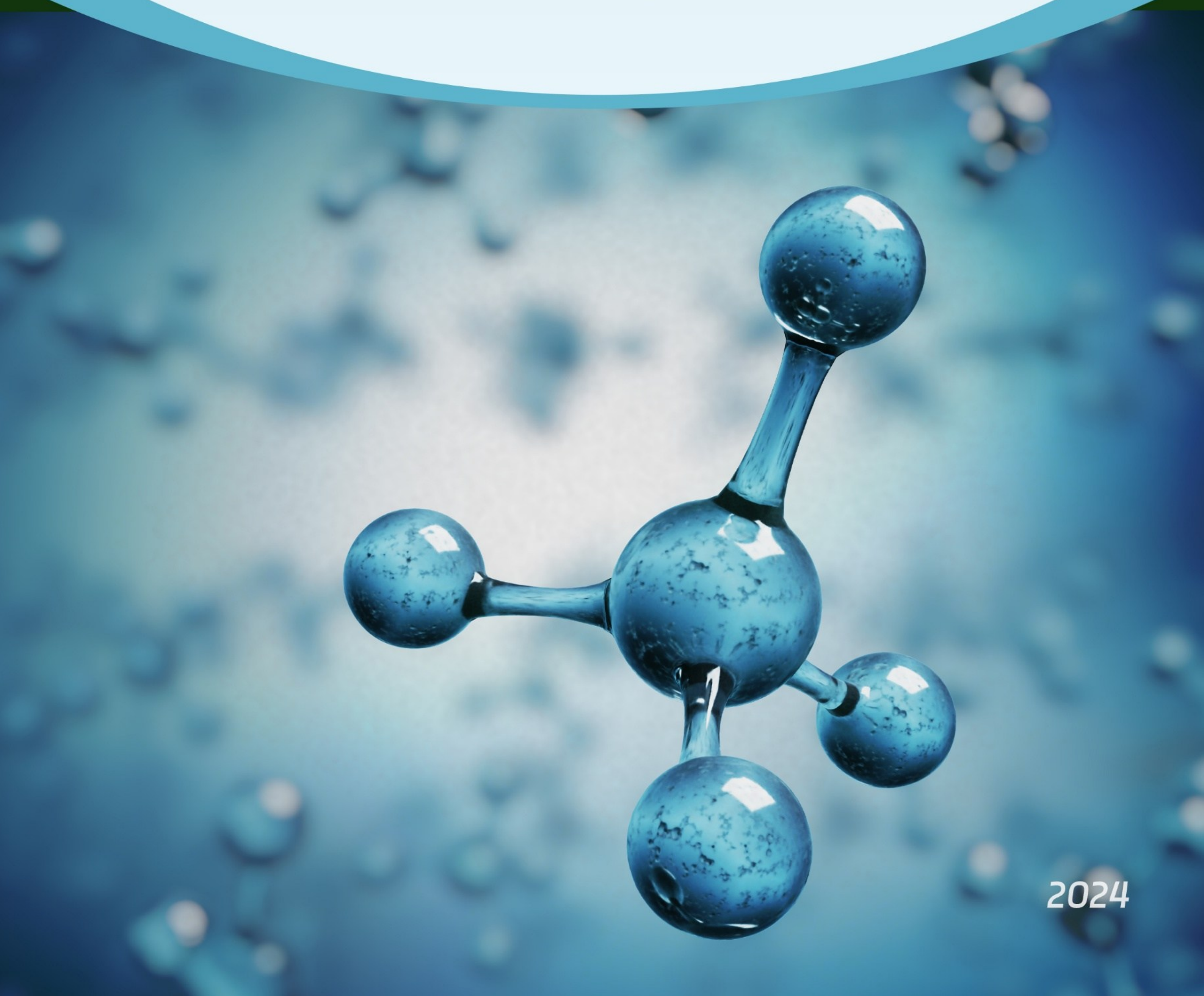
Frontier Interdisciplinary Strategy

A Strategic Study Report on Ammonia-Hydrogen New Energy Scientific and Technological Interdisciplinary Frontiers

Ammonia-Hydrogen New Energy Scientific
and Technological Interdisciplinary Frontiers Research Team

Funded by National Natural Science Foundation of China
and Chinese Academy of Sciences



2024

List of Panel Members and Chapter Contributors

1. Panel Members

Hui-Ming Chen, Academician of Chinese Academy of Sciences, Shenzhen Institute of Advanced Technology, Chinese Academy of Sciences

Yong Chen, Academician of Chinese Academy of Engineering, Guangzhou Institute of Energy Conversion, Chinese Academy of Sciences

Yi-Bing Cheng, Fellow of the Australian Academy of Technology and Engineering, Foshan Xianhu Laboratory

Ya-Ling He, Academician of Chinese Academy of Sciences, Xi'An Jiaotong University

Ying-Hong Li, Academician of Chinese Academy of Sciences, Air Force Engineering University

Jun Li, Academician of Chinese Academy of Engineering, Foshan Xianhu Laboratory, Tsinghua University

Ce-Wen Nan, Academician of Chinese Academy of Sciences, Tsinghua University

Chang-Yu Shen, Academician of Chinese Academy of Sciences, China National Intellectual Property Administration

Bao-Lian Su, Fellow of Royal Academy of Belgium， Fellow of European Academy of Sciences, University of Namur

Zai-Ku Xie, Academician of Chinese Academy of Sciences, Chief Engineer at Sinopec Group

Dong-Yuan Zhao Academician of Chinese Academy of Sciences, Fudan University

Zhi-Gang Zou Academician of Chinese Academy of Sciences, Nanjing University

Jin-Yang Zheng, Academician of Chinese Academy of Engineering, Zhejiang University

Qing-Jie Zhang, Academician of Chinese Academy of Sciences, Wuhan University of Technology, Foshan Xianhu Laboratory

2. Chapter Contributors

Foreword: **Bo-Fei Xue**, Foshan Xianhu Laboratory; **Li Zhang**, Wuhan Univeristy of

Technology; **Qing-Jie Zhang**, Wuhan University of Technology, Foshan Xianhu Laboratory

Chapter 1: **San-Ping Jiang**, Foshan Xianhu Laboratory; **Bao-Lian S**u, University of Namur, Belgium; **Zai-Ku Xie**, Sinopec Group

Chapter 2: **Yu Wang**, Foshan Xianhu Laboratory, Wuhan University of Technology; **Yi-Bing Cheng**, Foshan Xianhu Laboratory

Chapter 3: **Yu-Xin Liu**, Foshan Xianhu Laboratory; **Jun Li**, Foshan Xianhu Laboratory, Tsinghua University

Chapter 4: **Yun Wu**, Air Force Engineering University; **Ying-Hong Li**, Air Force Engineering University

Chapter 5: **Hua Zhang**, China United Gas Turbine Technology Co. Ltd.

Chapter 6: **Qun-Jie Lu**, Foshan Xianhu Laboratory; **Gai Huang**, Foshan Xianhu Laboratory; **Hua Huang**, Foshan Xianhu Laboratory; **Chao-Hua Gu**, Zhejiang University; **Shu-Xin Li**, Wuhan University of Technology, Foshan Xianhu Laboratory

Chapter 7: **Xin-Chun Yang**, Shenzhen Institute of Advanced Technology, Chinese Academy of Sciences; **Li Zhang**, Wuhan Univeristy of Technology; **Bo-Fei Xue**, Foshan Xianhu Laboratory; **Yi-Bing Cheng**, Foshan Xianhu Laboratory; **Hui-Ming Chen**, Shenzhen Institute of Advanced Technology, Chinese Academy of Sciences; **Qing-Jie Zhang**, Wuhan University of Technology, Foshan Xianhu Laboratory

Abstract

In recent years, a significant progress in hydrogen energy applications has been made in fuel cell vehicle technologies and industries, key materials and components, and hydrogen infrastructure construction. However, in terms of large-scale hydrogen energy applications, including large-scale storage, long distance transportation, and safety in hydrogen distribution network, significant bottlenecks and difficulties still exist, hindering the development of the hydrogen energy industry globally.

In this strategic study, we put forward an interdisciplinary science and technology frontier of innovative combination of ammonia and hydrogen as new energy or energy carriers, i.e. ammonia-hydrogen new energy, and its associated key research directions. Ammonia-hydrogen new energy refers to a new energy system with ammonia and hydrogen as direct energy or energy carriers. Both hydrogen and ammonia (NH3) are carbon-free fuels. They can be obtained through renewable energy, and they can be converted into each other; Ammonia can be synthesized through green hydrogen, and hydrogen can be efficiently prepared by green ammonia cracking, and the two can be used separately in different application scenarios, or they can be mixed and utilized synergistically.

Ammonia is an efficient hydrogen storage medium, with a hydrogen mass fraction of 17.6% and can be liquefied easily at -33 Celsius degree at atmospheric pressure or 1 MPa at room temperature. The large-scale storage and long distance transportation infrastructure of liquid ammonia are well developed. More importantly, both NH3 and H2 are zero-carbon fuels. The successful implementation of the ammonia-hydrogen new energy strategy will provide a complete solution to the large-scale application and true industrialization of hydrogen energy.

Ammonia-hydrogen new energy has become a forward-looking and strategic development direction in the field of clean energy worldwide. In 2019, Ammonia Energy Association (AEA) put forward the new concept of “Ammonia = Hydrogen 2.0,” aiming at promoting hydrogen economy via ammonia, specifically “Building an energy export

industry using Green Ammonia.” Countries around the world are making plans to develop ammonia-hydrogen new energy, including Japan, South Korea, the Netherlands, Norway, Australia, etc. China also puts forward a plan to include hydrogen and ammonia as energy storage vectors.

Ammonia-hydrogen new energy science and technology is a major frontier in multidisciplinary interdisciplinary fields, including energy science and technology, material science and engineering, chemistry and chemical engineering, power engineering and engineering thermophysics, transportation engineering, etc. Developing high-temperature industrial kiln ammonia-hydrogen zero-carbon combustion technology, ammonia-hydrogen zero-carbon transportation equipment technology, ammonia-hydrogen zero-carbon combustion technologies for aircraft engines and gas turbines, ammonia-hydrogen high-temperature combustion nitrogen oxide emission control technology and other disruptive technologies can open up new major application scenarios of hydrogen energy, and provide innovative and disruptive technologies for high-temperature manufacturing, transportation, power generation and other industries to achieve carbon peaking and carbon neutrality targets.

In this study, five key research and development areas are discussed, including low-cost, large-scale green ammonia production technologies; ammonia-hydrogen zero-carbon combustion technologies for high-temperature manufacturing industry; ammonia-hydrogen zero-carbon technologies for vehicles applications; ammonia-hydrogen zero-carbon combustion technologies for aircraft engines and gas turbines; ammonia-hydrogen safety technologies and standards. Critical science and technology challenges in these areas are also discussed.

This study also puts forward policy proposals to strengthen the researches of interdisciplinary frontiers of scientific and technological issues, so as to provide strategic guidelines to solve the major difficulties facing hydrogen energy storage and transportation technologies and to address challenges in expanding and implementing application scenarios of hydrogen energy.

Content

Chapter 1 A Strategic Study on Low Cost and Scalable Production Technologies of Green Ammonia

Solar and wind energies are the most commercialized renewable energy technologies. As of 2022, the installed capacity of photovoltaic and wind power in China has reached 390 million kilowatts and 370 million kilowatts, respectively (http://www.nea.gov.cn/2023-01/18/c_1310691509.htm). The current renewable or green electricity cost is approximately 0.3-0.4 yuan/kWh, and is expected to decline further. However, photovoltaic and wind power generation varies due to weather conditions, time, location, and season, resulting in difficulties in grid connection and severe abandonment of solar and wind energies. Therefore, there is an urgent need to develop clean energy carriers and large-scale energy storage technologies based on green electricity. Hydrogen, as a carrier of renewable energy, is a clean energy source that can be efficiently converted into electricity through fuel cell technologies. It can also be used as a zero-carbon fuel and does not emit greenhouse gases during its use. However, there are no natural hydrogen resources on Earth, and hydrogen must be produced through hydrocarbons (such as natural gas reforming) or electrolysis of water. On the other hand, hydrogen has the lowest density in the periodic table and extremely low liquefaction temperature (-253 ºC). Its storage and transportation have become the biggest technical and economic obstacle to the large-scale implementation of hydrogen-based energy routes or "hydrogen economy".

Ammonia (NH_3) has a high volumetric energy density (13.6 $GJ \cdot m^{-3}$) and high hydrogen content (17.65 wt% H_2). With its easy storage and transportation characteristics (liquefied at -33 ºC under atmospheric pressure or under 0.8 MPa at room temperature), NH_3 is a highly potential hydrogen energy carrier and zero-carbon fuel and can be used for large-scale low-cost storage of renewable energy. Due to the fact that ammonia is an essential fertilizer for agriculture and food production, the storage and distribution of ammonia has reached commercial maturity and global scales with an annual global production of over 180 million tons.

The traditional ammonia synthesis Haber-Bosch method, abbreviated as HB method, has a history of over 100 year, and requires high temperatures (400-500 ºC) and high pressures (15-30MP). In China 70% of the raw materials for ammonia synthesis process come from coal, making it a high energy consumption and high greenhouse gas emission industry. Developing advanced HB ammonia synthesis technology based on green electricity and green hydrogen, as well as new electrochemical large-scale ammonia synthesis technology, is an urgent and significant requirement for the China's "dual carbon" strategy.

1.1 Green electricity and green hydrogen based advanced HB ammonia synthesis technology

As an agricultural fertilizer, the traditional high temperature and high-pressure HB production process of ammonia uses iron-based catalysts. Its annual CO_2 emission accounts for about 1.5% of the global total emissions, and the annual energy consumption is about 2-3% of the global total energy consumption [1]. The emission of CO_2 in the traditional ammonia synthesis process directly comes from natural gas or coal-based hydrogen production, and indirectly comes from non-green electricity energy consumption. Therefore, the ammonia produced by the traditional HB process is referred to as "grey ammonia".

In the HB process, using green hydrogen generated by renewable energy electrolysis of water to replace hydrogen generated by natural gas reforming or coal gasification can reduce CO_2 emissions by 50%. Green electricity from renewable energy sources can be used to provide the energy required for the HB high temperature and high-pressure process. Combined with green hydrogen, the ammonia produced is thus called "green ammonia".

