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The Development and Challenges of Sustainable Aviation Fuel: Addressing Carbon Emission Reduction in the Civil Aviation Industry

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Abstract: Aircraft aviation fuel combustion is a major contributor to carbon emissions in the civil aviation industry, the most efficient approach to abate carbon in this industry is to use sustainable aviation fuel (SAF). However, the suppressive market atmosphere for the new SAF industry and the issues from production are severely limiting its scale usage. This paper starts from the current situation of SAF, with the qualitative study of its current data and provides methods for its large-scale use. This passage discovers a widespread neglect of civil aviation carbon emissions, people have just gotten started in replacement fuel exploration, which is located at the detrimental position of the investment curve. So the article interprets the existing hindering factors of SAF through price analysis, investment curve analysis and market incentive policy, then proposes the path of SAF from the selection of raw material extraction, adaptation to market incentive environment and potential development of synthesis technology according to the existing issues. Consequently, the proper exploitation of SAF needs multiple stimuli from both markets and policies, which can lead to a long-term prospective elimination of carbon emissions in the civic aviation industry.

Keywords: Sustainable aviation fuel (SAF), carbon emission, marketing incentive, potential technology.

1. Introduction

The demand for population migration rebounded dramatically since the impetus of COVID-19 was suppressed, which induced the reviving of the civil aviation industry. Jet fuel emission is considered the chief source of contamination, the huge carbon emissions have to be considered in solemnly due to the explosive development of civil aviation: If this industry sector growth that paralleling the condition before 2019 comes into vogue, this will reflect about 0.1 Celsius ascend on the global temperature fluctuation by 2050 [1]. However, a series of problematic issues are hindering the aviation industry from getting a breakthrough in terms of improving fuels. The extremely exorbitant costs for the preliminary phase evolution and the sluggish technology for exploiting non-fossil energy sources are the cardinal reasons. Upgrading existing flying machines can reduce carbon emissions to some extent, but even the alpha advanced Airbus 350-900 (359) can only abate carbon to a limited extent, which does not alter the soaring carbon emissions trend in this industry, we have to turn attention to sustainable aviation fuels (SAF) [2]. Since the Sustainable Aviation Fuel Users Group

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(SAFUG) was founded in 2008, the International Civil Aviation Organization (ICAO) has been struggling to utilize sustainable aviation fuel on a large scale, aiming to achieve the objective of energy conservation and emission reduction in the aviation industry. But the SAF is far from commercial maturity until recent times, carbon abating may be hard to become a reality if people do not have breakthroughs on both technical and market function aspects. How to remove these obstacles and consequently obtain a high percentage mixing of SAF, is up to us.

2. Status and Trend of Civil Aviation Emissions

It is generally assumed that the civil aviation industry does not generate enough carbon waste to compare with other severely contaminating producers, The data from past decades are able to demonstrate this viewpoint. However, the plot thickens if we take time to 2050, when a series of emission targets deadline is approaching according to the Paris Agreement. The huge impact of aviation to carbon neutrality is underestimated [3].

2.1. Current Fuel Emissions Data for Civil Aviation

The existing fuel of civil aviation is mainly aviation kerosene, which results in an abundant number of emissions in the civic aviation industry. Despite the aviation corporations are working in progress to replace high-emission aircrafts, The quantity of civic planes around the world still makes emissions significant.

