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Apart from kerosene, what is the next aviation fuel?

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Abstract. Against the backdrop of worsening global energy crises and environmental pollution, the civil aviation industry, which relies heavily on kerosene, faces severe challenges due to its massive annual fuel consumption and significant emissions, searching for new energy alternatives to aviation kerosene an urgent issue. This paper focuses on researching next-generation energy sources for the aviation industry, aiming to identify alternative energy options to kerosene and their development prospects. By reviewing the development history of passenger aircraft and the technical principles of new energy aircraft, and integrating the current development status, it conducts in-depth exploration into the applications of electric aircraft, hydrogen-powered aircraft, and Sustainable Aviation Fuels (SAF) in the aviation sector. It analyzes their technical maturity, applicable scenarios, bottlenecks, and future trends, intending to provide references for the green transformation of the aviation industry.

Keywords: new-energy aviation, electric aircraft, hydrogen-powered aircraft, Sustainable Aviation Fuels (SAF), green transformation

1. Introduction

In the constantly changing aircraft sector, the fate of passenger aircraft is a big issue. In recent years, we have come quite far: from the advent of the wide-body jet facilitating long-haul travel to the constant development of fuel-efficiency technologies. Airlines and aircraft manufacturers work on improving aircraft, improving the efficiency of fuels by using more efficient engines and lightweight elements; improving aerodynamics: improving wing structures; blended wing types of designs [1].

However, there are many challenges. One of the primary difficulties is the pressing need to reduce environmental impact. With growing global concerns about climate change, the aviation industry, which is a significant emitter of greenhouse gases, must find ways to cut emissions substantially. This requires the development of more sustainable fuels and more energy-efficient aircraft designs. Aviation accounts for approximately 2-3% of global CO_2 emissions, but its high-altitude emissions contribute significantly to climate change. In 2021, aviation emitted 915 Mt CO_2 (million metric tons) [2]. Aircraft emissions include CO_2, Nitrogen Oxides (NOx), water vapor, and soot particles, which intensify the greenhouse effect [3].

Explore the development direction of energy and power technologies for passenger aircraft. Some alternative energies are being explored, including hydrogen fuel (zero-carbon emissions but requires new infrastructure), electric aircraft (suitable for short-haul flights but limited by battery energy density), and sustainable aviation fuels (drop-in replacement for fossil fuels, reducing emissions by up to 80%) [4, 5].

In terms of hydrogen energy, the European Union has been actively promoting the development of hydrogen-powered commercial aircraft. Airbus, a leading aerospace manufacturer, announced plans to develop hydrogen-powered commercial aircraft by the mid-2030s. However, as of February 2025, Airbus has delayed these plans, citing slower-than-expected technological advancements [6]. Airbus has been actively exploring hydrogen as a sustainable aviation fuel. In June 2023, the company successfully tested a hydrogen fuel cell system, achieving a full power level of 1.2 megawatts, marking a significant milestone in aviation fuel cell testing. However, in February 2025, Airbus announced a delay in developing its hydrogen-powered commercial aircraft, originally targeted for the mid-2030s, due to slower-than-expected advancements in necessary technology. This postponement reflects the challenges in developing the supporting infrastructure, production, distribution, and regulatory frameworks required for hydrogen adoption in aviation [6].

In terms of solar energy, in 2011, JinkoSolar, a well-known solar energy enterprise in China, faced environmental scrutiny. The company was charged with discharging untreated wastewater, which had extremely high fluoride levels, into local rivers. The fluoride content in the wastewater was ten times higher than the permitted limits. This event brought to light the environmental issues within the photovoltaic industry, especially those related to the management of hazardous substances such as hydrofluoric acid, which is used in the manufacturing procedures [7].

In terms of sustainable fuel, the aviation industry is exploring Sustainable Aviation Fuel (SAF) and hydrogen as potential energy sources for next-generation aircraft. While SAF is currently the primary focus due to existing infrastructure compatibility, hydrogen offers a promising long-term solution for reducing aviation's carbon footprint. However, the development of hydrogen-powered aircraft faces challenges, including technological readiness and the need for extensive infrastructure development [8].

Due to these problems, it is very important to explore the viable aeronautical energy of the next generation. This article will be discussed from two aspects: review and discussion. The review section summarizes the development history of the propulsion system of passenger aircraft, as well as the existing problems, and analyzes the technical principles of existing new energy technologies, such as solar energy, pure electric propulsion, and hydrogen energy, as well as the application of various new energy technologies in aircraft.

2. Review

2.1. Principles of passenger aircraft and development history

The development of passenger aircraft engines is divided into three processes: piston propeller engine, turbine jet engine, and turbine fan engine. The first one is a piston propeller engine, which is simple in structure and inexpensive. In order for the propeller to rotate and produce traction, the piston should only return to the cylinder. However, the disadvantage of this engine is that the power is limited, and the flight speed and altitude are limited (Figure 2). For example, as shown in Figure 1, the Douglas DC-3 airliner uses two piston propeller engines. The second is a turbojet engine, which improved flight speed and altitude compared to the piston propeller engine (Figure 3). The engine uses a gas turbine to drive the compressor, so that the air is compressed and mixed with the fuel, and then produces high-temperature gas and high-pressure gas sprayed from behind to generate electricity. But its disadvantage is high fuel consumption. The British passenger plane Comet was the first airliner to use a turbojet engine. The third type is a turbine fan motor, divided into a low-channel turbine fan motor and a high-channel turbine fan motor (Figure 4 and Figure 5). The turbine jet with a low duct coefficient adds an external air duct to the base of the engine, and part of the air comes out of the external air duct, thereby creating additional thrust and reducing fuel consumption and noise. For example, Boeing 727 and Boeing 737 use turbine fan engines with a low duct coefficient. The high ratio of the culvert is higher than that of the turbine fan motor, and the air flow of the external culvert is greater, which increases fuel efficiency and has a large thrust, which is suitable for large passenger aircraft. For example, Boeing 747, Airbus A300, etc.