One of the key technologies for the green electricity and green hydrogen based advanced HB ammonia synthesis process is the high-efficiency, low energy consumption and large-scale water electrolysis hydrogen production technology. The main methods for producing hydrogen by water electrolysis include alkaline water electrolysis (AWE), proton exchange membrane water electrolysis (PEMWE), and high-temperature solid oxide electrolysis cell (SOEC) [2]. Among them, SOEC has received widespread attention due to its low cost, excellent thermodynamic and kinetic characteristics, and extremely high conversion efficiency.

A key issue of the green electricity and green hydrogen based advanced HB ammonia synthesis process is to reduce temperature and pressure in order to reduce energy consumption. In the early 1970s, BP and M.W. Kellogg Company jointly developed a new type of carbon supported ruthenium catalyst (Ru/C). Kellogg Company applied this new Ru based catalyst to produce ammonia at lower temperatures (370-400 ºC) and pressures (5-10 MPa), significantly reducing energy consumption and production costs. The University of Warwick in the UK has developed a new type of iron-based cerium oxide nitride catalyst without Ru doping, improving the stability and activity of iron catalysts in ammonia synthesis [3]. Fuzhou University has conducted extensive research on the modification of CeO_2 supported Ru catalysts in ammonia synthesis [4, 5]. At 400 °C and 10 MPa, the NH_3 yield reached ~0.11 mol NH_3/g/h [4].

1.2 New technologies for large-scale ammonia synthesis

In addition to the HB method, other methods for the ammonia synthesis include electrochemical, plasma assisted, chemical looping and indirect methods.

The method of electrochemical synthesis of green ammonia mainly refers to the technologies of synthesizing green ammonia through electrochemical (including photoelectrochemical) methods in electrolyte solutions or high-temperature solid electrolytes, using green electricity from renewable energy sources such as wind and solar energy. The electrochemical synthesis of ammonia can be carried out in an aqueous solution electrolysis cell at room temperature and pressure, or in a solid-state electrolysis cell based on oxygen ion or proton conducting electrolytes at high temperature and pressure. Overall, the electrochemical ammonia synthesis devices can be divided into three categories: non-separated, separated, and membrane electrode components based electrochemical reactors. The main challenge of the electrochemical synthesis of ammonia is the very low ammonia yield (~10^{-10-9} mol/s·cm^2), owing to the high inherent energy barrier of N≡N bond cleavage under mild conditions, low N_2 solubility and high competitiveness of hydrogen evolution reaction (HER). In the electrochemical synthesis of ammonia, activating inert nitrogen is the key to increasing ammonia yield. Among them, the new lithium nitrogen reduction reaction cell based on proton shuttle has reached a Faraday efficiency (FE) of 69% and an ammonia yield of 53 nmol/s·cm^2 [6]. Although its large-scale synthesis feasibility has not yet been proven, it shows a promising potential as a new technology for ammonia synthesis.

Plasma assisted ammonia synthesis (PAAS) and chemical looping ammonia synthesis (CLAS) are two other methods for synthesizing ammonia. PAAS achieves ammonia synthesis through the synergistic effect of plasma and catalyst, but the PAAS process is a high energy consumption process. Without considering the energy consumption of hydrogen production, the energy cost of using N_2 and H_2 for PAAS is higher than that of the fossil fuels-based HB process [7]. CLAS synthesizes ammonia through two chemical cycles of nitration and hydrogenation of metal hydrides and imides [8]. The main issues with the scalability of the CLAS process include the high temperature required for both nitrification and hydrogenation processes, the economy of metal hydride and imide raw materials, and sensitivity to moisture.

Recently, Foshan Xianhu Laboratory and Hunan University jointly developed an indirect electrochemical method for synthesizing ammonia, based on the carbon dioxide (CO_2) nitrogen fixation green synthesis of ammonia [9]. In this process, CO_2 and N_2 are catalyzed to form urea in a potassium bicarbonate solution, followed by catalytic cracking of urea to obtain NH_3 and CO_2. The CO_2 released during this process is captured by the potassium hydroxide solution to form potassium bicarbonate, thus forming a complete CO_2 cycle for nitrogen fixation and ammonia synthesis [9]. This new process for synthesizing ammonia bypasses the need to break the N≡N bond in the conventional direct electrochemical method, achieving high efficient synthesis of urea and ammonia.

In theory, at a high current (100 mA/cm^2), the synthesis rate of ammonia could reach 10^{-6}g/cm^2·min, which is much higher than the current rate of electrochemical/photoelectrochemical reduction of nitrogen to ammonia in aqueous solution (10^{-10}g/cm^2·min). This method of CO_2 cycle nitrogen fixation for green ammonia synthesis has a CO_2 utilization rate of over 90%. The process is sustainable and has a potential to achieve large-scale production of green ammonia.

1.3 Prospects

In the long run, the prospects of ammonia as a renewable energy carrier depend on technological innovation and breakthroughs in the green synthesis of ammonia through new catalytic and/or electrocatalytic processes. The main challenges faced by the catalytic and electrocatalytic synthesis of ammonia are how to effectively activate inert N_2 reactants, and how to scale-up ammonia production at both practical and industrial levels. The NH_3 yield of a chemical reactor is related to the weight or surface area of the catalyst, while the yield of an electrochemical reactor is related to the geometric area of the electrode surface. Although the use of nanoscale electrodes can expand the reaction area of the electrodes, this poses a huge technical challenge for the scalability of electrochemical reactors, especially in electrolysis cells based on aqueous electrolytes. Adopting a solid electrolyte cell configuration and capitalizing on the stacking advantage of solid electrolyte cells can greatly reduce the technical barriers to scaling up issues.

The method of CO_2 nitrogen fixation for green synthesis of ammonia is a recyclable and sustainable process, with practical application prospects for large-scale production of green ammonia. The key technology is to develop efficient and stable electrocatalysts, especially multi-element single atom catalysts, to directly synthesizing urea from CO_2 and N_2 [9].

References

[1] Wang L, Xia MK, Wang H, Huang KF, Qian CX, Maravelias CT, Ozin GA. Greening Ammonia toward the Solar Ammonia Refinery. *Joule* 2018; 2: 1055-1074.

[2] Sapountzi FM, Gracia JM, Weststrate CJ, Fredriksson HOA, Niemantsverdriet JW. Electrocatalysts for the generation of hydrogen, oxygen and synthesis gas. *Progress in Energy and Combustion Science* 2017; 58: 1-35.

[3] Humphreys J, Lan R, Chen S, Walker M, Han Y, Tao S. Cation doped cerium oxynitride with anion vacancies for Fe-based catalyst with improved activity and oxygenate tolerance for efficient synthesis of ammonia. *Appl. Catal., B* 2021; 285：119843（1-15）

[4] Lin B, Liu Y, Heng L, Wang X, Ni J, Lin J, Jiang L. Morphology Effect of Ceria on the Catalytic Performances of Ru/CeO2 Catalysts for Ammonia Synthesis. *Industrial & Engineering Chemistry Research* 2018; 57: 9127-9135.

[5] Lin B, Fang B, Wu Y, Li C, Ni J, Wang X, Lin J, Au C-t, Jiang L. Enhanced Ammonia Synthesis Activity of Ceria-Supported Ruthenium Catalysts Induced by CO Activation. *ACS Catal.* 2021; 11: 1331-1339.

[6] Suryanto BHR, Matuszek K, Choi J, Hodgetts RY, Du HL, Bakker JM, Kang CSM, Cherepanov PV, Simonov AN, MacFarlane DR. Nitrogen reduction to ammonia at high efficiency and rates based on a phosphonium proton shuttle. *Science* 2021; 372: 1187-1191.

[7] Chang F, Gao WB, Guo JP, Chen P. Emerging Materials and Methods toward Ammonia-Based Energy Storage and Conversion. *Adv. Mater.* 2021; 33: 2005721.

[8] Gao WB, Guo JP, Chen P. Hydrides, Amides and Imides Mediated Ammonia Synthesis and Decomposition. *Chinese Journal of Chemistry* 2019; 37: 442-451.

[9] Zhang XR, Zhu XR, Bo SW, Chen C, Qiu MY, Wei XX, He NH, Xie C, Chen W, Zheng JY, Chen PS, Jiang SP, Li YF, Liu QH, Wang SY. Identifying and tailoring C–N coupling site for efficient urea synthesis over diatomic Fe–Ni catalyst, *Nat. Commun.* 2022; 13: 5337(1-9).

Chapter 2 A Strategic Study on Zero-Carbon Ammonia Combustion Technologies for High-Temperature Manufacturing Industries

Decarbonization of high-temperature industries, including thermal power generation, building materials manufacturing, metal processing and metallurgy etc., have two main directions: (1) using renewable energy substitutions and electrified thermal equipment based on green power, and (2) using thermal equipment based on renewable zero-carbon fuels [1]. Despite the rapid growth of solar and wind-based green power production in recent years, the power capacity required for complete electrification of high-temperature industries is still too large for the grid to cope with. Meanwhile, there exist certain contradictions between the continuous operation of large-scale industrial production and the intermittency of green electricity. In addition, technically it is not viable yet for the radiation-dominated heat transfer mode in electrified kilns to match existing combustion-based production line structure and production processes. Moreover, large-scale electrification of kilns may incur huge economic costs so that it is not likely be carried out in the short term . With these reasons, high-temperature industrial combustion kilns are not expected to be replaced.

Using zero-carbon fuel such as ammonia and hydrogen to replace conventional fossil fuels is the most direct, effective and economical way to achieve carbon emission reduction in high-temperature industries. Figure 1 shows the effect of carbon reduction by mixing different proportions of ammonia/hydrogen in natural gas. As can be seen, the optimal balance between fuel economy and de-carbon effect can be achieved at different stages by adjusting the mixing ratio, demonstrating that the use of zero-carbon ammonia-hydrogen fuel is an effective and practical way to help high-temperature industries meet the goal of “carbon peaking and carbon neutrality” in a gradual manner.

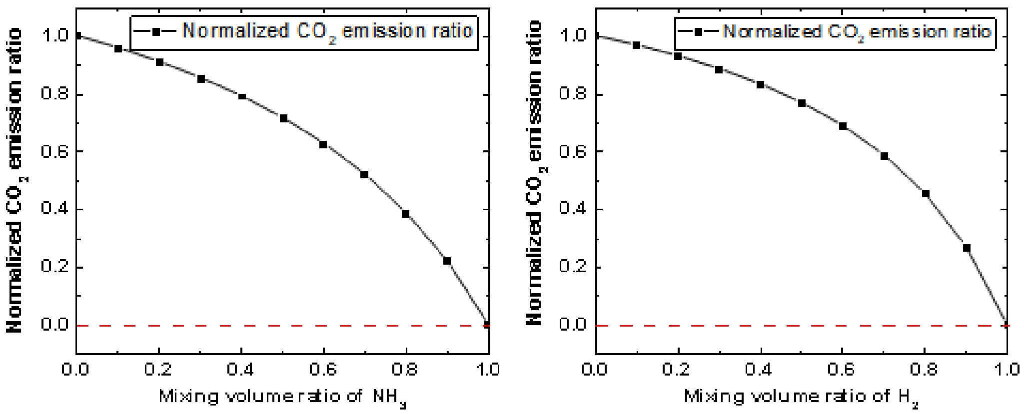


Figure 1. Normalized CO_2 emission ratio of natural gas combustion mixed with different volume ratios of ammonia/hydrogen

2.1 Basic physicochemical properties of ammonia-hydrogen fuel and the main challenges of ammonia combustion in industrial applications

Hydrogen has a high flame speed and a wide flammable range, but its low volume energy density, high explosion risks, and high storage and transportation costs (mainly due to its extremely low liquefaction temperature of -253 ºC) limit its wide application as an industrial fuel. Ammonia, a carrier for hydrogen, has high-volume energy density [2] and is a much safter fuel for industrial application than hydrogen, thanks to its relatively low chemical activity. Furthermore, since ammonia has been used as a raw material in chemical industry and a fertilizer in agriculture for over a hundred years [3], the relevant production processes, storage and transportation infrastructures, safety standards and regulations are already mature. Additionally, the storage and transportation costs of ammonia are much lower than hydrogen on a per energy content basis, making ammonia a zero-carbon fuel with great potential [4]. Nevertheless, there are still some challenges for ammonia combustion applications due to specific properties of ammonia. Table. 1 gives a comparison of key physicochemical properties among ammonia, hydrogen and natural gas. It can be seen that ammonia has a very low calorific value and flame speed. This would pose challenges in terms of flame stability under high thermal power conditions. Secondly, ammonia features a high ignition temperature and a narrow flammable range which may cause problems for reliable ignition and complete combustion. Thirdly, fuel-type nitrogen oxides (NOx) can be produced in huge quantities because of the presence of nitrogen element in ammonia molecules. Therefore, to develop ammonia combustion technology with high efficiency, high stability and low NOx emission is a prerequisite for ammonia's industrial application as a fuel.

Table 1. Physicochemical properties of ammonia, hydrogen and natural gas [2]

Fuel	Ammonia NH_3	Hydrogen H_2	Natural gas CH_4
Boiling point (1 atm, °C)	-33.4	-253	-161
Condensation pressure (25 °C, atm)	9.90	N/A	N/A
Low heating value (MJ/kg)	18.6	120	50.0
Mass stoichiometric ratio	6.0	34.3	17.1
Maximum laminar combustion speed (m/s)	0.07	2.91	0.37
Adiabatic flame temperature (°C)	1800	2110	1950
Flammability limit (i.e., equivalent ratio)	0.63~1.40	0.10~7.1	0.50~1.70
Minimum autoignition temperature (°C)	650	520	630

With the support of Japan's Strategic Innovation Promotion (SIP) plan, many studies on ammonia industrial combustion have been carried out by Japanese enterprises and research organizations with significant progress made [5]. In 2017, Mizushima Power Plant successfully realized the co-firing of pulverized coal and ammonia (with an ammonia calorific ratio of 0.6% ~ 0.8%) in its 155 MW power generation boiler [6]. In March 2021, IHI Corporation demonstrated the co-combustion of natural gas and ammonia (70% liquid ammonia co-firing ratio) in a 2 MW gas turbine [7]. In July 2023, the world's first ammonia-fueled glass production demonstration was successfully conducted by Asahi Glass Corporation in a flat glass kiln [8].