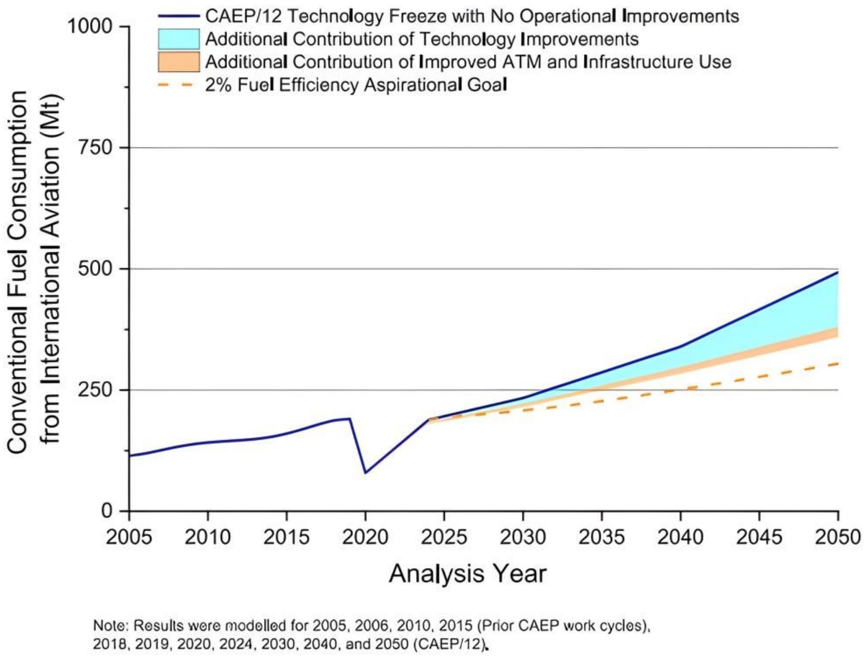

Figure 1: The conventional fuel consumption from international aviation [4].

The traditional annual fuel consumption of civic planes rebounds after a brief lag during 2020-2021, which has now recovered to pre-epidemic growth levels. Figure 1 indicates very clearly that the consumption level will increase to double size in 2050 without intervention.

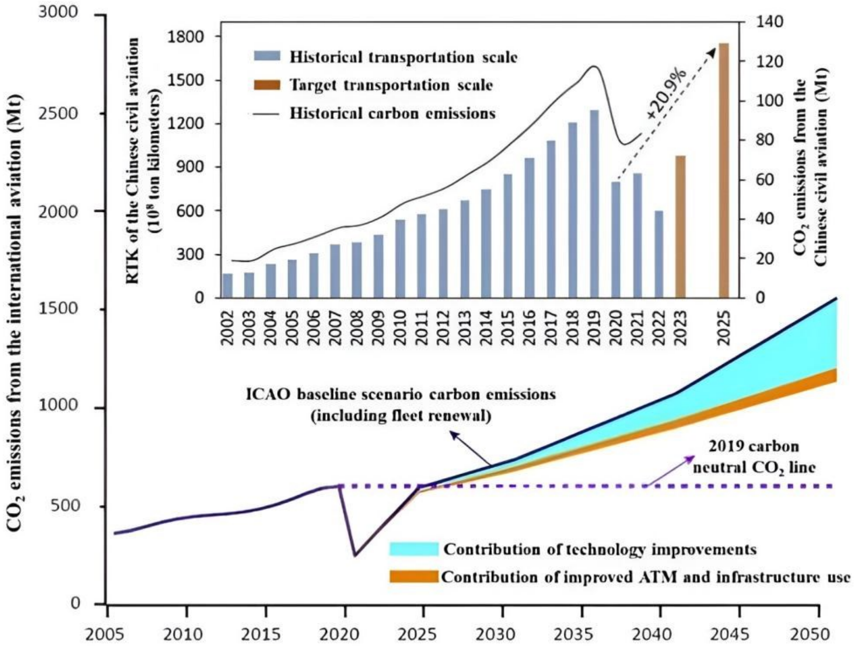

Figure 2: CO_2 emission from conventional international aviation [5].

Carbon dioxide is one of the most imperative components of aircraft emissions, which has a positive correlation with Figure 1. Correspondingly, Figure 2 makes a declaration about CO2 emission tendency. 650Mt CO2 was released by civic aviation in 2019, accounting for merely 2% of total carbon emissions. But about 1610Mt carbon emission, with a proportion nearly 25% of total, will become a reality around 2050 if people lack emphasis on this issue [5].

2.2. The Effects of Emission Trends on the Future

Although the proportion of carbon emissions generated by the aviation industry is on the appropriate scale, the above chart demonstrates that this can affect the environment unabashedly within decades. This is mainly due to the long lifetime of Carbon dioxide in the atmosphere; therefore, it is a particularly effective greenhouse gas. According to a study in 2022, After being emitted, 30 percent of a given quantity of the gas is removed from the atmosphere naturally over 30 years, an additional 50 percent dissolved within several hundred years, the remaining 20 percent stays in the atmosphere for thousands of years [6]. The cities in each nation, especially small-scale cities, are tied by more intensive flights. The carbon emissions generated by civil aviation will become a cardinal obstacle to carbon balance and carbon neutrality in the future. Furthermore, a proportion of 25% for aviation carbon output can dramatically alter the carbon cycle of both terrestrial and marine, which is able to trigger a series of ecological disorders.

