Research on the Integrated Development of Nuclear Energy and Aviation Industry under the Background of 'Dual Carbon' Goals

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Abstract: The aviation sector, which is predominantly reliant on fossil fuels, confronts a monumental challenge in striving for net-zero CO_2 emissions by the year 2050. Within the spectrum of decarbonization initiatives for the aviation industry, Sustainable Aviation Fuels (SAF) are recognized as the most viable carbon emission mitigation strategy. This study systematically reviews the technological trajectories of SAF and posits that Electrofuels, derived from the power-to-liquid (PtL) conversion process, will serve as a pivotal nexus for the synergistic development of nuclear energy and aviation. This integration is poised to facilitate the decarbonization of the conventional aviation sector. This paper introduces a conceptual framework for Nuclear-Derived Sustainable Aviation Fuel (ND-SAF).

1．Introduction

Air travel has become essential since the 21st century, with a rising count of commercial, private, and military planes globally. The aviation industry is currently highly dependent on fossil fuels, especially aviation kerosene. The combustion of aviation fuel is the primary source of carbon emissions in the aviation industry, accounting for about 79% of the total emissions [1]. The aviation industry faces immense challenges in achieving the goal of net-zero emissions.

The International Energy Agency's (IEA) "Net-Zero Emissions Roadmap" delineates that the aviation sector is accountable for a significant proportion of global CO_2 emissions, specifically 1.8%. According to the International Civil Aviation Organization (ICAO), if no additional emission reduction measures are taken, by 2050, the carbon dioxide emissions from the aviation industry will account for 7.0% of the total global emissions [2].

Within the aviation industry's comprehensive suite of decarbonization strategies, the scope for emission reduction through technological innovation in aircraft and improvements in operational efficiencies is notably limited. The advent of electric and hydrogen-powered aircraft marks a nascent yet promising development, primarily suited for short-haul flights given the current technological landscape. Considering that long-haul flights over 1500 kilometers are the predominant contributors to global CO_2 emissions, the industry consensus favors Sustainable Aviation Fuels (SAF) as the most effective mitigation measure [3].

There is a critical strategic opportunity to increase the production and application of Sustainable Aviation Fuel (SAF) between 2025 and 2050 to align with the sector's emission reduction objectives. Electrofuels, produced via the power-to-liquid (PtL) process, using Low-Carbon electricity, signify a potential convergence point for the aviation industry and nuclear energy, potentially catalyzing a transformative shift towards a decarbonized aviation sector.

Power to Liquid (PtL). PtL is a technology that converts electrical energy into liquid fuels, typically through the electrolysis of water to produce hydrogen, which is then combined with carbon dioxide to synthesize fuels such as methanol, ethanol, or diesel.

Electrofuels. Also known as "e-fuels", are synthetic fuels produced using PtL technology. They are created through processes like electrolysis, where water is split into hydrogen, which can then be combined with carbon dioxide to form hydrocarbons. Electrofuels can be used as a carbon-neutral alternative to traditional fossil fuels in various sectors, including transportation and industry, offering a sustainable solution to energy storage and usage.

Sustainable Aviation Fuel (SAF). SAF is a liquid hydrocarbon fuel utilized in commercial aviation, the final product's chemical composition is akin to that of kerosene. Compared to conventional fossil-based fuels, SAF can achieve an average reduction of 85% in CO_2 emissions. From a cradle-to-grave lifecycle perspective, the feedstocks, such as discarded biomass, absorb more CO_2 during their growth or synthesis than they emit during combustion, thereby earning the designation of "sustainable" aviation fuel [4].

Electronic Sustainable Aviation Fuel (eSAF). Broadly speaking, fuels synthesized via the PtL route are collectively referred to as Electrofuels (E-fuels), which can be utilized across various transportation sectors such as aviation, automotive, and maritime industries. In a more specific sense, the term Electronic Sustainable Aviation

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Fuel (eSAF) is used to denote SAF synthesized using the PtL route.

