pipeline network companies. In December of the same year, the National Oil and Gas Pipeline Network Group Co., Ltd. was established, breaking the original monopoly pattern, realising the independence of the pipeline business, promoting the standardisation of the oil and gas market, paving the way for the "X+1+X" market-based institutional mechanism, and initially forming the framework of "one national network" [4].

In 2020, the national pipeline network group to take over the relevant assets and personnel, to achieve the operation of the network, the reform has entered a new stage. Since then, many provinces and cities have established infrastructure policy objectives to improve the efficiency of facility utilisation. 2022, the open service and trading platform went online to promote fairness and openness. 2023, the price of inter-provincial natural gas pipeline transport was approved for the first time in a subregion, an important step forward in the pricing mechanism. 2024, the Energy Law came into force, clarifying the status of independent operation of the pipeline network in accordance with the law, etc., which provides a solid guarantee for the reform of oil and gas system, and strongly promote the "double carbon" goal [5].

3.2. Existing Problems of Natural Gas Pipeline Network

(1) Lagging development of pipeline network and imbalance of regional layout

China's natural gas pipeline network "a national network" pattern has basically formed, but compared with developed countries, China's natural gas pipeline network construction started late, pipeline construction has a certain lag. According to the National Energy Board released "China's natural gas development report (2024)", in 2023 the world's major natural gas production and consumption of regional pipeline mileage gap is significant: North America 550,000 kilometres, Europe 240,000 kilometres, Asia-Pacific 220,000 kilometres, Russia -

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Central Asia 210,000 kilometres, China is only 120,000 kilometres. This data visually reflects the relative lag of China's natural gas pipeline network construction, with a prominent gap with the world's major regions. Although the construction speed of China's natural gas pipeline network basically matches the continuous growth of the total demand for natural gas, but the layout of China's natural gas pipeline network shows an obvious "east dense west sparse" characteristics. As a natural gas resource-rich region, the western region is the starting point of the "West-East Natural Gas Pipeline" and other trunk pipelines, which mainly bear the function of resource transmission, and the density of its pipeline network is relatively low, which restricts the optimal allocation of clean energy resources. In contrast, the eastern region, as a centre of energy consumption, receives natural gas through pipelines such as the China-Russia Eastern Route and the West-East Natural Gas Pipeline, and has formed a dense network of branch lines.

As the "dual-carbon" goal advances, the structural contradiction between the lagging construction of the natural gas pipeline network and the imbalance in its layout has been further magnified, and has become a bottleneck restricting China's low-carbon energy transition. On the one hand, the insufficient transmission capacity of the pipeline network is difficult to match the rapid growth of clean energy demand, which makes it difficult for natural gas to reach the end market efficiently and on a large scale, hindering the increase of its consumption ratio and restricting the process of energy structure clean-up. On the other hand, the "dense east and sparse west" layout exacerbates regional conflicts, with the eastern region being forced to maintain a high-carbon energy mix due to transmission and distribution capacity constraints, while the western region is unable to release the full potential of its resources to substitute for high-carbon energy sources in the neighbourhood due to the weakness of its local pipeline network. This pattern has seriously weakened the substitution efficiency of natural gas as a low-carbon bridge energy source, posing a serious challenge to the "dual-carbon" goal.

(2) Data silos are hard to break, and smart applications lag behind

Despite the breakthroughs achieved in the digital intelligence of natural gas pipeline networks, the promotion of natural gas pipeline networks still faces many challenges. First, data integration and sharing barriers are prominent, data silo phenomenon and standardisation shortcomings co-exist, different equipment, systems, data formats and communication protocols vary greatly, cross-platform data integration difficulties, information flow is blocked, efficient and collaborative data network is difficult to build; old pipeline renovation due to the lack of standards, the difficulty of adapting to the new digital technology, high cost, resulting in the transformation of the progress of the obstacles; second, the depth of technology application is insufficient. Intelligent technology in the pipeline network operation and maintenance, risk prediction and other key scenarios of the landing is still immature, the coverage of intelligent equipment is low, part of the region is still dependent on manual, real-time monitoring of the pipeline network and operation and maintenance management of the accuracy and efficiency of the poor; intelligent pipeline network foundation support is weak, the construction of the digital body is incomplete, incoherent, the construction of digital twins is slow, limiting the value of data mining and simulation of decision-making advantages of the play; third, the safety and standards system is weak, the digitalization of oil and gas pipeline network is difficult to build due to the lack of standards. Thirdly, the security and standards system is weak, the digitisation of oil and gas pipeline network involves a huge amount of sensitive data, facing the risk of hacker attacks and data leakage, and the existing encryption and protection system has limitations in dealing with complex threats, and is in urgent need of upgrading and strengthening [6].