A series of work on ammonia industrial combustion was also carried out in China in recent years. In 2021, Foshan Xianhu Laboratory, in collaboration with its industrial partners of Foshan DLT Technology Co., Ltd and Foshan Oceano Ceramic Co., Ltd. launched a research and development project to convert a 30-meter-long roller kiln to run on 100% ammonia fuel. One year later, the world's first zero-carbon ammonia-fired ceramic tile was rolled out. Through the innovative three-stage de-NOx techniques, NOx emission from this ammonia-fired kiln was kept at 17 mg/m^3, far below the local and national standard limits for NOx emissions [9]. In January 2022, Longyuan Electric Power, a subsidiary of National Energy Group [10], completed a demonstration test of co-combustion of pulverized coal and ammonia in a 40 MW pulverized coal power generation boilers. In April 2022, a 8.3 MW pure ammonia burner, jointly developed by the Energy Research Institute of Hefei Comprehensive National Science Center and Waneng Group, was ignited and ran stably for more than 2 hours in a 300 MW thermal power unit of Tongling Power Plant [11].

2.2 Key technologies of ammonia industrial combustion

Key technologies for reliable ignition and stable combustion of ammonia. As a result of ammonia's high ignition energy, low calorific value and low combustion speed, it is a major challenge to ensure reliable ignition and stable combustion of ammonia in large-scale industrial applications. Consequently, it is necessary to investigate mechanisms for ammonia stable combustion and to propose combustion intensification technologies. The following five specific technologies are deserved to be considered. 1) Swirl and blunt-body assisted steady combustion technology, with which a recirculation zone gathering heat and active free radicals is formed near the fuel outlet with the effect of extending the fuel residence time, enhancing the combustion reaction intensity and subsequently achieving fully stable combustion of ammonia; 2) Preheat-assisted combustion technology, with which the unburned mixture can be preheated through flue gas recirculation, leading to the improvement of fuel reactivity, flame speed and ignition success rate; 3) Catalytic /plasma-assisted fuel cracking technology, with which the proportion of hydrogen is increased in the fuel through partial cracking of ammonia, reducing ignition energy and increasing flame speed; 4) Flexible high-energy ignition technology, with which the mixture components near the ignition arc can be within the flammable limit range of ammonia through optimizing ignition position and ignition mode, guaranteeing reliable ignition; (5) Ammonia and traditional fuels (gas, liquid or solid) mixing combustion technologies.

Key technologies for NOx emission control. Compared to traditional hydrocarbon fuels such as natural gas, NOx emission from ammonia combustion can be increased by orders of magnitude. Therefore, multi-level de-NOx technologies through combustion organization and flue gas reduction are needed to achieve ultra-low NOx emission in the industrial application of ammonia fuel. These include 1) Staged combustion technology: to optimize burner structure and combustion organization through elucidating the influence of parameters including first-stage equivalence ratio, second-stage air blending position and global equivalence ratio, to prevent NOx formation via fuel-type NO while ensuring complete combustion; 2) Selective non-catalytic reduction technology (SNCR): a precise ammonia injection control strategy is established through analyzing parameters including ammonia injection amount, position and angle; 3) Selective catalytic reduction technology (SCR): a high-efficiency and low-cost NOx treatment equipment is set up, researching the influences of catalysts' type, load and placement.

Key technologies for ammonia combustion flue gas monitoring. The ignition and complete burning are relatively difficult for ammonia, leading to the possibility of trace ammonia escape in the flue gas. Since the combustion products of ammonia are mainly water and nitrogen gas, the water vapor concentrations in ammonia combustion flue gases are much higher than that of hydrocarbon fuels. The large amount of water vapor poses new challenges for traditional flue gas detection methods, especially those for trace ammonia. Consequently, equipment with special functions is needed for *in-situ* detection of ammonia flue gases. The following technologies are deserved to be developed: 1) High temperature, high humidity trace ammonia slip detection based on industrial laser gas sensor technology; 2) Wide dynamic range, multi-component NOx (NO_2, NO and N_2O) measurement technology; 3) Ammonia combustion feed-back control based on quantitative flue gas monitoring.

High temperature process adaptability for ammonia combustion. The combustion products of ammonia fuel are mainly composed of water vapor and nitrogen (N_2) and do not contain strongly thermal radiating substances such as soot particles and CO_2. As a result, the thermal radiation intensity of ammonia flames is far lower than that of traditional hydrocarbon fuels, which would have an impact on production processes that rely on flame thermal radiation for heating (e.g. in power generation boilers). In addition, due to differences in basic combustion properties, the morphology of ammonia flames can be notably different from traditional hydrocarbon flames, which would affect production processes that rely on direct interaction between high temperature flame and working medium to achieve heating of the working medium (e.g. in metal heating furnace). Therefore, it is necessary to investigate the energy transport mechanisms in industrial furnaces so as to develop efficient numerical models that can effectively characterize combustion, fluid motion and heat transfer processes in furnaces. Based on this, the influence of energy transport mechanism and heat transfer characteristics on furnace temperature distribution and eventual product quality can be clarified, and in-furnace heat flow optimization using ammonia as a fuel can be achieved.

2.3 Prospects

Replacing fossil fuels with zero-carbon ammonia-hydrogen fuels is an important technical approach to reduce carbon emission in high-temperature industries. Developing zero carbon ammonia combustion technologies not only can help achieve the "dual-carbon" strategic targets for manufacturing industry but can also provide a solution for fully utilizing photovoltaic and wind power. In a long run, developing ammonia/hydrogen zero carbon combustion technologies will offer new opportunities for the industries including green ammonia/hydrogen production, new materials for ammonia-hydrogen new energy, high-end ammonia/hydrogen-related equipment, and will eventually give new momentum for China's high-quality economic growth.

References

[1] Zhang L, Xue BF, Liu YX, Wang Y, Wu Y, Zhang H, Yang XC, He S, Jiang SP, Li J, Zhang QJ. A strategic study of ammonia-hydrogen new energy interdisciplinary science frontiers. *Chinese Science Bulletin*, 2023, 68: 3107-3112. [张莉，薛勃飞，刘玉新，王宇，吴云，张华，杨新春，何帅，蒋三平，李骏，张清杰. 氨氢融合新能源交叉科学前沿战略研究. *科学通报,* 2023; 68: 3107-3112.]

[2] Kobayashi H, Hayakawa A, Somarathne KKA, Okafor EC. Science and technology of ammonia combustion. *Proceedings of the Combustion Institute*, 2019; 37: 109-133.

[3] Liu H. Ammonia synthesis catalyst 100 years: Practice, enlightenment and challenge. *Chinese Journal of Catalysis*, 2014, 35: 1619-1640.

[4] MacFarlane DR, Cherepanov PV, Choi J, Suryanto BHR, Hodgetts RY, Bakker JM, Vallana FMF, Simonov A. A roadmap to the ammonia economy. *Joule*, 2020, 4: 1186-1205.

[5] Brown T. Japan's Road Map for Fuel Ammonia. 2021-02-25. https://www.ammoniaenergy.org/articles/japans-road-map-for-fuel-ammonia/.

[6] Yoshizaki T. Test of the co-firing of ammonia and coal at mizushima power station. *Journal of the Combustion Society of Japan*, 2019, 61(198): 309-312.

[7] IHI C. IHI becomes world's first to attain 70% liquid ammonia co-firing ratio on 2000-kilowatt-class gas turbine. 2021-03-26. https://www.ihi.co.jp/en/all_news/2020/resources_energy_environment/1197060_2032.html#:~:text=IHI%20Corporation%20announced%20today%20it%20has%20raised%20the,with%20natural%20gas%20while%20constraining%20nitrogen%20oxide%20emissions.

[8] Atchison J. Ammonia fuel for glass production demonstrated in Japan. 2023-09-19. https://www.ammoniaenergy.org/articles/ammonia-fuel-for-glass-production-demonstrated-in-japan/.

[9] Long Y, Wang Y. Foshan released the world's first green ceramic tile fired by zero-carbon ammonia fuel. *Science and Technology Daily*, 2022-12-23. http://www.stdaily.com/index/kejixinwen/202212/4445975acea649489a839deb3691edc8.shtml. [全球首块零碳氨燃料烧制绿色瓷砖在佛山出炉,*科技日报*，2022-12-23]

[10] Niu T, Zhang W, Liu X, Hu DC, Wang TK, Xie Y, Wang HY. Industrial-scale experimental investigation of ammonia-coal cofiring in coal-fired boiler. *Clean Coal Technology*, 2022, 28(3): 193-200. [牛涛，张文振，刘欣，胡道成，王天堃，谢妍，王赫阳.燃煤锅炉氨煤混合燃烧工业尺度试验研究. *洁净煤技术*, 2022; 28: 193-200.]

[11] Wang F, Chen Q. Waneng Tongling Power Generation Company: Success ignition of the first 8.3 MW pure ammonia burner in China in a 300 MW class thermal power unit. China power enterprise management, 2022 (12): 96. [汪芳，陈秋远. 皖能铜陵发电公司：国内首创8.3兆瓦纯氨燃烧器在30万千瓦火电机组点火成功. 中国电力企业管理, 2022 (12): 96.]

Chapter 3 A Strategic Study on Ammonia-Hydrogen New Energy Zero-Carbon Transportation Equipment

The carbon emissions in China's transportation sector account for approximately 10.4% of the national total carbon emissions, with road vehicles accounting for 86.7% of the carbon emissions in the transportation sector. Commercial vehicles, accounting for only about 12.5% of the total vehicle ownership, however, are an important source of carbon emissions from road vehicles in China, the proportion of carbon emissions is as high as 55.4%, with commercial heavy-duty trucks accounting for approximately 83.5% of the carbon emissions from commercial vehicles [1].

Utilizing traditional energy-saving technologies to reduce carbon emission for commercial heavy trucks has its own limitations. For example, as for diesel internal combustion engines, thermal efficiency of 55-60% is already the highest possible upper limit [2]. In addition, there are still certain technical bottlenecks in the application and promotion of the new energy technologies in the commercial heavy trucks, to achieve carbon reduction targets. For example, pure electric heavy trucks cannot adapt to most driving scenarios due to the constraints of low battery energy density, short driving range, low load utilization, poor low temperature adaptability and long charging time. In the meantime, for hydrogen fuel cell heavy trucks, due to contraints of the physical characteristics of hydrogen energy and the slow progress of hydrogen energy industry, they are facing problems such as high price of hydrogen, difficulties in hydrogen storage and transportation and scarcity of hydrogen stations. In recent years, the development of large-scale hydrogen energy transportation industry has been slow.

Internal combustion engines will still be the dominant power of heavy commercial trucks for a long time in the future, therefore, zero-emission internal combustion engines will become an important development direction for heavy trucks to achieve carbon neutrality.

3.1 Development status and trend of ammonia-hydrogen new energy transportation vehicles

In 2020, SK Innovation Co. from South Korea, Amazon Climate Fund, British venture capital AP Ventures and Saudi Aramco jointly invested and established the company Amogy. Amogy focuses on the development and application of ammonia and hydrogen energy, and provides ammonia-based, zero emission, high energy density power solutions, aiming to achieve decarbonization in the heavy transport sector.

The first ammonia-hydrogen new energy internal combustion engine in China, which was jointly developed by Academician Li Jun of Foshan Xianhu Laboratory and FAW Jiefang, was successfully ignited on June 28, 2023 [3], This is an important step in China in designing and developing of liquid ammonia internal combustion engine, constructing combustion system and building core components of electronically controlled high-pressure common rail ammonia fuel supply system. Also in 2023, Fuda Zijin Hydrogen Technology Co., Ltd. and Xiamen Jinlong United Automobile Industry Co., Ltd. jointly built the first ammonia hydrogen fuel cell bus in China.

Ammonia-hydrogen new energy will become an ideal green power solution for transportation vehicles [4]. However, there are still some technical difficulties for ammonia to be used as a vehicle fuel: high energy consumption is required for the highly efficient cracking of ammonia to produce hydrogen, resulting in low conversion efficiency of "hydrogen-ammonia-hydrogen- electricity system"; Stable combustion of ammonia and NOx emission control technology are still very challenging; Ammonia’s toxicity and corrosiveness make leakage and corrosion problems need to be effectively solved in production, storage, transportation and use.

3.2 Technical requirements for ammonia-hydrogen heavy transport vehicles

Ammonia-hydrogen drive-power application scenario: high power demand, vehicle rated power ≥ 320kw; long life requirements, vehicle mileage in the whole life cycle ≥ 1.8 million km, durability index ≥ 30000 hours; Fuel economy is required to be high, and the fuel cost accounts for more than 50% of the operating cost. The efficiency of the power system represents the most important product competitiveness; The driving range is required to be long, and the maximum driving range of heavy-duty long-distance vehicles reaches ≥ 1500km; The dynamic response shall be fast, and the response time of 0-90% maximum power (0-300kw) shall not exceed 1s.

Applicability of ammonia-hydrogen drive-power: ammonia is a zero -carbon fuel with high hydrogen density [5]; It is easy to liquefy, store and transport and it has mature infrastructure for production, storage and transport; The volumetric energy density is higher than that of liquid hydrogen; ammonia features low cost and high safety [6]. Heavy duty transport vehicles are the main application objects of ammonia-hydrogen power [7, 8], including road heavy-duty transport vehicles, engineering dump trucks, modified vehicles, special vehicles, buses and other vehicles.

Requirements for on-board ammonia storage system: Based on the vehicle operating temperature and ammonia liquefaction working pressure, the working temperature of the ammonia storage tank is in the range of -30-50℃, and the maximum working pressure should be greater than the saturated vapor pressure (2.03 MPa) of ammonia at 50℃ to reduce evaporation loss. Liquid ammonia is toxic, flammable, explosive, volatile and corrosive. The on-board ammonia storage tank shall have the functions of anti-leakage, anti-corrosion and anti-vibration.

Requirements for on-board ammonia supply system: the ammonia fuel supply system involves a few steps, including high-pressure direct injection of liquid ammonia, low-pressure precombustion injection of ammonia hydrogen mixture, and injection of mixed gas inlet port [9, 10]. It is difficult to measure the intake volume. Therefore, it is necessary to develop accurate measurement and control technology for multi-channel ammonia supply and fuel injection for the supply system. In the meantime, it is necessary to develop a dedicated ammonia fuel supply system, including a high-pressure direct injection supply system for liquid ammonia, a low-pressure pre-injection supply system for ammonia hydrogen mixture, a high-pressure gaseous ammonia cracking unit (DU) supply system [11], and a mixture inlet port injection system.