2. Sustainable Aviation Fuel (SAF) Technology

2.1. Overview of Sustainable Aviation Fuel (SAF) Technological Pathways

To ensure "sustainability", SAF is generally required to meet industry-recognized sustainability criteria and certification. SAF products that are certified to relevant standards (ASTM D7566) are considered to be directly co-mingled with current fossil aviation fuels, with the highest blend ratio recognized internationally reaching up to 50%. Furthermore, there is no need for any modifications to aircraft or engines, ensuring no impact on aircraft operation, safety, and maintenance. The existing transportation infrastructure for conventional aviation fuel can also be directly utilized. The ASTM standards have recognized a total of 9 SAF technological pathways[4]. Among these, the aviation industry widely anticipates significant future development potential in 4 pathways.

2.1.1. Three officially recognized pathways

The Hydroprocessed Esters and Fatty Acids (HEFA) pathway involves the hydrogenation of animal and vegetable oils, waste oils, or fats to produce SAF. This process typically encompasses hydrodeoxygenation, isomerization, cracking, and distillation steps.

The Fischer-Tropsch (FT) synthesis pathway, also known as Gas-to-Liquids (GTL), involves the conversion of carbon-containing feedstocks into synthesis gas, which is then reassembled into SAF and other fuels. Synthesis gas is generally produced by gasifying biomass (such as agricultural and forestry residues or municipal solid waste).

The Alcohol-to-Jet (AtJ) pathway, which converts sugars and starches into alcohols through fermentation or other pathways, and then transforms them into aviation fuel through dehydration, oligomerization, hydroprocessing, and distillation.

2.1.2. One pathway that is yet to be recognized

The Power-to-Liquid (PtL) pathway, which involves the production of hydrogen through water electrolysis and its subsequent synthesis with CO_2, or co-electrolysis of H_2O and CO_2 to produce synthesis gas, which is then further converted into hydrocarbon fuels.

2.1.3. Evolution of Sustainable Aviation Fuel Technologies

Before 2030, based on the maturity of existing technologies, the HEFA pathway is expected to continue to dominate the market. However, considering the supply constraints of its feedstocks (waste fats and food crops), the overall production capacity is not anticipated to grow rapidly.

Between 2030 and 2050, as the FT and AtJ pathways become increasingly mature, and with a variety of feedstock options such as agricultural and forestry residues, municipal solid waste, and industrial waste, their market share is expected to rise.

After 2040, the PtL pathway is projected to become the primary technological route. Although the PtL pathway is currently far from full commercialization, it has significant emission reduction potential compared to conventional aviation fuel. Its feedstocks do not impact food security. Therefore, if it receives policy support in its early development stage and achieves cost reductions through market expansion and technological breakthroughs, it is poised to capture a major market share[4.]

2.2. Power-to-Liquid (PtL) Pathway

2.2.1. The first technological route. Route 1 involves the production of hydrogen through water electrolysis, which is then coupled with CO_2 to convert into methanol and other rich products. CO_2 and H_2 are adsorbed on the surface of polynuclear metal cluster catalysts, gradually transforming into gaseous methanol. The catalysts predominantly used in this process are from the Cu-Zn-Al system. This route is a more mature direction in the short term. Currently, there are two main challenges with this route:

- The conversion efficiency of water electrolysis for hydrogen production needs to be improved. The efficiency of commercial alkaline water electrolyzers is around 60% to 80%, and it is anticipated that proton exchange membrane (PEM) electrolyzers and solid oxide electrolyzers are effective methods to enhance efficiency.
- The catalysts for CO_2 hydrogenation to methanol require further improvement. There is a need for the subsequent development of new CO_2 catalysts and catalytic devices that are low-cost, highly selective, and stable [5].

2.2.2. The second technological route. Route 2 is the co-electrolysis of H_2O and CO_2 driven by electricity to prepare synthesis gas (H_2+CO), which is then coupled with a Fischer-Tropsch (FT) unit to produce SAF fuel with carbon-neutral attributes.

