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Pioneering Sustainability: The Development and Policy Framework of Ammonia Fuel Technology in China

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ABSTRACT

This article investigates the complex dynamics of ammonia as an alternative fuel within the ambit of China's strategic initiatives aimed at attaining carbon neutrality. Given ammonia's distinctive characteristics as a fuel, this analysis delves into the nascent development status and the multifaceted challenges confronting this sector within China. Through a comprehensive examination of the plethora of new energy policies promulgated by the Chinese government, this article underscores the initial phase of accelerated growth in the ammonia fuel domain. The imposition of carbon emission restrictions, coupled with the momentum generated by technological innovations, positions green ammonia as an efficacious solution for hydrogen storage and utilization, thereby fostering a symbiotic relationship with the hydrogen energy industry chain. The proactive policy framework adopted by China significantly enhances the pivotal role of ammonia fuel technology, making it one of possible principal technological pathways for China to realize its carbon neutrality ambitions in the future.

Keywords: Ammonia Fuel Technology, China, Energy Policies, Sustainable Energy Solutions

JEL Classifications: N45, N75, O2, Q42, Q48

1. INTRODUCTION

Ammonia emerges as a green, efficient, carbon-free, and broadly applicable new energy source amidst the rapid iterative advancements in hydrogen electrolysis and ammonia synthesis technologies. As a pivotal component of the hydrogen industry chain, ammonia, with its superior hydrogen storage properties, is increasingly becoming a focal point of industrial attention as an emerging technological solution. On one hand, China's heightened energy conservation and emission reduction requirements for high-energy-consuming industries underscore the urgency of high-quality new energy development. Despite the recent surge in domestic electricity demand rendering coal-fired power generation irreplaceable for supply security, on the other hand, regions like Inner Mongolia and Xinjiang in China experience significant wind and solar power abandonment due to the inherent characteristics of wind and solar electricity generation. This scenario demands innovative approaches for electricity grid load balancing and new energy storage. The hydrogen-ammonia industry chain, supported by mature infrastructure, leverages ammonia's ease of storage and hydrogen's excellent combustion properties to form a complementary relationship. This synergy is beginning to scale in downstream applications such as ammonia blending combustion and ammonia-fueled ships, where there is a significant market demand for ammonia blending modifications. In this context, strengthening research on ammonia fuel technology, its market prospects, and China's new energy policies will enhance the academic understanding and comprehension of technological transformations in China's new energy sector.

This study aims to explore the impact of China's new energy policies on the development and promotion of ammonia fuel technology. The key research questions guiding this study are:

1. What are the current advancements, technological innovations, and practical applications of ammonia fuel technology in China?
2. How do China's new energy policies influence the growth and development of the ammonia fuel industry?
3. What challenges and opportunities exist for integrating ammonia fuel into China's energy landscape?

By addressing these questions, this paper seeks to enhance the academic understanding of the technological transformations in China's new energy sector and provide insights into the strategic role of ammonia fuel technology in achieving carbon neutrality goals. Through a comprehensive analysis of policy frameworks, market developments, and technological advancements, this study aims to underscore the significance of ammonia as a sustainable energy solution within China's broader energy strategy.

2. CHARACTERISTICS OF AMMONIA AS A FUEL

2.1. The Physicochemical Properties of Ammonia

Ammonia serves as a foundational chemical raw material pivotal to national economies and public welfare, extensively employed across domains such as fertilizers, environmental protection, steel production, chemical industry, and refrigeration.

1. Ammonia is recognized as an exemplary hydrogen storage medium, composed of nitrogen and hydrogen elements, with a hydrogen content reaching 17.7 wt%. It is characterized as a colorless gas at ambient temperature, possessing a pungent odor and high corrosiveness. Compared to certain carbon-containing fuels, ammonia exhibits the advantage of a higher hydrogen content.
2. The physical properties of ammonia are more stable than hydrogen. Upon cooling or pressurization, it can transition into a liquid form, exhibiting high storage density, transportation safety, and combustion safety characteristics. Through simple pressurization (1 MPa), ammonia can be converted into liquid at room temperature. It boasts a higher mass energy density (22.5 MJ/kg) and volumetric energy density (13.6 MJ/L) compared to hydrogen, methanol, and compressed natural gas, with its per-unit energy cost significantly lower than other fuels (Yang et al., 2023).
3. Ammonia exhibits relatively good safety characteristics and is easy to transport. It has a high-octane value, demonstrating excellent anti-knock properties, which enhances the safety of ammonia fuel during use. The combustible volume range in air is 15.0% to 28.0%, narrower than that of hydrogen, which ranges from 4.7% to 75.0%, thus making it safer and less prone to ignition and explosion during storage and transportation. In terms of volume, liquid ammonia occupies approximately 1/800th of its gaseous form for the same mass, making it more suitable for transportation in vessels where space is a critical factor compared to ammonia gas. In contrast, hydrogen is characterized by its propensity to leak, diffuse, and ignite or explode easily, and its boiling point of −253°C is significantly lower than that of ammonia at −33.5°C. Therefore, liquid hydrogen, with its ultra-low temperature characteristics, poses higher risks when applied on ships (Yang et al., 2023).

2.2. Combustion Characteristics of Ammonia

1. The combustion flame properties of ammonia differ significantly from those of hydrocarbon fuels. Compared to hydrocarbon fuels like methane, ammonia fuel combustion produces a wider and longer flame, with a distinctly different color. The flames of hydrocarbon fuels such as methane exhibit a blue hue due to the high-temperature luminescence of CHx radicals, whereas ammonia fuel flames display a yellow coloration due to NH_2 radicals. Furthermore, the concentration of NH_2 radicals increases sharply with the equivalence ratio of ammonia fuel, resulting in a deeper flame color, indicating differing radiative heat transfer properties between methane and ammonia. The flame propagation speed of ammonia is slower. At room temperature, the laminar flame speed of ammonia is only around 7 cm/s, which is one to two orders of magnitude lower than that of methane and hydrogen. Ammonia fuel exhibits a lower flame temperature, attributable to its lower calorific value compared to other gaseous fuels and the higher specific heat capacity of the combustion-generated flue gases (Li et al., 2021).
2. Complete combustion of ammonia produces only nitrogen and water (with the chemical reaction formula: $NH_3 + O_2 \rightarrow N_2 + H_2O$), generating no CO_x, SO_x, or other greenhouse gases (Kobayashi et al., 2019). In addition to the traditional Haber-Bosch process, renewable energy sources can be integrated into the ammonia synthesis process, further reducing carbon emissions during ammonia production.
3. Ammonia's combustion rate is exceptionally low. Under the same flow rate and equivalence ratio conditions, the air-fuel ratio for ammonia fuel is 35.24% and 17.62% of that for methane fuel and hydrogen fuel, respectively. This means that a unit mass of fuel requires less combustion air, potentially saving energy consumption for auxiliary equipment. Furthermore, compared to conventional hydrocarbon fuels like natural gas and petroleum, ammonia has a lower laminar combustion speed and lower calorific value, and requires higher ignition energy, resulting in high resistance to auto-ignition (Chiong et al., 2021). Typically, ammonia fuel must be mixed with other fuels during combustion, using the other fuels as ignition agents. Therefore, the use of ammonia fuel imposes higher requirements on the combustion environment within burners, such as turbulence levels and preheat temperatures (Duan and Li, 2022).

