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Industrial Development of Hydrogen Blending in Natural Gas Pipelines in China

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Abstract: The development of the hydrogen industry, which is highly dependent on the efficiency of hydrogen transportation, is crucial for realizing the green and low-carbon transformation of the terminal energy consumption. Blending hydrogen in natural gas pipelines can improve the scaling and efficiency of hydrogen distribution within a short time, while providing a method for expanding the scale of hydrogen applications. Based on the definition of the industrial chain for hydrogen blending in natural gas pipelines, a discussion on the necessity for the development of the blending industry with regard to promoting the hydrogen industry, resolving renewable energy consumption, ensuring energy supply security, realizing deep carbon reduction in the terminal energy consumption, and encouraging energy technology innovation is provided in this study. Moreover, a summary of the international progress and current domestic status of the blending industry is presented, where the key issues concerning the hydrogen blending proportion, adaptability of pipes and terminal equipment, and their safety use and technical economy are outlined. Furthermore, the following suggestions are proposed: (1) strengthening the top-level design, (2) building standards for safety supervision and technology and operation management of hydrogen blending in natural gas pipelines, (3) actively deploying demonstration projects through multi-participation activities, and (4) exploring diversified application scenarios and business models. This will assist in cultivating a sustainable industrial ecosystem to steadily promote the scaled development of the industry.
Keywords: hydrogen blending in natural gas pipelines; hydrogen transportation; natural gas pipeline networks; renewable energy consumption; industrial scale development

1 Introduction

As a clean and efficient energy with diversified application scenarios, hydrogen bridges the gap between fossil energy and renewable energy, and it has become an important resource for the development of the current energy industry. The development of the hydrogen industry can effectively optimize the energy structure, reduce traditional fossil energy consumption, and promote the transformation and upgrading of the energy structure. It can also effectively reduce carbon emissions and environmental pollution to support the carbon peaking and carbon neutrality goals. Therefore, employing hydrogen as one of the elements when building a clean, low-carbon, safe and efficient modern energy system is important for the implementation of the new energy security strategies and promotion of energy revolution. Moreover, it is also crucial for energy transformation and development in the new period.

The hydrogen energy industry is divided into upstream hydrogen production, midstream storage and transportation, and downstream applications. It is composed of a long chain with a strong correlation and wide radiation comprising the production, storage, hydrogenation, and utilization of hydrogen [1]. Presently, there is a

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significant spatial imbalance in the upstream and downstream of China's hydrogen chain; therefore, large-scale centralized hydrogen production and long-distance transmission are required to enhance the development of the hydrogen industry. Moreover, the storage and transportation efficiency have become crucial for the large-scale development of the hydrogen industry owing to the reduced cost of hydrogen production. The feasible technical solutions for large-scale hydrogen energy transportation mainly include tube bundle container transportation, pipelines transportation, and liquid hydrogen tank transportation [2]. Among them, pipeline transportation has the advantages of a large transportation volume, long distance, low energy consumption, and low cost [3]. Currently, the total length of hydrogen pipelines in the world exceeds 4600 km owing to the advancement in the construction and transportation technologies for long-distance hydrogen pipeline in developed countries [2–4]. In China, the construction progress of pure hydrogen pipelines is below the expected targets (the total length is approximately 100 km) because the hydrogen pipeline transmission system is still in its development stage [3,4], and cannot meet the requirements for large-scale hydrogen application. Owing to the large initial investment and long construction period of pure hydrogen pipelines, it is difficult to quickly formulate a transportation scale that matches the development demand of hydrogen.