Under the strategic requirement of accelerating the achievement of the "dual carbon" goal, the lagging contradiction of the development of digital intelligence has become more and more

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prominent, and directly restricts the effectiveness of low-carbon energy transformation. Firstly, data integration and sharing barriers hinder the accurate analysis of energy information and optimisation of low-carbon strategies, affecting the effectiveness of clean energy synergy. Secondly, the lack of technology application depth significantly reduces the efficiency of pipeline network operation and energy use, superimposed on the lack of system responsiveness and the risk of energy supply stability due to the weakness of basic support such as digital twins, seriously inhibiting the efficient use of natural gas as a low-carbon energy potential. Finally, shortcomings in security and standards systems continue to amplify energy data security risks, threatening the stable operation of critical infrastructure and national energy security. These problems have systematically weakened the ability of digital and intellectual technologies to support low-carbon energy transformation, constituting a deep-rooted obstacle to the realisation of the "dual-carbon" goal.

(3) Blurring of regulatory boundaries and obstacles to market reform

Although the reform of the natural gas system is advancing, many problems exist. First, the basic legal framework is not sound, the Energy Law and the Oil and Gas Pipeline Protection Law and other applicable boundaries are not clear, easy to trigger law enforcement disputes; although the principle of fairness is proposed, but did not specify the rights and obligations of independent operation of natural gas pipeline network, pricing model and reform of synergistic approach, the rate of return of the dynamic adjustment of the conditions have not been spelled out, resulting in pipeline prices and market supply and demand may be out of touch, inhibiting social capital investment. At the same time, there is a lack of Natural Gas Law covering the whole chain of the industry, the midstream transmission and distribution links of the operating behaviour of the law is missing, the key links are not clearly defined, triggering duplication of investment in infrastructure, regional barriers and other structural contradictions [7]; Secondly, the process of diversification of the market is slow, the exploration and development of the state-owned enterprises dominated by the state-owned enterprises, and the vitality of the lack of vitality. The construction of competitive mechanisms in the sales market is lagging behind, and price formation lacks transparency and rationality. Infrastructure interconnection level is low, the emergence of regional gas source "island" and other issues, restricting the efficiency of the market; Third, the pipeline price and benchmark gate station price parallel mode, and the trend of market-oriented reform is inconsistent, the scope of the government regulation is wide, inhibiting the vitality of market competition, impede the optimisation of the price mechanism [8].

In the strategic period of "dual-carbon" target accelerated landing, the negative impact of institutional barriers has been significantly amplified, and has become a deep-seated constraint on the transformation of low-carbon energy structure. Firstly, the imperfect legal framework makes it difficult to build a favourable market environment, hindering the development of the natural gas industry and low-carbon technological innovation. Secondly, a single market player and fragmented infrastructure have led to inefficient resource allocation, weakening the ability to deploy natural gas across regions and making it difficult to meet the demand for clean energy. Most critically, the distorted pricing mechanism inhibits the cost competitiveness and optimal allocation of natural gas, restricting its "bridging role" and posing a systemic challenge to the timely realisation of the "dual-carbon" goal.