2.3. Reaction Principles

The combustion mechanism of ammonia reflects critical information and pathways within the combustion process, playing a vital role in the selection and development of models for numerical simulations, as well as in the control of NO_x emissions. Macroscopically, the overall reactions for ammonia combustion can be summarized as follows:

$$4NH_3+3O_2 \rightarrow 2N_2+6H_2O \quad (1)$$

$$4NH_3+5O_2 \rightarrow 4NO+6H_2O \quad (2)$$

$$4NH_3+6NO \rightarrow 5N_2+6H_2O \quad (3)$$

Microscopically, ammonia combustion involves a series of complex chemical processes, including dozens of reactants and several to hundreds of consecutive elementary reactions. The high-temperature generation of nitrogen oxides (NO_x) from ammonia fuel partly originates from ammonia itself, but also through indirect reactions with ammonia combustion, linked by intermediates such as NO, NH, HNO, and HCN (Liu et al., 2023). In practical applications, the formation of NO_x is inevitable, necessitating the development of advanced ammonia combustion technologies to reduce nitrogen oxide emissions.

2.4. Ammonia Production Methodologies

In China, Ammonia production methodologies are presently differentiated into three distinct categories based on their respective production processes: Grey ammonia, blue ammonia, and green ammonia (Luo et al., 2023).

Grey ammonia is synthesized predominantly through the conventional Haber-Bosch process, wherein hydrogen is obtained from natural gas or coal via steam methane reforming (SMR) and nitrogen is separated from air. The SMR process is particularly notable for its high CO_2 output, accounting for approximately 80% of total carbon emissions across the entire ammonia production cycle. This method also significantly contributes to climate change through methane leakage during gas extraction and processing. The environmental ramifications of hydrogen production via the SMR method are substantial, owing to the extensive release of greenhouse gases (Smith et al., 2021).

Blue ammonia, by comparison, utilizes a production process analogous to that of grey ammonia but incorporates carbon capture and storage (CCS) technologies. This integration significantly mitigates carbon emissions: when natural gas is used in conjunction with CCS, the carbon emissions per ton of ammonia can be reduced from 1.8 tons to merely 0.1 ton. Similarly, when coal is used with CCS, emissions can be decreased from 3.2 tons per ton of ammonia to just 0.2 tons, representing a substantial reduction in the carbon footprint of ammonia production (Johnson and Anderson, 2019).

Green ammonia production continues to rely on the Haber-Bosch process but shifts towards sustainability by using “green hydrogen,” which is produced using renewable energy sources. The critical aspect of green ammonia synthesis is the effective integration of water electrolysis, which generates hydrogen, with the ammonia synthesis process. Typically, the production chain for green ammonia comprises air separation (to produce nitrogen and oxygen), water electrolysis (for hydrogen production), and ammonia synthesis. These steps are characteristic of the technological setups employed in contemporary green ammonia demonstration projects across China, emphasizing a pivot towards more sustainable industrial practices (Chen et al., 2020).

3. AMMONIA FUEL MARKET IN CHINA

3.1. Analysis of the Ammonia Fuel Industry Chain in China

The ammonia fuel industry chain in China exemplifies a strategic integration of renewable energy resources and advanced chemical processes, structured into three distinct segments: Upstream, midstream, and downstream.

The upstream component of the ammonia fuel industry chain primarily consists of renewable energy producers who specialize in the construction and operation of photovoltaic, wind, and hydropower systems. These producers are pivotal in delivering clean electricity to the national grid, establishing a foundation for sustainable energy consumption. The role of these renewable sources is not just to provide energy but to ensure that the production of ammonia fuel adheres to environmentally friendly practices, thereby supporting China’s green energy targets and reducing the dependency on fossil fuels (Wang et al., 2022).

In the midstream sector, the focus shifts to the synthesis of hydrogen and the manufacturing of equipment critical for ammonia production. The ammonia synthesis pathway involves converting green electricity into hydrogen through the process of water electrolysis. This hydrogen is then used to synthesize ammonia, which integrates the sectors of hydrogen and ammonia production tightly. The electrolysis cells, critical for the hydrogen production, and the ammonia crackers, central to ammonia fuel technology, represent significant innovations in this sector. These technologies are essential for ensuring the efficiency and environmental compatibility of ammonia production, highlighting the industry’s commitment to sustainable manufacturing practices (Lee and Zhang, 2021).

The downstream segment of the industry involves the application of ammonia as an alternative fuel in commercial vehicles, maritime transport, and thermal power stations, particularly in projects aimed at co-firing ammonia to reduce CO2 emissions. This segment is crucial for demonstrating the practical applications of ammonia as a clean energy vector. Although still in the experimental and developmental stages, these applications show promise for significant contributions to reducing global carbon emissions and enhancing air quality. The transition to ammonia fuels in these sectors could lead to a revolutionary change in energy utilization, aligning with global trends towards decarbonization (Chen et al., 2023).

The integration of these three segments forms a robust framework for the development and application of ammonia fuel technologies in China. This alignment is not only vital for meeting the energy demands of a growing economy but also crucial in addressing the environmental challenges posed by traditional fossil fuels. As China continues to invest in and expand its ammonia fuel industry, it is expected to lead to significant advancements in energy technology, contributing to a sustainable and low-carbon future.

