Biofuel–Electric Hybrid Aircraft Application—A Way to Reduce Carbon Emissions in Aviation

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Abstract: As global warming intensifies, the world is increasingly concerned about carbon emissions. As an important industry that affects carbon emissions, the air transportation industry takes on the important task of energy saving and emission reduction. For this reason, major airlines have designed or will design different kinds of new-energy aircraft; however, each aircraft has a different scope of application according to its energy source. Biofuels have an obvious carbon emission reduction effect in the whole life cycle, which can offset the drawback of the high pollutant emission of traditional fossil fuels in the preparation and combustion stages. At the same time, a battery has zero emissions in the operating condition, while the low energy density also makes it more applicable to short-range navigation in small aircraft. In this paper, the development direction of a biofuel–electric hybrid aircraft is proposed based on the current development of green aviation, combining the characteristics of biofuel and electric aircraft.

Keywords: new-energy aircraft; sustainable aviation fuel (SAF); fuel–electric; biofuel; specific energy; electric aircraft

1. Introduction

The air transportation industry has witnessed rapid development, resulting in a significant increase in carbon emissions from the aviation sector [1]. The aircraft engine exhaust is the main source of aviation carbon emissions [2]. Emissions close to the ground affect the air quality in the area around the airport, while emissions at high altitude increase cloud cover and black carbon concentration, causing damage to the ozone layer [3–5]. According to data provided by the International Air Transport Association (IATA) in 2013, the global aviation industry consumes more than 5 million barrels of petroleum daily, with CO₂ emissions-to-fuel usage ratio of approximately 3.15 [6]. Furthermore, CO₂ emissions from international aviation have been consistently rising in recent times. Projections suggested that by 2020, carbon emissions from aviation would account for about 2.5% of the world’s energy-related carbon emissions [7].

Hence, achieving carbon reduction in the aviation industry can be accomplished by exploring alternative energy sources to replace fossil fuels [8]. Green aviation alternative energy sources encompass various options such as alternative fuels, electricity, hydrogen, and solar energy. In the short term, the prominent method for emission reduction and carbon mitigation is through the adoption of alternative fuels. Compared to traditional petroleum-derived aviation fuels, alternative fuels have demonstrated the ability to reduce carbon emissions by over 60% [9]. Biofuels, in particular, have gained significant popularity as an alternative aviation fuel due to their exceptional environmental friendliness and compatibility with existing equipment [10]. The combustion of biofuels releases CO₂,
but much of this is balanced by the CO\textsubscript{2} absorbed during the growth of the feedstock biomass. This means that the CO\textsubscript{2} is effectively recycled throughout the life cycle of the biofuel, making the utilization of bio-aviation fuels a highly effective method for achieving carbon reduction.

Indeed, the adoption of biofuels in the aviation industry is not without its challenges. The relatively high production costs of biofuels and the dependency on specific feedstock sources present significant barriers to their widespread implementation. Moreover, the annual production of biofuels is directly linked to the availability and scalability of these feedstock sources, which further complicates their large-scale adoption. As we look toward the future and the long-term objective of halving carbon emissions from the aviation sector by 2050, it becomes apparent that relying solely on alternative fuels may not be a feasible solution. Therefore, the aviation industry is increasingly turning its attention to electric aircraft as a promising avenue for progress. Electric aircraft offer a compelling alternative to traditional fossil-fuel-powered planes. By utilizing electricity as their primary energy source, these aircraft can significantly reduce carbon emissions and environmental impact. The advancements in battery technology and electric propulsion systems have paved the way for the development of electric aircraft with improved range, performance, and efficiency.

Electric aviation refers to the utilization of electrical energy to power aircraft, encompassing both propulsion systems and on-board operating systems [8]. Electric propulsion systems are acknowledged for their potential to be locally zero-emission, although this outcome depends on the manner in which the electricity is generated [11]. The consensus in the aviation industry is to incorporate more electricity into the power system, with electric aircraft technology emerging as the most promising avenue for achieving decarbonized aviation and ensuring sustainability [12]. In October 1973, the first-ever manned electric aircraft successfully completed a test flight. Today, numerous electric aircraft projects are underway, exemplified by initiatives like the Pipistrel Alpha Electro, Eviation Alice, and NASA X-57 Maxwell, although some projects have been discontinued during their development. As of early 2020, only one ultralight and three electric gliders have achieved commercial success [13]. Battery technology stands out as the primary power source for electric aircraft. However, the first generation of nickel-cadmium batteries falls short in terms of energy density [14], while the new generation of lithium-ion batteries lacks certain safety features, demanding further development and improvement in battery technology.

Furthermore, purely electric aircraft encounter challenges related to battery life, charging time, and accessibility to battery materials [15]. The production of batteries necessitates substantial amounts of nickel, lithium, and cobalt, all of which are finite resources [13]. Given these constraints, a viable solution for long-range aircraft lies in adopting a hybrid powertrain approach, integrating an internal combustion engine to generate electricity. This concept, known as a fuel–electric hybrid aircraft, offers a promising solution for transitioning conventional fuel-based aircraft to the realm of purely electric aviation.

By combining the clean power of an electric propulsion system with the long endurance of an internal combustion engine, fuel–electric hybrid aircraft showcase several compelling benefits. They notably reduce fuel consumption compared to conventional fuel-fired aircraft, resulting in enhanced environmental friendliness. Moreover, these hybrid aircraft offer increased flight range when compared to their purely electric counterparts [16], making them more versatile for longer journeys. Most importantly, this integration significantly contributes to the reduction of CO\textsubscript{2} emissions, a crucial step in achieving a more sustainable aviation sector. Numerous scholars and airlines have been actively engaged in researching and developing fuel–electric hybrid aircraft, evolving from small-scale prototypes to larger and more sophisticated models [17,18]. The promising outcomes of these endeavors underscore the potential application and positive impact of fuel–electric hybrid aircraft, paving the way for a greener and more sustainable future in aviation.

Obviously, the fuel–electric hybrid option does not free aircraft from dependence on fossil fuels. However, by combining the bio-aviation alternative fuel technologies
mentioned above, biofuels can be used in the internal combustion engine part of the hybrid system, which can further achieve carbon reduction based on the fuel–electric hybrid aircraft. In this paper, we will analyze the application potential of biofuel–electric hybrid aircraft in terms of carbon reduction and the outlook on its future development based on the elaboration of biofuel, electric aircraft, and the application of fuel–electric hybrid.

2. Classification of New-Energy Aircraft

Depending on the energy source, the new-energy aircraft currently in production or under development in the world can be divided into four types: electric aircraft, hybrid aircraft, hydrogen-powered aircraft, and sustainable aviation fuel (SAF) aircraft. Electric thrusters are used in a wide range of military, homeland security, and civilian applications due to the advantages of enhanced safety, quiet operation, and precise power management and control [19,20]. The specific energy of a battery pack is a key determinant of energy intensity and a critical enabler of electric flight. For flight energy reserve considerations, aviation batteries cannot be discharged to low levels and only a small fraction of their reserve specific energy is available for mission use. In one example, only 45% of the specific energy of a new battery, excluding packaging, aging, safety, etc., is used for flight, of which 26% is used for mission execution and 19% is required as a minimum flight reserve [21]. Due to the limitations of current battery technology, the range of electric aircraft is relatively short, and the number of seats and maximum takeoff weight are relatively small compared to traditional aircraft [22]. Improving the energy density of the battery, optimizing the wing geometry and propulsion system, finding efficient aircraft configurations, and rationally reducing the weight of the aircraft are the foci of future research to maximize the flight range of all-electric aircraft [23].