4. Three-dimensional Enhancement Measures of Natural Gas Pipeline Network

4.1. Layout Optimisation and Regional Balance

Firstly, accelerate the construction speed. Closely follow the positioning of natural gas as an important transitional energy source and support for the development of renewable energy

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under the "dual-carbon" goal, formulate a carbon-neutral medium- and long-term plan for the construction of natural gas pipeline network, and scientifically determine the annual target of new pipeline mileage based on the national "dual-carbon" goal strategy and the trend of natural gas demand growth. The annual target for additional pipeline mileage should be set scientifically based on the national "dual carbon" target strategy and the trend of natural gas demand growth. Increase capital investment in the construction of natural gas pipeline networks. On the one hand, the government should provide support through financial subsidies and special bonds; on the other hand, it should encourage the participation of social capital and broaden financing channels. Actively introduce foreign advanced pipeline construction technology and management experience, combined with China's actual situation for innovation and application, improve the quality and efficiency of pipeline construction, and gradually shorten the gap with North America, Europe and other developed regions in the pipeline mileage, to provide a solid transmission guarantee for large-scale clean energy substitution.

Secondly, optimise the regional layout. For the contradiction of "dense east and sparse west", increase the construction of natural gas pipeline network in the western region. In the resource-rich areas around the planning and construction of feeder pipelines and gas storage facilities, the formation of a perfect regional pipeline network system, not only to ensure that the surplus of natural gas and the future delivery of clean energy, but also to enhance the ability of the local gas instead of coal, gas instead of oil, and directly reduce regional carbon emissions. Strengthen the interconnection of pipeline networks in the eastern and western regions, and realise the flexible deployment of natural gas resources through the construction of new inter-regional liaison pipelines, so as to balance the gas demand of the eastern and western regions. For example, in the transition zone between the west and the east, more connecting pipelines will be constructed to improve the flexibility of natural gas transmission and help optimise the national energy structure.

Lastly, strengthen co-ordinated planning. Driven by the "dual-carbon" goal, establish a unified planning and coordination mechanism for the natural gas pipeline network across the country. The national energy department should take the lead and join hands with various regions and major energy enterprises to jointly formulate a pipeline network construction plan that is in line with the national carbon peak and carbon neutral pathway and renewable energy development plan, so as to avoid duplicated construction and waste of resources among regions. In the planning process, the resource distribution, energy demand, economic development level and other factors of each region are fully considered to achieve synergy between pipeline network construction and regional development. At the same time, strengthen the cooperation and sharing of pipeline network construction among different enterprises, break down the barriers between enterprises, maximise the efficiency of existing and new pipeline networks, and build a more efficient and synergistic natural gas pipeline network system to ensure the stable supply of clean energy.

4.2. Digital Intelligence Upgrade and Security Enhancement

First, break data barriers and realise data integration and sharing. Formulate unified data standards and communication protocols, standardise the data formats of different equipment and systems, reduce the difficulty of cross-platform data integration, and build an efficient and collaborative data network. For the transformation of old pipelines, introduce digital transformation standards and guidelines focusing on improving energy efficiency and sealing to reduce methane leakage, and clarify the requirements and specifications for new digital technologies, so as to reduce the difficulty and cost of transformation. Set up special transformation funds or provide financial subsidies to incentivise enterprises to speed up the transformation of old pipelines and promote the integration of new and old data systems. At

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the same time, the establishment of data sharing incentives to encourage enterprises to take the initiative to share data and improve the efficiency of data flow.

Secondly, deepen the application of technology and improve the level of intelligent application. Increase R&D and investment in intelligent technology in key scenarios such as intelligent regulation and optimisation, risk prediction, etc., and promote the landing of intelligent technology. Set a milestone target for the coverage rate of intelligent equipment and support corresponding subsidy policies to incentivise enterprises to increase the proportion of intelligent equipment used and reduce reliance on manual labour. Strengthen the basic support construction of intelligent pipeline network, improve the construction of digital body, and ensure its integrity and coherence. Accelerate the pace of digital twin construction, integrate multi-source data, build an accurate digital twin model, give full play to the data value mining and simulation decision-making advantages, improve the real-time monitoring of pipeline networks and the accuracy and efficiency of operation and maintenance management, and ensure the efficient use of clean energy.