Recently, the remaining natural gas pipeline networks in China were completed to achieve the interconnection of natural gas pipelines across the country [5]. To significantly improve the scale and efficiency of hydrogen distribution and promote the rapid development of China's hydrogen industry, it is advised to blend a certain proportion of hydrogen into natural gas and transport it to terminal users through natural gas pipelines; then the natural gas blended with hydrogen can be used directly or separately after hydrogen extraction. However, the technological research and application demonstration of the hydrogen blending process in natural gas pipelines is still in its infancy, making the maturity of the technological system, use efficiency, and potential impact uncertain. Therefore, the necessity for the development of the blending industry to achieve the high-quality development of China's energy industry is outlined based on the hydrogen blending proportions in natural gas pipeline chains. Furthermore, a summary of the international progress, current domestic status, and key issues in the blending industry is presented. Finally, suggestions for the cultivation of the blending industry are outlined to provide a basic reference for the high-quality development of research in related fields.

2 Industrial hydrogen blending chain in natural gas pipelines

The *Opinions of the Central Committee of the Communist Party of China and the State Council on Completely, Accurately, and Comprehensively Implementing the New Development Concept to Achieve Carbon Peak and Carbon Neutralization (2021)* is expected to promote the development of the entire hydrogen energy storage, transportation, and utilization chain. As an important aspect in hydrogen energy storage and transportation, the blending industry requires substantial technical support to ensure the development of all aspects of the industrial chain, from upstream hydrogen production to downstream terminal utilization.

The main technical routes for hydrogen production include hydrogen production via fossil fuel reforming (such as from coal and natural gas), industrial by-product hydrogen (such as coke oven gas by-product hydrogen and chlor-alkali industry by-product hydrogen), hydrogen production via clean energy water electrolysis, and other hydrogen production technologies (such as from solar energy water electrolysis and biological activities) [6]. China is currently the largest producer of hydrogen worldwide with a hydrogen production output of approximately 3.3×10^7 t/a [7]. Hydrogen production using coal, which is currently the main method being employed, has a high technological advancement and relatively low cost; however, it results in the production of high carbon emissions and exacerbates environmental pollution. Therefore, large-scale hydrogen production using renewable energy and water electrolysis can be employed in the future when the cost of power generation using renewable energy such as wind and solar energy has reduced to decrease the carbon emissions during hydrogen production [4,6,8].

The midstream of the industrial chain for hydrogen blending in natural gas pipelines comprises hydrogen blending, blended gas storage, and transportation. Based on various application scenarios, it can be divided into the use of long-distance natural gas pipelines and urban gas pipelines, which involve the blending of a certain proportion of hydrogen to realize gas transportation. Despite the significant differences in the energy density, explosion limit, and diffusivity coefficient of natural gas and hydrogen, they are both clean energy gases. Moreover, the natural gas storage, transportation infrastructure, and key equipment have a certain adaptability to hydrogen. However, there are specific requirements on the adaptability of pipes for the transportation of blended gases, which has a potential impact on key equipment such as the compressor, voltage regulator, gas storage,

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storage tank, and valve [9–11]. Studies have shown that the use of natural gas pipeline networks to transport natural gases with a low hydrogen ratio and adaptability to the original pipeline networks results in better results. However, for natural gases with a high hydrogen ratio, it is necessary to renew (or reconstruct) the original pipes and equipment and upgrade the safety prevention and emergency technical systems [12].

The downstream of the industrial chain for hydrogen blending in natural gas pipelines mainly comprises a terminal diversified application ecosystem. Residential, commercial, industrial, and other terminal users can either use the blended gas directly or separate it and store it for future use. For instance, in the architectural field, blended gas has a variety of applications such as in gas stoves, gas water heaters, gas wall-hung boilers, and small boilers. In the industrial field, blended gases can be used in industrial boilers, gas turbines, gas engines, industrial furnaces, and industrial burners [9,13,14]. Blended gases also have potential applications in the field of transportation, for example, using blended gas fuels can effectively improve the thermal efficiency of natural-gas internal combustion engines and reduce pollutant emissions [15].