Hybrid aircraft use both electric motors (EM) and conventional fuel engines to increase range and efficiency. Unlike a combustion engine, the power capability of an electrical system does not scale with flight speed or altitude [24]. Batteries are very responsive and the best phases for using batteries to power an aircraft are the take-off and landing phases [25]. The design of hybrid aircraft varies as well as the specifics of the hybrid power system. For example, the aforementioned NASA Maxwell X-57 utilizes Li-ion batteries with a 47 kWh battery capacity to form two packs with eight modules as a distributed propulsion system; with the Airbus E-Fan X hybrid electric aircraft currently under development, one of the aircraft’s four gas turbine engines is replaced by a 2 MW electric motor [26]. Once the system matures, provision will be made to replace a second gas turbine with an electric motor.

Aircraft manufacturer Boeing demonstrated the feasibility of a hydrogen-powered aircraft in 2008, with the demonstrator being powered by a Proton Exchange Membrane Fuel Cell (PEMFC) and the aircraft being converted from a two-seat Diamond motor glider [27]. There are two primary types of hydrogen-powered aircraft: fuel cell aircraft and hydrogen combustion aircraft. Fuel cell aircraft use a hydrogen fuel cell to generate electricity to power electric motors, which drive the aircraft’s propellers. The hydrogen fuel cell works by converting hydrogen and oxygen into electricity, with the only byproduct being water vapor [28]. Hydrogen combustion aircraft, conversely, use hydrogen as a fuel for a combustion engine, similar to how traditional aircraft use fossil fuels. The difference is that hydrogen-powered aircraft require a change in the design of conventional fuel-based aircraft. From an aircraft design perspective, liquid hydrogen (LH2) must be kept in low-temperature and highly insulated tanks, and the wings cannot be used as storage locations due to lack of space and inability to be properly insulated. For short-medium range aircraft, hydrogen tanks, which are much heavier than conventional fuel tanks and may increase energy consumption by 6–19%, can be placed above the passenger cabin, while for long-range aircraft, hydrogen is stored in two large integrated tanks located behind the cockpit and passenger compartment, which improves energy efficiency by 12%. From the engine point of view, the flame propagation speed, flammability range, and diffusion coefficient of hydrogen are substantially different from those of aviation kerosene, and traditional combustion chambers are not suitable for the combustion of
hydrogen fuel [29]. While hydrogen-powered aircraft have the potential to revolutionize the aviation industry, there are still significant challenges to overcome, such as the high cost of producing and storing hydrogen, the infrastructure required to support hydrogen-powered aircraft, and the safety concerns associated with handling hydrogen, etc. SAF aircraft are aircraft that use alternative fuels that are more sustainable and environmentally friendly than traditional fossil fuels. SAFs are made from renewable resources, such as biomass, waste, and synthetic materials, and are designed to reduce greenhouse gas emissions and other harmful pollutants associated with aviation. SAFs are designed to be drop-in fuels, meaning they can be used in existing aircraft. SAFs can be blended with traditional jet fuel, with blends ranging lower than 50% SAF [30]. According to ASTM D7566-24a, the maximum blending ratio for Fischer–Tropsch hydrotreated synthesized paraffinic kerosene (FT-SPK), synthesized paraffinic kerosene, hydrotreated esters, and fatty acids (HEFA SPK), Fischer–Tropsch hydrotreated synthesized paraffinic kerosene plus aromatics (FT-SPK/A), alcohol-to-jet synthetic paraffinic kerosene (ATJ-SPK), catalytic hydrothermolysis jet (CHJ), and alcohol-to-jet synthetic paraffinic kerosene with aromatics (ATJ-SKA) is 50 vol%, while the maximum blending ratio for synthesized iso-paraffins (SIP) and hydrotreated hydrocarbons, esters, and fatty acids (HC-HEFAs) is 10 vol% [31]. The restrictions on blending ratios stem from the different physical properties or chemical compositions of SAF compared to conventional aviation fuel, which can affect the combustion performance of the blended fuel in combustion chambers, engines, and aircraft. For example, the amount of SIP in the final blend may be limited by viscosity, and the amount of FT-SPK/A in the final blend may be constrained by density or aromatic content. As research progresses, the composition and properties of neat SAF or biofuel are expected to become increasingly similar to conventional aviation fuel, potentially allowing direct use without blending and without altering existing engine and aircraft designs. Therefore, research on 100% SAF or biofuel is as important as research on blend fuels.

Ji et al. [32] summarized the advantageous intervals of four kinds of new-energy aircraft with 100% energy supply (without hybrid), as shown in Table 1. New-energy aircraft can be divided into urban airliners (mainly eVTOL and commuter aircraft) [33], regional airliners, medium-sized mainline airliners, large mainline airliners, and ultra-large mainline airliners according to their usage, range, and passenger (cargo) capacity. Due to the limitation in the energy density of energy storage batteries, the range and passenger capacity of electric aircraft are the smallest among the four types of aircraft. Therefore, purely electric aircraft are more often used in small aircraft for urban transportation. Hydrogen fuel cell aircraft are suitable for regional airliners or medium-sized mainline airliners with a passenger capacity of fewer than 80 seats and a range of less than 1500 km. Hydrogen turbine aircraft are suitable for medium or large mainline passenger aircraft with a passenger capacity of 300 seats or fewer and a range of 10,000 km or less. SAF aircraft can be certified for test flights directly on existing complete aircraft, and have a wider range of applications, from medium-sized passenger aircraft to super-large passenger aircraft with a lower application threshold.

Table 1. Advantageous interval of new-energy aircraft with different 100% energy supply [32].

<table>
<thead>
<tr>
<th>Type of Aircraft</th>
<th>Voyage (km)</th>
<th>Seating Capacity (Person)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electric aircraft</td>
<td>0–500</td>
<td>0–20</td>
</tr>
<tr>
<td>Hydrogen fuel cell aircraft</td>
<td>300–1500</td>
<td>6–80</td>
</tr>
<tr>
<td>Hydrogen turbine aircraft</td>
<td>1000–10,000</td>
<td>11–400</td>
</tr>
<tr>
<td>SAF aircraft</td>
<td>600–16,000</td>
<td>30–500</td>
</tr>
</tbody>
</table>

Based on information shown in the literature and on websites, a summary of the mainstream new-energy aircraft that have been produced or are planned to be produced is shown in Table 2. The passenger capacity of all-electric aircraft is below 20, and most of the models are urban air transport models with a seating capacity of 2–4. SAF aircraft can carry the same passenger capacity and range as conventional passenger aircraft while effectively
improving carbon emissions. SAF aircraft could be one of the most promising new-energy aircraft. Compared to conventional fuels, SAF blends are theoretically expected to have minimal or negligible impact on aircraft performance. Parameters such as flight altitude, cruising range, and maximum takeoff weight are related to the chemical properties of the fuel. Although the heat value and energy density of SAF might be slightly lower than those of traditional aviation fuels, in practical applications, the impact on performance is typically limited and negligible through appropriate blending ratios and adjustments to fuel loading and flight planning. Furthermore, reports on the use of SAF blends in conventional aircraft generally do not address parameters such as flight altitude, cruising range, and maximum takeoff weight. Most literature on SAF and its blends focuses on combustion and emission performance. Therefore, the section on SAF aircraft in Table 2 is explained using the parameters of conventional aircraft as mentioned in the reports.
Table 2. Summary of parameters of different new-energy aircraft.