Requirements for ammonia internal combustion engine system: high performance, high reliability and high adaptability are the basic requirements for ammonia internal combustion engine system, among these, the key requirement and chanllenge is high power transient response ability.

Requirements for on-board ammonia after-treatment system: mainly for nitrogen oxide (NOx) emissions and residual ammonia in exhaust gas, including efficient selective catalytic reduction (SCR) system, precise control system and safe and reliable ammonia leakage detection system [12].

Requirements of on-board hydrogen production system using ammonia: fast dynamic response rate (hydrogen production rate of is 0.42g/s for a 350kW engine); The temperature required for ammonia cracking is low (below 400 ℃); The device size is small.

Technical requirements for ammonia-hydrogen powered vehicles: to optimize power configuration to be the most appropriate under various operating conditions; coordinate the energy management of on-board ammonia to hydrogen generation system, waste heat recovery system, heat management system, multi-axis and multi-motor drive system, power battery system, and so on, at the whole vehicle level; focus on vehicle dynamic collaborative control technology to achieve high dynamic energy supply response of the whole powertrain.

3.3 Key technologies of ammonia-hydrogen drive-power system

Key technologies of on-board ammonia storage system: Ammonia is used as a fuel for long-distance and heavy-duty vehicles, and the volume of ammonia storage tank shall be greater than $2m^3$. Ammonia is easy to volatilize when heated. The on-board ammonia storage tank shall be protected from the sun and away from heat sources. According to the operating characteristics of heavy vehicles and characteristics of ammonia, taking economy, efficiency and safety into consideration, it is necessary to comprehensively optimize vehicle chassis space layout and study materials, shapes, volume and layout of the ammonia storage tank.

Key technologies of on-board ammonia supply system: To studying the jet development law of liquid ammonia spray in cylinder as well as the influencing factor of back pressure, flow rate and temperature on the morphology, particle size distribution, droplet and gas velocity fields of direct injection flash boiling spray in liquid ammonia high-pressure cylinder. To explore the collapse mechanism and constructing the quantitative relationship between spray parameters and spray characteristics. To study the interaction mechanism between the flash boiling spray and the air flow in the cylinder, as well as the influence mechanism of injection time, multi-stage injection and injection duration on the temporal and spatial distribution of gas mixture concentration. To construct the flow metering model of fuel multiphase flow, and establish the cross-domain collaborative control method of fuel supply system based on flow metering feedback. To study the medium pressure supply of the mix-fuel in the precombustion chamber and the direct injection of liquid ammonia into the high-pressure cylinder of the engine, analyzing the hysteresis characteristics under steady-state and transient conditions, establishing the system control model, and using the flow metering feedback method to construct the control strategy of the supply system.

Key technologies of on-board ammonia internal combustion engine system: In order to achieve the goal of high thermal efficiency of high-power zero carbon internal combustion engine with ammonia-hydrogen fuel, taking into consideration the characteristics of fuel spray and mixture formation, basic combustion characteristics, numerical simulation and internal combustion engine bench test, to study methods to accelerate ammonia fuel combustion with ammonia-hydrogen fuel, to reveal the basic combustion mechanisms, proposing the combustion strategy for internal combustion engine with ammonia hydrogen fuel. The research focuses on the chemical reaction kinetics mechanism of ammonia-hydrogen fuel [13, 14], the ignition method and combustion principle of premixed multi-source jet of ammonia hydrogen fusion fuel, and the efficient combustion thermodynamic cycle and control of ammonia-hydrogen fuel internal combustion engine.

Key technologies of vehicle on-board ammonia after-treatment system: The key technology of on-board ammonia after-treatment system converts the leaked ammonia through additional devices. The exhaust pipeline can improve the conversion efficiency by improving the thermal insulation and increasing the gas temperature in SCR, so as to optimize the exhaust system; Through the measurement method with high sensitivity, rapid response and free from the interference of background gas, the change of ammonia amount can be accurately reflected in real time, and an effective early warning and control system for ammonia leakage is developed and applied; Studying the formation mechanism of pollutants in ammonia fuel combustion and the reaction path of N_2O formation, and adopting the appropriate combustion strategy to prevent N_2O formation; Considering the engine operating parameters, ammonia supply, catalyst activity, temperature and other factors, system-level control and adjustment are carried out to reduce the generation and emission of nitrogen oxides by optimizing the combustion chamber structure, combustion process control, fuel injection system, etc.

Key technologies of on-board ammonia to hydrogen generation system: To study and develop low-temperature, low-energy consumption, high-efficiency ammonia cracking catalysts and reaction devices to meet the needs of small volume and high-throughput vehicles [15]; To study and develop membrane reactor ammonia cracking separation unit with low-cost, high reaction flux and high stability, as well as relatively independent ammonia cracking system and ammonia cracking separation unit by applying pressure swing adsorption hydrogen separation techniques (which is helpful to make smaller devices).

3.4. Prospects

Through technical research and demonstration in various related fields, ammonia-hydrogen zero-carbon power is one of the most appropriate ways to achieve the goal of carbon neutrality for transportation equipment. Ammonia-hydrogen zero-carbon drive-power and vehicles will become the mainstream of the market. It effectively solves the challenges faced by pure electric vehicles and hydrogen fuel cell vehicles, in terms of technical realization and operation economy. More importantly, since upstream and downstream industrial chains of ammonia-hydrogen zero-carbon drive-power are very similar to those the traditional internal combustion engines, ammonia-hydrogen new energy technologies can extend the vitality of the internal combustion engine industry and revitalize the whole industry.

References

[1] Ou GL, Ning J. Policies and pathways for promoting green and low carbon development of highway transportation in China, Journal of Sustainable Development Economics, 2022；7: 39-42. [欧国立，宁静，促进我国公路运输绿色低碳发展的政策与路径，*可持续发展经济导刊*，2022；7:39-42.]

[2] Amar P, Li J, Volvo SuperTruck 2:Pathway to Cost-Effective Commercialized Freight Efficiency,2019-06-12, https://www.energy.gov/eere/vehicles/articles/volvo-supertruck-ii-pathway-cost-effective-commercialized-freight-efficiency .

[3] First in the world: zero-carbon ammonia hydrogen internal combustion engine was successfully ignited, developed by Foshan Xianhu Laboratory Academician Jun Li Workstation and FAW JieFang [佛山仙湖实验室李骏院士工作站与一汽解放合作研

发的氨氢融合直喷零碳内燃机全球首发点火成功]，2023-06-28，http://xianhulab.com/gzdt/1221.html

[4] Rouwenhorst KHR, Van der Ham AGJ, Mul G, Kersten RA. Islanded ammonia power systems: Technology review & conceptual process design. *Renewable & Sustainable Energy Reviews*, 2019； 114:109339-109339(1-15).

[5] Wang G, Mitsos A, Marquardt W. Conceptual design of ammonia-based energy storage system: system design and time-invariant performance. *AIChE Journal*, 2017；63: 1620-1637.

[6] Bicer Y, Dincer I. Life cycle assessment of ammonia utilization in city transportation and power generation. *J. Cleaner Production*, 2017; 170:1594-1601.

[7] Palys MJ, Daoutidis P. Using Hydrogen and Ammonia for Renewable Energy Storage: A Geographically Comprehensive TechnoEconomic Study. *Computers & Chemical Engineering*，2020; 136: 106785.

[8] Kandemir T, Manfred F. The Haber-Bosch Process Revisited: On the Real Structure and Stability of "Ammonia Iron" under Working Conditions. *Angewandte Chemie*, 2013; 52:12723-12726.

[9] Mørch C S, Bjerre A, Gøttrup MP, Sorenson SC, Schramm J. Ammonia/hydrogen mixtures in an SI-engine: engine performance and analysis of a proposed fuel system. *Fuel*, 2011; 90:854-864.

[10] Frigo S, Gentili R. Analysis of the behaviour of a 4-stroke SI engine fuelled with ammonia and hydrogen. *International J. Hydrogen Energy*, 2013;38:1607-1615.

[11] Kyunghyun R, Zacharakis-Jutz G. Performance enhancement of ammonia-fueled engine by using dissociation catalyst for hydrogen generation. *International J. Hydrogen Energy*, 2014; 39:2390-2398.

[12] Lesmana H, Zhang ZZ, Li XM, Zhu MM,Xu WQ, Zhang DK. NH_3 as a Transport Fuel in Internal Combustion Engines: A Technical Review. *J. Energy Resources Technology*, 2019; 141: 070703-070703(1-12).

[13] Dimitriou P, Javaid R. A review of ammonia as a compression ignition engine fuel. *International J.Hydrogen Energy*, 2020; 45: 7098-7118.

[14] Gray J T, Dimitroff E, Meckel, N, Quillian R. Ammonia Fuel-Engine Compatibility and Combustion. *SAE Transactions*, 1967; 75: 785-807.

[15] Ezzat M F, Dincer I. Development and assessment of a new hybrid vehicle with ammonia and hydrogen. *Applied Energy*, 2018; 219:226-239.

Chapter 4 A Strategic Study on Ammonia-Hydrogen New Energy Zero-Carbon Aircraft Engines

The aviation industry is one of the significant contributors to global carbon emissions. Carbon dioxide emission from aviation accounts for 2% of the world's total carbon emissions, corresponding to 3.5% in terms of its impact on climate change [1]. In 2018 alone, global aviation carbon emissions reached 1.04 billion tons, and this figure is growing rapidly with the rapid growth of the aviation transport sector. The International Civil Aviation Organization (ICAO) has established the "Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) ", which will be implemented from 2021 to 2035. This scheme aims to set a unified emission reduction target for the global aviation industry and implement a market-based mechanism for achieving this target [2]. In 2021, the Aviation Transport Action Group (ATAG) also issued a statement pledging that the global civil aviation transport industry will achieve net-zero carbon emissions by 2050 [3].

The key to achieving net-zero emission in aviation industry lies in innovative developments in aviation power carbon reduction technology. Zero-carbon aircraft engines based on ammonia-hydrogen new technology is of great significance to the innovative development of aviation power carbon reduction technology. This chapter reviews the development status and key technologies of ammonia-hydrogen zero-carbon aircraft engines, aiming to provide technical guidance for solving the major problems of achieving zero carbon emissions in the aviation field, and put forward strategic suggestions for the future zero-carbon development route of the aviation transport industry.

4.1 Development Status of Ammonia-Hydrogen Aircraft Engines

Reducing carbon emissions in the aviation sector primarily relies on three methods: improving the efficiency of existing energy utilization technologies, utilizing alternative energy sources, and employing carbon capture, storage, and utilization technologies. Among these three methods, utilizing zero-carbon alternative energy sources represents the most effective approach for the aviation transport industry to achieve net-zero emissions. The International Air Transport Association (IATA) passed the resolution *"Global Air Transport Industry to Achieve Net Zero Carbon Emissions by 2050"* at its 77th Annual Meeting, explicitly stating that aviation fuel innovation is a main direction for future zero-carbon development in the aviation transport industry. The *Aviation Climate Action Plan* released by the United States in 2021 lays out a zero-carbon aviation development roadmap with sustainable aviation fuel (SAF) at its core [4]. Europe explicitly supports hydrogen-powered aircraft research in the *Hydrogen-Powered Aviation* report published in 2020 and *Clean Sky II* published in 2022 [5].

Hydrogen-powered aviation has seen rapid development in recent years. In September 2020, Airbus unveiled the ZEROe concept aircraft, which utilizes hydrogen as its primary energy source [6]. In December 2021, the UK's Aerospace Technology Institute (ATI) introduced the FlyZero concept aircraft and, in March of the following year, unveiled a detailed technical plan for using a hydrogen-fueled aircraft engine [7]. In the same year, Rolls-Royce conducted its first test of hydrogen-fueled modern turboprop engine [8]. In 2023, ZeroAvia carried out flight testing with an aircraft equipped with the largest hydrogen fuel cell [9].

While the concept and prospects of hydrogen-powered aircraft are promising, they also face significant challenges. Liquid hydrogen needs to be stored in tanks at temperatures as low as -253°C. Hydrogen has an mass energy density roughly 3 times that of traditional aviation kerosene, but its density is only 9% of kerosene's, so the size of hydrogen fuel tank is approximately 4 times that of conventional aircraft fuel tank for storing an equivalent amount of energy [10]. This leads to substantial increases in tank size and weight, significantly affecting aircraft design. Taking narrow-body aircrafts like the C919, A320 or B737 as examples, the layout of hydrogen-powered aircraft would differ significantly from the most common wing-mounted engine configurations, canard wings must be introduced to counter the shift of the aircraft's centre of gravity [11]. In addition to storage and transportation challenges, hydrogen fuel is highly flammable and explosive, and it has a wide self-ignition concentration range (4% to 75%). It also exhibits "hydrogen embrittlement" in metals. All these properties of hydrogen make necessary stringent safety measures for fuel storage, transportation, refueling, and use, leading to additional economic costs [12]. Addressing the challenges associated with the use of pure hydrogen as an aviation power source requires the development of disruptive technologies. Ammonia-hydrogen power is an important technical path for zero-carbon aviation industry.

Ammonia-hydrogen aircraft engines currently have two technological pathways: ammonia-hydrogen fuel cells and ammonia-hydrogen turboprop engines, each of them has their specific field of applications (see Figure 1). Ammonia-hydrogen fuel cells are suitable for short-range flights with limited passenger capacity, whereas ammonia-hydrogen turboprop engines are better suited for medium to long-range flights with larger passenger capacities. In the long term, ammonia-hydrogen turboprop engines are the key focus in the development of ammonia-hydrogen hybrid aircraft power.