Figure 1. Classic propeller-driven aircraft [9]

Figure 2. Piston engine (V-shaped) [9]

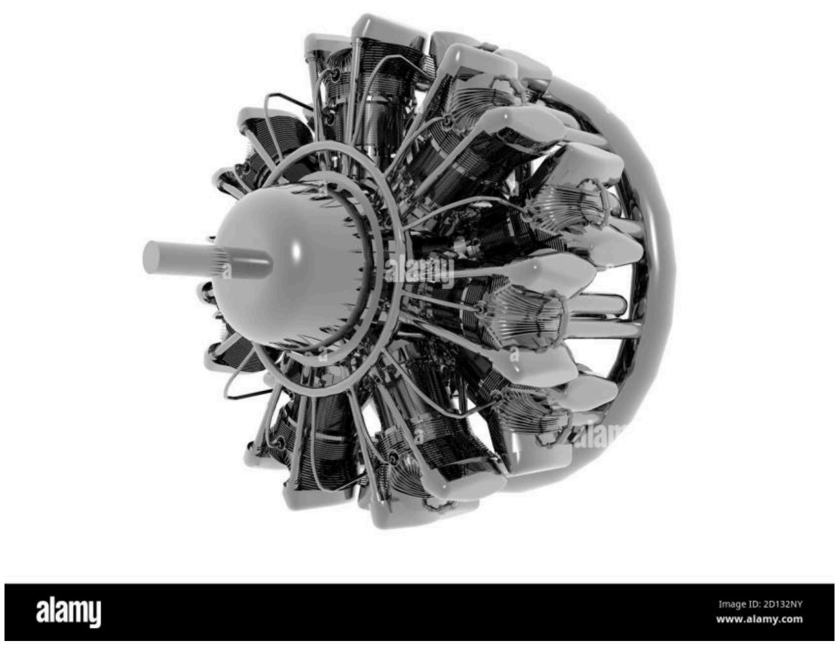

Figure 3. Piston engine (Star-shaped) [10]

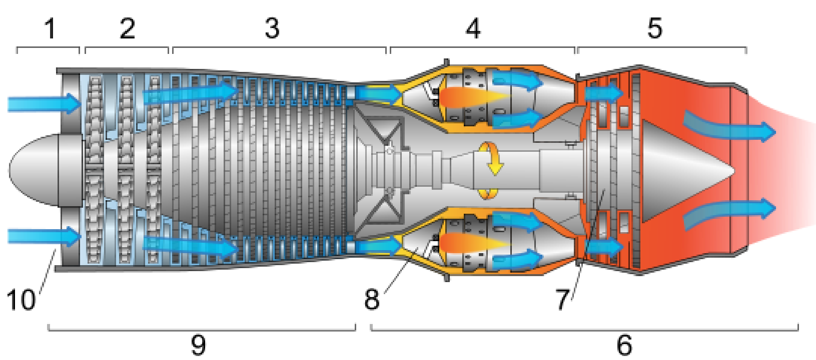

Figure 4. Turbojet engine [11]

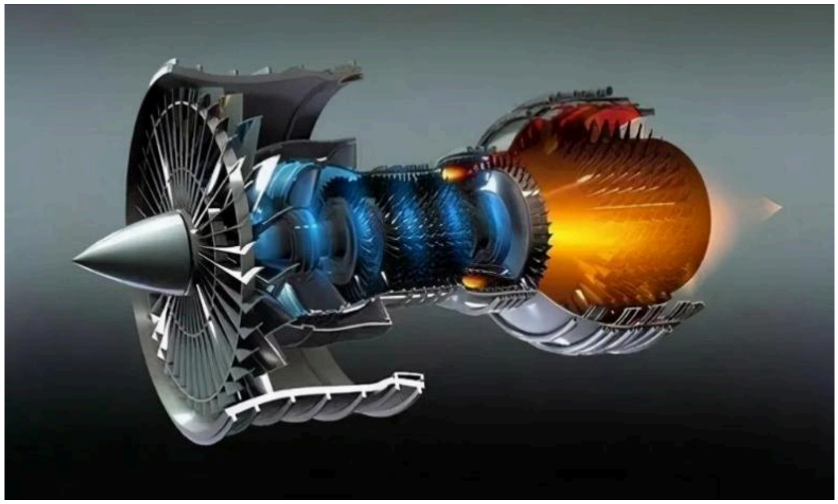

Figure 5. Fanjet [12]

Table 1. A comparison table of aviation regulatory authorities, aviation fuel standards, and corresponding fuel names in different countries and regions [13]

Regulatory agency	Country	Standard/resolution	Jet fuel name
Agência Nacional do Petróleo, Gás Natural e Biocombustíveis (ANP)	Brazil	Resolution nº37	Jet A1
Federal Aviation Administration (FA)	USA	ASTM D1655 / ASTM 6615	Jet A, Jet A1, Jet B
Transport Canada Civil Aviation (TCCA)	Canada	CAN/CGSB-3.23, CAN/CGSB-3.22	Jet A, Jet A1, Jet B
Civil Aviation Authority (CAA)	UK	DefStan 91–91	Jet A1
European Aviation Safety Agency (EASA)	EU	AFQRJOS	Jet A1
Federal Air Transport Agency (FATA)	Russia	GOST 10227 / GOST R 52050	TS-1, Jet A1
Civil Aviation Administration of China (CAAC)	China	GB 6537	No 3

At first, the plane used gasoline, but when the aircraft's performance improved, aviation kerosene replaced gasoline. Aviation kerosene has a higher energy density than gasoline. And has better performance and safety at low temperatures. As shown in Table 1, in recent years, to reduce aviation pollution and achieve low-carbon development of the aviation industry. Sustainable Aviation Fuel (SAF) has become a research connection point. SAF means the use of recycled raw materials to replace aviation kerosene. SAF produces fewer hydrocarbons and sulfides than aviation kerosene. And there is no need to redesign to replace the current aircraft [14].

2.2. Technical principles of new energy aircraft

Due to the significant environmental issues associated with fuel emissions, countries around the world have begun to focus on aviation fuels. Currently, feasible options include SAF, electric, hybrid, solar, and hydrogen energy. This section will briefly introduce the situations of these various fuels.

2.2.1. Substainable Aviation Fuels (SAF)

The first fuel is the sustainable aviation fuel. The principle of sustainable aviation fuel refers to the production of alternative aviation kerosene by specific chemical reactions using recyclable oils and fats, such as biological raw materials (animal and vegetable oils) and synthetic raw materials (trough oils) (Figure 6). SAF is sustainable and renewable. Depending on the type, it can be divided into biofuel, advanced biofuel, and synthetic fuel. SAF reduces carbon emissions during production (Figure 7). And as the sulfur content decreases, particle emissions decrease. SAF can be mixed with conventional fuels such as aviation kerosene, reducing carbon dioxide emissions by up to 80% without changing the mechanism of aircraft and engines [15].

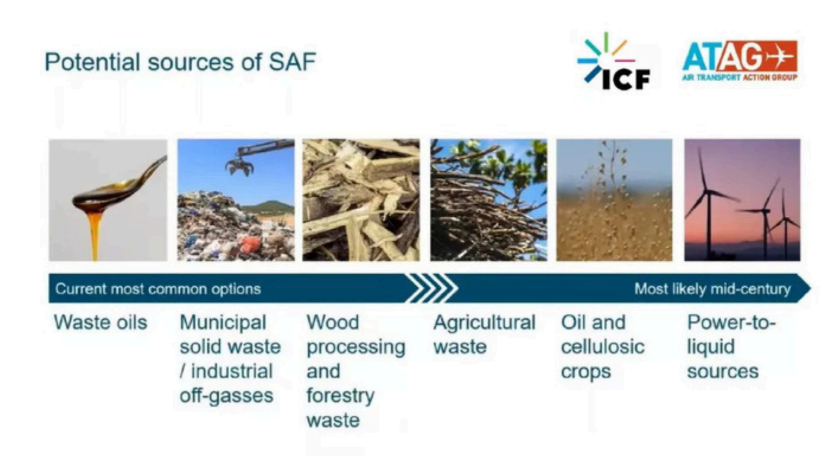

Figure 6. The potential raw material sources of Sustainable Aviation Fuel (SAF) [16]

Currently, the production volume of SAF is extremely small, less than 2% of the total demand for aircraft fuel, and the selling price is high, 2 to 3 times higher than the price of conventional aircraft fuel [17]. Due to the complexity, high cost, and low production of SAF production technology, SAF's research and development and production are at a relatively low level worldwide [18].