<table>
<thead>
<tr>
<th>Type</th>
<th>Model</th>
<th>Seating Capacity</th>
<th>Max. Cruising Speed (km/h)</th>
<th>Max. Takeoff Weight/kg</th>
<th>Lift Limit/m</th>
<th>Voyage/km</th>
<th>Endurance</th>
<th>Companies</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electric aircraft</td>
<td>RX1E</td>
<td>2</td>
<td>110</td>
<td>500</td>
<td>300</td>
<td>1 h</td>
<td>Liaoning General Aviation</td>
<td>[34]</td>
<td></td>
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<tr>
<td></td>
<td>RX1E-A</td>
<td>2</td>
<td>190</td>
<td>400</td>
<td></td>
<td>2 h</td>
<td>Academy (LGAA) (Liaoning, China)</td>
<td>[34]</td>
<td></td>
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<tr>
<td></td>
<td>RX1E-S</td>
<td>2</td>
<td>160</td>
<td>650</td>
<td></td>
<td>100 min</td>
<td>Pipistrel d.o.o. (Slovenia)</td>
<td>[36]</td>
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<tr>
<td></td>
<td>Pipistrel Alpha</td>
<td>2</td>
<td>250–300</td>
<td>550</td>
<td></td>
<td>300</td>
<td>Pipistrel d.o.o. (Slovenia)</td>
<td>[36]</td>
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<tr>
<td></td>
<td>Electro</td>
<td>2</td>
<td>6350</td>
<td>1040</td>
<td></td>
<td>400</td>
<td>Pipistrel d.o.o. (Slovenia)</td>
<td>[36]</td>
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<td></td>
<td>Lilium jet</td>
<td>9</td>
<td>300</td>
<td>1 h</td>
<td></td>
<td>100</td>
<td>Pipistrel d.o.o. (Slovenia)</td>
<td>[36]</td>
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<tr>
<td></td>
<td>Eviation Alice</td>
<td>19</td>
<td>400</td>
<td>1 h</td>
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<td>100</td>
<td>Pipistrel d.o.o. (Slovenia)</td>
<td>[36]</td>
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<td></td>
<td>Heart Aerospace ES-19</td>
<td>19</td>
<td></td>
<td></td>
<td></td>
<td>100</td>
<td>Pipistrel d.o.o. (Slovenia)</td>
<td>[36]</td>
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<tr>
<td></td>
<td>H55 electric aircraft</td>
<td>2</td>
<td>200</td>
<td>1 h</td>
<td></td>
<td>160</td>
<td>Pipistrel d.o.o. (Slovenia)</td>
<td>[36]</td>
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<tr>
<td></td>
<td>Harbour Air ePlane</td>
<td>6–8</td>
<td></td>
<td></td>
<td></td>
<td>1 h</td>
<td>Pipistrel d.o.o. (Slovenia)</td>
<td>[36]</td>
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<tr>
<td></td>
<td>Dufour Aerospace aEro 2</td>
<td>4</td>
<td>170</td>
<td>150</td>
<td></td>
<td>100</td>
<td>Pipistrel d.o.o. (Slovenia)</td>
<td>[36]</td>
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<tr>
<td></td>
<td>Skyworks Global eGyro</td>
<td>2–4</td>
<td>241</td>
<td></td>
<td></td>
<td>161</td>
<td>Pipistrel d.o.o. (Slovenia)</td>
<td>[36]</td>
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<tr>
<td></td>
<td>Vertical Aerospace</td>
<td>4</td>
<td>160</td>
<td>240</td>
<td></td>
<td>1 h</td>
<td>Pipistrel d.o.o. (Slovenia)</td>
<td>[36]</td>
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<td></td>
<td>VA-X4</td>
<td>4</td>
<td>1200</td>
<td>1200</td>
<td>250</td>
<td>2.5 h</td>
<td>Pipistrel d.o.o. (Slovenia)</td>
<td>[36]</td>
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<tr>
<td></td>
<td>RX4E</td>
<td>2</td>
<td>680</td>
<td>300</td>
<td></td>
<td>1.5 h</td>
<td>Pipistrel d.o.o. (Slovenia)</td>
<td>[36]</td>
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<tr>
<td></td>
<td>SureFly</td>
<td>2</td>
<td>200</td>
<td>300</td>
<td></td>
<td>1 h</td>
<td>Pipistrel d.o.o. (Slovenia)</td>
<td>[36]</td>
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<td></td>
<td>Centro Dragon 4</td>
<td>5</td>
<td>200</td>
<td>250</td>
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<td>Pipistrel d.o.o. (Slovenia)</td>
<td>[36]</td>
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<tr>
<td></td>
<td>Elektra Trainer</td>
<td>2</td>
<td>600</td>
<td>300</td>
<td></td>
<td></td>
<td>Pipistrel d.o.o. (Slovenia)</td>
<td>[36]</td>
<td></td>
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<tr>
<td>Hydrogen-powered aircraft</td>
<td>Spirit Sparrow H</td>
<td>180</td>
<td>500</td>
<td></td>
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<td></td>
<td>Commercial Aircraft Corporation of China Ltd. (Shanghai, China)</td>
<td>[34]</td>
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<tr>
<td></td>
<td>ZeroAvia HyFlyer</td>
<td>10–20</td>
<td>4</td>
<td>200</td>
<td>2134</td>
<td>480</td>
<td>ZeroAvia, Inc. (England)</td>
<td>[48]</td>
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<tr>
<td></td>
<td>HY4</td>
<td>4</td>
<td>1500</td>
<td>1500</td>
<td></td>
<td></td>
<td>H2FLY (Germany)</td>
<td>[49]</td>
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<tr>
<td>Hybrid aircraft</td>
<td>Airbus E-Fan X</td>
<td>100</td>
<td>2250</td>
<td>1127</td>
<td></td>
<td></td>
<td>Airbus (Toulouse, France)</td>
<td>[26]</td>
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<tr>
<td></td>
<td>Zunum Aero</td>
<td>10–50</td>
<td>920</td>
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<td>Zunum Aero (SEA, USA)</td>
<td>[50]</td>
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<td></td>
<td>Ampaire Electric EEL</td>
<td>6</td>
<td>920</td>
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<td></td>
<td>Ampaire (CA, USA)</td>
<td>[51]</td>
<td></td>
</tr>
<tr>
<td>SAF aircraft (Testing with SAF on conventional aircraft)</td>
<td>Boeing 787 Dreamliner</td>
<td>248–336</td>
<td>1041</td>
<td>254,700</td>
<td>14,010</td>
<td></td>
<td>The Boeing Company (VA, USA)</td>
<td>[52]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Bombardier Challenger 350</td>
<td>10</td>
<td>1017</td>
<td>18,416</td>
<td>5926</td>
<td></td>
<td>Bombardier Inc. (QC, Canada)</td>
<td>[53]</td>
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<tr>
<td></td>
<td>Gulfstream G280</td>
<td>10</td>
<td>1041</td>
<td>17,962</td>
<td>6667</td>
<td></td>
<td>Gulfstream Aerospace Corporation (GA, USA)</td>
<td>[54]</td>
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<tr>
<td></td>
<td>Airbus A321neo</td>
<td>180–220</td>
<td>840</td>
<td>97,000</td>
<td>7400</td>
<td></td>
<td>Airbus (Toulouse, France)</td>
<td>[55]</td>
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</table>
3. Status of Electric Aircraft
3.1. Carbon Reduction in Electric Aircraft

Significant reductions in fuel consumption have been achieved through iterations and developments in vehicle propulsion systems, such as the development of high-bypass-ratio turbofan engines and winglets [56]. These efforts have resulted in sustained economic and environmental benefits. CO\(_2\) intensity is declining at a relatively low rate of 2% per year due to continued improvements in engine efficiency, aerodynamics, and aircraft capacity utilization [57]. However, the approximately 4–5% annual growth in air transportation since 1980 has more than offset the carbon reductions achieved through propulsion system design optimization [58].