3 Necessity for the development of the blending industry

3.1 To promote the large-scale development of the hydrogen industry

Presently, the cost of hydrogen storage and transportation accounts for approximately 30%–40% of the total cost of the entire industrial chain (production, storage, transportation, and utilization) [10] owing to various challenges that have delayed the development of hydrogen storage and transportation infrastructure in China. The transportation methods for hydrogen are classified according to its different states: gas, liquid, and solid. Gas hydrogen is mainly transported using long-tube trailers, pure hydrogen pipelines transportation, and hydrogen blending via natural gas pipeline transportation. Liquid hydrogen is mainly transported using liquid hydrogen tank vehicles, liquid hydrogen barges, and liquid hydrogen pipelines. It is generally believed that long-tube trailers have the best cost advantage for a transportation distance less than 200 km, and although the use of long-distance liquid hydrogen transportation is cheaper, liquefaction has a high energy consumption and requires a large initial investment under the existing technical conditions [2–4].

In comparison, pure hydrogen pipelines and natural hydrogen blending in natural gas pipelines are characterized by a long distance, large scale, and low energy consumption. However, the planning and construction of pure hydrogen pipelines in China has only just begun, and the development of a large-scale hydrogen transport capacity will take time. With the completion of the “one national network,” the total length of China’s natural gas pipeline networks is approximately 1.1×10^5 km, and it is expected to reach 1.63×10^5 km by 2025 [16], which provides a solid foundation for the development of the blending industry. Therefore, the storage, transportation, and utilization of hydrogen in the form of blended gas is currently the best method for achieving the large-scale development of hydrogen.

3.2 To resolve renewable energy consumption

The western region of China has rich wind and solar energy resources, but the unbalanced regional economic development makes it difficult to realize the local consumption of renewable energy. The generation of renewable energy faces problems such as intermittency, volatility, randomness, and difficulty in peak shaving, which results in the serious abandonment of wind and light resources. Therefore, using renewable energy to produce and store hydrogen will promote the scaling and efficiency in renewable energy distribution while increasing the level of renewable energy consumption and use. The current capacity of renewable energy generation in China exceeds 1×10^9 kW (in 2021) and is expected to continue growing, which creates a good opportunity for the supply of hydrogen. With the improvement in renewable energy hydrogen production and reduced cost, the development of the blending industry will allow the utilization of the hydrogen produced from renewable energy on a larger scale, thereby effectively resolving renewable energy consumption. This will promote the comprehensive development of wind, solar, and other renewable energy resources, and consequently increase the production of renewable energy.

3.3 To relieve the pressure on the natural gas supply

In 2021, China’s total energy consumption is 5.24×10^9 tce, the apparent natural gas consumption was 3.726×10^{11} m^3 (year-on-year growth is 12.7%), and the natural gas production was 2.076×10^{11} m^3 (year-on-year growth is 7.8%) [17]. This shows that a gap exists between the supply and demand for natural gas in China. To realize carbon peaking and carbon neutrality, natural gas, which is a clean and low-carbon terminal energy source, can be coupled with renewable energy to form a benign and complementary energy supply pattern. Moreover, since China's annual natural gas consumption is expected to range from 5.5×10^{11}–6×10^{11} m^3 by 2030, and the annual production is expected to rise to only approximately 2.5×10^{11} m^3, the supply pressure will further increase [5,18]. Hydrogen in the form of blended gas can be used to replace a portion of the natural gas consumption. When calculated using a hydrogen blending ratio (volume ratio) of 10%–20% and similar calorific values, hydrogen can be used to replace approximately 1×10^{10}–2×10^{10} m^3 of natural gas per year, which has the potential of alleviating the shortage of the natural gas supply to a certain extent. The diversified terminal application of blended gas will promote the production and terminal use of hydrogen and ensure the security of the natural gas supply.