3.2. Current Status of Ammonia Fuel Market Promotion in China

In China, prominent state-owned and private enterprises such as Guoneng Group (China Energy Investment Group), Guodian Investment(State Power Investment Corporation), Jidian Shareholding (Jilin Power Share Corporation), China Tianying, Mingtuo Group, and Jingneng Group(Beijing Energy International Holding Co) are actively pursuing projects in green hydrogen and green ammonia. However, as of the second half of 2023, most ammonia fuel projects remain in the stages of initiation, registration, and commencement, with the actual production capacities yet to be realized.

On July 12, 2022, Guoneng Group's Guohua Investment's project in the Ganqimaodu Border Processing Park in Urad Middle Banner, Bayannur City, Inner Mongolia, received approval. This project, with an investment of 2.3 billion yuan, is expected to produce approximately 300,000 tons of green ammonia annually. Spanning about 300 acres, the project plans a total investment of 2.3 billion yuan, with an accompanying new energy installation capacity of 1.1 million kilowatts, including 800,000 kilowatts from wind and 300,000 kilowatts from photovoltaics. Utilizing wind and solar power to electrolyze water for high-quality hydrogen production, which is then used for ammonia synthesis, the project aims to supply green ammonia for industrial chemical production in the Mongolian West region. Upon completion, it is expected to save an equivalent of 109,200 tons of standard coal annually due to its significantly lower energy consumption compared to traditional fossil fuel-based hydrogen production methods (Guoneng Group, 2022).

On June 22, 2022, the Damao Banner Wind and Photovoltaic Hydrogen Production and Green Flexible Chemical Integration Project, led and contracted by the National Electric Investment Smart Energy (State Nuclear Power Institute), began construction in Baotou, Inner Mongolia. The project includes 200 megawatts of wind power and 200 megawatts of photovoltaics, expected to generate 1.25 billion kilowatt-hours per year. It employs wind and solar power for hydrogen production, projected to produce 17,800 tons of hydrogen annually, and synthesizes liquid ammonia with an annual output of 100,000 tons (Guodian Investment, 2022).

In September 2022, Jidian Shareholding's Da'an Wind and Photovoltaic Green Hydrogen Ammonia Synthesis Integration Demonstration Project received official approval and registration. The total investment for this project is 6.332 billion yuan, with 2.549 billion yuan allocated specifically for hydrogen and ammonia synthesis. The plan includes constructing a 700-megawatt wind power project and a 100-megawatt photovoltaic project, accompanied by a 40 megawatt/80 megawatt-hour energy storage facility, and constructing new facilities for hydrogen production, hydrogen storage, and a 180,000-ton ammonia synthesis plant. Expected to commence operations in 2024, it will primarily use its capacity for self-consumption, poised to become the first officially operational green ammonia project in China (Jidian Shareholding, 2022).

China Tianying Inc. focuses on environmental protection infrastructure projects and the R&D, production, and sale of environmental protection equipment. In September 2023, the Inner Mongolia Autonomous Region Energy Bureau approved China Tianying's implementation of the Kezuozhongqi Wind, Photovoltaic, and Hydrogen Ammonia Integration Industrial Park Demonstration Project, supporting a new energy scale of 1.3 million kilowatts and a hydrogen production capacity of 50,000 tons/year. The hydrogen is intended for a synthetic ammonia project with an annual production of 480,000 tons (China Tianying, 2023).

Mingtuo Group Co., Ltd. ("Mingtuo Group"), a new metallurgical enterprise group with investment from China Minmetals, collaborated with Hualu Company in April 2022 on a new energy hydrogen production and carbon-free fuel project in the Jiuyuan Industrial Park in Baotou, Inner Mongolia. The project involves constructing the nation's largest wind power project with a capacity of 5 million kilowatts, a 1.5 million kilowatt photovoltaic power generation, and a 300,000-ton water electrolysis green hydrogen project. It also includes the construction of China's first set of green ammonia chemical projects using hydrogen-electric catalytic synthesis technology, producing 1.2 million tons of green ammonia annually, promoting the formation of a green and low-carbon chemical industry chain, and achieving carbon neutrality in the metallurgical and chemical industries (Mingtuo Group, 2022). The Table 1 is a summary of current major ammonia fuel projects in China.

3.3. Applications and Current Status of Ammonia Fuel in China

3.3.1. Ammonia co-firing

The principle of ammonia co-firing technology is to use combustible ammonia gas to replace a certain proportion of pulverized coal, which is then mixed and burned together in a boiler. By controlling the axial temperature and air-fuel ratio of the flame, the generation of nitrogen oxides within the flame is suppressed.

In January 2022, China Energy Group announced the independently developed ammonia co-firing technology for coal-fired boilers by Yantai Longyuan Power Technology Co., Ltd. This technology was applied to a 40MW coal-fired boiler with a 35% ammonia-coal fuel blend. The operation was stable, and the efficiency was higher than that of pure coal under the same load conditions. The NOx concentration at the boiler's tail end was lower than that of pure coal, with an ammonia combustion rate of 99.99%. Compared with pure coal fuel, the carbon reduction of the ammonia-coal mix exceeded 35% (Yantai Longyuan Power Technology Co., Ltd., 2023). On November 30, 2023, China Energy Group conducted a high-load power generation test of ammonia co-firing in a 600MW coal-fired unit at China Shenhua Guangdong Taishan Power Plant. This was the largest capacity unit in China and abroad to have completed an ammonia co-firing test validation (Science and Technology Daily, 2023).

3.3.2. Ammonia Fuel Cells

Ammonia fuel cells can be categorized into Direct Ammonia Fuel Cells (DAFC) and Indirect Ammonia Fuel Cells (IAFC) based on the ammonia supply method. DAFCs are further divided into Direct Ammonia Solid Oxide Fuel Cells (SOFC), Direct Ammonia Alkaline Fuel Cells, and Direct Ammonia Alkaline Membrane Fuel Cells. SOFCs have attracted increasing attention due to their high-power density, fuel flexibility, cogeneration capability, and lack of need for expensive catalysts.