The use of biofuels can reduce full life-cycle CO\(_2\) emissions to some extent; however, the biofuel preparation process and combustion process still generate greenhouse gas emissions. Electric aircraft use only electrical energy and power for propulsion, so no in-flight emissions occur. Therefore, in the long term, only electric aircraft can provide the potential opportunity for zero flight emissions [56]. The advantages of electric aircraft are that electric propulsion allows for higher energy conversion efficiency because there is no thermodynamic efficiency limit, the electric ducted fans used primarily for electric aircraft are scaled more efficiently than gas turbines, and electric-powered aircraft do not produce any emissions during flight [59].

Stefan et al. [38] conducted a cross-sectional comparison of the CO\(_2\) emissions of the most frequently used conventional-fuel-based passenger aircraft and purely electric passenger aircraft in Finland. Conventional aircraft were selected from the ATR72 turbo-prop aircraft and the Airbus A320 family of aircraft. The first generation electric aircraft (FGEA) include Eviation’s 9-seater Alice and Heart Aerospace’s 19-seater ES-19, which will be certified and ready for commercial use in 2025. The battery power of the two electric aircraft is 900 kWh and 575 kWh, respectively. At a 62% load factor, their energy consumption is 0.154 kWh/pkm and 0.122 kWh/pkm, respectively. The CO\(_2\) emissions of the four aircraft were calculated (as shown in Figure 1), which clearly reflects the carbon reduction potential of electric aircraft. It should be noted that in calculating CO\(_2\)-equiv, the author did not consider only CO\(_2\) emissions during the flight. The electricity consumed during electric-powered flight was calculated based on Finland’s current energy mix, where producing 1 kWh of electricity generates 633 g CO\(_2\)-equiv. Although FGEA will still heavily rely on electricity primarily generated from fossil fuels, CO\(_2\)-equiv emissions are approximately half that of standard aircraft.

![Figure 1. CO\(_2\) emissions per kilometer for aircraft and FGEA.](image)

By evaluating the energy and environmental impact of all-electric aircraft, Schafer et al. [60] concluded that they reduce greenhouse gas emissions in addition to air pollutants.
The degree of emission reduction depends on the specific energy of the battery pack. A capacity of 800 Wh/kg is representative of a mature Li-S battery [56]. With 800 Wh/kg, for example, aircraft range is typically up to 600 nautical miles. If half of the aircraft departures were replaced, NOx emissions in the airport area would be reduced by 40%, and fuel use and direct CO2 emissions would be reduced by 15%. If the range could reach 1200 nautical miles and replace more than 80% of aircraft departures, NOx emissions in the airport area would be reduced by more than 60%, and fuel use and direct CO2 emissions would be reduced by approximately 40%. In addition, an all-electric aircraft has the potential to reduce noise, especially during takeoff [60]. In the long term, all-electric aircraft have the potential to achieve zero emissions during flight, a feat difficult for other emission reduction technologies in aviation, such as biofuels, hybrid- or turbo-electric aircraft, and combustor technology upgrades [56]. These significant environmental benefits give us a glimpse of the potential for electric aircraft.

3.2. Limitations of Purely Electric Aircraft

NASA’s 2017 Battery Symposium provided insights into the specific energy of battery systems, a development bottleneck for current aircraft propulsion electrification efforts. Results indicate that the specific energy of batteries available for aircraft applications is expected to reach 500 Wh/kg by the 2030 timeframe, which is a significant decrease from previous expectations [61].

Because of the limited size of the wings and fuselage available for energy storage, the specific energy of the battery is important for the design of the aircraft, the range of the aircraft, etc. [22]. Battery technology has evolved to the point where Li-ion batteries offer the best prospect for developing high-energy and high-power batteries. This is attributed to the fact that lithium is the third lightest element with the highest oxidation potential of all known elements (3 V higher than the standard hydrogen potential) [62]. The current specific energy of batteries of different materials (achieved as of 2022) compared to conventional fossil fuels is shown in Table 3 [63–65]. It can be seen that the energy density of conventional fossil fuels is still more than 28 times higher than that of today’s higher specific energy batteries. It can also be observed that RP-3 and Jet-A fuels exhibit slight differences in specific energy performance but are generally similar.

Table 3. Specific energy of different batteries and fossil fuels.

<table>
<thead>
<tr>
<th>Chemistry</th>
<th>Theoretical Limit (Wh/kg)</th>
<th>Specific Energy (Wh/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Battery</td>
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<td></td>
</tr>
<tr>
<td>LiCoO2/C6</td>
<td>568</td>
<td>275</td>
</tr>
<tr>
<td>Pd-Acid</td>
<td>171</td>
<td>55</td>
</tr>
<tr>
<td>NiMH</td>
<td>240</td>
<td>116</td>
</tr>
<tr>
<td>Li-S</td>
<td>2654</td>
<td>420</td>
</tr>
<tr>
<td>Na-S</td>
<td>792</td>
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<tr>
<td>Gasoline</td>
<td>-</td>
<td>12,012</td>
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<tr>
<td>RP-3</td>
<td>-</td>
<td>11,984</td>
</tr>
<tr>
<td>Jet-A</td>
<td>-</td>
<td>11,917</td>
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</table>

While electrical energy is utilized much more efficiently than the thermal cycle, the total efficiency of an all-electric propulsion system may reach (optimistic estimate) 76–82%, depending on the loss of energy storage and the efficiency of the electric motor and propeller. The thermal efficiency of internal combustion engines ranges from 24% to 50%, and with other losses in the engine (such as friction, exhaust, etc.) and the efficiency of the drive and propeller system, the total efficiency of conventional propulsion systems is only 20–36% [22]. That is, about 2.4–4.3 kWh of energy in 1 kg of kerosene is used for vehicle thrust. Assuming a current battery technology level of 400 Wh/kg, approximately 7–14 kg of battery can store the same amount of useful energy. In other words, 1 kg of kerosene has
a similar amount of useful energy as a 7–14 kg battery pack. For these reasons, all-electric aircraft are better suited for small, short-range transport.

4. Application of Hybrid Power

The shortcomings of all-electric aircraft in terms of range and passenger capacity can be complemented by hybrid aircraft [66]. This section briefly describes the application of hybrid power in aviation.

4.1. Hybrid Drones

With the development of artificial intelligence and related technologies in recent years, drones are receiving more and more attention. With their safety, ease of use, and environmental friendliness, drones are widely used in military and civilian applications to perform dangerous or long-range missions, and countries around the world are developing drone technology to facilitate different tasks [67–69].