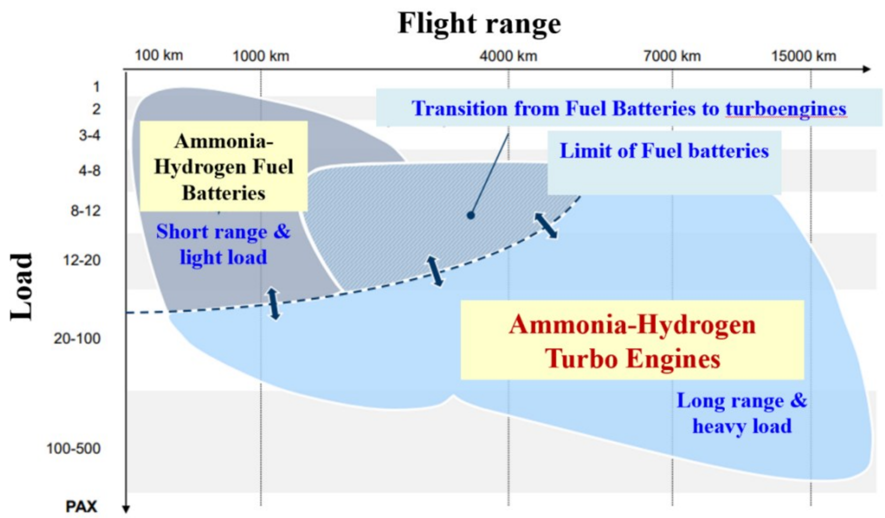


Figure 1 Load-range of ammonia-hydrogen hybrid engines

In recent years, various ammonia-hydrogen turboprop engine concepts have been proposed internationally. In 2020, Reaction Engines Limited in the UK presented an ammonia-fueled engine concept that is similar to traditional aviation kerosene turboprop engines [13]. In 2021, Aerojet Rocketdyne in the United States conducted research on a liquid ammonia-fueled turboprop electric propulsion system with support from the U.S. Department of Energy [14]. In August 2022, the University of Central Florida, in collaboration with major U.S. aviation research and manufacturing companies, initiated an ammonia-powered aviation project for narrow-body airliners with funding from NASA. This project comprises three phases: fundamental research, technology demonstration and full-scale flight and ground testing [15].

In China, research on ammonia-hydrogen aircraft engines is still in its early stage and includes areas such as ammonia-fueled turbo-electric hybrid power systems [16], the kinetics of ammonia-hydrogen mixture combustion reactions and NOx generation mechanisms [17] and studies on ammonia combustion control [18].

4.2 Key Technologies of Ammonia-Hydrogen Aircraft Engines

The development of ammonia-hydrogen aircraft engines is a complex and systematic endeavor that requires comprehensive consideration of factors such as liquid ammonia characteristics, fuel control, low-emission combustion, heat transfer and cooling, flying comfort and safety, supporting infrastructure etc. It involves making breakthroughs in designing advanced and efficient cycle for ammonia-hydrogen aviation power and designing highly stable, low-emission combustion chambers. Currently, ammonia cracking and heat exchange equipment used in ground-based ammonia-hydrogen power systems are not directly applicable to aircraft engines due to aircrafts' weight and volume limitations. Key technologies in lightweight liquid-to-gas heat exchange and efficient ammonia cracking are still needed for ammonia-hydrogen aircraft engines.

Advanced and Efficient Overall Design of Ammonia-Hydrogen Aviation Power: In terms of the design of aircraft engine itself, it is necessary to consider the unique properties of ammonia fuel and overcome new technological challenges, including unconventional thermodynamic cycles, high thrust-to-weight ratio designs based on lightweight materials and efficient turbomachinery schemes, low fuel consumption, low NOx emissions, long service life, system integration, and the use of numerical simulations and experimental verification. Regarding onboard ammonia-hydrogen fuel delivery, one must consider the variations in the physical properties of onboard ammonia-hydrogen fuel under different pressures and temperatures to enable rapid flow control. For onboard ammonia-hydrogen storage, there is a need to redesign low-temperature, reusable liquid ammonia tanks and make breakthroughs in tank shape design technologies to adapt the shape of aircrafts and to address issues such as taking up too much aircraft space and significant range reduction.

Highly Stable Low-Emission Combustion Organization Technology: For ammonia-hydrogen reaction kinetics, there is an urgent need for high-resolution experiments, high-precision quantum chemical modeling and macroscopic modeling to develop highly accurate and universally applicable ammonia combustion models. This will help overcome the current challenges of accurately predicting NOx concentration, flame propagation speed and ignition delay time at the same time. Regarding combustion chamber design, given that fuel-type NOx is a major source of ammonia combustion pollution, innovation should be focused on new combustion methods such as lean combustion and staged combustion. In terms of safety and flying comfort, the ignition/extinction characteristics of ammonia-hydrogen hybrid aircraft engines under extreme conditions are still unknown. Therefore, it is necessary to develop emerging technologies, such as plasma-assisted ignition, to broaden the boundaries of ignition/extinction.

Lightweight and Efficient Liquid-Gas Heat Transfer and Ammonia Cracking Technologies: For ammonia lightweight and efficient liquid-gas heat transfer technology, the conversion of liquid ammonia fuel into gaseous ammonia, followed by its delivery to the cracking chamber or combustion chamber, is critical for efficient fuel utilization, energy efficiency, aircraft performance and safety. To achieve this, breakthroughs are required in highly efficient heat-conducting materials, compact heat exchangers, lightweight design techniques based on lightweight materials and structures, and the rational design of heat recovery systems to utilize waste heat for additional power generation or improved system efficiency. Concerning ammonia lightweight and efficient cracking technology, traditional catalytic cracking solutions may not be suitable for aviation environments. For instance, on a Boeing B737, the ammonia consumption rate is approximately 7.5 tons per hour, and the volume of the catalytic device needs to be greater than 30 cubic meters, posing challenges for onboard implementation [15]. Therefore, it is imperative to develop revolutionary lightweight and efficient cracking technologies, e.g. plasma and high-performance catalysts in synergy, to enable rapid cold starts.

4.3 Prospects

The development of zero-carbon aircraft engines is becoming a focal point of competition in the future. Currently, we are at a critical crossroads in choosing technological pathways, thus it becomes more important to make comprehensive planning and to demonstrate the future development of ammonia-hydrogen hybrid zero-carbon aviation power. The development of ammonia-hydrogen hybrid zero-carbon aviation power relies on the dual drivers of "strategic research" and "technology development," involving the exploration and nurturing of disruptive technologies. It needs "synergistic resonance among multiple departments", including civil aviation, energy, industry and information technology, science and technology, aviation, aero-engines, and chemical industries. Furthermore, it requires a coordinated approach in different research areas, including ammonia-hydrogen internal combustion engines, gas turbines, and aircraft engines. It also requires mutual development of pure hydrogen aircraft engines and ammonia-hydrogen hybrid aircraft engines.

References

[1] Lee DS, Fahey DW, Skowron A, Allen MR, Burkhardt U, Chen Q, Doherty SJ, Freeman S, Forster PM, Fuglestvedt J, Gettelman A, Leon RR, Lim LL, Lund MT, Millar RJ, Owen B, Penner JE, Pitari G, Prather MJ, Sausen R, Wilcox LJ. The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. *Atmospheric Environment*. 2021;244:117834(1-29).

[2] International Civil Aviation Organization. Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA). https://www.icao.int/environmental-protection/CORSIA/Pages/default.aspx.

[3] International Civil Aviation Organization. ICAO welcomes new net-zero 2050 air industry commitment. https://www.icao.int/Newsroom/Pages/ZH/ICAO-welcomes-new-netzero-2050-air-industry-commitment.aspx.

[4] Federal Aviation Administration:Aviation Climate Action Plan. https://www.faa.gov/sustainability/aviation-climate-action-plan.

[5] European Commission: Clean Sky 2 - the largest research programme for aviation ever launched in Europe. https://ec.europa.eu/research-and-innovation/en/projects/success-stories/all/clean-sky-2-largest-research-programme-aviation-ever-launched-europe.

[6] ZEROe Towards the world's first hydrogen-powered commercial aircraft.

https://www.airbus.com/en/innovation/low-carbon-aviation/hydrogen/zeroe.

[7] Aero Space Technology Institute. FlyZero. https://www.ati.org.uk/flyzero.

[8] Rolls-Royce announces leading-edge hydrogen programme and developments in hybrid-electric research. https://www.rolls-royce.com/media/press-releases.aspx.

[9] ZeroAvia Flight Testing Hydrogen-Electric Powerplant. https://zeroavia.com/flight-testing/.

[10] Verstraete D. *The Potential of Liquid Hydrogen for long range aircraft propulsion.Dissertation of Cranfield University*, 2009.

[11] Wang XY. Analysis of zero-carbon aviation development prospectives.*Aerospace Power*, 2022;3:24-27. [王翔宇. 英国零碳飞行发展远景分析. *航空动力* 2022;3:24-27.]

[12] Ball M, Wietschel M. The future of hydrogen–opportunities and challenges. *International J. Hydrogen Energy,* 2009,34:615-627.

[13] Reaction Engines. https://reactionengines.co.uk/.

[14] Zero-carbon Ammonia-Powered Turboelectric (ZAPTurbo) Propulsion System. http://www.arpa-e.energy.gov/technologies/projects/zero-carbon-ammonia-powered-turboelectric-zapturbo-propulsion-system.

[15] University of Central Florida News:UCF to Lead $10M NASA Project to Develop Zero-Carbon Jet Engines. https://www.ucf.edu/news/ucf-to-lead-10m-nasa-project-to-develop-zero-carbon-jet-engines/.

[16] Xu L G, Mao JK, Liang FL, Wang ZX, Yang ML. Direct Ammonia SOFC-GT Hybrid Power and Application in Aerospace, *J. Aerospace Power*, 2023,doi:10.13224/j.cnki.jasp.20220346. [徐乐根，毛军逵，梁凤丽，王在兴，杨孟林. 直接氨 SOFC-GT 混合动力系统性能及航空应用. *航空动力学报,* 2023,doi:10.13224/j.cnki.jasp.20220346.]

[17] Yin GY, Wang CJ, Zhou M, Zhou YJ, Hu EJ, Huang ZH. Experimental and kinetic study on laminar flame speeds of ammonia/syngas/air at a high temperature and

elevated pressure. *Frontiers in Energy,* 2022; 16: 263-276.

[18] Sun JG, Huang Q, Tang Y, Li SQ. Stabilization and Emission Characteristics of Gliding Arc-Assisted NH3/CH4/Air Premixed Flames in a Swirl Combustor. *Energy & Fuels,* 2022,36:8520-8527.

Chapter 5 A Strategic Study on Ammonia-Hydrogen New Energy Zero-Carbon Gas Turbines

Gas turbine typically uses natural gas or diesel as fuel. Gas turbine technology using hydrogen or ammonia as fuel represents an emerging technology of the industry. Gas turbine technology using green hydrogen or its vector of ammonia can play a vital role in achieving zero carbon emission in this energy transformation. This technology will manifest in the following three areas.

(1) **Transportation.** Ammonia can be used as fuel for micro/small gas turbines to provide electrical energy for vehicles, ships, even aeronautical vehicles using hybrid power technology. Hybrid power technology is the major emerging trend of mobility power industry as seen in electric vehicles (EVs). Since the energy density of ammonia is higher than that of power batteries, hybrid power vehicles powered by ammonia-fueled gas turbines will provide a viable solution for decarbonizing the transportation sector.

(2) **Micro-grid power generation.** Ammonia can be used as fuel for micro and small combustion turbines (~500kW-10MW) for power generation to serve local communities. Gas turbines have the advantages of high thermal efficiency, small carbon footprint, flexible fuel, and high quality of waste heat. All of these can provide distributed micro-grids with different forms of energy to meet various demands, leading to a comprehensive transformation of the energy structure.

(3) **Large-scale grid power generation.** Large-scale storage using salt caverns or rocky caves and large-scale transportation using major pipelines for hydrogen gas can be economical. As such it enables the large-scale centralized power generation scenarios with heavy-duty gas turbines (>50MW) to peak shaving as well as provide ancillary services for large power grids. In the time when renewable penetration is extensive into the grid, gas turbine power can **serve as the "spine" of a new power system** achieving stability and high quality of electricity supply.

5.1 Recent development on hydrogen gas turbine

Since gas turbines have a wide range of applications as power in various industrial sectors, hydrogen-fueled gas turbines are essential for reducing carbon emissions and achieving the goal of carbon neutrality. Hydrogen gas turbine power generation has the following advantages: (1) it enables large-scale, continuous, and stable consumption of hydrogen as a mode of operation with which it can save the cost of hydrogen transportation and storage; (2) the application of hydrogen by gas turbines can be initiated quickly to stimulate the rapid growth of hydrogen energy industry; (3) it can use poor-quality hydrogen and does not require a high degree of purity, which offers opportunities to reduce the cost of hydrogen production and storage.

The major gas turbine OEMs [1, 2] are confident in the future of hydrogen-fueled gas turbines and designated high priority for related technology development. Currently, gas turbines in the market can use hydrogen-blended fuels to varying degrees. Older models of industrial gas turbines can generally burn a higher percentage of hydrogen fuel, and these machines can even burn pure hydrogen if diluents are used, for examples diffusion flame with nitrogen addition or steam blending. However, modern advanced, high-efficiency heavy duty gas turbines with dry low NOx burners are relatively limited on the percentage of hydrogen blending capability (see Table 5-1 for details).

Table 5-1 Hydrogen Combustion Capacity of Representative Models of Mainstream Manufacturers [3]

Company	**Hydrogen combustion capacity of representative models**	
GE	Models	Hydrogen Combustion Adaptability

	HA	0~50%
	FA	0~100%
	B/E	0~100%
	Aeroderivatives	0~65%
Siemens	HL	0~30%
	H	0~30%
	F	0~30%
	Aeroderivatives	60%
Mitsubishi	F/J	0~30%
	B/D	0~100%
Ansaldo	GT36 (H)	0~50%
	GT26 (F)	0~30%
Baker Hughes	GE10-1	0~100%
	NovalLT-16	0~100%
Man Energy	THM	0~50%
Sola	Titan130/ Taurus60	0~60%
Kawasaki	MIA	0~100%

As can be seen from Table 5-1, small industrial gas turbines (with relatively low efficiency) such as Mitsubishi's B/D class, Baker Hughes' NovalLT-16, and Kawasaki's MIA can burn pure hydrogen. But among the large heavy duty H-class gas turbines models with high efficiency low NOx emission, only GE's micro-mixer combustor and Ansaldo GT36's two-stage combustor have relatively higher hydrogen burning capability, up to 50%. Currently, the mainstream high-efficiency low-NOx heavy-duty industrial gas turbines do not have a large amount of hydrogen blending capacity. The high-efficiency low NOx emission hydrogen combustion technology needs to be further developed to achieve the goal of hydrogen gas turbines using technologies such as in GE's micro-mixing combustor.

On the other hand, ammonia gas turbines are still in the development stage. There are no mature commercialized products.