3. The Necessity for Sustainable Aviation Fuel

The trend of emission and fuel consumption make us realize that civil aviation needs to be decarbonized as soon as possible. Unfortunately, we cannot simply rely on augmenting the efficiency of conventional fuels to reduce emissions. Fresh aircraft can only reduce consumption within a limited range, our exploration needs to focus on sustainable aviation fuels, which can suppress carbon emission in terms of structure. Let alone the SAF have edges that other than environmentally friendly: A wave of international cooperation will come into vogue in the aviation industry due to the technological and commercial attributes of SAF.

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3.1. Slow Saving Process for Current Fuels

The main fuel for recent years is aviation kerosene, which has not been replaced by low carbon, commercially assessed sustainable fuel on a certain scale. Thus, to suppress carbon emissions, airlines have to maximize the savings on flight fuel in the circumstance that without the introduction of new, environmentally friendly fuels. The replacement of airplane type can partially resolve this problem. Nevertheless, The Airbus 350-941 (359) and Boeing 787-9 (789), which are known as brand-new fuel-efficient aircraft, are account for only a fraction of civil aircraft. Despite we believe that most planes can be improved to fuel-efficient versions before 2050, we still struggle to achieve the goals set out in the Paris Agreement without changing the main components of the fuel, kerosene. Take the fuel consumption for several aircraft types in certain loading and general cruise altitude as an example: The European Environment Agency (EEA) concluded that the Airbus 350, as one of the most fuel-efficient new models, saves more fuel than its commercial counterparts like Airbus 380 (Table 1) [2]. But that is still not enough to make up for the surge in carbon emissions caused by the fleet expansion of aerial vehicles.

Table 1: The fuel consumption comparison of different aircraft types

Aircraft Type	Fuel Consumption, EEA Master Emission Calculator (kg/km/seat)
Airbus 350-941 (359)	0.01880
Boeing 787-9 (789)	0.02056
Airbus 380-861 (388)	0.02595

3.2. SAF and Carbon Emissions

It is a great triumph if we are capable of jumping out of the traditional aviation fuel and applying SAF. The specific extent of carbon reduction varies with the different incorporation ratios of scenarios. According to Figure 3, the rate of increase in carbon dioxide emissions will barely ascend after 2025 in the case of more than 50% percent SAF mixing, which is known as Intermediate scenario. Furthermore, The Maximum scenario (100% SAF is added for aviation fuels) will shift the peak year of CO2 emissions to 2025. Although this is merely the theoretical model, we can briefly realize the significance of the proportion of SAF interposition, which is correspond with policies that gradually enlarge the proportion of SAF inclusion currently proposed by the energy bureaus.

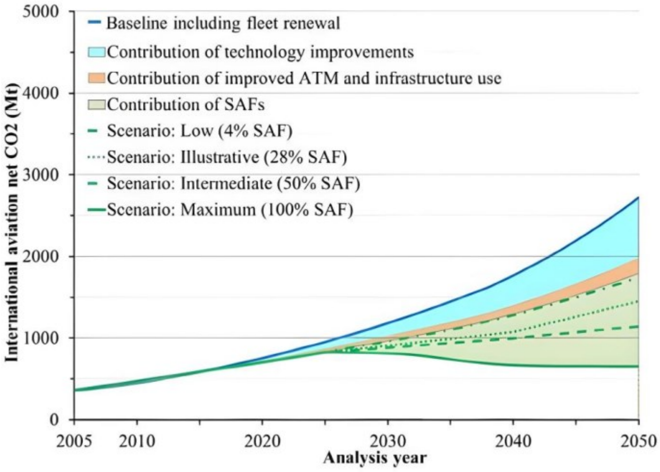

Figure 3: International aviation net CO_2 trends under different scenarios [7].

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3.3. SAF can promote pristine international cooperation in the civil aviation industry

Since the middle of the last century, most countries have erected elaborate oil refining industries, the traditional fuel industry chain has entered the saturation stage of process, So the international co-operation relationship in this field is disintegrating to some extent. SAF, recognized as the most effective measure to reduce emissions in civil aviation, is a technical issue that countries need to cooperate and overcome. Countries will tightly couple with each other with the impetus of carbon reduction and their own aviation economic transformation. Statistics indicate that in the past decade, the entities led by the U.S., China, Germany and the United Kingdom have connected the cosmopolitan study partnerships for SAF. China has published 153 papers in cooperation with other nations, compared with 234 papers form the United States [8]. Hardly can be omitted that the SAF can entail the trend of international alliance.