There are different classifications of UAVs according to different criteria. Arjomandi et al. [70] classified UAVs according to their weight, range, payload, and other parameters. They classified UAVs into super heavy UAVs, heavy UAVs, medium UAVs, light UAVs, and micro UAVs. Watts et al. [71] classified UAVs into military and civilian aspects and classified them based on characteristics such as flight endurance, such as NAV (Nano Air Vehicles), VTOL (Vertical Take-Off & Landing), LASE (Low Altitude, Short-Endurance), LALE (Low Altitude, Long Endurance), and HALE (High Altitude, Long Endurance).

According to the propulsion system, UAVs can be classified as conventional-fueled UAVs, fuel–electric hybrid UAVs, and purely electric UAVs [72]. Turbine engine drones, particularly those equipped with turboshift or turbojet engines, represent an advanced technological branch in the UAV field. These drones are typically used for missions requiring long endurance, high reliability, and the ability to operate in complex environmental conditions. However, the incorporation of turbine engines also results in high research, production, and maintenance costs. Specifically, turbojet engines have low fuel efficiency, increased maintenance difficulty, and higher failure rates. Additionally, turbine engines are usually noisy and generate strong infrared heat signals, which are detrimental to covert operations. UAV applications with purely electric systems are hindered by the constraints of battery energy density. The advantages and disadvantages of pure electric drones and the aforementioned turbine engine drones are complementary. In the case of fuel–electric hybrid drones, the engine and generator provide power together, combining the advantages of turbine engine UAVs and pure electric UAVs. Fuel–electric hybrid drones can achieve higher energy utilization efficiency, better adapt to different environmental conditions, and perform long-endurance and high-performance flight missions. Hybrid power systems are typically equipped with more complex energy management systems and intelligent control algorithms, enabling drones to automatically adjust power modes based on task requirements, remaining battery power, and flight status, thus enhancing autonomous decision-making capabilities. This efficient management grants fuel–electric hybrid drones greater flexibility and reliability, ensuring mission continuity and enabling automatic energy-saving measures in emergencies, such as finding suitable landing locations. Hybrid-electric propulsion systems are divided into series, parallel, and power-split configurations (as shown in Figure 2). In the series system, the engine drives the generator to generate electrical energy, which in turn drives the electric motor to work. In a parallel system, if the engine power is too low, the generator will convert the excess power into electrical energy and store it in the battery. If the engine power is insufficient, the battery will release electrical energy to drive the motor and compensate for engine power. This mode can further improve the efficiency of the UAV propulsion system to reduce fuel consumption and further increase its flight time and range. When the UAV is operating at low speed, the hybrid power system mainly works in series, and when flying at high speed, the system works in parallel [72]. Although the hybrid system combines the advantages of
engines are usually noisy and generate strong infrared heat signals, which are detrimental to covert operations. UAV applications with purely electric systems are hindered by the complexity and cost of battery systems, leading to increased UAV cost and system complexity [73].

In the military field, fuel–electric hybrid UAVs have the advantages of long flight time, high efficiency, and good stealth performance, which can be effectively applied [73]. Such UAVs can also be used in national security and disaster monitoring missions involving intelligence, surveillance, and reconnaissance (ISR). Frederick G et al. [66] designed and simulated a UAV using a parallel hybrid propulsion system and concluded that the UAV consumed 54% and 22% less energy than a four-stroke gasoline-powered UAV for 1 h and 3 h ISR missions, respectively. In the civilian field, UAVs are widely used. They can take images of farms, provide information to agriculturists, and even conduct pesticide spraying. Drones can help researchers conduct geological surveys and take pictures of landforms, and they can also be applied to emergency supplies, logistics in remote areas, and special logistics [75].

For UAVs, ultra-long endurance is a very important capability, so in addition to fuel–electric hybrid systems, there are also fuel cells, lithium battery/FC hybrid power systems, lithium battery/supercapacitor hybrid power systems, and many other power sources [76,77]. With the development of the times, all these technologies will be better applied to drones to serve mankind.

4.2. Hybrid Airliner

Based on the same problems as those faced by vehicles and drones, hybrid power units are gradually beginning to be used in aircraft. However, unlike hybrid vehicles, the application of hybrid power units in aircraft is still immature, and there are no large passenger aircraft with hybrid power units officially in use. Some components that could be used in vehicles are too low in specific power to be used in aircraft. The most significant technical difficulties faced by hybrid airplanes in practical applications stem from energy density and weight constraints. The energy density of existing batteries is not sufficient to support the demand for long flights while increasing the battery capacity as well as additional hybrid components, such as electric motors and control systems, will increase the total weight of the aircraft. This has a direct impact on the performance, efficiency,
and economics of the aircraft. Only ultralight hybrid aircraft have been developed [78]. Stakeholders are preparing to put electric and hybrid-electric aircraft into operation by 2035 [22].

Hybrid aircraft are also divided into series and parallel types. Hybrid aircraft can be driven by a propeller, which in a parallel hybrid aircraft can be rotated by either an electric motor driven by batteries or by an internal combustion engine [79,80]. In a series hybrid aircraft, no mechanical power transfer is required between the electric motor and the internal combustion engine, and the generator can provide additional power during takeoff if needed.

In order to put hybrid aircraft into service like conventional aircraft, scholars have been designing and simulating aircraft after applying a hybrid system approach, based on the concept of conventional aircraft. The benefits of using hybrid-electric systems in general aviation are very little, and there is little reduction in maximum takeoff weight and primary energy consumption compared to a conventional propulsion system [81]. For narrow-body airliners, the application of hybrid power units may reduce energy consumption and pollutant emissions [66].

Figure 3 shows the performance of the B737-800 and the hybrid aircraft based on it. The 2 MW EM and 4 MW EM configurations represent a B737-800 aircraft equipped with CFM56-7 gas turbine fans, each with 1 MW and 2 MW electrical boost, respectively. Due to the additional weight of the batteries, both hybrid aircraft are heavier and thus require more energy to meet the basic mission scenarios of the given airframe. Across the entire flight scenario, the energy consumption of the three configurations varies slightly. However, compared to the baseline B737-800, the 2 MW EM and 4 MW EM configurations reduce fuel consumption by 5.4% and 10.1%, respectively. Fuel efficiency increases from 29.2% to 33.0% and 37.3%, respectively, while energy efficiency improves from 29.2% to 31.1% and 32.9% [82]. In 2030, the HEA-A320 narrow-body aircraft is designed to be able to carry 125 passengers with a range of 1633 km, while allowing a fuel saving of 1500 kg per mission. For this purpose, a lithium-air battery system with a total energy capacity of 23 MWh is required [83]. This indicates that battery technology still needs to be developed significantly. Julian Hoelzen et al. [84] studied the role of batteries in hybrid propulsion systems in a regional aircraft and concluded that HEA with a 350 NM range in the regional aircraft category would be cost-competitive compared to conventionally powered aircraft.