5.2Key technologies for hydrogen gas turbines

Diffusion combustion systems with diluents of nitrogen or steam are the current technologies that can burn 100% hydrogen. However, this type of system has two major disadvantages, firstly, comparing with the system without dilution, the efficiency is reduced; secondly, NOx emissions are high requiring additional after-treatment system. Generally, there are two technical paths in addressing these problems, details as follows.

Hydrogen combustion technology: Dry lean premixed combustion (Dry Low NOx, or DLN) is currently the mainstream technology for natural gas combustion, and it is essential for modern low-emission (NOx) efficient gas turbines [4, 5]. DLN is at the cutting edge of gas turbine combustion technology attracting intensive development efforts. However, the technology is currently not good enough for burning fuels with high hydrogen content.

DLN can be expected to enable fuel to operate at 0-100% hydrogen content, but realizing this goal requires more works in the following areas to meet the challenges associated with high hydrogen content in the fuel [6].

1) NOx control. Compared with natural gas combustion, high NOx emissions is due to the lower specific gravity of hydrogen and its combustion products, the adiabatic flame temperature of H_2 is higher at the same level of turbine ignition temperature and mass flow rate (to ensure the same level of power and efficiency). Additionally, the different organization of the hydrogen combustion flames and the different distribution of the temperature fields can also lead to a higher NOx emission. It is possible to reduce the flame temperature by reducing the rated output power, but this leads to a reduction in machine efficiency and power output. New configurations of burners as well as new strategies of control need to be developed to address these emission problems.

2) **Flash back**. Flash back is caused by the faster flame propagation speeds and shorter ignition delays of hydrogen-rich fuel combustion compared with natural gas. In the design of modern heavy-duty gas turbines of high pressure ratio, the higher inlet air temperature for combustors often leads to increased risk of flash back and requires measures in combustion organization and protection.

3) **Combustion instability**. In terms of thermo-acoustic oscillation modes and frequencies, the characteristics of hydrogen flames are significantly different compared with those of natural gas. Therefore, the risk of combustion oscillation problems increases when using hydrogen-rich fuels. To address this issue, it calls for the combustion chamber structural redesign with high fidelity modeling and simulations, while further researches on acoustic suppressor technology can also help to reduce the level of vibration inside the combustion chambers.

4) **Reliability and part life**. For pure hydrogen combustion, the water in the flue gas increases resulting in higher heat transfer coefficients of the gas turbine hot-gas path components. Consequently, it leads to an increase in the operating temperatures in turbine section and an increase in the temperature gradient, as a result, leads to an increase in the thermal stresses that severely impacts part life. Since the material capabilities of modern advanced gas turbines are largely used to their limits, it can be sensitive to small temperature increases. In addition, due to the higher water content, they may be more susceptible to thermal corrosion, which poses a challenge to the engineering design.

Oxy-combustion Cycle: Another idea for addressing the issues of gas turbines with hydrogen fuel is to rethink the fundamentals. As modern gas turbine technology has been developed for the combustion of natural gas, fuel changes may call for a new type of cycle. If it is for the combustion of hydrogen while the supply of oxygen is economically viable, in specific scenarios such as the electrolysis of water to produce hydrogen utilizing renewable energy sources, it offers opportunity to dramatic changes in terms of turbine basic structure. Given the fact that hydrogen is produced while oxygen is also generated as a by-product, and the amounts of hydrogen and oxygen are matched in molar ratio, as an inverse reaction of electrolysis, Oxy-combustion technology can be explored. Analytical studies [7, 8] have shown that if a closed cycle is used, with water vapor as the working fluid, together with partial recompression and optimization of the overall system, the cycle efficiency may reach more than 70% for using hydrogen fuel. One of the major advantages is that it has no NOx emission and is an ideal power production process without any pollutants.

5.3Key technologies for ammonia gas turbine

Although there are no ammonia gas turbine products on the market, ammonia is widely recognized as a viable gas turbine fuel [9, 10]. Ammonia has a high volumetric energy density, comparable to that of methanol and dimethyl ether, and about 50% higher than that of liquid hydrogen. Nitrogen oxide (NOx) emissions are a major problem in ammonia gas turbines, but ammonia combustion products are free of carbon and other harmful pollutants such as CO_2, CO, HCs (hydrocarbons), SOx and particulate matters.

Pollutant emission (NOx) control is a vital issue for ammonia gas turbines. Essentially, there are two probable routes to solve this problem. One is to crack ammonia into hydrogen and nitrogen and then burn the mixed product of N_2 and H_2. The difference between an ammonia gas turbine and a hydrogen gas turbine is that a mixture of hydrogen and nitrogen is used as fuel instead of pure hydrogen. Since the nitrogen in the fuel is a very effective diluent, it actually helps to suppress pollutant emissions. The other path is the Rich-Quench-Lean (RQL) staged combustion technology that ammonia is injected into combustion chambers directly without cracking [11, 12].

RQL divides the combustion into two stages, the first stage is rich combustion, the second stage is lean combustion, in between cold air is injected to cool down the flue gas of the first stage combustion products. The main principle to reduce NOx emissions are as follows. In rich combustion zone, due to the abundance of ammonia gas, the production of NOx is inhibited due to the lack oxygen; In the poor combustion zone, ammonia gas has a reduction reaction function for reducing NOx, so that the emission of the entire pollutant is controlled.

The RQL are typically having three combustion chambers, with equivalent ratio and residence time of the three zones as the design parameters. The emission of combustion pollutants can be minimized by optimizing these critical parameters.

5.4 Ammonia catalytic cracking technology

As mentioned above, the gas turbine using hydrogen fuel is technically feasible. To crack ammonia for hydrogen with equipped ammonia cracking system, emission compliance can be achieved for an ammonia gas turbine. In this case, the ammonia cracking technology is the crucial factor [13]. According to the characteristics of the gas turbine system, system efficiency can be improved by integrating ammonia cracking and consequent combustion.

The key elements on the improvement of ammonia evaporation and cracking in gas turbines include evaporation of liquid ammonia by utilizing waste heat, or even using ammonia as gas turbine coolants; pre-cracking or partial cracking by utilizing exhaust heat at a relatively low temperature (~500ºC); final cracking of the residual ammonia at high temperature inside the combustor (~800ºC) by catalysts. After these processes, ammonia in the combustion fuel mixture is expected to be less than a certain percentage (for example, less than 1%). Such small percentage ammonia in the fuel mixture may help achieve low-emission of ammonia gas turbines.

The design of a high-efficiency ammonia cracking system in an ammonia gas turbine requires addressing several key factors carefully, including reaction temperature, activation energy of the catalytic element, reaction time, catalyst surface area, reaction pressure, temperature field and flow field, and selectivity of catalyst surface. Meanwhile, a high-fidelity catalytic reaction model of ammonia cracking provides fundamentals in designing the integrated system of cracking-combustion chamber for gas turbines. Through design optimization, a cracking process of near-zero residual ammonia can be realized. Such technology can help achieving NOx emission compliance and laying foundations for the accomplishment of a lightweight and cost-effectiveness system.

5.5Prospects

Gas turbine industry using hydrogen or ammonia as fuel is an enabler for the goal of deep decarbonization in the energy sector. A crucial factor for achieving high efficiency hydrogen gas turbines is to control pollutant emissions from combustion products. Evidently, micro-mixer combustion technology is an effective path to solve the problem, laying the foundation for the development of hydrogen-fired heavy-duty gas turbines with high efficiency and low emission. On the other hand, ammonia fueled gas turbine technology will have a better application prospect in the transportation field, but it calls for major innovations on ammonia-cracking technology as it is critical to reduce the weight and volume of the system. Catalytic cracking technology based on new efficient and low-cost catalysts, e.g. high-entropy alloy catalysts [14], may provide the possibility of lightweight and low-emission for ammonia-fueled gas turbines.

References

[1] GE Gas Power: Hydrogen fueled gas turbines, https://www.ge.com/gas-power/future-of-energy/hydrogen-fueled-gas-turbines

[2] Siemens: Renewable hydrogen for Germany's heavy industry,https://www.siemens-energy.com/global/en/home/stories/renewable-hydrogen-trailblazer.html

[3] ETN Global: Hydrogen gas turbines - the path towards a zero-carbon gas turbine,2020, https://etn.global/wp-content/uploads/2020/01/ETN-Hydrogen-Gas-Turbines-report.pdf

[4] Oberg S, Odenberger M, Johnsson F, Exploring the competitiveness of hydrogen-fueled gas turbines in future energy systems，*International J. Hydrogen Energy*，2022; 47: 624-644.

[5] Davis LB，Black SH， Dry Low NOx Combustion Systems for GE Heavy-

Duty Gas Turbines， GE Power Systems, GER-3568G, https://www.ge.com/content/dam/gepower-new/global/en_US/downloads/gas-new-site/resources/reference/ger-3568g-dry-low-nox-for-hdgt.pdf

[6] York WD, Ziminsky WS, Yilmaz E. Development and Testing of a Low NOx Hydrogen Combustion System for Heavy-Duty Gas Turbines，J. Eng. *Gas Turbines Power*. 2013;135:022001(1-8).

[7] Kindra V, Rogalev A, Oparin M, Kovalev D, Ostrovsky M. Research and Development of the Oxy-Fuel Combustion Power Cycle for the Combined Production of Electricity and Hydrogen, *Energies*, 2023;16(16):5983

[8] Internal Report of China United Gas Turbine Technology Co. Ltd, Research on efficient and zero-carbon advanced gas turbine integrated cycling system, 2023. [中国联合重型燃气轮机技术有限公司内部报告:高效、零排放先进燃气轮机联合循环系统研究，2023.]

[9] GE Gas Power: Ammonia as a gas turbine fuel, 2021, https://www.ge.com/content/dam/gepower-new/global/en_US/images/gas-new-site/future-of-energy/GEA34985-ammonia-power-gen.pdf

[10] Masanori Yuri, MHI Energy Transition and Ammonia firing Gas Turbine, Presentation at Ammonia Energy APAC 2023, https://www.ammoniaenergy.org/wp-content/uploads/2023/08/Masanori-Yuri_APAC-2023.pdf

[11] Mashruk S, Xiao H, Valera-Medina A, Rich-Quench-Lean model comparison for the clean use of humidified ammonia/hydrogen combustion systems, *International J. Hydrogen Energy*, 2021;*46(5):* 4472-4484

[12] Herbinet O, Bartocci P, Dana AG, On the use of ammonia as a fuel – A perspective, *Fuel Communications*,2022; 11: 100064(1-16).

[13] Lucentini I, Garcia X, Vendrell X, Llorca J. *Review of the Decomposition of Ammonia to Generate Hydrogen, Ind. Eng. Chem. Res.,* 2021;60(51): 18560–18611.

[14] Xie PF, Yao YG, Huang ZN, Liu ZY, Zhang JL, Li TY, Wang GF, Shahbazian-Yassar R, Hu LB, Wang C. Highly efficient decomposition of ammonia using high-entropy alloy catalysts, *Nature Communications*, 2019; 10: 4011(1-12).

Chapter 6 A Strategic Study of Safety Technologies and Standards for Ammonia-Hydrogen New Energy

For ammonia-hydrogen new energy, ammonia (NH_3) energy based on green hydrogen (H_2) has the dual attributes of efficient storage and transportation of hydrogen energy as well as high application potential as a zero-carbon fuel. Under the supply system of green hydrogen, ammonia energy and hydrogen energy can be converted into each other, forming an integrated system for efficient energy storage, transportation and new applications. [1-3,17]. Hydrogen is easy to leak, flammable, and explosive. Hydrogen environment can result in failure of materials due to hydrogen embrittlement and hydrogen permeation. Ammonia is corrosive, flammable and prone to leakage. It can cause failures in materials and can cause combustion and explosion. Therefore, building a safety and standard system for the entire industrial chain of production, storage, transportation, and use of ammonia-hydrogen new energy is of vital importance for its development. In this context, conducting strategic research on ammonia-hydrogen new energy safety technologies and standards will provide safeguards for the establishment and improvement of this entire new energy industry system.

In this chapter, based on the analysis of the current development status of hydrogen and ammonia safety technologies and standards at home and abroad, the problems, risks and challenges faced in safety and standard research are systematically summarized, from the perspectives of hydrogen, ammonia, and ammonia hydrogen new energy respectively. Suggestions are also proposed for the development of safety technologies and standard systems for ammonia hydrogen new energy in China.

6.1 Development and challenges of safety technologies and standards for ammonia-hydrogen new energy

In terms of hydrogen, hydrogen has the characteristics of low density, large diffusion coefficient, low ignition energy, wide combustion and explosion range, fast flame propagation speed, so hydrogen is easy to leak, highly flammable and highly explosive. In addition, when the equipment is operated in high-pressure hydrogen environment for a long time, the performance of metal materials is prone to deterioration due to hydrogen embrittlement, while non-metallic materials is prone to deterioration due to hydrogen penetration and aging. Therefore, the main focuses of hydrogen safety are material compatibility, leakage and diffusion of hydrogen, as well as prevention and control of hydrogen combustion and explosion risks [4]. Among them, material durability testing and evaluation are the fundamental assurances for the safe and reliable operation of high-pressure hydrogen systems. The safety testing capability of materials, parts and systems under high-pressure hydrogen environment has been preliminarily established internationally and in China [5], but the testing and evaluation capability of materials for hydrogen storage and transportation equipment under extreme service conditions such as liquid hydrogen still needs to be further improved. The safety and standard system for some hydrogen storage and transportation equipment as well as hydrogen fuel vehicles, such as GB/T34583-2017, UNGTR13, ECER134, GB/T24549-2020, etc., has been established. The research on hydrogen leakage and diffusion, including detection technology, has made some progress, but it is not mature yet. Some progress has been also made in the study of hydrogen combustion and explosion, including the mechanism of spontaneous combustion. In terms of hydrogen energy application, there is still a need for life cycle safety and reliability evaluation technology, online (in-situ) testing and monitoring technology, and standards for maintenance cycle and method.

In terms of macro-management, there are two methods for hydrogen risk assessment. They are rapid risk ranking (RRR) and quantitative risk assessment (QRA) respectively [6]. RRR is an empirical qualitative risk assessment method, while QRA is a quantitative assessment of risk. QRA can scientifically evaluate the risk level and has become the mainstream method for hydrogen risk assessment [6-8], but the accuracy of the model and the correctness of the simulation conditions still need to be further improved. In terms of fire safety, most of the basic research results of on fire safety in the hydrogen energy industry have not yet been transformed into effective fire safety technologies and equipment, and there is still a certain distance from market applications [9].