3.4 To realize deep carbon reduction in the terminal energy consumption

As a clean and low-carbon fuel, blended gas is currently being transported via natural gas pipelines to terminal energy consumption equipment in various industries and fields with a high difficulty in carbon reduction to reduce the carbon emission of terminal energy consumption. A blending project conducted in the Netherlands in 2007 showed that blended gases can significantly reduce the carbon oxides and nitrogen oxides produced during combustion [10]. In the architectural field, the use of blended gases for heating serves as the most promising method for the realization of a low-carbon transformation of the energy consumption. In the transportation field, blended gas can be used to improve the thermal efficiency of natural gas internal combustion engines and reduce the exhaust losses and methane emissions in from the vehicle exhaust. Based on the existing technology, the addition of hydrogen below a certain proportion into natural gas pipelines does not require the upgrading of existing natural gas pipeline network facilities. Therefore, the development of the blending industry can improve the overall peak shaving capacity of natural gas pipeline networks and support the realization of deep carbon reduction in terminal energy consumption.

3.5 To encourage the innovation of hydrogen technology

The development of the blending industry requires the comprehensive development of all the technologies in the industrial chain involved in hydrogen production using renewable energy, hydrogen storage, hydrogen blending, hydrogen transport, hydrogen extraction, and hydrogen utilization. Compared with the leading countries in the field, China's blending industry begun very late and therefore lacks a comprehensive technical system and mature engineering practice, with only a few projects existing for the entire blending industrial chain. Based on the actual needs of the economy and society, the development of blending technology will promote technological innovation in the industrial chain from energy production to consumption, improve the technical level of high-end equipment manufacturing in China's energy field, and generate new impetus for the transformation and upgrading of the energy industry. It is estimated that approximately 2.7×10^{6}–6.3×10^{6} t of hydrogen will be blended into the natural gas pipeline networks by 2030. Based on a lifecycle cost of 30 CNY/kg for production, storage, transportation, and utilization, this industrial chain can generate as much as 80–180 billion CNY/year.

4 Development status in the blending industry

4.1 International progress

The concept of hydrogen blending in natural gas pipeline transmission networks was proposed in 1972. With the rapid growth of the renewable energy generation capacity and iterative upgrade of fuel cell technology, the development of related industries has received more attention. Developed countries such as Germany, France, and the United States have all released hydrogen energy strategies, and they believe that the use of hydrogen blending in natural gas pipeline transmission networks and transformation of natural gas infrastructure into hydrogen energy infrastructure are key for promoting the development of hydrogen economy (Table 1) [19–25]. At the standards level, international long-distance hydrogen pipeline technology has matured, and their corresponding design standards such as ASME B31.12—2019 in the United States, CGAG-5.6—2005 in Europe, and AIGA 033/06—2006 in Asia have become relatively comprehensive [9,26]. Moreover, natural gas pipeline transportation technologies have relatively complete standards systems such as ASME B31.8—2018 in the United States, ASCEALA—2001, and CSA Z662—2011 in Canada. However, a special technical standards for hydrogen blending in natural gas pipeline transmission systems still needs to be established.

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Table 1. Relevant plans for the development of the blending industry in major countries and regions.