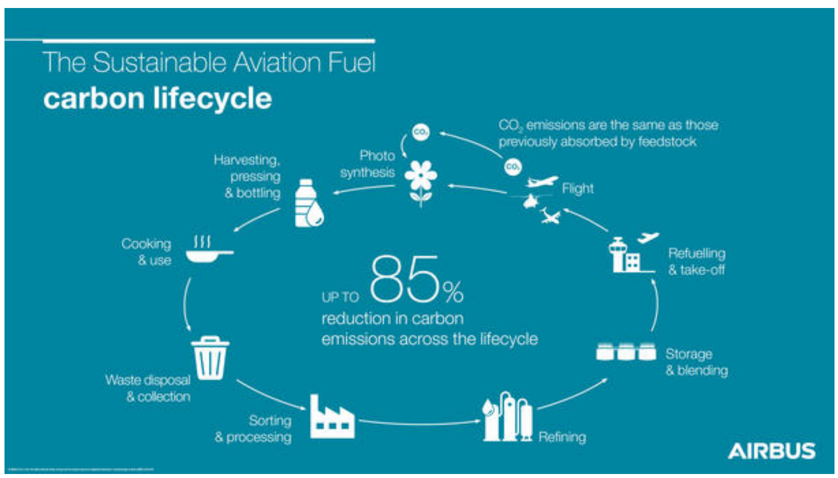

Figure 7. The carbon circulation process of the Sustainable Aviation Fuel (SAF) life cycle [1]

2.2.2. Electric aircraft

With more attention to environmental pollution and the energy crisis, the development of new energy aircraft is a must. Electric planes are powered by electric motors. Currently, electric aircraft are divided into three categories according to the electric propulsion system: solar-powered aircraft, electric aircraft, and hybrid aircraft. The first reason for the development of electric aircraft is that the production cost is low, and the cost of fuel can be reduced by 50-75%. Second, electric aircraft can reduce carbon dioxide emissions by 49%-88% [19]. The thermal efficiency of the traditional machine is 40%, and the thermal efficiency of the battery is > 95%.

2.2.2.1. Pure electric

The first kind introduced is the electric airplane. Only battery-powered aircraft have a purely electrical energy system. Purely electric planes do not emit any emissions while operating and have high thermal efficiency and energy savings. But as all kinds of electric aircraft obtain energy from batteries, the range that this kind of aircraft can fly lies in the capacity of the battery. From the table, it can be found that the energy density of a lithium battery is 0.25 MJ/kg, which is far short of 42-46 MJ/kg of the aviation fuel. Including the gas turbine is unwise. The unit mass of the battery that it can emit is significantly less than aviation fuel. Then, after calculating the motor efficiency and gas turbine efficiency, the energy output from Lithium batteries was 0.23~0.65MJ/kg, and the Energy output from aviation fuel was still 16~18.4 MJ/kg. That is to say, if it was an equally good aircraft but with full electric. The battery has to have at least 69 power densities of the current power. Therefore, for now, it seems unrealistic for large passenger aircraft to use purely electrical systems for energy.

Small Electric Vertical Take-off and Landing Vehicles (EVTOLs) can be fully powered, but the range is very short. The range of the first pure electric cars is usually around 100 kilometers [20]. Due to the short life of the battery, it often has to be charged during use, and insufficient charging systems have become a problem. At the moment, the number of charging stations is insufficient, and the distribution of the installations is uneven [21].

However, as shown in Table 2, the energy density of the battery is low. Its energy density is 0.25 MJ/kg, which cannot withstand long flight distances. The batteries contribute too much to the weight of the plane, much heavier than ordinary fuel. Therefore, the performance of the battery is the key to the development of aircraft. Research on long-life, high-energy, high-power-density battery technology is the key technology in the development of electric aircraft [22].

Table 2. Energy density comparison

Type	Energy density （MJ/kg）	Explain
Aviation fuel (taking kerosene as an example)	about 42-46	Chemical energy storage forms, which release energy through combustion, are the core energy source for traditional aviation propulsion.
Lithium batteries (taking the typical lithium-ion battery as an example)	about 0.25-0.7	The form of electrical energy storage releases energy through electrochemical reactions and is limited by the material system (such as the graphite/lithium cobalt oxide system)

In energy supply and energy systems, the most important factor is the difference in energy density between fuel and battery. Figure 8 shows that the energy density of aircraft fuel (for example, kerosene) is about 42-46 MJ/kg. This energy is released by combustion, which is the core of traditional aviation power [23]. The energy density of lithium batteries (typical lithium-ion batteries) is about 0.25 to 0.7 MJ/kg, which is limited by the material system [24]. In order to achieve the same energy supply in the configuration of the power system and propulsion system, it is necessary to increase the weight of the battery because the energy density of the battery is much lower than that of the fuel, and the energy system affects the overall design, efficiency, and application scenarios. For example, in aviation and other weight-sensitive areas, fuel capacity advantages are emphasized in terms of energy density [25].

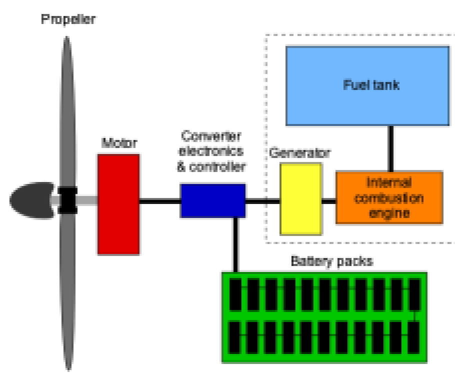

Figure 8. Schematic diagram of the working process of the energy and power system of the electric aircraft (electrically-powered aircraft—introduction to aerospace flight vehicles) [26]

2.2.2.2. Solar energy

As shown in Figure 9, solar aircraft operate on solar energy. Solar panels are installed on the wing surface of a solar aircraft. When there is light, solar energy is converted into electrical energy by solar cells and then transmitted to the motor by the battery.