The establishment of hydrogen energy standard system has made great progress both at home and abroad. The "Guidelines for the Construction of the Standard System of Hydrogen Energy Industry (2023 version)" jointly issued by the National Standards Commission and other five ministries and commissions has established a standard framework system for the whole hydrogen industry chain, as shown in Figure 1. At present, the relevant standards for gaseous hydrogen have gradually been established, but standards for hydrogen energy equipment performance verification and evaluation are still to be developed, especially in the application of hydrogen energy in different industries. The current goal is to formulate and revise more than 30 national and industrial standards for hydrogen energy by 2025.

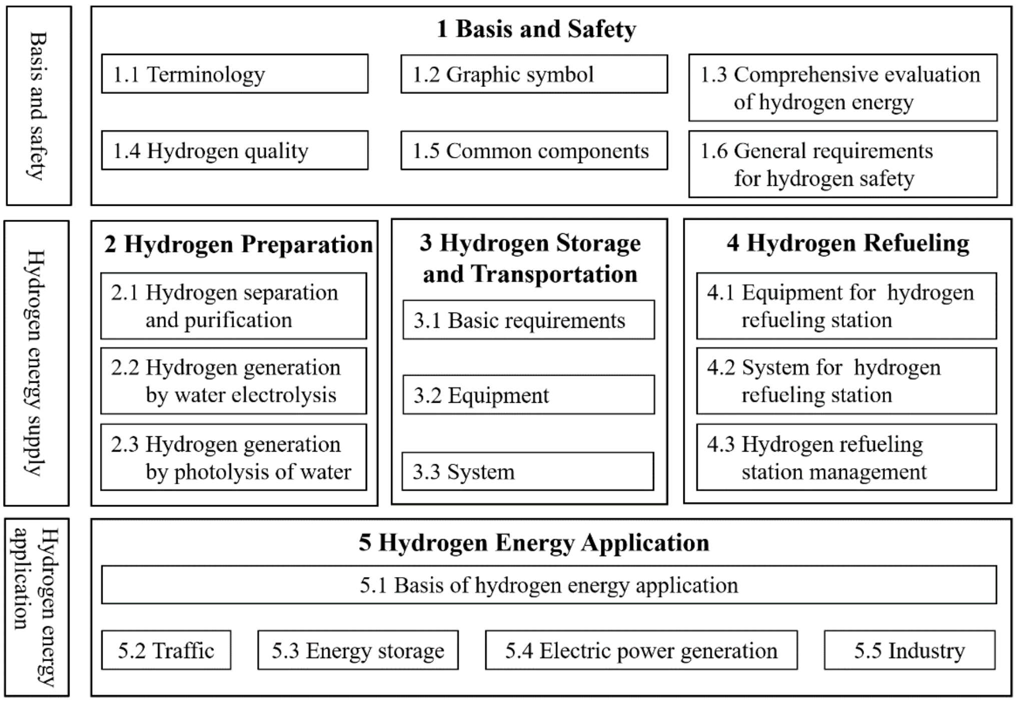


Fig.1 The chart of standard system structure of hydrogen energy industry [10]

In terms of ammonia, it is a colorless and irritating gas at room temperature. Liquid ammonia is classified as a toxic hazardous chemical according to Clause 2.3 of the national standard GB6944-2012. GB/T 18218-2009 specified that liquid ammonia of more than 10 tons is defined as a major hazard source. Corrosion leakage of metal materials and combustion or explosion are two possible failure modes in the utilization of liquid ammonia [11,12]. In addition, since ammonia is corrosive and highly soluble in water with high latent heat of vaporization, high concentration of ammonia can irritate and corrode human respiratory tract, causing corrosive injuries, GB/T 536-2017 classified liquid ammonia as a highly corrosive toxic substance [13].

For large scale storage of liquid ammonia, the corresponding design, manufacturing and testing standards system in China is relatively complete. However, there are differences in safety management and other related aspects due to the differences in storage scale and using sites. Taking a chemical industry park with ten thousand tons of ammonia as an example, in addition to developing and selecting materials with good compatibility with ammonia and designing and manufacturing high-quality ammonia storage equipment, it is also necessary to formulate risk prevention and control plans for dangerous areas, establish and improve the equipment operation and management system, and also form a diversified and multi-level monitoring and emergency management strategies and equipment system.

For the ammonia-hydrogen new energy system, as an efficient hydrogen carrier and a fuel, China has not issued a clear regulation for liquid ammonia storage of more than 10 tons in non-chemical parks (e.g. densely populated urban zones) . At the same time, there is a lack of methods and technical standards for environmental evaluation and risk prevention, assessment, and management.

In terms of long-distance liquid ammonia transportation pipelines, the construction of liquid ammonia pipelines mostly draws on the experience of mature oil and gas pipelines. There is no unified design standard for liquid ammonia pipelines. Internationally, American federal safety Regulations CFR Title 49 Part 195-2022 Transportation of Hazardous Liquids by Pipelines, ASME B31.3-2020 and other design standards are usually used as a reference. In China, there is a lack of design standard for liquid ammonia pipelines, and the design specifications for long-distance crude oil long pipelines are still implemented as reference, such as SYJ 14-1985 and GB 50028-2020. There are obvious differences between liquid ammonia pipeline transportation and existing oil and gas pipeline transportation in terms of phase state control, process flow, corrosion protection, leakage risk, etc. Therefore, it is necessary to put forward higher requirements in corrosion and emergency protection, safety management and monitoring technology for liquid ammonia pipelines. The corresponding safety technical requirements and standards should be formulated as well.

In terms of the application of ammonia energy, the development of ammonia as a fuel and an energy source has been included in strategic innovation plans at home and abroad in recent years. China has not yet incorporated ammonia energy into the national energy planning and energy system. Therefore, the safety technology research and development and standard system of ammonia-hydrogen zero carbon combustion in high temperature manufacturing, transportation equipment, aero engine, gas turbine, etc, have just started and are basically blank.

In the field of ammonia-hydrogen new energy, as a forward-looking development direction in the field of new energy, the research and development of various technologies, including safety technologies and standards, has just begun. The safety technologies and standards for the mutual conversion and complementary use of ammonia and hydrogen as direct energy sources or energy carriers are yet to be developed.

6.2 Key technologies of safety and standards for ammonia-hydrogen new energy

For hydrogen energy, we need to further improve the durability testing and evaluation technology of high-pressure hydrogen systems, and the safety testing capability of materials, components and systems in extreme environments such as high-pressure hydrogen and liquid hydrogen. Further improve is especially required for the basic testing and evaluation capability of materials under extreme service conditions such as liquid hydrogen, and for the development of the online (*in-situ*) detection and monitoring technology for hydrogen storage and transportation equipment. Research and development of key technologies for hydrogen leakage detection, hydrogen combustion and explosion, hydrogen injection fire, spontaneous combustion mechanism etc. should be systematically carried out to provide a basis for establishment of accident prevention and consequence mitigation measures. In the areas of hydrogen energy application, safety and reliability evaluation technology as well as the online detection and monitoring technology in the whole life cycle should be developed, and the maintenance cycle and maintenance method standards of equipment and systems need to be further established. Inspection capability and evaluation system of the whole chain of "materials + components + equipment + system" is to be developed and reinforced. Hydrogen risk assessment methods, especially QRA, is to be further improved. In accordance with the "Guidelines for the Construction of the Standard System of the Hydrogen Energy Industry (2023 version)" issued by the state government, the standard system of the whole industry chain should be gradually improved.

For ammonia energy, firstly the difference between ammonia as a traditional chemical raw material and ammonia energy in the whole industrial chain of production, storage, transmission and application should be examined. Then, the safety technology and standard system must be developed according to the characteristics of ammonia energy. In view of the large-scale storage of liquid ammonia as an efficient energy carrier and fuel in non-chemical parks, methods and standards such as risk assessment, safety prevention and management, as well as environmental protection evaluation must be developed. For the long-distance ammonia pipelines, based on the special factors of ammonia leakage and diffusion caused by pipeline rupture such as overpressure, aging and corrosion, and external impact, further research on corrosion and emergency protection, safety management and monitoring technology must be carried out. The corresponding technical standards such as quantitative risk assessment should be setup. In terms of the application of ammonia as an energy source, it is important to incorporate ammonia safety and standard into the national energy system and to further develop the common safety technology and standard system for ammonia-hydrogen energy. At the same time, considering the special requirements of different industries, the research and development of industrial safety technologies and standards for ammonia-hydrogen zero carbon combustion in high temperature manufacturing, transportation equipment, aero engine, gas turbine, etc. should also be started. This will support and promote the state government to issue guidelines for the construction of ammonia energy industry standard system.

In the field of ammonia-hydrogen new energy, the special safety issues under the use of ammonia and hydrogen as direct energy or energy carriers and mutual conversion and synergistic use should be studied, such as the safety risks caused by the coupling effect of hydrogen and ammonia. On the basis of the common hydrogen and ammonia standard systems, a supplementary standard system for the practical application scenarios of ammonia and hydrogen new energy should be established.

6.3 Prospects

Safety is of paramount importance for hydrogen and ammonia energy industry. The key to the development of this forward-looking and strategic field is to systematically develop the safety technology and standard system of the whole industrial chain of production, storage, transportation and application of ammonia-hydrogen new energy. At present, hydrogen energy has been incorporated in the national energy planning and energy system. Ammonia, as an efficient hydrogen carrier and also zero-carbon fuel, has been widely included in strategic innovation plans in many countries. The continuous development of large-scale storage and transportation of ammonia energy and zero-carbon combustion technology at home and abroad, especially the development of ammonia energy safety technology and related standards, will provide strong support for the integration of ammonia energy into the national energy planning and energy system. Building and improving the safety and standard system of the whole industry chain of ammonia-hydrogen new energy will support and promote rapid advancements of this strategic field.

References

[1] Xu YM, Zheng CM, Zhang YH. Application prospect of ammonia energy as clean energy. *Chemistry*, 2019, 82(3): 214-220. [徐也茗, 郑传明, 张韫宏. 氨能源作为清洁能源的应用前景. *化学通报*, 2019; 8 2(3): 214-220.]

[2] Yong RS, Yang CR; Xue M, Nie F, Zhao XL. Application status and prospect of ammonia energy. *Strategic Study of CAE*, 2023; 25(2): 111-121. [雍瑞生, 杨川箬, 薛明, 聂凡，赵兴雷. 氨能应用现状与前景展望. *中国工程科学*, 2023; 25(2): 111-121.]

[3] Li WD, Li YL, Teng L, Yin PB, Huang X, Li JQ, Luo Y, Jiang LL. Research progress on ammonia energy technology and economy under “Carbon Emission Peak” and “Carbon Neutrality” targets. *Chemical Industry and Engineering Progress*, 2023: 1-18. [李卫东, 李逸龙, 滕霖, 尹鹏博，黄鑫，李加庆，罗宇，江莉龙. “双碳”目标下的氨能技术与经济性研究进展. *化工进展*, 2023: 1-18.] https://doi.org/10.16085/j.issn.1000-6613.2023-0066

[4] Zheng JY, Liu ZL, HUA ZL, Gu CH, Wang G, Chen LX, Zhang YW, Zhu SY, Han WL. Research status-in-situ and key challenges in hydrogen safety. *Journal of Safety and Environment*, 2020; 20(1): 106-115. [郑津洋, 刘自亮, 花争立, 顾超华，王赓，陈霖新，张一苇，朱盛依，韩武林. 氢安全研究现状及面临的挑战. *安全与环境学报*, 2020; 20(1): 106-115.]

[5] Zheng JY, Zhou CL, Gu CH, Li ZY, Zhao YZ, Xu P, Zhang L, Liu PF. Research of materials testing apparatus in high-pressure hydrogen. *Acta Energiae Solaris Sinica*, 2015; 36(5): 1073-1080. [郑津洋, 周池楼, 顾超华, 李智远，赵永志，徐平，张林，刘鹏飞. 高压氢气环境材料耐久性试验装置的研究. *太阳能学报*, 2015; 36(5): 1073-1080.]

[6] Li ZY, PAN XM, Ma JX. Quantitative assessment on hydrogen releases of

hydrogen refueling station by consequence modeling. *J. Tongji Univ. (Natural Science)*, 2012; 40(2): 286-291. [李志勇，潘相敏，马建新. 加氢站氢气事故后果量化评价，*同济大学学报（自然科学版）*, 2012; 40(2): 286-291.]

[7] Middaha P, Hansen OR. CFD simulation study to investigate the risk from hydrogen vehicles in tunnels. *International Journal of Hydrogen Energy*, 2009; 34(14): 5875-5886.

[8] Li ZY, Pan XM, Ma JX. Quantitative risk assessment on 2010 Expo hydrogen station. *International Journal of Hydrogen Energy*, 2011; 36(6): 4079-4086.

[9] Chen Y, Li Y, Ji C, Liu XY. Discussion on the current situation of fire safety in the hydrogen energy industry at home and abroad. *Proceedings of 2020 Annual Science and Technology Meeting of China Fire Protection Association.* [陈晔, 李毅, 纪超, 刘晅亚. 浅谈国内外氢能源产业消防安全现状. *2020 中国消防协会科学技术年会论文集*.] DOI:10.26914/c.cnkihy.2020.065589

[10] Standardization Adminstration, Guidelines for the construction of the hydrogen energy industry standard system (2023 Edition). [国家标准化管理委员会, 氢能产业标准体系建设指南（2023 版）

[11] Wang HN, Yang W, Huang W, Li HH. Research on XGBoost prediction method for emergency rescue area of liquid ammonia leakage. *Journal of Safety and Environment*, 2023; 23(5): 1482-1489. [王海宁, 杨威, 黄惟, 李海航. 面向液氨泄漏应急救援区域的 XGBoost 预测方法研究. *安全与环境学报*, 2023；23(5): 1482-1489.]

[12] He WJ. Combustion and explosion risk of ammonia and its disposition method. *Fire Science and Technology*, 2016; 35(7): 1023-1025. [何汶静. 氨燃爆危险性与处置方法探讨. *消防科学与技术*, 2016; 35(7): 1023-1025.]