Finally, ensure data security and strengthen the security and standard system. Upgrade the existing encryption and protection system, introduce advanced encryption algorithms and protection technologies, and improve the ability of the oil and gas pipeline network digital system to cope with hacker attacks, data leakage and other complex threats. Establish a network security monitoring and early warning mechanism to monitor the network security situation in real time, and identify and dispose of potential security risks in a timely manner. Formulate perfect oil and gas pipeline network digitisation security standards and regulations, clarify the responsibilities and obligations of enterprises in data security protection, strengthen supervision, and carry out regular security audits and assessments to ensure the effective implementation of security standards and regulations.

4.3. Improvement of Regulations and Fair Competition

Firstly, improve the natural gas pipeline network policy and coordination mechanism. Under the framework of the "dual-carbon" goal, clarify the boundaries of the application of existing regulations, and clearly define the functions and obligations of the Energy Law, the Oil and Gas Pipeline Protection Law and other laws in the energy transition and carbon emission reduction. When formulating regulations covering the whole chain of the industry, it is necessary to stipulate in detail the operational behaviour of the midstream transmission and distribution chain, and precisely define the key links, so as to prevent duplicated construction of infrastructure and regional barriers. At the same time, for the independent operation of natural gas pipeline network, the rules and regulations must incorporate the consideration of carbon emission costs, clarify their rights and obligations, refine the pricing model and reform the synergistic approach, and determine the conditions for dynamic adjustment of the rate of return, so that the pipeline price closely matches the market supply and demand, and enhance the operability and stability of the regulations.

Secondly, rationally adjust the rules of market access and competition. Set market access thresholds scientifically, and take the enterprises' ability to apply low-carbon technologies, environmental compliance records, methane emission reduction targets and actions, as well as their potential ability to support renewable energy consumption as important assessment dimensions, and ensure that new entrants have the ability to operate stably and fulfil their carbon emission reduction obligations through a strict assessment system. Dynamically adjust the entry thresholds according to the market development trend and policy direction, and on the premise of preventing market monopoly, appropriately relax the entry conditions to introduce more competitive forces and avoid disorderly competition. In addition, transparent and open assessment standards and procedures should be established to ensure that the access

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process is fair and equitable, so as to create a fair starting point for competition for all types of market players.

Finally, create a fair and orderly market competition environment. Strengthen market supervision and crack down on unfair competition such as price manipulation, false propaganda and setting up market barriers to maintain normal market order. Establish a comprehensive information disclosure system, requiring enterprises to regularly publish key information such as operational data, financial status, and price composition to enhance market transparency. At the same time, encouragement policies are introduced to motivate enterprises to carry out technological innovation and service innovation, and through the combination of policy guidance and market incentives, industry technological progress and service quality enhancement are promoted to form a virtuous cycle of competitive environment.

5. Conclusion and Outlook

Driven by the goal of "dual-carbon", China's natural gas pipeline network, as a key link connecting gas field production, storage and peaking, and terminal consumption, has far-reaching significance in the study of its spatial layout, digital development and institutional reform for the purpose of guaranteeing national energy security, implementing the green and low-carbon development strategy, and promoting the energy revolution. Currently, China's natural gas pipeline network has made significant progress in scale expansion, digital transformation and institutional reform, but still faces challenges such as imbalance in regional layout, difficult to break through data silos, and obstacles to market reform. China's natural gas pipeline network is gradually developing in the direction of high efficiency, intelligence and greenness through rational planning of spatial layout, promotion of digital and intellectual innovation, deepening institutional reform and other measures.

In the future, all parties involved in China's natural gas pipeline network should continue to optimise the spatial layout, increase the construction of pipeline network in the central and western parts of the country, improve the transmission efficiency and coverage, and strengthen the construction of feeder distribution pipeline network; deepen the innovation of digital intelligence, build a unified ecosystem, and promote the application of digital intelligence to improve the efficiency and safety of operation and maintenance; and promote the institutional reform, improve the rules and regulations, build a coordinated supervision, and deepen the market pricing reform.

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