In terms of domestic progress, the University of Science and Technology of China researched the preparation and performance of thin-film proton conductor SOFCs. They attempted to use ammonia as a fuel for proton conductor or oxide ion conductor SOFCs and compared the performance of ammonia/hydrogen

Table 1: Current ammonia fuel projects in China (summarised by authors)

No	Project Name	Participating Companies	Nature of Enterprise	Geographic Location	Installed Capacity/ Power Generation	Annual Ammonia Production (10,000 tons)	Planned Investment (100 million yuan)	Project Status
1	Wind and Solar Hydrogen Ammonia Integration Demonstration Project	State Energy Group Guohua Investment Inner Mongolia Company	State-owned enterprise	Inner Mongolia	800MW wind power, 300MW photovoltaic	30	23	Recorded in July 2022
2	Damao Banner Wind and Photovoltaic Hydrogen Production and Green Flexible Chemical Integration Project	Joint investment by State Power Investment and Tsinghua Strait Research Institute, Smart Energy (State Nuclear Power Institute) as the EPC leader	State-owned enterprise and research institution collaboration	Inner Mongolia	200MW wind power, 200MW photovoltaic, expected to generate 1.25 billion KWh	10	45	Recorded in March 2022, started in July
3	Da'an Wind and Solar Green Hydrogen Ammonia Synthesis Integration Demonstration Project	Jidian Shareholding	State-owned enterprise	Jilin	700MV wind power, 100MV photovoltaic	18	59	Recorded in September 2022, started in July 2023
4	Ten-Megawatt Level Hydrogen Ammonia Integrated Zero-Carbon Industrial Park	Tongliao City Government, China Investment Association, China Tianying	Private enterprise and government institution collaboration	Liaoning	6GW wind power, 4GW photovoltaic	30	600	Signed in September 2022
5	Wind, Solar, and Storage Hydrogen Green Ammonia Project	Jingneng Group and People's Government of Duolun County, Xilin Gol League, Inner Mongolia	State-owned enterprise and government institution collaboration	Inner Mongolia	500MW	60	/	Initiated in August 2022
6	Wind and Solar Power Hydrogen Production and Carbon-Free Fuel Project	Mingtuo Group, Shuimu Mingtuo Hydrogen Energy Technology Co., Ltd., Beijing Tsinghua Industrial Development Research Institute	Private enterprise and research institution collaboration	Inner Mongolia	150MW wind power	39	25.49	Recorded in 2022, started in May 2023
7	Wind and Solar Green Hydrogen Ammonia Integration Demonstration Project	Envision Energy	Private enterprise	Inner Mongolia	4.55GW wind power, 1.02GW photovoltaic	30	105	Recorded in August 2023, planned to start in March 2024

SOFCs, demonstrating the technical feasibility of using ammonia instead of hydrogen as SOFC fuel under equivalent performance conditions (Ma, 2006). Another lab from the Chinese Academy of Sciences prepared thin and dense electrolyte films using vacuum impregnation and successfully fabricated anode supported tubular SOFCs. They experimented with hydrogen and ammonia as fuels, finding that at 800°C, the maximum power densities of the cells using hydrogen and ammonia were 202 and 200 mW/cm², respectively. The similar power densities indicated that ammonia could be a substitute fuel for SOFCs (Zhang et al., 2007). In February 2023, Fuzhou University's Zijin Hydrogen Energy Technology Co., Ltd. successfully delivered a 3kW indirect ammonia supply fuel cell power station, which operated stably. Overall, due to the immaturity of SOFC technology and the scarcity of relevant fuel cell suppliers, ammonia fuel cells are not the primary direction for the current development of ammonia fuel (Li, 2023).

3.3.3. Marine Transportation

Marine transportation is the primary mode of international trade cargo, handling over 90% of global trade transport volume. Marine engines, especially those for ocean-going vessels, require high power output and currently rely mainly on fuel oil. Ocean-going ships have high tonnage, long voyages, low port call frequency, and relatively inconvenient fuel refilling, necessitating high energy density fuels and powerful engines. Green ammonia-powered ships have a much higher energy density than hydrogen and can utilize existing ammonia supply chains and infrastructure, making them promise for application in large ships such as container vessels.

At the end of 2019, the 180,000-ton ammonia-fueled bulk carrier designed by the Shanghai Ship Research and Design Institute received Principle Approval (AIP) from Lloyd's Register of Shipping, with the entire voyage powered by ammonia to meet the main engine's zero-emission requirements. In December 2021, Jiangnan Shipyard (Group) Co., Ltd., part of China State Shipbuilding Corporation, signed a memorandum of cooperation with China Shipbuilding Trading Co., Ltd. and JS&Co for two plus two 93,000 cubic meter Very Large Ammonia Carriers (VLAC). In terms of zero-carbon fuel ammonia application, the Shanghai Ship Research and Design Institute is also advancing the design of several ship types, such as the 2,700TEU ammonia-fueled container ship, the 180,000-ton ammonia-fueled bulk carrier, and the 210,000-ton ammonia-fueled bulk carrier, with ongoing risk analysis work in conjunction with China Classification Society (Li, 2024). However, due to the current imperfections in ammonia fuel engine technology, refueling facilities, network layout, and related regulations, many shipowners are seeking more flexible design solutions, pre-designing ammonia fuel power systems to facilitate future power system retrofits.

3.3.4. Ammonia-powered Vehicles

With the development of ammonia-hydrogen co-firing technology, the complexity of hydrogen storage and transportation and fuel supply systems has spurred research into pure ammonia fuel engine combustion technology. One approach is to use ammonia as a hydrogen storage method, catalytically decomposing ammonia to produce hydrogen as a combustion aid, improving ammonia combustion performance in the cylinder with nitrogen and residual ammonia. The use of engine exhaust to drive a turbocharging system increases ammonia intake, enhancing engine volumetric efficiency and output efficiency. Waste heat from the exhaust provides part of the reaction temperature for the ammonia catalytic decomposition device, recovering engine loss heat. Another approach is to use a dual-fuel engine with in-cylinder direct injection of catalytically decomposed ammonia and port injection of gasoline, where catalysts decompose ammonia to produce hydrogen, and the mixture is directly injected into the engine cylinder. Heat recovery from the exhaust and catalytic decomposition devices reduces the energy consumption of electric auxiliary devices. Research results show that hydrogen combustion from catalytically decomposed ammonia improves engine performance, reduces CO, HC, and NOx emissions in the exhaust, and ammonia conversion efficiency is very effective at low to medium flow rates, significantly increasing engine power and reducing fuel consumption (Zhang et al., 2023).