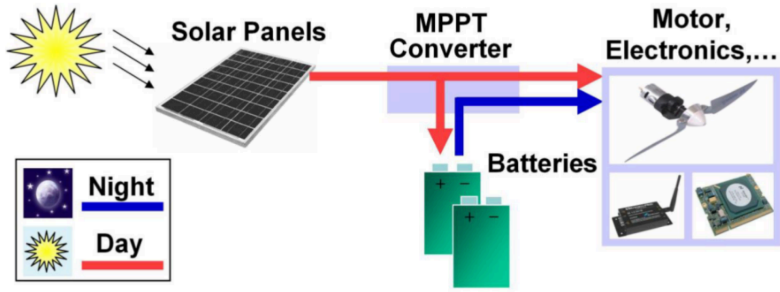

Figure 9. Schematic diagram of energy conversion and power supply system for solar-powered aircraft [27]

The main reason for using solar-powered aircraft is that it is a green, environmentally friendly, and durable aircraft. During the day, the battery has the main effect of powering the aircraft and then charging the energy storage battery with the excess electricity; during the night or when there isn't enough light, it can provide energy for flying through the energy storage battery. During the following day, a new wave of energy starts to supply until infinite endurance. An energy storage battery is the heart of a solar plane. Another really heavy part is the battery, which is between 30-50% of a plane. And as the mass of the energy storage battery is large, the solar aircraft becomes large in size, and the amount of energy required increases and leading to narrow solar aircraft.

Due to the relatively low energy density of the battery, a large number of solar panels are needed to convert solar energy to ensure a sufficient power supply for the flight. This explains why today's solar planes usually adopt a layout with a long wing width and many electric motors. The long width of the wing offers enough space to install a large number of solar panels and allows the batteries to be charged continuously during the flight. On the other hand, multi-engines distribute energy demand and allow airplanes to maintain flight efficiency by depending on the solar panel power supply and battery energy storage [28]. As shown in Figure 10, the "Sun God" solar-powered unmanned aircraft of the United States employs this technology.

Figure 10. The "Helios" solar-powered drone of the United States [29]

2.2.2.3. Hybrid (engine-generated electricity)

The third one introduced is the hybrid aircraft. In a hybrid aircraft, it is a system that combines fuel and electricity. Hybrid systems include parallel, tandem, and hybrid. This type of aircraft can solve the resistance problem, save fuel, and have fewer technical difficulties (Figure 11 and Figure 12). In the mixed power series, the generator is driven by the engine, and power is supplied to the engine to drive the propeller. At the parallel mixing point, the motor and the motor push the propeller at the same time. The mixed point combines the benefits of the chain and the parallel connection, which can be flexibly changed across several stages. Hybrid aircraft still have a low battery energy density, the plane cannot fly for long periods of time, and higher battery performance will change the structure of the aircraft. In addition, hybrid aircraft still use fuel, so this, in short, does not solve the problem of environmental protection [30].

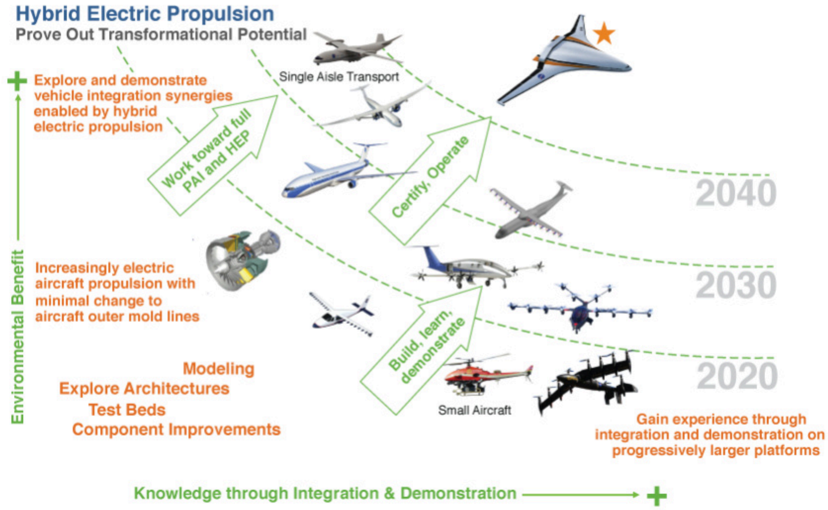

Figure 11. The development road map of hybrid electric propulsion technology [31]

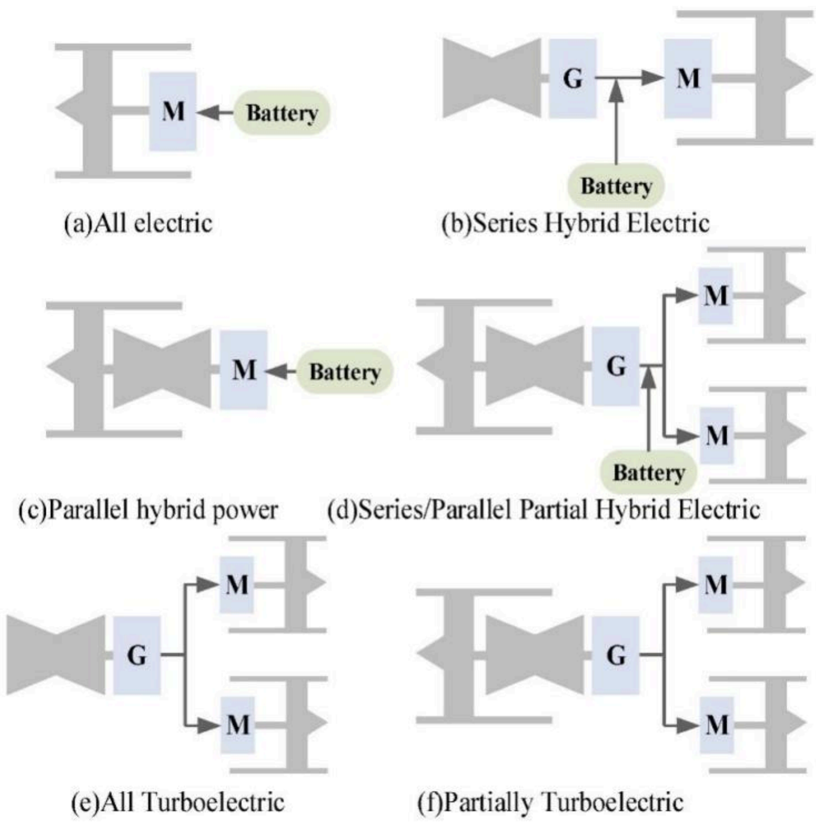

Figure 12. Schematic diagram of the power system architecture of the aircraft [32]

2.2.2.4. Hydrogen energy (hydrogen fuel power generation)

Hydrogen is a clean source of energy. To achieve carbon reduction in aviation, hydrogen energy is used in aviation. Current research progress focuses on the power of hydrogen turbines. There are two forms of hydrogen turbine technology. The first is the hydrogen turbine fan engine, which is upgraded to a traditional turbine engine and replaces aviation fuel with hydrogen fuel (Figure 13). The power of hydrogen turbines has excellent thrust that is suitable for large passenger aircraft. The second is the hydrogen turbine electric fan motor (Figure 14), which produces electricity through a generator driven by the driving turbine, then the fan generates energy. In electric aircraft, Hydrogen fuel cells are also an important technology, its working principle of the hydrogen fuel cell electric fan engine is shown in Figure 15. Hydrogen fuel has a high electrochemical reaction efficiency

(40%-50%), which increases the resistance of the aircraft. However, compared to aviation oil engines, powered by hydrogen also have a short and low payload. The internal combustion engine of hydrogen fuel aviation is burned by changing the fuel supply system.