[13] Kojima Y. Safety of ammonia as a hydrogen energy carrier. *International Journal of Hydrogen Energy*, 2023. https://doi.org/10.1016/j.ijhydene.2023.06.213

[14] Chen XD, Fan ZC, Chen YD, Cui J, Zhang XH, Wang B, Ai ZB. Green and

intelligent design, manufacturing and maintenance of pressure vessels in China. *Pressure Vessel Technology*, 2017; 34(11): 12-27. [陈学东，范志超，陈永东，崔军，章小浒，王冰，艾志斌. 我国压力容器设计制造与维护的绿色化与智能化. *压力容器*, 2017; 34(11): 12-27.]

[15] Zhang L, Xue BF, Liu YX, Wang Y, Wu Y, Zhang H, Yang XC, He S, Jiang SP, Li J, Zhang QJ. A strategic study of ammonia-hydrogen new energy interdisciplinary science frontiers, *Chinese. Science. Buletinl.,* 2023; 68: 3107-3112. [张莉，薛勃飞，刘玉新，王宇，吴云，张华，杨新春，何帅，蒋三平，李骏，张清杰. 氨氢融合新能源交叉科学前沿战略研究. *科学通报,* 2023; 68: 3107-3112.]

[16] Regulation No. 134 of the Economic Commission for Europe of the United Nations (UN/ECE) — Uniform provisions concerning the approval of motor vehicles and their components with regard to the safety-related performance of hydrogen-fuelled vehicles (HFCV).

[17] United Nations Global Technical Regulation No.13 on Hydrogen and Fuel Cell Vehicles.

Chapter 7 Policy Suggestions for Development of Ammonia-Hydrogen New Energy Science, Technology and Industry

Ammonia-hydrogen new energy technology offers an efficient solution to address two major bottlenecks faced by the hydrogen energy industry. One is hydrogen large-scale storage and cross-regional transportation with low cost and high safety. The other is expanding new major application scenarios for hydrogen energy. Ammonia-hydrogen new energy technology is of vital importance for the deep decarbonization, upgrading and transformation of energy-intensive industries such as high-temperature manufacturing, transportation, metallurgy, construction, and power generation in China [1]. It is imperative for China to promptly incorporate ammonia energy into the national energy system, launch the project of "West Ammonia Transporting to East" and develop projects of offshore wind power for hydrogen and ammonia along southeast coast, embark on the "One Belt, One Road" international collaboration and establish demonstration projects on ammonia-hydrogen new energy. These actions are crucial in our pursuit of securing a dominant position in the global stage of ammonia-hydrogen new energy technology industry.

7.1 Incorporating ammonia energy into the national energy planning and energy system

Given that hydrogen energy has already been incorporated into the national energy system, we strongly recommended the prompt inclusion of ammonia as both an energy carrier and fuel in the national energy planning and system. In order to formulate China's own medium- and long-term plans and an industrial application roadmap for ammonia energy, a comprehensive survey should be conducted to ensure national energy security by examining ammonia energy resources. Innovative technologies for ammonia energy, including its production, storage, transportation and application, need to be developed to cultivate sustainable and stable market demand and actively promote practical applications of ammonia energy. Furthermore, safety detection technologies, safety evaluation methods, and standards and regulations for ammonia-hydrogen new energy should be developed.

Presently, over 70% ammonia in China is synthesized from coal [2]. Globally, challenges persist in terms of cost and application scenarios for green ammonia production and ammonia dissociation technologies. We recommend that the central government promptly conducts a thorough survey and analysis of ammonia energy resources, including their sources, users, energy consumption, carbon emissions, storage and transport capacity, production capacity, enterprise status, national distribution, price trends, new technology development and application. Based on this survey, we suggest formulating medium- and long-term development plans and an industrialization roadmap for ammonia energy. To achieve this, we propose developing full-chain innovative technologies on ammonia energy, covering production, storage, transport and utilization. This can be achieved through dedicated research and development funds, the development of cutting-edge technologies with intellectual property rights, and collaboration with other countries. Key areas of technology development should focus on low-cost green ammonia synthesis, ammonia and ammonia-hydrogen combustion technologies, and one-stop ammonia cracking technology for producing and refilling hydrogen. Planning and constructing large-scale ammonia storage stations would facilitate centralized supply and distributed supply. The government should implement measures, such as tax reductions, subsidies, incentives, financing options, loans to proactively stimulate the adoption of ammonia and ammonia-hydrogen as alternative fuels to natural gas and promote widespread application of ammonia energy. The establishment industrial funds can further support this initiative. Moreover, there is a need to actively encourage enterprises, universities, research institutes to introduce ammonia energy to the general public by demonstrating its environmental benefits, safety attributes and high efficiency.

The sstablishment of a national standard system for ammonia energy is crucial for its extensive industrial application. We propose that the government collaborates with energy suppliers, equipment manufacturers, transport operators, and academic institutes to conduct research on safety monitoring technologies, safety assessment methods and mechanisms for ammonia-hydrogen new energy. This collaboration can help formulate relevant safety standards and regulations. By leaning from natural gas management methodologies, emergency management schemes and land-use policies related to both ammonia energy and ammonia-hydrogen new energy, including production, storage, transportation, and utilization should be devised and supported. Furthermore, the construction and management of one-stop hydrogen station by ammonia dissociation should be regulated and supported.

7.2 Launching the project of “West Ammonia Transporting to East” and projects of offshore wind power for hydrogen and ammonia along southeast coast

Launching the “West Ammonia Transporting to East” Project. The northwestern region of China possesses abundant renewable energy resources. The combined installed capacity of photovoltaic power and wind power has reached 128.28 GW, with an on-grid price ranging from 0.24 to 0.35 yuan/kWh. Despite this, the local capacity for consuming green electricity is insufficient, leading to frequent waste (abandonment) of solar and wind power in this region [3]. On the contrary, the southeastern coastal areas, being industrially developed, have a significant energy demand but limited access to photovoltaic and offshore resources. To meet the growing demand for ammonia-hydrogen new energy in those economically advanced regions, we propose that the government fully utilize financial support and policy guidance. Collaborative effort among scientific research teams and industries should focus on developing crucial technologies for producing large-scale, low-cost green hydrogen and green ammonia utilizing affordable green electricity. Additionally, the establishment of green hydrogen and green ammonia energy storage stations, coupled with the construction of liquid ammonia transportation pipeline networks from the west regions to southeastern coastal areas, is recommended.

Notably, liquid ammonia long-distance pipelines and waterway transportation technologies are well established, with transportation costs approximately 1/1000 of hydrogen transportation of via roads [4]. Examples include the US Gulf Central Ammonia Pipelines, operational for 50 years over a span of 3,057 kilometers, and the 2471 km liquid ammonia pipelines from Tolyatti, Russia to Odessa, Ukraine, in operation for 40 years, transporting 1.3-3 million tons of liquid ammonia annually [5,6]. Green hydrogen produced in regions like the Middle East, Australia, and Latin America is already transported to destination countries via liquid ammonia [7]. However, in China, while there are 780,000 kilometers of natural gas pipelines (at a construction cost of approximately 201 million yuan per 100 kilometers) there exist only 161.7 kilometers of liquid ammonia pipelines (at a construction cost of about 224 million yuan per 100 kilometers) [8]. Thus, the construction of build liquid ammonia transportation pipelines from west to east deemed imperative.

Launching offshore wind power projects for hydrogen and ammonia along the southeast coast. China's southeastern coastal areas possess abundant offshore wind power resource, with a total installed capacity of 30.61 GW, including 8.04 GW in Guangdong, 3.4 GW in Fujian, and 3.55 GW in Zhejiang. Predictions indicate that, by 2030, offshore wind power costs may reduce to less than 0.2 yuan/kWh. However, due to the challenges of integrating offshore wind power into the grid, economically developed southeastern areas are unable to fully utilize this inexpensive green electricity. To meet the urgent demands for ammonia-hydrogen new energy in these developed areas, we propose the government maximize financial support and policy guidance. Collaboration among scientific research teams and industries should focus on developing key technologies to produce large-scale, low-cost green hydrogen and green ammonia utilizing offshore wind power. Additionally, establishing green hydrogen and green ammonia energy storage stations, coupled with the construction of liquid ammonia transportation pipeline networks within the southeastern coastal areas, is recommended. For instance, taking Hainan province as an example, nearly 50 GW wind power plants could be established within 100 kilometers offshore, potentially producing 3.5 million tons of green hydrogen and 19 million tons of green ammonia annually. In comparison, in Guangdong province, with its power generation, ceramics and metal processing industries, could consume 200 million tons of zero-carbon liquid ammonia fuel (where the current annual production of liquid ammonia in Guangdong is less than 0.1 million tons).

7.3. Launching international joint projects on ammonia-hydrogen new energy with countries along the “One Belt, One Road”

Some countries along the “One Belt, One Road”, historically reliant on fossil fuel exports, are actively seeking opportunities to transition from exporting fossil fuels to exporting clean energy [9]. For instance, Saudi Arabia’s ambitious ‘Vision 2030’ aims to replace oil exports by exporting ammonia-hydrogen energy, with aspiration to build a trillion-dollar new energy market. Notably, liquid ammonia marine transport technology is highly developed, with over 120 liquid ammonia transport terminals worldwide [10]. We strongly recommend that China enhances international collaboration in energy sector and establishes international connections between the ‘One Belt, One Road’ initiative and the new energy policies of countries along this route (such as Saudi Arabia ‘Vision 2030’). This collaboratin would ensure a long-term and stable supply of ammonia energy for China.

7.4. Implementing key regional demonstration projects of ammonia-hydrogen new energy

The key regional demonstration projects for ammonia-hydrogen new energy are comprehensive initiatives utilizing ammonia-hydrogen as the primary energy source. These projects employ advanced technologies to build complete scenarios, encompassing industry, transportation, consumption and ecology considerations, aiming to reduce regional carbon emissions or achieve zero-carbon emissions. We recommend that the government strengthens the policy guidance and issues comprehensive policies outlining the overall objectives, key tasks, key regions, regulatory mechanisms, financial strategies and incentives for these key regional demonstration projects in ammonia-hydrogen new energy. It is of great importance to provide guidance and encouragement to regions with strong economic foundations and abundant resources to prioritize the implementation of regional demonstration projects of ammonia-hydrogen new energy based on their unique local realities. These regional demonstration projects will actively foster the integrated application and innovation of ammonia-hydrogen new energy technologies, including green ammonia production, zero-carbon combustion of hydrogen-ammonia, establishment of large-scale ammonia storage stations and one-stop ammonia cracking stations for hydrogen production and hydrogen refilling, and utilization of ammonia-hydrogen fuel cells. The success of these projects will significantly contribute to the swift transformation of the national energy structure and promote higher economic development.

7.5 Establishing special funds on the development of ammonia-hydrogen new energy

We propose the establishment of specialized funds dedicated to advancing ammonia-hydrogen new energy. These funds should cover various aspects, including the R&D of low-cost and large-scale green ammonia synthesis technology, zero-carbon combustion technology for ammonia-hydrogen in high-temperature industries, zero-carbon aircraft engines, gas turbine technology, zero-carbon heavy commercial vehicles and shipping equipment, as well as safety technology and standards for this emerging field. These allocation of these funds will play a crucial role in propelling China's advancement in this disruptive industrial technology, positioning the country as a frontrunner in the global arena of ammonia-hydrogen new energy technology industry.

Reference

[1] Valera-Medina A, Xiao H, Owen-Jones M, David WIF, Bowen PJ. Ammonia for power. *Prog Energy and Combust Sci* 2018; 69: 63-102.

[2] Xiong Y, Liu W, Gao P, Dong B, Zhao M. Research on the hydrogen energy demand and carbon-reduction path in China's synthetic ammonia industry to achieve the "carbon peak" and "carbon neutrality" goals. *Energy Storage Sci Technol* 2022; 11(12): 4048-4058. [熊亚林，刘玮，高鹏博，董斌琦，赵铭生. "双碳"目标下氢能在我国合成氨行业的需求与减碳路径. *储能科学与技术*, 2022; 11(12): 4048-4058.]

[3] Niu SW, Wang YP, Qu W, Qiang WL. Difficulties and Solutions for Wind Power Electricity in Western China: Thoughts about Abandoned Wind Power. *Science and Technology Review,* 2017; 35(10): 11-12. [牛叔文，王义鹏，曲玮，强文丽. 西部地区风电产业的困境与出路—关于"弃风限电"的思考. *科技导报*, 2017; 35(10): 11-12.]

[4] Zhang L, Xue BF, Liu YX, Wang Y, Wu Y, Zhang H, Yang XC, He S, Jiang SP, Li J, Zhang QJ. A strategic study of ammonia-hydrogen new energy interdisciplinary science frontiers. *Chin Sci Bull* 2023; 68(23): 3107-3112. [张莉，薛勃飞，刘玉新，王宇，吴云，张华，杨新春，何帅，蒋三平，李骏，张清杰. 氨氢融合新能源交叉科学战略研究. 科学通报, 2023; 68(23): 3107-3112.]

[5] Bartels JR. A feasibility study of implementing an ammonia economy. *Master Dissertation*. Ames: Lowa State University, 2008.

[6] Leighty WC, Holbrook JH. Alternatives to electricity for transmission, firming storage, and supply integration for diverse, stranded, renewable energy resources: Gaseous hydrogen and anhydrous ammonia fuels via underground pipelines. *Energy Proc* 2012; 29: 332-346.

[7] Carbon Fixing, Hydrogen Storage, Aircraft Fuel, Power Generation by Fuel Blend: Green Ammonia Overview and Outlook, *KPMG China*, 2022. [固碳、储氢、航运燃料、掺混发电：绿氨行业概览与展望. *毕马威中国*, 2022.]

[8] Chen WY. Leaking risk analysis and countermeasure research of liquid ammonia long-distance pipelines (in Chinese), *Master Dissertation*. Beijing: Capital University of

Economics and Business, 2011. [陈文艳. 液氨长输运管道泄漏风险分析及对策研究. 硕士学位论文. 北京: 首都经济贸易大学, 2011]

[9] Salam MA, Khan SA. Transition towards sustainable energy production-A review of the progress for solar energy in Saudi Arabia. *Energy Exploitation*, 2018; 36: 3-27.

[10] Nayak-Luke RM, Forbes C, Cesaro Z, Banares-Alcantara R, Rouwenhorst KHR. Chapter 8-Techno-economic aspects of production, storage and distribution of ammonia. In the book of *Techno-Economic Challenges of Green Ammonia as an Energy Vector*. Cambridge: Academic Press, 2020; pp191-207.