Chinese technical teams have achieved some results in several technical areas of ammonia-powered vehicles. Xiamen University developed an on-board ammonia hydrogen production device using ammonia thermal cracking and ammonia water electrolysis, replacing high-pressure hydrogen storage bottles with buffer tanks to increase vehicle range (Zhang et al., 2023). Direct ammonia fuel cells for vehicles are at the prototype stage, with no significant progress in ammonia-tolerant fuel cell material systems and single-cell structure optimization, facing multiple technical barriers before practical application. In December 2021, The Hong Kong Polytechnic University launched the first ammonia-powered electric vehicle, where ammonia stored in liquid form in tanks is depressurized into ammonia gas and sent to a decomposition furnace. The furnace, containing catalysts, decomposes 99.9% of the ammonia into nitrogen and hydrogen, with residual ammonia filtered by a gas purifier. This process allows the electric vehicle to obtain hydrogen for power generation (The Hong Kong Polytechnic University, 2021). On December 16, 2022, the first ammonia-powered heavy truck was launched by Changfeng Hydrogen Technology Co., Ltd. in Gangji Town, Changfeng County. This ammonia-natural gas hybrid heavy truck project is a technology transfer result from the Energy Research Institute of the Hefei Comprehensive National Science Center (Li, 2022). GAC Group released the world's first passenger car ammonia engine, achieving 120kW of power and a 90% carbon reduction rate by controlling the phase transition process of liquid ammonia fuel and using ultra-high energy ignition technology to solve the problem of rapid combustion of liquid ammonia (Wang, 2023).

3.3.5. Ammonia energy storage

Ammonia energy storage systems store and release energy by synthesizing ammonia, storing electricity generated from renewable energy in the form of ammonia, and releasing it as thermal or electrical energy when needed (Yang et al., 2023). According to the China Electricity Council's power and structure forecast, around 2025, when renewable energy accounts for 20% of the power generation, it will reach the grid stability limit, urgently requiring long-cycle large-scale energy storage technology.

Conventional electrochemical storage depends on imported raw materials and some control chips and IGBTs (Insulated Gate Bipolar Transistors), unable to fundamentally solve the problem (Wei, 2023). Ammonia energy storage systems have significant utilization value on the power supply side, grid side, and user side.

Value on the Power Supply Side: (1) Consumption of Curtailed Power: Addressing China's curtailed power issue, ammonia energy storage systems convert curtailed energy into ammonia for storage, reusing curtailed power. Electrolytic water hydrogen production technology produces hydrogen, which is then combined with nitrogen from air separation to synthesize ammonia. This process uses curtailed power, avoiding carbon emissions and providing a new approach for carbon reduction. (2) Renewable Energy Storage: Deploying storage systems in wind and photovoltaic projects significantly reduces curtailment rates. Ammonia storage technology can store excess electricity generated by renewable energy locally as ammonia. (3) Ammonia Flue Gas Treatment: Designing ammonia production processes based on power plant conditions and integrating flue gas treatment systems can achieve ammonia desulfurization, denitrification, and carbon capture. This provides a technological path for the strategic transformation of the power industry under the dual-carbon background, supporting the diversified development of traditional thermal power plants (Yang et al., 2023).

Value on the Grid Side: (1) Peak Shaving Capacity Improvement: Ammonia energy storage systems provide peak shaving capacity on the grid side, "cutting peaks and filling valleys" to improve equipment utilization and reduce energy consumption, enhancing grid safety, stability, and reliability. (2) Large-Scale, Long-Duration Storage: Ammonia, with its high energy storage density and long storage cycle, can store excess electricity generated during peak power generation periods in the form of ammonia. This allows regulation of renewable energy generation fluctuations over longer periods, addressing the imbalance of wind and photovoltaic power generation across seasons and periods, achieving large-scale, cross-regional peak shaving (Yang et al., 2023).

Value on the User Side: (1) Emergency Backup Power: As an emergency backup power source, ammonia energy storage systems convert stored ammonia into electricity during extreme weather or emergencies, providing rapid switching and reliable emergency support. (2) Peak-Valley Electricity Price Arbitrage: Industrial users can use ammonia storage devices to convert electricity into ammonia during low-price periods and release it as electricity during peak-price periods, achieving peak-valley price arbitrage and reducing electricity costs (Yang et al., 2023).

The current application scenarios of ammonia fuel in China encompass ammonia co-firing, ammonia fuel cells, marine transportation, ammonia-powered vehicles, and ammonia energy storage. Despite the numerous challenges that ammonia fuel technologies still face, they exhibit clear application prospects across various sectors in China. As technology continues to advance and improve, ammonia fuel is poised to play a pivotal role in China's energy transition.

4. CHINA'S NEW ENERGY POLICIES AND IMPACTS ON AMMONIA FUEL TECHNOLOGY

China's energy structure reveals a stark contrast compared to Western countries and the global average, primarily due to its significant reliance on coal. While coal accounts for <20% of energy consumption in Western countries, resulting in a more balanced energy distribution, China's coal consumption remains high at around 55.3% (Hou et al., 2021). This reliance poses challenges for China's ambitious environmental goals of peaking carbon emissions by 2030 and achieving carbon neutrality by 2060 (Mao and Yan, 2021).

The 14th 5-Year Plan (The State Council of the People's Republic of China, 2021) outlines stringent targets for reducing energy consumption per GDP unit by 13.5% and carbon emissions per GDP unit by 18% from 2020 levels by 2025. However, as of the end of 2023, progress has been slower than anticipated, with reductions of 7.3% and 4.9%, respectively. The COVID-19 pandemic has exacerbated these challenges by causing economic shifts that led to increased energy consumption and carbon emissions, notably a rebound in carbon emission intensity in 2023 (Li, 2024).

To address these challenges, the "2024-2025 Energy Conservation and Carbon Reduction Action Plan" (State Council of the People's Republic of China, 2024) emphasizes enhanced measures for energy conservation and emission reduction. The plan aims to reduce GDP energy consumption by 13.5%, save approximately 50 million tons of standard coal, and cut around 130 million tons of CO_2 by the end of 2025. Additionally, it sets specific goals for reducing GDP energy consumption by 2.5%, GDP carbon emissions by 3.9%, and energy consumption per unit of value-added industrial output by 3.5%. The plan also targets an increase in the share of non-fossil energy consumption to about 18.9% by 2025.