![Graph showing required and consumed energy](image)

**Figure 3.** Performance of the B737-800 and its hybrid aircraft. (a) required energy; (b) consumed energy.

Based on the above studies, it can be seen that the complete application of hybrid power units to medium and large aircraft is currently not possible. However, with the upgrading and improvement of battery technology and hybrid power units, the future development of medium to large fuel–electric hybrid aircraft will be an important trend to reduce pollutant emissions.
5. Biofuel Emission Reductions

Currently, the main technical routes for biomass aviation fuels that comply with the American Society for Testing and Materials (ASTM) standard include Fischer–Tropsch synthetic paraffinic kerosene (FT-SPK) [85], hydroprocessed esters and fatty acids synthetic paraffinic kerosene (HEFA-SPK) [86], synthesized iso-paraffins from hydroprocessed fermented sugars (HFS-SIP) [87], alcohol-to-jet synthetic paraffinic kerosene (ATJ-SPK) [87], gasification and Fischer–Tropsch synthesis (GFT) [88], and direct sugar to hydrocarbon (DSHC) [88]. Different processes produce biofuels with different characteristics, and the goal of these processes is to make the chemical composition of biofuel as close as possible to that of aviation kerosene. There are numerous research results available.

The process of preparing jet fuel from fossil crude oil and biomass is shown in Figure 4. Although biofuels require the same negative entropy flow input, hydrogen consumption, and greenhouse gas emissions during preparation and combustion as conventional fossil fuels, biomass is capable of absorbing large amounts of greenhouse gases (GHG) during the growth and cultivation phase [89,90]. Therefore, from a whole life cycle perspective, the carbon emissions of biofuels are much lower than those of petroleum-based fuels. In addition, because the sulfur content of biomass is much lower than that of petroleum, fewer harmful substances are produced during the refining process [91].

Figure 4. Process of preparing jet fuel from petroleum and biomass.

5.1. Preparation Process

From a preparation perspective, while the process method determines the type of biofuel, the choice of feedstock has a more important impact on carbon emissions. Three generations of biofuel have been developed depending on the source of the feedstock: crop-based waste grease (first generation), lignocellulosic (second generation), and algal biomass (third generation). The first generation of biomass is mainly waste grease and other oil-bearing biomasses are less used in biofuel applications due to competition with people for grain. Gonca et al. [92] calculated total CO2-equivalent life-cycle GHG emissions for the preparation of jet fuel and diesel fuel in the range of 16.8–21.4 g·MJ−1 and 12.2–16.9 g·MJ−1, respectively, using butterfat derived from used cooking oil as a feedstock. This corresponds to 76–81% and 81–86% reductions in life-cycle GHG emissions, respectively, compared to conventional aviation fuel.
Lignocellulose is mainly composed of cellulose, hemicellulose, and lignin. In its conversion to bio-jet fuel, it usually needs to go through the process of depolymerization, condensation, and hydrodeoxygenation [93]. The process is usually accompanied by high-temperature heating and the use of chemical reagents, catalysts, etc. At the same time, the high amount of carbohydrates in the feedstock makes the oxygen content relatively high, resulting in a low energy density of the feedstock. However, the wide range of feedstock sources and the huge annual production volume make cellulosic biomass a huge advantage as a raw material for biofuel [94]. Karol et al. [95] conducted a Life Cycle Assessment (LCA) on CO₂ emissions of biodiesel (FAME), conventional diesel oil (ON), and bio-butanol prepared from lignocellulose in the manufacture and service life stages. It was obtained that the CO₂ emissions in the manufacture stage were ON > butanol > FAME, and in the service life stage were FAME > ON > butanol, while in the whole life cycle, FAME had much lower CO₂ emissions than the other two fuels, as shown in Figure 5. Biodiesel falls under the category of biofuels but is not considered SAF. However, from a full lifecycle perspective, it can reduce CO₂ emissions, and the synthesis process generates FAME, making it a useful reference.

Algal biomass has a higher energy density compared to lignocellulose. More importantly, there are algae with high oil content that are more suitable for biofuel preparation and microalgae with high protein content that can be used to produce feed, fertilizer, and other nutrients [96,97]. The degree of polymerization in the microalga feedstock is much lower, so the reaction conditions in the preparation process are much milder. Since the carbon chain length of fatty acid molecules in algal biomass is relatively long, and in some algae, even matches the alkane carbon chain length in kerosene [98], the additional condensation step in lignocellulose to lengthen the carbon chain is not required. Also, since the oxygen content of fatty acid molecules is lower than that of reducing sugars, there will be lower hydrogen consumption in the hydrodeoxygenation step. These reduce the input of negentropic flow during the preparation process and reduce the energy consumption during the preparation process.
5.2. Combustion Process

Although biomass preparation minimizes differences in composition from traditional fossil fuels, differences still exist. For example, aviation kerosene contains about 27% naphthenic and aromatic hydrocarbons, which are more likely to form soot than alkanes [99]. The total content of naphthenes and aromatics in biofuels is significantly smaller than that in aviation kerosene RP-3 [100], which means that biofuels produce less soot in combustion than aviation kerosene RP-3. Several studies have been conducted to test the combustion performance and emissions of biofuels and conventional fuels from different biomass sources in comparison.

5.2.1. Gaseous Emissions

Balaji et al. [101] conducted combustion and emission tests of corn biofuel with Jet-A, a U.S. civil jet fuel, in a small gas turbine. The experiments tested the engine performance and emission performance at different engine speeds (30,000, 40,000, 50,000, 60,000, and 70,000 rpm) and different blending ratios (0%, 10%, 20%, and 30% of biofuel-to-Jet-A ratio). The results showed a significant decrease in CO and NO\(_x\) emissions from the blended biofuel, while CO\(_2\) emissions increased above 40,000 rpm (as shown in Figure 6a–c). This may be due to the relatively high aromatic content in Jet-A resulting in a lower H/C ratio, which tends to cause inadequate fuel combustion [102]. In the study by Corporan et al. [103], JP-8 was blended with Fischer–Tropsch synthetic jet fuel at different volume ratios. When the blending ratios were 0%, 25%, 50%, and 75%, the sulfur content in the blend fuels was 0.06%, 0.05%, 0.04%, and 0.02% by mass, respectively. In combustion experiments using a T63 engine, the SO\(_2\) emissions for these four blending ratios were approximately 34, 23, 15, and 7 ppm, respectively. Additionally, the SO\(_2\) emission levels and trends remained consistent across different equivalence ratios.

Figure 6. Cont.
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Corporan et al. [103], JP-8 was blended with Fischer–Tropsch synthetic jet fuel at different volume ratios. When the blending ratios were 0%, 25%, 50%, and 75%, the sulfur content in the blend fuels was 0.06%, 0.05%, 0.04%, and 0.02% by mass, respectively. In combustion experiments using a T63 engine, the SO2 emissions for these four blending ratios were approximately 34, 23, 15, and 7 ppm, respectively. Additionally, the SO2 emission levels and trends remained consistent across different equivalence ratios.

Figure 6. Combustion emissions (CO2, CO, NOx) from corn biofuels (a–c) and microalgae biofuels (d–f).

Boomadevi et al. [104] carried out combustion tests of Spirulina biofuel and Jet-A in a small experimental jet engine. The experiments were selected for turbine speeds of 30,000 rpm–80,000 rpm and blending ratios (biofuel/Jet-A) of 0%, 20%, 40%, 60%, 80%, and 100%. The results showed that CO2 and CO emissions increased with increasing blending ratio at the same speed, while NOx emissions were more influenced by turbine speed, with lower NOx emissions from Jet-A than biofuel at 40,000–70,000 rpm and higher emissions from Jet-A than biofuel at 80,000 rpm. The results are shown in Figure 6d–f.