This route is a hot topic in the PtL research field, but its technological maturity and industrialization process are slightly behind the first route. The core reaction of this route is the reduction of CO_2 molecules to CO, thereby reducing water production and more efficiently utilizing hydrogen to convert CO_2 into methanol and dimethyl ether.

The main issues currently are that:

- the CO_2 reduction reaction is quite demanding, requiring very high energy and extremely active catalysts.
- due to the high energy of the reaction, side reactions and decomposition reactions are easily triggered, resulting in low conversion rates, many by-products, and facing

technical challenges such as poor product selectivity, low single-pass conversion rates of CO, and high energy consumption for product separation [6].

2.2.3. industrial-scale application. Rational design and optimization of the electrocatalytic system are needed, including the development of highly selective and efficient electrocatalysts, the design of gas diffusion electrodes with high stability and mass transfer rates, optimization of the microenvironment in the electrolyte, and the design of low-energy, high-reliability electrolysis devices [5].

2.3. Electrosynthetic Sustainable Aviation Fuel (eSAF)

Nuclear-Derived Synthetic Fuels. It is important to note that, within the European and American industries, the term eSAF is typically associated with electricity derived from renewable sources like solar and wind energy. However, the report titled "Synthetic Fuels: The Opportunity for Economic Production of Nuclear-Derived Synthetic Fuels" (hereinafter referred to as "Synthetic Fuels"), published by the Nuclear Industry Association (NIA) in March 2023, has brought the concept of nuclear-derived eSAF into public view. While wind and solar energy are intermittent sources that provide electricity but not direct heat, nuclear energy offers greater sustainability compared to renewable sources. It can supply both stable electricity and heat, with higher energy utilization efficiency, thus holding greater potential for large-scale production and commercial promotion.

2.4. Principle of Nuclear-Derived eSAF

Electricity and heat provided by nuclear energy can support the synthesis of aviation fuel in various aspects, including:

- Desalination: Providing clean water necessary for hydrogen production.
- Hydrogen Production: Delivering electricity and steam to electrolyzers for efficient hydrogen generation.
- Carbon Capture Technology: Extracting carbon dioxide directly from the environment to form a closed carbon cycle in the production and use of synthetic fuels.
- Carbon Monoxide Synthesis: Reducing carbon dioxide to carbon monoxide, which is needed for fuel synthesis, through electrolysis or water-gas shift reactions.
- Synthetic Fuel Production: Power-driven traditional or innovative processes for large-scale production.
- Hydrocracking: Supplying hydrogen for the cracking of long-chain hydrocarbons to produce fuel [7].

Among these, hydrogen production, carbon dioxide capture, and synthesis are the three most critical steps.

2.5. Conceptual Scheme of Nuclear-Derived eSAF

2.5.1. Pressurized Water Reactor (PWR) Coupling Scheme. Utilizes residual heat to provide low-temperature heat and electricity for the eSAF preparation process.

- Reactor Type: Typical million-kilowatt pressurized water reactor;
- Thermal Power: ~3000 MW;
- Residual Heat Power: ~2000 MW;
- Hydrogen Production: PWR supplies electricity for electrolytic hydrogen production;
- Carbon Capture Technology: Utilizes residual heat to provide low-temperature heat and electricity for Solid Direct Air Capture (S-DAC) technology;
- Synthetic Fuel: Supplies electricity for low-temperature electrocatalytic technology.

2.5.2. Very High-Temperature Gas-Cooled Reactor (VHTR) Coupling Scheme. Provides high-temperature heat and electricity for the eSAF preparation process after heat exchange.

- Reactor Type: Very high-temperature gas-cooled reactor;
- Thermal Power: ~500 MW;
- Residual Heat Power: ~300 MW;
- Hydrogen Production: High-temperature steam electrolysis for hydrogen production;
- Carbon Capture Technology: Supplies high-temperature heat and electricity for Liquid Direct Air Capture (L-DAC) technology;
- Synthetic Fuel: Supplies high-temperature heat and electricity for high-temperature electrocatalytic technology.