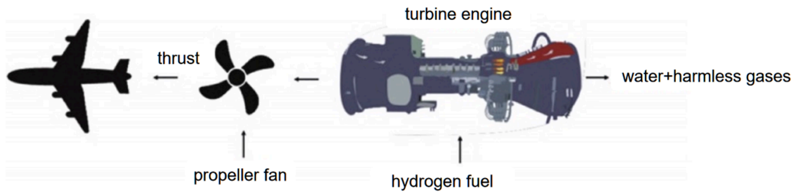

Figure 13. The working principle of hydrogen turbofan engines [33]

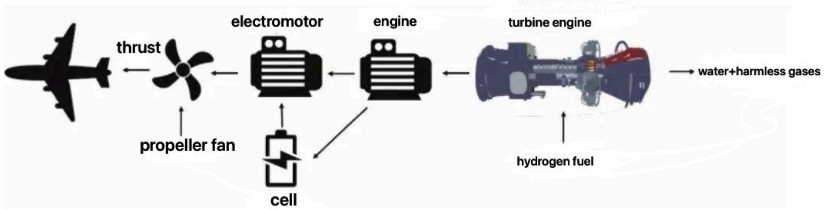

Figure 14. The working principle of hydrogen turbine electric engine

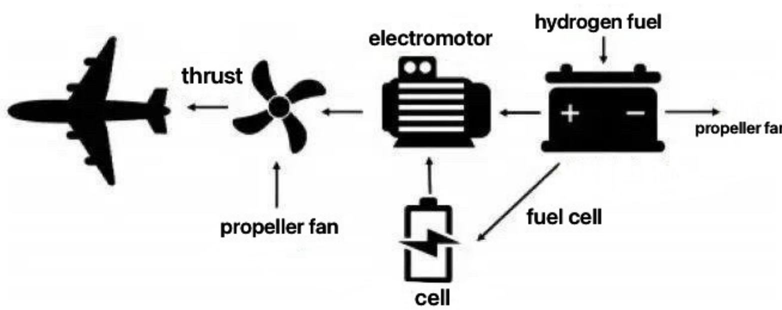

Figure 15. The working principle of the hydrogen fuel cell electric fan engine

However, hydrogen storage is very difficult, and technology is quite difficult. Currently, hydrogen storage methods used in aviation include hydrogen gas storage at high pressure. Liquid hydrogen storage at low temperature and cyanide metal. The physical properties of hydrogen are shown in Table 3. The difficulty of hydrogen storage is mainly explained in many aspects, such as low energy density, high technical requirements for storage and transport, cost problems, safety risks, and technical challenges. In addition, although the technology for storing hydrogen under high pressure is mature, there are safety risks such as explosion, leakage, and material disturbance, and the standards for the preparation and use of the equipment are not perfect [34]. Although the liquid hydrogen storage technology has a high volume density, the liquefaction process consumes a lot of energy, and the thermal abatic performance of the storage system is difficult to achieve to perfection [35]. Although solid-state hydrogen storage materials are very safe, their kinetic hydrogen absorption and release properties and cyclical stability are insufficient, and the costs are high. In addition, the flammability and explosive properties of hydrogen pose a risk of leakage and explosion during storage and transport. The development of highly safe hydrogen storage materials and hydrogen storage technologies is an important condition for ensuring the application of hydrogen energy [36].

Table 3. Hydrogen physics properties

Density at STP	1 mole of hydrogen	volume of 1kg of hydrogen	High-pressure hydrogen storage
0.0899 g/L	mass: 2.01588 volume: 22.4L	11,112.19 L	35 MPa

2.3. Current situation and development of new energy aircraft

2.3.1. Large passenger aircraft

As the world's leading aircraft manufacturer, Airbus has launched the ZEROe project. As Figure 16 shown, The main technologies of this project include water combustion turbines, electric propulsion systems, and hybrid energy systems. In addition, hydrogen turbine combustion technology is the key to achieving zero carbon emissions. Boeing has also launched a new series of energy aircraft SUGAR. Among them are two aircraft, Freeze and Volt, which use electric drive systems and hybrid systems, respectively. The Freeze aircraft is an all-electric aircraft, while the Volt aircraft is a hybrid aircraft [37].

Figure 16. Example of the effect of "Zeio" [38]

2.3.2. Electric small passenger aircraft

Currently, flying cars and eVTOLs have attracted much attention as manned aircraft. In this field, many countries and enterprises are actively conducting research and launching related products. For example, China's EHang has launched the EH216-S unmanned aircraft, which has obtained the eVTOL aircraft airworthiness certificate. In addition, EHang has also launched a new flying car with a range of up to 400 kilometers. This flying car adopts a design combining multi-rotors and fixed wings to improve its endurance [39]. Besides EHang, XPeng Motors has also made a layout in this field. The land-air dual-purpose aircraft launched by XPeng has completed a manned flight test. This aircraft uses completely independently developed technology, and all the parts used can be produced independently [40]. Internationally, America's Joby Aviation has been promoting the research and development of eVTOL products, which are committed to realizing short-distance manned transportation in cities and are planned to be put into commercial operation in the future [41]. Germany's Volocopter has also launched a number of eVTOL prototypes and has conducted demonstration flights on many international occasions, aiming to provide solutions for urban air transportation [42]. The explorations of these countries and enterprises are promoting the development of eVTOL electric small passenger aircraft towards a more mature and widely applied direction.

In the case of small electric passenger aircraft, the EH216-S unmanned aircraft launched by Yihang received an eVTOL aircraft qualification certificate. Yihang also launched a new flying car with a range of up to 400 kilometers. The combination of multi-rotor and fixed-wing design adopted by Yihang has increased durability. As shown in Figure 17, the land-based aircraft carrier launched by Xiaopeng also completed a manned flight test. Xiaopeng uses technology that is completely self-developed, and the parts used can be produced independently [30].

Figure 17. XPeng HT aero's land aircraft carrier [43]

3. Discussion

Aviation is key to global connection and trade, but it produces a lot of greenhouse gases. From the International Energy Agency's standpoint, aviation causes around 2.5% of the world's yearly carbon dioxide emissions, with the ratio projected to go up as the remaining sectors reduce carbon emissions faster [44]. The need for action on climate change is urgent, and this, along with the particular energy and performance demands of flying, has generated a frantic search for alternative propulsion systems and fuels. The transition to sustainable aviation is not a simple matter of swapping out one fuel for another; it requires a fundamental rethinking of aircraft design, energy supply chains, and regulatory frameworks [45].