5.2.2. Particulate Matter (PM) Emissions

SAFs generally yield fewer particulate emissions upon combustion when contrasted with conventional jet fuels [105]. In an experimental study by Edwin et al. [106], the combustion emissions of two distinct SAF types, Fischer–Tropsch (FT) and Hydroprocessed Renewable Jet Fuels (HRJ), produced by different manufacturers, were assessed across various combustion states on a T63 engine. It was observed that both FT and HRJ fuels consistently demonstrated reduced particle number and smoke number emissions in comparison to JP-8, in both engine idle and cruise states. This noteworthy trend exhibited an inverse relationship with the hydrogen content of the fuel, signifying that SPK fuels characterized by lower hydrogen content yielded higher particulate emissions. Lobo et al. [107] reported the results of combustion PM emissions from biofuels and FT fuels blended with conventional jet fuel (Jet-A1) on a commercial jet engine CFM56-7B. The findings substantiate the substantial potential of alternative fuel blends, when integrated with Jet-A1, to notably curtail PM emissions. Particularly noteworthy is the performance of a 50% FT fuel blend, which aligns with current aviation fuel standards and demonstrated a commendable reduction in emissions. This blend achieved a 34 ± 7% reduction in emissions based on PM values and a 39 ± 7% reduction based on mass. Liu et al. conducted combustion experiments on the ZF850 jet engine, revealing that blending 5% and 10% hydrothermal–condensation–hydrotreating jet (HCHJ) fuel with RP-3 fuel reduces PM2.5 emissions by 9.5% and 77.5%, respectively, while increasing combustion efficiency by 0.05% and 0.36% across all thrust outputs [108]. Liu et al. suggest that engine-level UHC and PM2.5 emissions can be categorized as engine-influence and fuel-influence (EIIFI) parameters, whereas CO and NOx emissions can be categorized as engine-influence and fuel-less-influence (EIFILI) parameters, which are primarily influenced by the engine [109]. Calcote et al. [110] have provided a qualitative relative ranking of hydrocarbon soot tendencies in premixed flames, which can be summarized as follows: acetylene < olefins < isoparaffins < olefins < monocyclic aromatics < naphthalenes. Given that alternative fuels typically exhibit a substantially lower aromatic content compared to conventional jet fuel, as mentioned previously, it follows that the combustion particulate matter (PM) emissions associated with alternative fuels are notably reduced in comparison to those stemming from conventional jet fuel.
Engine and aircraft manufacturers have conducted comprehensive comparisons regarding the impact of Biofuel/SAF on engine performance and emissions [111]. GE compared the emissions of a 25/75 and 50/50 Jatropha-Algae/Jet A blend fuel with Jet A using a CFM56-7B engine. Bio-SPK showed a slight reduction in NO\textsubscript{x} emissions (1–5%) and increases in CO (5–9%) and UHC (20–45%) emissions due to changes in hydrocarbon ratios leading to lower flame peak temperatures, as well as variations in atomization quality and flame position. Smoke emissions significantly decreased (13–30%) due to the lower aromatic content in biofuel. Rolls Royce’s tests with the full annular AE3007 combustor indicated that CO, NO\textsubscript{x}, and UHC emissions from Syntroleum Fischer–Tropsch fully synthetic aviation kerosene were similar to those from JP-8. Pratt & Whitney tested Jet A-1, a 50% Jet A-1 and 50% Neste Oil blend, and 100% Neste Oil in a small turbofan engine, observing no significant differences in HC, NO\textsubscript{x}, and CO emissions across different thrust levels. However, the 50% blend fuel and 100% Neste Oil reduced core smoke by 30–50% and 80–100%, respectively, with greater reductions observed at lower thrust levels. All three companies concluded that alternative fuels had little impact on engine performance.

In summary, the results of a large number of studies show that bio-alternative fuels are superior to conventional jet fuels in terms of carbon emissions during the production and preparation phase, as well as GHG, SO\textsubscript{2}, and PM emissions during the combustion phase of the fuel.

6. Concept of Biofuel–Electric Hybrid Aircraft

The application of fuel–electric hybrid in different products shows its advantages. The low emissions of batteries and the high energy density of fossil fuels make this technology widely available. However, the development of fuel–electric hybrids is aimed at further reducing pollutant emissions, while the uneven distribution of petroleum resources around the world makes the price of petroleum susceptible to large fluctuations due to political factors. Conventional hybrid units do not completely escape from dependence on fossil fuels. Therefore, the concept of biofuel–electric hybrid aircraft was proposed.

The advantages of biofuel–electric hybrid aircraft include the following: (1) Reduced emissions. Compared to conventional aircraft, using biofuels significantly lowers carbon dioxide and other greenhouse gas emissions, as biofuels are derived from renewable resources rather than fossil fuels. The addition of electric components can further reduce reliance on fossil fuels, thereby decreasing the overall carbon footprint. (2) Enhanced efficiency. Electric motors are more efficient at low speeds, while biofuel engines are more effective when high power output is needed. This combination optimizes energy efficiency during different flight phases, improving overall fuel efficiency. (3) Flexible power system. The hybrid system offers a diversity of power sources, enhancing flight safety and reliability. If one system fails, the other can still ensure the aircraft continues to fly. (4) Low noise. Electric motors operate more quietly than traditional fuel engines, helping to reduce noise pollution around airports. However, biofuel–electric hybrid aircraft also face significant technical challenges, such as aircraft weight and space planning, various costs, and infrastructure development. Table 4 presents a comparison of the advantages and disadvantages between biofuel–electric hybrid aircraft and other power-mode aircraft, including conventional aircraft/biofuel aircraft, electric aircraft, and hybrid aircraft. Ensuring key performance indicators like maximum takeoff weight, seating capacity, and flight time remain uncertain in the design of biofuel–electric hybrid aircraft. Firstly, the hybrid system can flexibly switch or combine the use of biofuel engines and electric motors through intelligent energy management strategies during different flight stages. For example, during the takeoff and climb phases, which require substantial power, both biofuel engines and battery-powered electric motors can be used simultaneously. During the cruise phase, the more efficient biofuel engine might be the primary source, with electric motors assisting or recharging. During descent, electric motors can recover and store energy, further improving energy utilization efficiency. Secondly, improving
battery energy density, using advanced lightweight materials, and optimizing aerodynamic design can also contribute to the performance.

Table 4. Comparison of advantages and disadvantages between biofuel–electric hybrid aircraft and other power mode aircraft. (Common issues with biofuel–electric hybrid aircraft = heavier aircraft weight; complex space planning; higher costs, etc.).