2.5.3. Early Deployment. In the preliminary stages of subsequent new nuclear power projects, it is possible to explore the construction of an integrated hydrogen production-carbon capture-synthetic fuel facility within the planned restricted area surrounding the nuclear power plant (according to GB/6249 "Regulations on Environmental Radiation Protection for Nuclear Power Plants," currently 5 km). This would provide electricity and thermal energy to the synthetic fuel integrated plant nearby, thus developing the commercial application market for nuclear energy.

3. Market Size and Demand

3.1. Market Forecast

3.1.1. Ramping Up SAF Usage. According to an assessment by the International Air Transport Association (IATA), to achieve net-zero emissions by 2050, the contribution rate of Sustainable Aviation Fuel (SAF) to the aviation industry's emission reduction will rise to 65%.

The application volume of SAF needs to increase dramatically from 63 million liters (about 53,000 tons) in 2020 to 4,490 billion liters (about 35.83 million tons) by 2050, as shown in Figure 1.

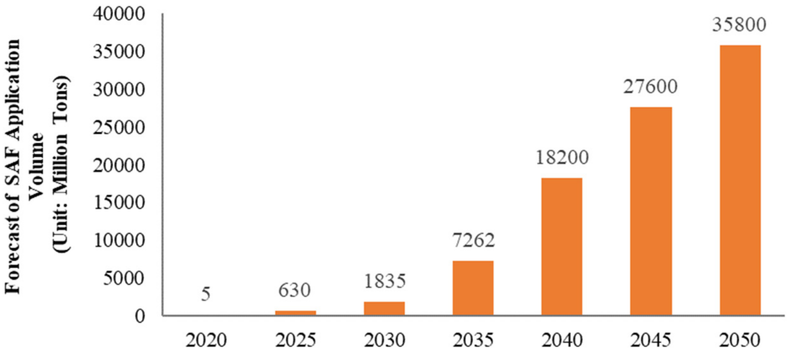

Fig.1 IATA Goal of SAF (data: IATA, 2021)

3.1.2. Market Prospects for SAF. In 2022, the global aviation fuel market size had reached approximately 170 billion US dollars and is expected to maintain an annual growth rate of over 10%. At this rate, by 2030, the global aviation fuel market size will reach 360 billion US dollars. Among them, as a type of aviation fuel, the market size of SAF is also continuously expanding. In 2021, the global market size of SAF had reached 219 million US dollars, and by 2030, it is expected to reach 15.716 billion US dollars, accounting for 4% of the market share. It is predicted that by 2050, the global SAF market size will reach 600 billion US dollars, with a market share exceeding 42% [8].

3.1.3. China's SAF market. China's "14th Five-Year Civil Aviation Green Development Special Plan" mentions striving for an accumulated consumption of SAF to reach 50,000 tons by 2025. The SAF consumption target for China in 2025 only accounts for 0.8% of IATA's planned development goal, which is inconsistent with the size of China's status as the world's second-largest aviation industry, also indicating the huge potential of China's SAF market.

3.2. Price Forecast

According to data from the non-profit research organization International Council on Clean Transportation (ICCT), the current production cost of eSAF is about 7 US dollars/L (approximately 50 yuan/L), about 8 times that of traditional aviation fuel, and 2-3 times the cost of synthetic fuels from routes such as HEFA. However, according to the assumptions of the German Future Transport Platform, by 2030, the production cost of synthetic fuels could be reduced to 1-2 euros/L (approximately 7.73-15.46 yuan/L).

The cost of domestic electro-synthesized fuels largely depends on electricity prices. After accounting for renewable energy sources, in areas with abundant renewable electricity and low electricity prices (0.1 yuan/kWh), synthetic fuels begin to have economic viability. Economic viability remains a significant factor constraining industrial development, in addition to technology.

4 . Current Status and Trends of SAF Development at Home and Abroad

4.1. International Development of Sustainable Aviation Fuel (SAF)

The domain of Sustainable Aviation Fuel (SAF) research, production, and application is predominantly concentrated in Europe and the United States, characterized by a notable "policy-driven" development trajectory.