Time	Country or region	Planning name	Planning content
July 2020	European Union	A hydrogen strategy for a climate-neutral Europe	The financial support for the natural gas pipeline network reuse project is provided. The key actions include reusing the existing Pan-European natural gas infrastructure after 2030 to provide necessary support for large-scale cross-border hydrogen transportation and the updating of the gas quality standards to ensure a smooth connection between the natural gas-hydrogen blending projects in different member countries.
June 2020	Germany	National Hydrogen Energy Strategy	The feasibility of the existing natural gas infrastructure to store and transport hydrogen or be transformed into pure hydrogen pipelines while expanding and adding pure hydrogen pipeline networks to improve the application potential of hydrogen energy is evaluated.
September 2020	France	National Strategy for the Development of Hydrocarbon Free Energy	From 2030, 20% hydrogen will be mixed into the natural gas pipeline network and transported with the natural gas to promote decarburization in the natural gas industry.
October 2020	Russia	Russian Hydrogen Energy Development Roadmap	An entire hydrogen energy industrial chain is to be established before 2024. Hydrogen will be produced from natural gas and transported while mixed with hydrogen in the existing natural gas pipeline network, or the existing natural gas pipeline will be transformed into a hydrogen pipeline.
December 2020	USA	Hydrogen Energy Project Planning	In the overall strategic framework for future hydrogen energy research, development, and demonstration, hydrogen blending transmission of natural gas will be taken as the medium- and long-term technology development option
December 2020	Canada	Hydrogen Strategy for Canada	The strategic vision for hydrogen energy by 2050 is proposed: (1) hydrogen energy infrastructure will be built and terminal applications will be promoted to accelerate Canada to a major global hydrogen energy supplier, and (2) hydrogen production should reach $2{\times}10^7$ t/a, meaning that over 50% of the hydrogen will be transmitted through the existing natural gas pipeline network or newly-built pure hydrogen pipeline network.
August 2021	UK	UK Hydrogen Strategy	The strategy pays attention to the role of hydrogen energy infrastructure construction in promoting the hydrogen economy. In 2022, the value evaluation of 20% hydrogen mixed with natural gas pipeline will be completed. In 2023, pilot community heating will be conducted. After 2025, hydrogen pipe networks and natural gas pipe networks will be integrated. After 2035, regional and national hydrogen energy pipe networks will be established to promote the conversion of natural gas pipe networks to hydrogen energy pipe networks.

At the demonstration level, many countries have performed feasibility studies on hydrogen blending in natural gas and construction of demonstration projects, and many countries have also tested the impact of different proportions of hydrogen on pipeline network infrastructure and terminal equipment [27,28]. The hydrogen blending ratio in the existing projects were mostly between 5% and 30%, and the hydrogen was mainly produced from renewable energy. In 2004, the European Union NaturalHy project mobilized 15 natural gas companies and conducted a study on the potential impact of hydrogen blending in natural gas pipelines. Their results indicated that the addition of 20% hydrogen into natural gas pipelines does not significantly increase safety risks such as explosions [9,28]. In 2008, the Netherlands conducted the VG2 project on hydrogen production from wind and power blending in natural gas pipeline networks to clarify the upper limit of the hydrogen blending ratio. In 2010, the average hydrogen blending ratio reached 12% [9,27,28]. In 2014, the French GRHYD project explored the blending of hydrogen produced from wind energy in natural gas pipeline networks at a proportion of less 20%, for use by residents and to provide blended gas with a hydrogen blending ratio of 6% to 20% to natural-gas-powered-buses via gas stations [9,27]. In 2019, the Italian National Natural Gas Pipeline Company investigated the blending of 5% hydrogen in the natural gas pipeline network, where the current hydrogen blending ratio has been increased to 10% [9,28]. In 2019, a British company blended 20% hydrogen in their natural gas pipeline networks to explore the impact of hydrogen blending in natural gas on residential users [27,28]. In 2020, Australia launched the hydrogen blending in natural gas pipelines demonstration project, where 10% hydrogen produced from the water electrolysis of renewable energy was blended in natural gas pipeline networks for users' use [21,27]. The HyBlend initiative in the United States focuses on the technical aspects of hydrogen blending in natural gas pipeline transportation, and the assessment of the hydrogen compatibility of natural gas pipelines and operations under long-term use conditions [29].

4.2 Current domestic status

Presently, China is the largest hydrogen producer worldwide and has the largest installed capacity of renewable energy. Moreover, the development potential for hydrogen production from renewable energy is still increasing, and an interconnected natural gas backbone network has already been built. China has mastered the main technology and production processes for the entire industrial chain in terms of hydrogen energy production, storage, transportation, and utilization, and the basic conditions for the development of blending industry are sufficient.