Given the dominance of carbon-containing fossil fuels in China's energy system, using ammonia as an additive in these fuels is seen as a viable short-term strategy for carbon reduction. This approach requires minimal adjustments to existing infrastructure, such as boilers, engines, and turbines, thus shortening the improvement cycle. While the complete replacement of coal with ammonia produced from renewable energy sources remains a long-term goal, the blending of ammonia with carbon fuels like coal and methane offers a practical interim solution. This strategy aligns with current policies and leverages the significant potential of ammonia as an alternative fuel in China's energy transition efforts.

In addition to the favorable impact of the overall policy environment on the development of ammonia energy, the Chinese government is also gradually clarifying the parallel development route of hydrogen and ammonia through a series of policy documents. These policies emphasize the hydrogen-based energy storage and low-carbon fuel attributes of ammonia, explicitly identifying hydrogen (ammonia) energy storage as one of the key routes for development. The Table 2 is a summary of relevant policies issued by various governmental department

Table 2: Summary of china's support policies for ammonia fuel (summarised by authors)

No.	Date	Institution	Policy/Project Name	Main Content
1	June 2023	Ministry of Industry and Information Technology	Implementation Plan for Carbon Peaking in the Industrial Sector	Optimize resource allocation structure, fully leverage resource synergy and carbon reduction, reduce carbon emissions in the industrial sector through efficient resource recycling. Promote the replacement of low-carbon raw materials and optimize the structure of coal chemical, synthetic ammonia, and methanol raw materials. Vigorously develop low-carbon clean energy equipment such as ammonia and hydrogen fuels (Ministry of Industry and Information Technology, 2023).
2	June 2022	Ministry of Transport and three other ministries	Implementation Opinions on Implementing the "Opinions of the Central Committee of the Communist Party of China and the State Council on Complete, Accurate, and Comprehensive Implementation of the New Development Philosophy for Carbon Peaking and Carbon Neutrality"	Actively develop new energy and clean energy transportation tools. Relying on the pilot construction of a strong transportation country, orderly carry out pilots of pure electric, hydrogen fuel cell, renewable synthetic fuel vehicles, and ships. Promote the application of new energy vehicles, explore the application of new power ships such as methanol, hydrogen, and ammonia, and actively promote the application of sustainable aviation fuels (Ministry of Transport et al., 2022).
3	April 2022	Ministry of Science and Technology	Notice on Issuing the 2022 Annual Project Application Guidelines for Key Special Projects of the National Key R&D Program "Advanced Structures and Composite Materials"	Promote technologies related to ammonia energy, including distributed ammonia decomposition hydrogen production technology and filling mother station integration, ammonia fuel cells, and ammonia-blended clean and efficient combustion (Ministry of Science and Technology, 2022).
4	March 2022	National Development and Reform Commission, National Energy Administration	Medium and Long-term Development Plan for the Hydrogen Energy Industry (2021-2035)	Actively guide the transformation of industries such as synthetic ammonia, synthetic methanol, refining, and coal-to-oil and gas from high-carbon processes to low-carbon processes, promoting green and low-carbon development in high-energy-consuming industries. Explore the use of renewable energy for hydrogen production in industries such as synthetic ammonia, methanol, refining, and coal-to-oil and gas as a demonstration to replace fossil energy (National Development and Reform Commission and National Energy Administration, 2022).
5	March 2022	Interdisciplinary Sciences Division of the National Natural Science Foundation of China	Basic Research Project on Zero-Carbon Power Systems for Heavy Vehicles Combining Ammonia and Hydrogen	Aims to address issues such as difficult ignition, slow combustion, and complex dynamic control of ammonia fuel for vehicles, laying the foundation for the technological innovation and application of zero-carbon power systems combining ammonia and hydrogen fuels for heavy-duty transport vehicles (Interdisciplinary Sciences Division of the National Natural Science Foundation of China, 2022).
6	March 2022	National Development and Reform Commission, National Energy Administration	14th 5-Year Plan for the Development of New Energy Storage	Develop ammonia energy storage technology, emphasizing the hydrogen-based energy storage and low-carbon fuel attributes of ammonia. Conduct pilot demonstrations of various technical routes, expand application areas such as hydrogen (ammonia) energy storage, and thermal (cold) energy storage, and carry out pilot demonstrations of hydrogen (ammonia) energy storage relying on renewable energy hydrogen (ammonia) production. Promote pilot demonstrations of new energy storage technologies with multiple time scales, focusing on longer-term storage technologies such as renewable energy hydrogen and ammonia production to meet multi-time scale application needs (National Development and Reform Commission and National Energy Administration, 2022).
7	February 2022	National Development and Reform Commission and three other departments	Implementation Guidelines for Energy Conservation and Carbon Reduction Renovation and Upgrading in Key Areas of High Energy Consumption Industries (2022 Edition)	By 2025, the proportion of capacity in the synthetic ammonia industry above the energy efficiency benchmark level will reach 15%, and the capacity below the energy efficiency baseline level will be almost zero, significantly enhancing the capability for green and low-carbon development. Conduct research and demonstrations on green and low-carbon energy-based synthetic ammonia technology. Accelerate the widespread adoption of mature process equipment. Strictly enforce policy constraints to eliminate outdated and inefficient capacities (National Development and Reform Commission et al., 2022).

(Contd...)

Table 2: ***(Continued)***

No.	Date	Institution	Policy/Project Name	Main Content
8	October 2021	China Classification Society	Guidelines for the Application of Ammonia Fuel in Ships (Draft for Comments)	The first domestic regulatory document for ammonia-powered ships, providing detailed reference standards for the layout of ammonia fuel tanks, containment systems, material and pipeline design, and ammonia engine parameters (China Classification Society, 2021).