4.1.1. The United States. A collaborative effort between government and industry has markedly accelerated the integration of Sustainable Aviation Fuel (SAF). The U.S. government's "Sustainable Aviation Fuel Grand Challenge," launched in 2021, has set a target for the domestic aviation fuel sector to produce no less than 3 billion gallons of SAF by 2030, with the goal of cutting carbon emissions in the aviation sector by 20%. The ultimate goal is the complete adoption of SAF by 2050. HIF Global, an international synthetic fuel company associated with American Ethane (AEM) and the German automotive manufacturer Porsche, has developed advanced synthetic electrofuel (E-fuel) plants in southern Chile, Texas, and Tasmania, Australia. The goal of these facilities is to produce 800 million liters annually of carbon-neutral methanol and synthetic gasoline, with the methanol being a direct component in electronic SAF (eSAF).

4.1.2. The European Union. EU is reinforcing the use of Sustainable Aviation Fuel (SAF) through legislative measures. The EU's "Fit for 55" legislative package includes the ReFuel EU Aviation initiative, which proposes to eliminate free emission allowances for the aviation sector and, in a novel approach, to incorporate maritime emissions into the EU Emissions Trading System (EU ETS). The initiative mandates a significant increase in SAF usage at EU airports, aiming for a 2% share by 2025 and a substantial 70% by 2050. Specifically, to stimulate the development of electronic SAF (eSAF), the European Commission has set a target of 28% eSAF by 2050, a target that the European Parliament aims to increase to 50%. Currently, SAF is produced at no less than eight facilities, with over 20 projects in various stages of planning or expansion, including five demonstration projects. The estimated production capacity for eSAF through the Power-to-Liquid (PtL) process by 2025 is around 200,000 metric tons.

4.1.3. The United Kingdom. UK is advancing policies to mandate the integration of Sustainable Aviation Fuel (SAF) into its aviation sector. In June 2023, draft regulations were introduced, requiring suppliers to blend SAF with conventional aircraft fuel starting from 2025, with the goal of achieving a 10% blending ratio by 2030. The Nuclear Industry Association (NIA) is lobbying for the inclusion of nuclear-derived electronic SAF (eSAF) in the final legislative framework, aiming to level the playing field for nuclear energy in the aviation fuel market against other technologies, including synthetic and biofuels sourced from renewable energy. The UK government recognizes the potential of nuclear energy as a key contributor to the development of sustainable aviation fuel solutions.

Owing to these policy mandates, all sectors of the SAF industry chain in the European and American markets are vigorously advocating for advancement, marking a consistent and steady growth trajectory.

4.2. Domestic Development of Sustainable Aviation Fuel (SAF)

4.2.1. China is in the early stages of adopting Sustainable Aviation Fuel (SAF) within its aviation industry. Despite initiating R&D and application efforts in 2010, the lack of mandatory regulations has led to a restrained industry engagement. From 2011 to 2017, a small number of SAF test flights were carried out, without a subsequent push towards widespread commercial adoption. As a result, China's current SAF production capacity is relatively modest at around 150,000 metric tons annually, compared to the global advancements in SAF integration.

4.2.2. A coalition of Chinese ministries and regulatory authorities has been promoting policies to support SAF development. The "14th Five-Year Special Plan for Civil Aviation Green Development" has set a target of achieving 50,000 metric tons of SAF consumption by 2025, which, while significant, is relatively minor in the context of China's substantial annual demand for aviation fuel, which is between 30 to 40 million metric tons. The strategic direction for SAF in China requires further definition and clarity. The Civil Aviation Administration of China proposed draft sustainability criteria for alternative aviation fuels in July 2023, outlining environmental, societal, and economic requirements, and suggesting a minimum blending ratio of 10% for SAF. This indicates that the industry is still in the phase of gathering information and knowledge.