The *14th Five Year Plan for Scientific and Technological Innovation in the Energy Sector*, *Opinions on Improving the System, Mechanism, and Policy Measures to Achieve Green And Low-Carbon Energy Transformation*, and the *Medium- and Long-Term Plans for the Development of the Hydrogen Energy Industry (2021–2035)* have been released. An evaluation of the safety, reliability, economy, adaptability, and integrity of the hydrogen-blended natural gas pipelines, key transportation equipment is to be performed in addition to the exploration of efficient hydrogen transport methods such as hydrogen-blended gas pipelines, carrying out pilot demonstrations of hydrogen-blended natural gas pipelines, and the gradual building of low-cost and diversified hydrogen energy storage and transportation systems. However, the blending industry in China is still in its infancy, and the government hasn't yet issued a national-level development plan. However, some provinces have issued local hydrogen industry plans and taken the blending technology as a breakthrough for hydrogen storage, transportation, and terminal application (Table 2).

The National Standardization Technical Committee for Hydrogen Energy and the National Standardization Technical Committee on Fuel Cells and Liquid Batteries have taken the lead in formulating and revising the standards in the hydrogen energy field. China has issued over 90 national standards related to hydrogen, but only the "Compressed Hydrogen Natural Gas Mixed Gas for Vehicles" (GB/T 34537—2017) involves hydrogen blending in natural gas pipelines. In addition, "Coal-based synthetic natural gas" (GB/T 33445—2016) stipulates that the hydrogen ratio (mole fraction) of first-class coal-gas to synthetic natural gas should not exceed 3.5%, and the hydrogen ratio of second-class coal-gas to synthetic natural gas should not exceed 5%. Moreover, the "Gas quality requirements for long-distance natural gas pipelines" (GB/T37124—2018) stipulates that the hydrogen ratio (mole fraction) in natural gas should not exceed 3%.

China's blending projects started relatively late, with only two projects preliminarily completed. In the first project is in Chaoyang City, Liaoning Province, where the hydrogen is produced via water electrolysis and the hydrogen blending ratio is 10%, the verification of entire chain for hydrogen production, storage and transportation, and blending and utilization was successfully realized. In the other project in Jincheng City, Shanxi Province, the hydrogen is produced from coal, and there are 12 demonstration projects currently under construction or being planned.

5 Key Issues for the development of the blending Industry

Hydrogen blending in natural gas pipeline transportation is a complex system engineering problem that needs to consider the technical feasibility, and is restricted by safety and economy. Although many countries including China are actively conducting demonstrations on the applications of blending transportation, the following key problems need to be systematically solved before large-scale promotion and application can be achieved.

5.1 Hydrogen blending proportion

Hydrogen blending in natural gas has an impact on the infrastructure and terminal energy equipment of natural gas pipeline networks. Because the hydrogen ratio in natural gas varies and the impact is different on different links and different equipment in the industrial chain, different countries have different regulations on the upper limit of the hydrogen blending ratio. In China, the impact of different blending ratios on gas transmission and gas consumption facilities and equipment is still unclear, and there is no unified standards for demonstration projects.

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To ensure the development of the blending industry, it is necessary to demonstrate and clarify the hydrogen blending ratio suitable for actual development in China. The adaptability of pipes, equipment, and processes should be comprehensively considered to determine the threshold value of hydrogen, to ensure the safety of transmission [30] and balance the corresponding technical and economic feasibility.

Table 2. Relevant plans for the blending industry in some provinces.