Here is a summary of relevant policies issued by various governmental department:

From the above policy documents, it is evident that China's current new energy policies emphasize the development of ammonia energy across the following dimensions:

1. Low-Carbon Processes: The policies prioritize optimizing industrial resource allocation to minimize carbon emissions. This involves actively transitioning from high-carbon to low-carbon processes in sectors such as synthetic ammonia, methanol, refining, and coal-to-oil and gas industries.
2. Technological Innovation: A significant focus is placed on the development of low-carbon clean energy equipment, specifically targeting ammonia and hydrogen fuels. The promotion of ammonia-related technologies includes advancements in distributed ammonia decomposition for hydrogen production, ammonia fuel cells, and foundational research on zero-carbon power systems integrating ammonia and hydrogen for heavy-duty vehicles.
3. Promotion of New Energy Transportation Tools: The development and deployment of electric vehicles, hydrogen fuel cells, and renewable synthetic fuel vehicles and ships are actively encouraged. This includes exploring the use of new power systems such as methanol, hydrogen, and ammonia for maritime applications.
4. Energy Storage Technology and Application: The development of hydrogen-based energy storage and low-carbon fuel technologies utilizing ammonia is highlighted. This is accompanied by pilot demonstrations focusing on hydrogen (ammonia) energy storage systems reliant on renewable energy-derived hydrogen (ammonia) production.
5. Improving Energy Efficiency and Carbon Reduction: The policies aim to enhance energy efficiency benchmarks within the synthetic ammonia industry. This involves accelerating the adoption of mature process equipment while phasing out outdated and inefficient capacities to significantly bolster green and low-carbon development capabilities.
6. Formulation of Industry Standards and Regulations: Establishing reference standards for ammonia-fueled ships, including guidelines for ammonia fuel tank layout, containment systems, and ammonia engine parameters, ensures the safe and effective implementation of ammonia as a maritime fuel.

China's strategic emphasis on ammonia energy represents a critical facet of its overarching commitment to carbon emission reduction and sustainable development. The shift from high-carbon to low-carbon processes within pivotal industrial sectors not only mitigates the national carbon footprint but also propels technological innovations with potential global applications. The focus on technological innovation, particularly in the context of low-carbon clean energy equipment such as ammonia and hydrogen fuels, is pivotal. These advancements facilitate the development of efficient methodologies for harnessing ammonia as a viable clean energy source.

The initiative to promote new energy transportation tools underscores a profound shift towards the decarbonization of the transportation sector, a major contributor to global greenhouse gas emissions. By fostering the adoption of electric, hydrogen, and ammonia-powered vehicles and maritime vessels, China is paving the way for a broader, more sustainable transition within the transportation industry.

Energy storage technology, especially hydrogen-based systems utilizing ammonia, is a critical area of focus due to its potential for high energy density and reduced carbon emissions. Pilot demonstrations in this domain are essential for validating the feasibility, scalability, and economic viability of these technologies, thereby supporting their integration into the national energy grid.

Improving energy efficiency and enforcing stringent carbon reduction measures within the synthetic ammonia industry reflects China's proactive approach to meeting its environmental targets. Setting higher energy efficiency benchmarks and phasing out inefficient technologies contribute to a more sustainable and competitive industrial framework.

The establishment of industry standards and regulations for ammonia-fueled ships is a crucial step in ensuring the safe, efficient, and environmentally responsible utilization of ammonia in maritime transportation. These standards provide comprehensive guidelines for the design, construction, and operation of ammonia-powered vessels, facilitating a seamless transition to cleaner maritime energy solutions.

In conclusion, China's multi-faceted policy framework for ammonia energy underscores its commitment to achieving carbon neutrality. It positions the country as a leader in the global shift towards sustainable energy practices, setting a benchmark for other nations to emulate in their respective journeys towards environmental sustainability.

These policy focus areas align closely with the technical routes currently being pursued in the development of ammonia energy in China. The overarching policy environment and specific guiding policies provide a robust foundation for the growth of the ammonia energy sector. This alignment between policy directives and technical developments ensures a coherent and supportive framework for the advancement of ammonia as a key component of China's sustainable energy future.

5. CHALLENGES FACING THE DEVELOPMENT OF AMMONIA ENERGY AS A SUSTAINABLE ENERGY SOURCE

Despite the clear prospects from both technical and policy sides for the development of ammonia energy as a sustainable energy source, significant challenges remain.

5.1. Weak Technical Standards

Establishing technical standards for each segment of the new ammonia energy storage industry chain and promoting the standardization of new ammonia storage technologies are prerequisites for achieving large-scale industrial development of ammonia energy storage. In the "Medium and Long-term Development Plan for the Hydrogen Energy Industry (2021-2035)" (National Development and Reform Commission and National Energy Administration, 2022), it was proposed to explore the innovative application demonstration projects of renewable energy hydrogen production for synthetic ammonia during the "14th 5-Year Plan" period, thus initiating the integrated development of ammonia and hydrogen. In 2022, the State Administration for Market Regulation issued the "2022 National Standardization Work Key Points," which included standards for risk prevention and control in the storage and use of liquid ammonia. However, other areas related to ammonia energy still lack robust technical standards at the national level. Therefore, the government needs to accelerate the development of standards related to ammonia production, storage, and the operation of electro-ammonia coupling systems. Enterprises also need to establish quality inspection standards and quality systems based on their actual needs, strengthen cooperation with national institutions like the Special Equipment Inspection Institute, and fill the gap in technical standards for ammonia fuel. Ammonia-blended combustors, as non-standard products, need to be adapted to different boiler environments, and standards need to be established for aspects such as mechanical strength, electric power, NOx escape coefficients, and ammonia burnout rates.

5.2. Stringent Ammonia Control

Currently, relevant regulations and standards in China still strictly manage and control ammonia as a hazardous chemical. The "Safety Management Regulations for Liquid Ammonia Tank Areas in Coal-Fired Power Plants" (National Energy Administration, 2014) issued by the National Energy Administration in 2014 imposed multiple requirements on the storage of liquid ammonia in coal-fired power plants. The "Identification of Major Hazardous Sources of Dangerous Chemicals" (State Administration for Market Regulation, 2018) issued in 2019 classified ammonia storage quantities of ≥10 tons as a major hazardous source. Studies related to the use of hazardous chemicals in various domestic thermal power plants have suggested that, according to the "Identification of Major Hazardous Sources of Dangerous Chemicals," ignition diesel tanks, hydrogen storage stations, and hydrogen production stations used by power generation companies are not considered major hazardous sources of hazardous chemicals. However, power generation companies with liquid ammonia flue gas denitrification systems have ammonia tanks (areas) that may constitute major hazardous sources of hazardous chemicals. Hence, in the context of rapid ammonia energy development, the management regulations for hazardous chemicals related to ammonia need to be adjusted accordingly.