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<td>Reduced emissions (vs. conventional aircraft); Enhanced efficiency; flexible power system; Low noise.</td>
<td>Better flight performance like maximum takeoff weight, seating capacity, max. cruising speed, and flight time.</td>
<td>Lower CO$_2$ emissions from a full lifecycle perspective; Lower SO$_2$ and PM emissions.</td>
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<tr>
<td>Disadvantages</td>
<td>Common issues; Infrastructure development; Need to change power structure of existing aircraft.</td>
<td>Common issues; More pollutant emissions.</td>
<td>The “drop-in” nature of biofuels needs to be verified.</td>
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Unfortunately, there is limited discussion about biofuel–electric hybrid aircraft. There are, however, some studies on biofuel–electric hybrids. Bioethanol is a common biofuel that can replace gasoline in automobiles. Its ability to reduce greenhouse gas emissions from vehicle exhaust in varying proportions when blended with gasoline has been shown to be effective [112], similar to the use of bio-aviation fuels in aircraft. It has been suggested that plug-in hybrids could provide a bridge between transportation electrification and renewable bioenergy sources such as ethanol [113]. However, it is unclear how this pathway could simultaneously achieve economic, energy, and environmental goals. He et al. [113] provided a comprehensive description of greenhouse gas emissions and their energy consumption from well-to-wheel (WTW) during the use phase of ethanol, gasoline, and grid electricity. The results show that plug-in hybrids perform better in terms of GHG emissions and energy consumption, with larger battery sizes and smaller engine displacements, but with higher cost-to-power ratios. In addition, the use of E25 (25% ethanol blend) in the hybrid propulsion system reduces energy consumption and GHG emissions by 5.9% and 12.3%, respectively. Zhang et al. [114] evaluated the synergistic effects of bioethanol and spark-induced compression ignition (SICI) combustion and relied on an efficient supervisory control system to reduce GHG emissions. The results show that blending of plug-in hybrid biofuel–electric vehicles (PHBEVs) ethanol from E20 to E100 in SICI-based internal combustion engines can reduce WTW CO$_2$ emissions by 28% to 75%, respectively, with more than 7% of the reduction coming from control system optimization using an adaptive equivalent minimization control strategy (A-ECMS).

It can be seen that biofuel–electric hybrid technology can predictably bring advantages to automobiles. In the case of aircraft, bio-aviation fuels have been shown to be able to fully or partially replace conventional fuels and reduce pollutant emissions. Therefore, biofuel–electric hybrid aircraft will be an important bridge between conventional aircraft and purely electric aircraft after the revolutionary breakthrough in battery technology to achieve carbon reduction.

7. Microturbine Engine Power Systems

Microturbine engines, as a new type of micro power device, have garnered significant attention from the scientific and industrial communities in recent years due to their high efficiency, low emissions, high flexibility, and potential for wide application. Microturbine engines are miniaturized power systems based on the principles of gas turbines, with core components including a compressor, combustion chamber, turbine, and power generation system. Compared to traditional large turbine engines, microturbine engines emphasize
compactness, lightweight design, and efficient energy conversion. Most microturbine engines use kerosene or diesel specified by manufacturers as fuel, with some manufacturers recommending both for turbojet and turboshaft micro engines. Research indicates that in micro-turbojet aviation engines at an idle state of 0 °C, the kerosene flow rate is approximately 0.78% higher than that of diesel, with kerosene providing about 1.92% more thrust. At 20 °C, kerosene consumption is approximately 5.56% higher than diesel, with a thrust increase of about 1.38%. Therefore, using diesel as fuel for microturbine engines is reasonable due to its lower consumption at both 0 °C and 20 °C [115]. However, one of the major drawbacks of diesel is its significantly higher freezing point compared to kerosene, thus limiting the application of diesel in aviation micro engines primarily to model aircraft or drones.

Clean energy sources such as biofuels can also be used as fuel for microturbine engines to reduce pollutant emissions. Cican et al. conducted combustion tests on a microturbine engine using biodiesel prepared from sunflower and palm waste oil, blended into Jet A fuel + 5% Aeroshell 500 oil at proportions of 10%, 30%, and 50%. The engine model was a Jet Cat P80® provided by Gunt Hamburg, Barsbüttel, Germany. Due to the lower carbon content compared to Jet A fuel, the blended fuels produced lower CO2 emissions during combustion. Certain fuel properties varied proportionally with the percentage of biodiesel in the mixture. For example, the freezing point increased with higher biodiesel concentrations, making fuels with high biodiesel blends unsuitable for high-altitude flights. Other properties, such as low calorific power, decreased with increasing biodiesel concentration, leading to higher fuel consumption. Overall, the integrity of the engine was never at risk during the experiments, and the blended fuels could be used for low-altitude aviation applications using microturbine engines [116]. Badami et al. tested the emission performance of Jet-A kerosene, a synthetic Gas-To-Liquid (GTL) fuel, and a blend of 30% Jatropha Methyl Ester (JME) and 70% Jet-A on a small-scale SR-30 turbojet. The three fuels showed only minor differences in air mass flow rates and engine thrusts in the combustion chamber, but UHC emissions from GTL fuel and JME-Jet-A blends were approximately 25–30% lower than pure Jet-A across the tested speed range. The three fuels exhibited similar trends in NOx and CO emissions [117]. Chiariello et al. tested the emission performance of Jet A-1 and blends with 10 vol% and 20 vol% rapeseed and sunflower oils on a 30 kW commercial micro gas turbine. NOx and CO emissions were largely insensitive to fuel composition and were more influenced by engine settings. However, soot emissions were determined by both engine settings and fuel composition. Lower loads resulted in higher soot emissions, and the addition of vegetable oils increased PM emissions, with sunflower oil blends producing more PM than rapeseed oil blends. This finding differs from most studies, which the authors attribute to the chemical structure of the tested vegetable oils [118].

Due to their efficiency and environmental benefits, microturbine engines exhibit significant potential in the field of UAV propulsion [119]. However, manufacturing high-performance microturbine engines is not as simple as miniaturizing existing gas turbine engines; merely scaling down individual components does not yield an optimal design. According to the square-cube law, as the overall engine size decreases, the new area-to-volume ratios of the components become improper, failing to maintain the same relative precision levels as larger turbines and compressors. In scaled-down engines, the Reynolds number significantly decreases. The viscous frictional losses and the mixing of fuel and air in the combustor are expected to increase and decrease, respectively, with the prevailing laminar flow, leading to reduced engine efficiency and power density. Additionally, smaller engines have a greater specific surface area, resulting in increased heat loss and lower engine efficiency. This may even lead to a scenario where heat loss exceeds heat generation, adversely affecting the cold start process. Internal heat transfer between the hot turbine and cold compressor in micro engines also warrants consideration. Furthermore, the increased friction, wear, and adhesion in scaled-down engines lead to greater resonance, instability, and noise, which require primary attention [120].
Microturbine engines, as a forward-looking power technology, are crucial not only for enhancing energy utilization efficiency but also for driving the transition towards green and low-carbon initiatives. In the face of current challenges, continual technological innovation and policy support will be key factors in advancing their commercialization. In the future, with technological maturity and increasing market acceptance, microturbine engines are poised to play a more significant role in the energy sector.

8. Conclusions

This paper summarizes the current models and parameter ranges of new-energy aircraft and summarizes and analyzes the current development status and carbon reduction of electric aircraft and SAF. The application of battery technology in aircraft can enable the air transportation industry to achieve zero emissions, while its low specific energy characteristics lead to a bottleneck in the development of purely electric aircraft. By analyzing the carbon reduction benefits of SAF in the feedstock growth, preparation, and combustion emission stages, biofuels not only have negative CO$_2$ emission characteristics in the feedstock growth cycle but also have emission reduction advantages in the preparation and combustion stages compared with traditional fossil fuels. Based on the current advantages of the application of fuel–electric hybrid in multiple fields, this paper presents the application prospects of biofuel–electric hybrid aircraft. In the context of global warming, biofuel–electric hybrid aircraft would be a feasible approach to achieve a balance between pollution emissions and range in the air transportation industry.

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