Time	Region	Planning name	Planning content
January 2020	Tianjin	Tianjin Hydrogen Energy Industry Development Action Scheme (2020–2022)	The application of hydrogen-doped natural gas in industrial, commercial, civil, and other fields will be explored.
September 2020	Sichuan Province	Sichuan Hydrogen Energy Industry Development Plan (2021–2025)	Research will be conducted on hydrogen transportation and safety of high-pressure and large-capacity pipelines, compatibility of natural gas pipeline materials with hydrogen, and safety of hydrogen-doped natural gas.
July 2021	Hebei Province	The 14th Five Year Plan for the Development of Hydrogen Energy Industry in Hebei Province	The pilot demonstration for hydrogen in the mixed transportation of natural gas pipelines will be carried out in 2022, and the promotion and application of hydrogen energy in the mixed transportation of natural gas pipelines field will be expanded in 2025.
August 2021	Beijing	Implementation Plan for Hydrogen Energy Industry Development in Beijing (2021–2025)	In the field of hydrogen energy storage and transportation, focus will be places on the breakthroughs for hydrogen-doped pipeline transportation technology.
December 2021	Guangdong Province	Shenzhen Hydrogen Energy Industry Development Plan (2021–2025)	The formulation of standards for hydrogen mixing in natural gas pipelines will be carried out. Hydrogen blending pipeline transmission and distribution technology will be explored, and the research and development of supporting hydrogen production technology and production of equipment will be investigated. Natural gas pipeline hydrogen blending and other pipeline hydrogen transmission projects will be piloted on a small scale, and hydrogen-doping technology for urban natural gas pipeline will be explored.
February 2022	Inner Mongolia Autonomous Region	The 14th Five Year Plan for Hydrogen Energy Development in Inner Mongolia Autonomous Region	The planning and construction of hydrogen blending in natural gas pipeline networks will be explored and promoted. The demonstration of hydrogen-doped gas pipeline transmission, research and application of hydrogen-doped technology in natural gas pipelines and hydrogen transmission technology for medium- and long-distance pipelines will be conducted in Tongliao, Ulanqab, Ordos, Wuhai, and other regions.

5.2 Adaptability of pipes and terminal equipment

Presently, the natural gas pipelines in operation are designed based on the transportation of natural gas, the industrial user processes involving natural gas as a raw material are designed based on natural gas, and the terminal energy equipment of commercial and residential users is mostly fueled by natural gas. After natural gas is blended with hydrogen, the quality conditions of the original natural gas in the pipelines must be changed. The pipeline, weld, compressor, flow meter, voltage regulator, and valve are exposed to high pressures and hydrogen-rich environments. The risk of damage due to hydrogen such as hydrogen embrittlement and hydrogen corrosion has increased [12,30], resulting in significant changes in the operating conditions, equipment performance, and safety maintenance of natural gas pipelines. For terminal users, combustion equipment such as gas appliances, gas turbines, boilers, and industrial furnaces have different adaptability to blended gas owing to their different combustion performance. It is therefore necessary to consider the interchangeability of blended gas and the influence on the combustion characteristics by conducting adaptability analyses of pipes and terminal equipment to blended gas.

5.3 Safety use

Compared with that of methane, the main component of natural gas and hydrogen has a larger explosion limit range, a faster leakage rate under high pressure, and is more prone to leakage and spontaneous combustion.

Correspondingly, the explosion risk of hydrogen blending in natural gas pipelines is also higher. For a terminal user, hydrogen blending in natural gas reduces the calorific value, Wobbe number, and other parameters, and accelerates the flame combustion speed, resulting in the decrease in the thermal load of the terminal equipment and increase in the risk of thermal tempering during use [28]. Therefore, hydrogen blending in natural gas pipelines increases the safety risk for the operation of natural gas long-distance and urban gas pipeline networks and increases the requirements for the safety of terminal energy consumption. Moreover, additional researching on the leakage diffusion law and safety risk control of hydrogen blending in natural gas is essential for the development of the blending industry.