4.2.3. Nuclear power groups' attempts. The State Power Investment Corporation (SPIC), a major nuclear energy group in China, has embarked on the development of electronic Sustainable Aviation Fuel (eSAF) based on renewable energy sources. In March 2023, SPIC's finance subsidiary in Hong Kong signed a partnership agreement with Cathay Pacific to develop SAF supply chain infrastructure in China, indicating a joint initiative to expand the use of SAF. Cathay Pacific has set a target of blending SAF to constitute 10% of its fuel consumption by 2030. SPIC is planning four Power-to-Liquid (PtL) facilities for SAF production, which will transform renewable energy into liquid fuels. These facilities are expected to be operational between 2024 and 2026, with each having an annual capacity ranging from 50,000 to 100,000 metric tons. In April 2023, SPIC initiated the bidding process for the first phase of its green aviation fuel project in Xinjiang Tacheng, which includes a 1.2 million-kilowatt wind power-to-hydrogen synthesis plant with an annual production capacity of 10,000 metric tons.

5. Thoughts and Suggestions

5.1. Reflections and Recommendations for the Coupling Development of Nuclear Energy and Electro-Synthetic Fuels

5.1.1. Nuclear energy for synthetic fuel production not only expands the application scenarios for the comprehensive utilization of nuclear energy but also explores a long-duration, large-scale chemical energy storage method. Currently, the comprehensive utilization of nuclear energy is mainly focused on regional heating, industrial steam supply, seawater desalination, and hydrogen production. The production of synthetic fuels from nuclear energy can be an extension of nuclear hydrogen production, broadening the scope of comprehensive nuclear energy utilization. Future, nuclear power will confront the challenges of gird peak shaving, the base load operation time of nuclear power will gradually decrease. Therefore, converting peak load electricity into synthetic fuels can extend the base load operation time of nuclear power plants, alleviating gird peak shaving challenges to some extent, and enhancing the operational flexibility and market competitiveness of nuclear power. As a new type of energy storage, synthetic fuels have advantages in terms of storage scale and duration, are easy to store and transport, and can achieve large-scale energy storage and wide-area sharing, with the potential to match the peak load requirements of nuclear power in the future.

5.1.2. It is necessary to call through various channels to include nuclear power in China's green and low-carbon trading system as soon as possible, so that nuclear power can gain a fair competitive opportunity with renewable energy in the field of electro-synthetic fuels. The electricity used in synthetic fuels is currently concentrated in renewable energy sources such as wind and solar energy, with the main idea being to convert valley electricity and abandoned electricity into synthetic fuels for storage in the form of chemical energy. However, wind and solar energy are intermittent energy sources that can only provide electricity and cannot directly provide heat. Nuclear energy is more sustainable, capable of providing stable electricity and heat simultaneously, with higher energy utilization efficiency, and has more potential for large-scale preparation and commercial promotion.

5.2. Suggestions

Currently, the first technological route of electro-synthetic fuel has industrialization capabilities and has been deeply coupled with wind and solar power; the second technological route is expected to achieve kilowatt-level demonstration verification by 2025. In terms of timing, it is the preferred technological route for nuclear energy to enter electro-synthetic fuels.

5.2.1. Technically. It is necessary to cooperate with scientific research teams with outstanding achievements, to jointly promote the conceptual design of nuclear energy for synthetic fuel production. Relying on high-temperature reactor or pressurized water reactor nuclear power engineering projects, jointly promote the preliminary research of nuclear power for synthetic fuel production, and evaluate from multiple perspectives such as technological maturity, key parameter range, and economic viability, and select the process route with the highest matching degree for nuclear energy in the short, medium, and long term.

5.2.2. Industrialization. Focus on tracking the industrialization progress and implementation of the first technological route of electro-synthetic fuel. Although it mainly uses new energy, the upstream and downstream raw material acquisition and chemical synthesis process of synthetic fuel preparation are to some extent common in other industrial segments, which can provide a certain industrial foundation for nuclear energy production of synthetic fuels after nuclear energy applicability assessment, and then find the right opportunity to promote the industrialization demonstration of nuclear energy production of synthetic fuels.

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