4. Policies

The use of SAF has been on the agenda since the SAFUG was founded in 2008. A few flights flew with a certain percentage of biodiesel within past years, recently a huge number of planes are operating in every continent with a disparate mixing ratio of SAF. This phenomenon partially attributes to the alter of policies: Early policies are merely appeal for vigorous research and development. But in recent years, both the compulsory policies that proposed the SAF proportion and the market incentive policies have been carried out, which accelerated the process of using SAF.

4.1. Compulsory Requirement Policy

In recent years, numerous regional organizations have contended with the mandatory use of SAF. The European Union has precisely proposed the proportion of SAF mixing, which inclining to commercialization and carbon-neutral goals. China has opened indigenous airport to establish the SAF commercial pilots. Furthermore, other countries have set the standards in succession, which guaranteed the baseline of SAF mixing. Table 2 enumerates some entities that are active pioneers of this domain.

Table 2: Compulsory requirement policy lists of several regions

Year of implement	Implementing region	Policy content
2024	Singapore	From 2026, flights from Singapore will need to use SAF, with the goal of increasing SAF consumption to 1% of total and work in progress to increase the ratio to 3% -5% by 2030 [9].
2023	European Union (EU)	Fuel suppliers will have to incorporate 2% SAF in 2025, 6% in 2030 and 70% in 2050. From 2030, 1.2% of fuels must also be synthetic fuels, rising to 35% in 2050 [10].
2024	China	China has opened indigenous airports to establish the SAF commercial pilots: Zhengzhou(CGO), Chengdu(CTU), Peking(PKX) [11].

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4.2. Market Incentive Policy

This incentive assists can basically be divided into output incentives or feedstock subsidies. But SAF is in the naive stages of applying certain suitable raw materials, so we chiefly focus on the latter type. The Inflation Reduction Acts (IRA), which has been implemented by the U.S. government in 2022, has introduced two imperative declarations for SAF producers, both of them indicate the extents of tax credit in certain conditions [12]. For other countries, the market incentive policies are quite naive in each country. The IRA is engendering a major effect of guiding SAF to marketization.

5. Challenges

Promoting SAF obviously needs to address a good deal of practical challenges. The cost for upfront stage is the first issue we have to encounter, which incorporates the cost for SAF itself and the bulky infrastructures that need to be erected. Besides, the investment process can be financially unstable. In this passage, we compare it with the product life cycle to illustrate the dilemmas in this certain regard. Finally, the market incentive policy may not be fixed with financial situations for some reason.

5.1. Exorbitant Cost

For more than decade, aviation and energy companies have been exploring to replace traditional fossil energy. A small amount initially, but gradually up to 100% using SAF operating wide-body commercial aircraft tentatively, which superficially accomplished the technical breakthrough theoretically. However, the consensus in the industry is that the current SAF capacity is far from enough to meet the industry demand. Exorbitant cost in long term is still an issue due to lack of scale, The price for importing SAF is approximately 3 times for ordinary fuels [13]. This magnification rate of price is accepted by some companies that are willing to reduce their carbon emissions, these companies always have already made public commitments to emission reduction targets or have a tighter focus on corporate sustainability compared to their market lust, thus their commitment sets a promising benchmark for the worldwide aviation industry [13]. Equally important, a great amount of infrastructure is needed to assist the production processes of SAF. The European countries, for instance, have explicitly proposed mixed proportions of SAF for the coming decades. With the estimated jet fuel demand increasing to 10 million barrels per day (BPD) by 2040, about 50 hydro-processing units with a capacity of 10,000 BPD would be needed to produce enough SAF for 5% blending [14]. Although the establishment of the plant is an imperative step after the scale production of SAF, the sources of SAF are multiple, which include the evolution in the landfill, biomass resources and agrarian attach productions. Thus, this needs cooperation involving many industries, people now have to take land source planning as a prerequisite of SAF industry, which entails it cost sky high.

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5.2. High risk of investment for SAF

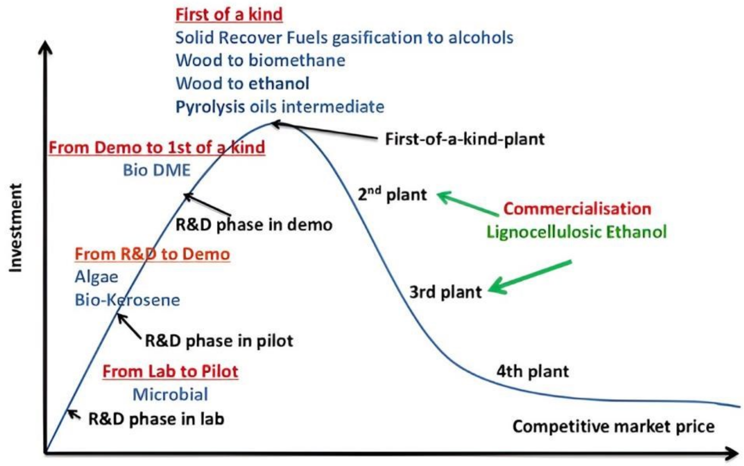

Figure 4: The curve of SAF investment in terms of innovative technology [7].