5.4 Economical efficiency

Hydrogen blending in natural gas pipelines can be used to achieve the long-distance and large-scale networked transportation of hydrogen with relatively little investment and within a short time, which is beneficial for efficiently connecting hydrogen energy production areas and consumption areas. It is noteworthy that the calorific value for the same volume of hydrogen is only 1/3 that of natural gas. Assuming that natural gas can provide the same calorific value to the terminal user after blending with hydrogen, the price of hydrogen should theoretically be 1/3 that of natural gas. Based on the natural gas gate price of 1.8 CNY/m^3, the hydrogen price should be 6–7 CNY/kg, and this price is much lower than the current cost of hydrogen production. From a blending industry development perspective, the commercial application of natural gas hydrogenation projects is not economically feasible. Therefore, it is necessary to explore diversified application scenarios for hydrogen blending in natural gas pipelines and design a blending industry ecosystem and business model suitable for China's national conditions to promote the steady development of the blending industry through a joint effort by hydrogen production enterprises, pipe network enterprises, terminal users, and other relevant entities.

6 Suggestions for cultivating the blending industry

6.1 Strengthening the top-level design and strategic research

The development of the blending industry is related to the high-quality development of the hydrogen and natural gas industries. To achieve this, China should strengthen the top-level design and macro research on the blending industry, critically analyze the technical route and key tasks for the development of the blending industry, and conduct basic research, equipment research and development, technical demonstrations, application research, specifications and standards formulation, performance testing, business model innovation, and education promotion. Moreover, the management mode for the blending industry should be improved, an incentive mechanism for the promotion of the blending industry should be established, and the financial support for the blending industrial chain should be reasonably increased.

6.2 Building a standards system for safety supervision and technology and operation management of hydrogen blending in natural gas pipelines

To construct a safety and emergency management system with a high standard for the blending industry, a safety supervision platform for the blending industry should be established based on information technology and digital technology. Moreover, communication and collaboration between management departments should be enhanced and the management model for the natural gas industry updated to clarify the responsibilities and obligations of the regulatory authorities in each link of the blending industry. Based on the current regulatory framework for natural gas pipeline networks, the regulatory approval process for the construction of blending projects should be improved, the key points of the standardization work in the blending industry should be sorted out, and the coordinated development of blended gas and hydrogen, natural gas, and urban gas should be maintained. Additionally, the construction of national and industry standards for the blending industry should be accelerated, the regulation and orderly development of the natural gas hydrogen blending industry should be promoted, and the supervision of works in the blending industry should be carried out by a technical support management department.

6.3 Promoting government-industry-education-research integration in hydrogen blending

A national science and technology development department should be established to support development projects based on the major blended gas transmission development and application needs for 2030 and 2060, considering the terminal utilization and the strengthening of the national and local research plans to support the

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localization of blending infrastructure, technology, and equipment. The industry backbone enterprises, universities, and scientific research institutes should jointly establish a comprehensive test platform and engineering technology center for the blending industry, which should concentrate on the scientific and technological research of key materials, technologies, processes, and equipment in the blending industry. Moreover, support should be offered to universities and research institutes conducting high-quality discipline construction and personnel training in hydrogen, natural gas, and comprehensive energy resources, which should encourage the formation of an international industrial innovation mechanism model, international cooperation, and technical exchanges in the blending industry field.

6.4 Establishing an innovative alliance in blending industry

To ensure the continuous development of the blending industry over the next 10 years, the principles of government guidance, business leadership, multi-party participation, and benefit sharing should be followed to ensure the active coordination of the relevant enterprises in the industrial chain, break down industrial barriers, and build an integrated hydrogen production–blending–storage–transportation–extraction–use industrial chain. Using diversified application scenarios and business models, a sustainable industrial ecosystem can be cultivated to steadily promote the scaled development of the industry. Moreover, encouraging oil and gas enterprises, pipe network companies, and urban gas enterprises to increase investment in renewable energy resources and establish an innovative alliance in the industry will attract the extensive participation of industrial chain enterprises, research institutes, universities, industry associations, and other relevant stakeholders. In addition, building a cross-industry communication platform and cooperation mechanism will assist in ensuring the large-scale development of the industry.

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