5.3. Corrosion Issues

Evaluating the impact of corrosive ammonia as a fuel on the lifespan of combustion and storage equipment is crucial for assessing the applicability of ammonia as a fuel in systems. Ammonia can cause corrosion and severe swelling in various materials, including metals, rubber, and polymers. Ammonia-blended combustion chambers can exhibit metal fatigue and ammonia corrosion, leading to the generation and propagation of transverse cracks in boilers. Additionally, ammonia-blended combustion reduces the exhaust gas temperature at the furnace outlet and increases the moisture content, exacerbating low-temperature corrosion in the tail flue and tail heat exchangers. Consequently, using ammonia as a fuel can directly impact the operational safety and lifespan of combustion equipment and increase operational and maintenance costs (Teng and Han, 2022).

5.4. NOx Pollutant Treatment

A critical issue with ammonia combustion is the high risk of NOx emissions. Unlike conventional hydrocarbon fuels, ammonia has a high nitrogen content (82%), leading to significant NOx and unburned NH3 emissions during combustion. Among these, N2O (nitrous oxide) is a major pollutant contributing to ozone depletion. A relatively mature method in ammonia internal combustion engines is the Selective Catalytic Reduction (SCR) technology for denitrification. By adding hydrogen as a catalyst, the combustion performance of ammonia internal combustion engines can be improved, allowing the reductant NH3 to preferentially react with NOx in the flue gas, reducing NOx to nitrogen and water and achieving complete combustion of ammonia fuel. However, related technologies are still under development (Si et al., 2024).

5.5. Market Risks of Ammonia Energy

The clean and low-carbon characteristics of ammonia fuel can meet the needs of high-energy-consuming users and address the survival challenges of fossil energy companies. By integrating clean energy suppliers through comprehensive utilization of ammonia energy technology, overall production efficiency can be improved, and operational and maintenance costs reduced. For example, steel and chemical companies in Eastern China, constrained by carbon emissions and environmental protection regulations, coal-fired power units needing emission improvements, and ocean shipping companies using ammonia-powered ships can replace traditional fossil fuels with ammonia fuel to reduce carbon emissions and operational costs while complying with environmental requirements. However, given the significant upfront investment required for ammonia energy and the need to retrofit existing equipment, the current profitability of using ammonia fuel is relatively low. Many private enterprises have a relatively low enthusiasm for the national carbon reduction strategy, and market demand needs time to grow and develop (Li et al., 2024).

6. CONCLUSION

Ammonia fuel is recognized for its high energy density and pollution-free characteristics, making it a versatile clean energy source with extensive applications. It can be used for power generation and plays a significant role in decarbonizing heavy industries such as electricity, transportation, fertilizers, steel, and cement. Ammonia serves as an excellent hydrogen carrier due to its easy liquefaction, low storage and transportation costs, and high safety. These attributes allow it to integrate deeply with the green hydrogen industry chain, addressing issues related to the difficulty and high cost of hydrogen storage and transportation.

As the proportion of new energy sources in the power grid increases, grid stability faces significant challenges. The blending of coal with ammonia to replace a portion of coal does not require extensive modifications to existing thermal power systems. This approach fully utilizes existing power grid infrastructure, providing a feasible solution to the dual challenges of carbon reduction and maintaining stable thermal power supply. The high safety characteristics of ammonia fuel also present challenges for its complete combustion. Low combustion efficiency and high ignition temperatures necessitate the use of auxiliary combustibles, such as oxygen, hydrogen, and other carbon-containing fuels. In stable conditions like coal-ammonia blending and maritime shipping, where output power is substantial, ammonia fuel demonstrates significant potential. Using ammonia crackers to convert pure ammonia into a hydrogen-ammonia mixture greatly enhances its efficiency, making these applications highly suitable for ammonia fuel.

The ammonia fuel market is entering a phase of rapid development. Driven by carbon emission constraints and related technological advancements, green ammonia, as a reliable hydrogen storage fuel, is becoming deeply integrated with the hydrogen energy industry chain. Benefiting from substantial market demand and stable operational conditions, coal-ammonia blending and maritime shipping represent highly compatible use cases for ammonia fuel at this stage. The Chinese government's long-term emission reduction targets, along with short-term goals outlined in the "14^{th} 5-Year Plan," present significant opportunities for the development of the ammonia fuel industry. The overarching policy environment, alongside a series of guiding policies, has established a favorable foundation for the development of the ammonia fuel industry. These policies are well-aligned with the current research and technological development routes of ammonia fuel in China.

However, gaps remain in hazardous chemical management, environmental policies, and market incentive policies. The government needs to further refine supportive policies and release favorable news to drive technological advancement, ultimately boosting the ammonia fuel technology industry in China.

Ammonia's role as a high-energy density fuel makes it a prime candidate for both stationary and mobile applications. Its integration into existing infrastructure without extensive modifications underscores its practical utility. The capability of ammonia to act as a hydrogen carrier further enhances its value in a hydrogen-integrated energy landscape. By addressing storage and transportation challenges, ammonia paves the way for more robust and economically viable hydrogen solutions.

The challenges associated with ammonia combustion, including its high ignition temperature and low combustion efficiency, necessitate ongoing research and development. The use of auxiliary combustibles can mitigate some of these issues, enhancing the feasibility of ammonia as a primary fuel source. In stable, high-power applications like industrial boilers and maritime engines, ammonia demonstrates significant promise due to its ability to integrate with existing combustion systems. The rapid market development for ammonia fuel is supported by stringent carbon emission regulations and the push for sustainable energy solutions. Green ammonia, in particular, aligns well with the goals of reducing greenhouse gas emissions and promoting renewable energy sources. The integration of green ammonia with the hydrogen energy industry chain can lead to more comprehensive and sustainable energy systems.

However, the full potential of ammonia fuel can only be realized with robust policy support. This includes clear regulations for hazardous chemical management, comprehensive environmental policies, and strong market incentives. The government's role in fostering a conducive environment for ammonia fuel technologies is crucial. By addressing these gaps, the policy framework can support the scaling and adoption of ammonia fuel, driving innovation and ensuring the industry's growth.

In conclusion, China's multi-faceted policy framework for ammonia energy underscores its commitment to achieving carbon neutrality. It positions the country as a leader in the global shift towards sustainable energy practices, setting a benchmark for other nations to emulate in their respective journeys towards environmental sustainability. Ammonia fuel represents a pivotal element in the transition to sustainable energy. Its unique properties and compatibility with existing systems make it a viable solution for both current and future energy needs. With continued policy support and technological advancements, ammonia fuel has the potential to significantly contribute to global decarbonization efforts.

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