This discussion thinks three big tech paths-electric motors, Hydrogen fuel, and Sustainable Aviation fuel (SAF)-could be used to cut airplane carbon out, so it takes them seriously for now. Each way is special, with different good parts and hard parts depending on stuff like whether the tech is already ready to go, if there's enough money to do it, how friendly it is to nature, and if more people would want to give it a shot. We look at it based on the latest literature, the reports from every single market, and our own analysis.

3.1. Electric aircraft

The concept of electrically powered flight is not new, but recent advances in battery technology, electric motors, and lightweight materials have rekindled interest [46]. Modern electric aircraft promise significant reductions in direct carbon emissions, noise, and maintenance costs, given the simplicity and reliability of electric motors compared to traditional gas turbines [47].

Battery energy density is an issue for electric aircraft because if we make batteries too heavy, they won't fly, so energy density is very important. Over the past decade, lithium-ion batteries have seen their energy density nearly double, reaching approximately 300 Wh/kg for commercial cells, with laboratory prototypes exceeding 400 Wh/kg [48]. Looking ahead, solid-state batteries, lithium-sulfur, and lithium-air chemistries could theoretically push energy densities toward 500-1,000 Wh/kg, though these remain at the experimental stage [48, 49].

Though they've come this far, whether or not fully electric planes could be used for big commercial air travel is still something people argue about. The proponent wants continuous improvements in battery's energy density, coupled with advances in lightweight composites and aerodynamic design, will eventually enable practical electric airliners [50]. They point to successful demonstrations of small electric aircraft, such as the Pipistrel Velis Electro (a two-seater trainer certified in Europe), and the growing number of electric regional aircraft projects targeting 9- to 19-seat segments [51].

But some critics insist that even on paper, the basic physics make it impossible to build big transcontinental airplanes from electricity. The current gravimetric energy from jet fuel (~12,000 Wh/kg) is 40x better than the best commercially available battery. Thus, this discrepancy means that an electric airliner that can fly 1,000 km would need to have a battery weight many times more than the aircraft's maximum takeoff weight [46]. Even with optimistic projections for future battery advances, most analyses suggest that electric propulsion will be confined to small aircraft on short-haul routes for the foreseeable future [50, 51]. For example, Airbus stated that only aircraft with a passenger capacity of up to 100 and a range under 1,000 km could use full-electric propulsion, even if battery development is the best possible scenario by 2050 [1]. For larger planes or longer flights, too many batteries would be needed, which makes them too heavy or take up too much space to bring along, and makes it too expensive to do so.

Battery life and cost are also issues. Aviation places extraordinary strains on batteries, fast charge/discharge cycles, a huge range of temperatures, and strict safety standards are all part of aviation's demands. Batteries degrading require them to be replaced periodically, every few hundred operations, which adds to the cost of operation [47]. Also, the benefits of the environment of electric aircraft are only really achieved if the electricity used to charge them comes from low-carbon sources [44].

Solar power holds the promise of achieving pollution-free flight. For example, the "Solar Impulse 2" solar-powered aircraft completed a round-the-world flight without consuming a single drop of fuel, relying solely on solar energy for power, which fully demonstrates the enormous potential of solar power in terms of environmental protection [52]. However, solar power also has some drawbacks. Firstly, there is the issue of energy density. The energy density of solar cells is relatively low. Solar-powered aircraft like the "Solar Impulse 2" need to be equipped with a large number of solar panels to obtain sufficient energy, but the power they can provide is limited, resulting in slow flight speeds and weak carrying capacity, being only able to carry one pilot [53]. Secondly, there is the problem of the area of solar panels. Due to the limited energy conversion efficiency of solar panels, a large area is required to collect enough energy for flight. The wingspan of the "Solar Impulse 2" reaches 72 meters, far exceeding that of ordinary airliners. This not only increases the difficulty of aircraft design but also has a certain impact on the flexibility and stability of its flight, making it difficult to adapt to complex air traffic environments and diverse flight tasks [53].

Solar-powered is where we can see our best hope of a no-emissions flight. The plane just gets its power from the sun. The Solar Impulse project strikingly demonstrated the technical practicability of solar-powered flight and achieved a round-the-world trip powered solely by solar energy [52]; however, it utilized extremely lightweight, low-speed aircraft capable of carrying only a pilot.

In practical terms, the power density of solar cells (~250 W/m²) and the limited surface area available on an aircraft severely constrain the amount of energy that can be captured in flight [53]. This restricts solar aviation to niche applications, such as high-altitude, long-endurance Unmanned Aerial Vehicles (UAVs) used for earth observation, communications, or atmospheric research [53]. There is currently no credible pathway to scale solar aviation to passenger or cargo aircraft.

The electric propulsion is best suited for small aircraft and short-range missions. For example, regional commuter flights under 500 km, urban air mobility (eVTOLs), pilot training, and general aviation are all promising early markets [46, 54]. Several electric aircraft, such as the Alice (Eviation), ES-19 (Heart Aerospace), and various eVTOL prototypes, are targeting entry into service between 2025 and 2030 [54]. They could fly runs that are now uneconomic with normal aircraft, which could develop fresh markets and reduce the impact on the environment of short-distance travel.

For medium- and long-haul flights, however, electric propulsion is unlikely to be viable without radical breakthroughs in battery technology, which are not expected before mid-century [50]. Hybrid electric setups that couple batteries with conventional or alternative fuels might give some advantages through electric taxiing or extra power, but they don't really handle the energy density trouble for big planes [51].

In summary, the application of electric aviation in small and short-term fields has already begun. However, in order to achieve greater applications, progress is still needed in many areas, including battery technology, infrastructure, and aircraft design. With continuous advances in technology, electric aviation is expected to play an important role in urban air transportation, short-term travel, and other future situations. However, in the field of large, medium, and long-range airliners, it is difficult to replace traditional fuel aircraft in a short period of time.

3.2. Hydrogen-powered aircraft

Hydrogen-powered aviation is seen as an important way for the aviation industry to reduce emissions deeply. The main product of hydrogen combustion is water. If it uses green hydrogen, truly zero carbon emissions can be achieved. But currently, there are many technical problems and cost problems for the development of hydrogen-powered aircraft, such as hydrogen storage, transport, and hydrogen station construction. But its huge emission reduction has still drawn people’s attention.

Hydrogen is seen as a good option for zero-emissions flying, especially for new planes [55]. Hydrogen is used directly in modified gas turbines, burned with air to generate thrust, or supplied to fuel cells for generating power for electric motors [50]. Again, here the main emission is water vapor, even though it’s possible to produce NOx at high combustion temperatures.

The chief advantage of hydrogen is its high gravimetric energy density (33,000 Wh/kg), which is nearly three times that of jet fuel and more than 100 times that of current batteries [45]. This means we should be able to power commercial flights with hydrogen in the future, without the weight penalty of using batteries.

When hydrogen is produced via electrolysis with renewable electricity (green hydrogen), it can provide a truly zero-carbon path for aviation [44]. This is something really great, since the clean resources are within reach for aviation without the constraints of battery storage.

Critics of hydrogen-powered aviation argue that hydrogen has a low volumetric energy density, requiring a huge amount of space for storage, which would disrupt the original aerodynamic layout of the aircraft and increase design difficulties [50]. For example, storing enough hydrogen for long-haul flights would require installing large and bulky storage tanks on the aircraft, which not only adds to the aircraft's weight but also affects its flight performance. Moreover, hydrogen storage and transportation have high technical requirements and are costly. Currently, the global production of hydrogen is mainly dependent on natural gas, known as "grey hydrogen," which cannot achieve true environmental friendliness. Meanwhile, the production of green hydrogen faces problems of high costs and limited supply [44].

Though hydrogen aviation sounds promising, it's got some big technical and infrastructure troubles. Hydrogen's volumetric energy density is far less compared to liquid hydrocarbons in all cases, even if compressed and cooled down to -253°C, which means it needs a very large volume to store it. As a result, hydrogen storage tanks must be larger and heavier, often resulting in bulky circular or spherical designs disrupting typical aircraft layouts [50]. Adding these tanks to the fuselage or wings without hurting its aerodynamics, safety, or people space is a big engineering challenge [56].

Cryogenic storage also introduces operational complexities, including boil-off losses, insulation requirements, and safety concerns related to hydrogen leakage or fire risk [45]. On the ground, airports would need entirely new infrastructure for hydrogen production, storage, distribution, and refueling—a multibillion-dollar investment with long lead times [44, 54].

Most current hydrogen aviation programs today are in the demonstrator or prototype phase. For example, ZeroAvia has conducted test flights of a hydrogen fuel cell-powered Dornier 228, targeting regional routes of up to 500 km [57]. Airbus has announced its ZEROe concepts, which envision hydrogen-powered commercial aircraft entering service by 2035 [56]. They mostly target regional and short-haul, where the amount of hydrogen needed is not great and the infrastructure can be developed at specific airports.

When it comes to high-capacity long-haul aircraft, hydrogen is a long-term fantasy. To carry and pass around enough hydrogen for intercontinental flights in the real world is physically impossible. Most experts think that hydrogen-powered widebody planes won't start operating before the 2040s [44, 45].

The climate benefit from hydrogen-powered aviation all depends on what makes the hydrogen. Right now, more than 95% of the world's hydrogen comes from natural gas using steam methane reforming, which creates a lot of carbon dioxide ("grey hydrogen") [44]. Only"green hydrogen" made by renewable-powered electrolysis is actually sustainable. However, green hydrogen is currently 2-3 times more expensive than grey hydrogen, and its availability is limited [44]. Large-scale deployment of green hydrogen will require massive investments in renewable energy, electrolyzers, and distribution infrastructure, as well as close coordination with other sectors competing for hydrogen, such as industry and shipping [45]. And another thing that would be contrails, and cirrus clouds could form from the water vapor emissions up high, so that could also have some non-CO_2 impacts on climate as well. Further examination and reduction of these effects is necessary [45].

Some industry leaders favor a phased approach, beginning with hydrogen-powered short-haul and regional aircraft and then progressing to larger aircraft as the technology and infrastructure mature [19]. Hybrid systems like hydrogen-electric propulsion can improve and lower emissions, too. In the short term, hydrogen could also be blended with other fuel types (including SAF) and thus lower the lifecycle emissions [51].

Hydrogen-powered aviation is considered an important way for the aviation industry to achieve deep emission reduction, as hydrogen combustion mainly produces water, and green hydrogen can realize true zero carbon emissions, with high gravimetric energy density being a major advantage. The application prospects of different hydrogen energy sources in passenger aircraft is listed in Table 4. However, it faces multiple challenges: low volumetric energy density causes storage space and aircraft design issues; hydrogen storage, transportation, and related infrastructure construction have high technical requirements and costs; most current hydrogen is "grey hydrogen" with poor environmental friendliness, while green hydrogen is expensive and in limited supply; there are also potential non-CO_2 climate impacts from water vapor emissions. Currently, most hydrogen aviation programs are in the demonstrator or prototype phase, focusing on regional and short-haul flights, with long-haul widebody aircraft expected to be operational no earlier than the 2040s. A phased approach, starting with short-haul and regional aircraft and possibly using hybrid systems or blending with other fuels, is favored by some industry leaders.

Table 4. Application prospects of different hydrogen energy sources in passenger aircraft

Type of passenger aircraft Sources of hydrogen energy	long-distance	branch
Green hydrogen	Best. Not achievable in the short term	In the near future
Grey hydrogen	Better. It cannot be achieved in the short term.	Has been implemented

3.3. Sustainable aviation fuels

Sustainable Aviation Fuel (SAF) is a type of liquid hydrocarbon produced from renewable or waste-based feedstock meant to be used by aircraft engines and can be used within an existing refinery or fuel network. "Drop-in"is a major benefit for SAF, as it can immediately reduce the world's emissions without delay in new aircraft design or large infrastructure changes [44]. In the current aviation sector, the most widely used fuel alternative in terms of environmental protection is SAF. This is because it can directly replace fuel for combustion, allowing for convenient replacement without the need for major modifications to existing aircraft and engines, nor the construction of a large amount of new infrastructure. However, there is much controversy surrounding it.

On one hand, some argue that SAF is environmentally friendly, as reflected in its low carbon emissions throughout the entire life cycle. For example, SAF produced from waste oils and fats can reduce life-cycle CO_2 emissions by 60-80% compared to traditional jet fuel [44]. Secondly, the use of SAF can reduce emissions of pollutants such as sulfur and particulate matter, which is beneficial for improving air quality. SAF can be produced from a variety of sources, including waste oils (used cooking oil, animal fats), biomass (agricultural residues, energy crops), municipal solid waste, and captured CO_2 (via power-to-liquid or electrofuels) [44]. Depending on the feedstock and production pathway, SAF can deliver lifecycle CO_2 reductions of 60-80% compared to fossil jet fuel [44].

On the other hand, some argue that SAF does not fundamentally solve the problem of carbon emissions. This is because SAF still releases CO_2 during combustion; it only achieves carbon cycling throughout its life cycle through the use of renewable raw materials, rather than achieving complete zero emissions. For instance, SAF produced using energy crops as raw materials may indirectly generate carbon emissions due to factors such as land use changes during crop cultivation, which affect its environmental benefits [45]. Secondly, the technical maturity of SAF is not high, making commercialization difficult. As of 2024, nine SAF production pathways have been certified for use in aviation, but only the Hydroprocessed Esters and Fatty Acids (HEFA) route—based on waste oils and fats—has achieved meaningful commercial scale [25]. Other pathways, such as Fischer-Tropsch synthesis (from biomass or waste), Alcohol-to-Jet, and power-to-liquid (electrofuels), remain at pilot or demonstration stage. Furthermore, the production of SAF may affect the yield of food crops. SAF can scale up with technology maturation and feedstock access. Waste oils and fats are relatively scarce resources, and the mass planting of energy crops can lead to competition for food crops and increase the risk of indirect land conversion [45]. Advanced pathways that use non-food biomass, waste, or captured CO_2 are more sustainable but more expensive and less mature [44]. Lastly, cost is the main barrier to SAF adoption. SAF is now 2-5 times more costly than fossil jet fuel due to higher feedstock prices, lower production volumes, and a lack of policy support [44]. Airlines have slim profit, so they can hardly bear such costs and will surely transfer these additional costs to the public. Furthermore, policy uncertainty is also a major factor affecting the development of SAF. The second main problem: uncertainty in policy. In contrast to some regions, such as the EU and California, which have issued blending mandates or policies, SAF blends or incentives, worldwide deployment is still low [51]. Clear and long-term policy signals are absent; investments for new SAF production capacity and supply chains are impossible. And thus, SAF comprises less than 1% of the jet fuel consumption globally by 2023 [44].

SAF is not as pollution-free as claimed., The environmental benefits of SAF depend mostly on their feedstuff & production procedure. Waste-based SAF is likely to show the most lifecycle emissions reductions, while crop-based SAF can come with unwanted consequences such as deforestation or biodiversity loss [45]. Advanced SAF, like those made using captured CO_2 and renewable electrical power, could give off almost zero emissions or maybe less; however, these products are now very costly and aren't technologically developed enough [44].

There are also issues with the supply of raw materials for SAF. Consider the used cooking oil used for SAF creation. This is competing with other uses, like animal feed or soaps, and carries new supply chain risks [44]: Make sure SAF feedstocks can be sustainable and can be tracked correctly to stop any bad stuff from happening by accident. While SAF has addressed the issue of carbon emissions to a certain extent, it is still immature at present, facing problems such as a small production scale, high costs, limited raw material supply, and insufficient policy support. However, with advancements in technology and improvements in policies, SAF is expected to occupy an important share in the aviation fuel market in the future and become one of the key means for emission reduction in the aviation industry. In order to deploy more SAFs, it is necessary to have technological innovations as well as policy and market incentives to scale up SAF usage at the same time. Key measures include: Expand the Certification for Production pathways, mainly for Advanced, non-food derived, and Waste-derived SAF. Offer support for production scaling by investing, granting a bank loan with a guarantee, or using a public-private partnership. Issue clean and/or long-distance mandate mixes or price to support the difference in costs of fossil jet fuel. Harmonization of sustainability criteria and certification schemes to maintain environmental integrity and market confidence [44]. With the right policy and market frameworks, SAF could supply 10-20% of global jet fuel demand by 2030, rising to 50% or more by 2050 [44, 51].

In the short term, as a "drop-in" fuel that can directly replace traditional aviation kerosene, Sustainable Aviation Fuel (SAF) has the advantage of enabling rapid carbon emission reductions without the need for large-scale modifications to existing aircraft, engines, or infrastructure. For example, SAF produced from waste oils can reduce lifecycle CO_2 emissions by 60%-80%, making it an important option for emission reduction in the current aviation industry. However, it also faces multiple limitations: it fails to achieve complete zero emissions, and some feedstocks (such as energy crops) may lead to indirect carbon emissions and competition with food crops; its technical maturity is limited, with only a few production pathways reaching commercial scale; it has high costs (2-5 times that of traditional jet fuel), limited feedstock supply, and insufficient policy support, currently accounting for less than 1% of global jet fuel consumption. Nevertheless, with technological progress, improved policies, and large-scale production, SAF is expected to expand its market share in the future and become one of the key means for emission reduction in the aviation industry.

4. Conclusion

To achieve green aviation and replace existing aviation fuel, numerous explorations have been conducted, which can be categorized into three directions: electric aviation, hydrogen-powered aviation, and Sustainable Aviation Fuel (SAF).

In terms of electric aviation, leveraging advantages such as low production costs, low fuel consumption, and high emission reduction potential, it shows promising application prospects in the field of short-haul and small passenger aircraft, such as electric Vertical Take-Off and Landing (eVTOL) vehicles and small regional aircraft. However, limited by issues like low battery energy density, short range, and insufficient charging infrastructure, it is difficult to be applied to large passenger aircraft and long-haul flights in the short term. Its future development highly depends on breakthroughs in battery technology.

Regarding hydrogen-powered aviation, as a clean energy source, it features high gravimetric energy density. If green hydrogen is used, it can achieve truly zero-carbon flight, thus being regarded as an important long-term direction for emission reduction in the aviation industry. Nevertheless, it faces challenges, including difficulties in hydrogen storage, low volumetric energy density, high costs of infrastructure construction, as well as high costs and limited supply of green hydrogen. Currently, it is mostly in the demonstration or prototype stage, and large-scale application, especially in large long-haul passenger aircraft, still requires time.

For SAF, as a "plug-and-play" fuel, it is compatible with existing aircraft and infrastructure and can reduce carbon emissions immediately, making it the main choice for alternative, environmentally friendly fuels in the current aviation industry. However, it also has many problems, such as a small production scale, high costs, the possibility that some raw materials may affect food crop yields, policy uncertainty, and environmental benefits being influenced by raw materials and production processes. Nevertheless, with technological innovation, policy support, and market incentives, SAF is expected to occupy a larger market share in the future.

In general, these three new energy aviation technologies each have their own advantages and disadvantages. They are likely to develop in parallel for a period in the future, jointly promoting the transformation of the aviation industry towards green and sustainable development. The specific application scenarios and development speed will depend on various factors such as technological breakthroughs, cost control, and policy guidance.

In terms of the green transformation path of the aviation industry, different new energy sources have their own focuses in applicable stages. In the short term, Sustainable Aviation Fuel (SAF), with its "drop-in" feature, can be quickly integrated into the current aviation system without large-scale modifications to existing aircraft, engines, and infrastructure. It is more in line with the industry's urgent demand for energy transition and serves as a practical option for emission reduction. In the medium to long term, although electric aircraft and solar-powered aircraft continue to make technological progress, their limitations, such as energy density, make them more suitable for scenarios like regional aviation or short-haul intercity flights, and they are unable to meet the needs of large-capacity passenger aviation. In the long run, hydrogen, as a clean energy whose main combustion product is water, is expected to completely solve the problem of carbon emissions if bottlenecks in storage, transportation, and infrastructure can be broken through. Hydrogen-based purely green aviation is likely to become the ultimate goal for the aviation industry to achieve zero emissions.

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