Figure 4 indicates the investment process. To put a brand-new fuel into a mature, well-equipped fuel market to serve civil aviation, we should go through a sophisticated demo stage before scale output, which is paralleling with the product life cycle to some extent. The introduction period requires immense promotional capital to promote if an entrepreneur is eager to take some market share. Even pulse-on the capital for the introduction is straightened for a bunch of entities, people are not willing to take risks on a pristine investment object. But the SAF is more than just a simple marketing product, it has to fuse with a huge transportation pillar industry, which can generate economic risks. The curve explains that the SAF entered the beginning of the experimental production only after the “first of a kind” showed up. At the time, the investment in SAF had reached its peak points, however, is the most conspicuous distinction from the life cycle of a marketing product. Currently, many countries have set up policies that mix the SAF into traditional fuels. In a other words, SAF is located in the last minute of proximity to the summit. David, the author of quote the graph, called this innovation pathways “Mountain of Death”, as many projects collapse at this stage, mostly for financial reasons [7]. Thus, the blocks we faced are not only from exterior markets but also fears derived from our inward due to financial fluctuation of the SAF.

5.3. Inappropriate Reasons

The market incentive policies we mentioned in the last part, indeed bring a series of merits for SAF plants. However, despite the positive effects for the producers’ appetites, this act may not match the production orderliness of the manufacturer. For IRA, the next tax credit starts in 2025 and expires at the end of 2027 [12]. In this case, producers could not easily generate standardized fuel before the credit become unavailable. Another drawback of incentive policies has taken place in the European countries: The Carbon Border Adjustment Mechanism (CBAM) is an EU regulatory measure under the act “Fit For 55”, which has covered the sustainable sphere. But this mechanism may affect GDP decline, trade retaliation leads to multiplied economic losses, which would be borne mainly by poor countries [15]. So, the impedes in terms of policies are one important causation because SAF cannot be used on scale.

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6. Development

People have been seeking approaches to enlarge the usage of SAF in time. Nowadays, we have to devote ourselves to its commercialization first by choosing the raw materials. Then the policies that do not match the market supply demands should be altered, coupled with the collaboration between the airlines and the leader in the SAF industry. Moreover, technological advances basically determine the prospects of its market share. The synthesis and production processes have made some progress recently, but are still far away from entering a mature industrial chain, which is a issue that requires persistent exploration.

6.1. The Commercialization of the SAF

This part can basically be divided into two aspects: The raw materials of SAF and the market demand stimulus. Both aim to abate the costs in different stages: The beginning stage for the former and the deepening stage for the latter.

6.1.1. Raw Material Selection

The commercialization of SAF is limited by the high extraction cost of catering and waste oil in industrial production, as well as the restricted production volume and sophisticated subsequent processing procedures. So, finding suitable crude materials plays a great part. The staple should not conflict with our food sources; thus, people should mainly concentrate on four kinds of potential sources from other aspects, rather than the part we eat [16]. (Elaborated in Table 3)

Table 3: Some potential sources of SAF

Potential sources	Elaborate classes
From our waste	Used Cooking Oil (UCO), municipal solid waste, recycled construction materials
From the soil	Corn husks, wood waste from mills, sugar cane and sugar beets
From the water	Seaweeds and algae, salt marsh grasses
From the air	CO_2

6.1.2. The Coordination of demand and supply

With the deepening of the civil aviation industry, the market competition for SAF has become increasingly fierce. To avoid the sluggishness of meeting producers' financial needs, oil manufacturers and aviation companies should be encouraged to coordinate, and the coordination between the fuel demand side and the supply side should be formed. To promote the SAF, Europe has introduced a combination of tax cuts, mandatory use and allowances to accelerate the low-carbon transformation of airline, then forced SAF into the airport supply chain. In addition, airlines should establish partnerships with global leaders in SAF to more accurately leverage their market edges. The SkyNRG, one of the SAF company with strong commitment, has cooperated with the KLM Royal Dutch Airlines in 2019, which can assist in erecting Dutch bio-fuel plants [17].This is a benchmark for demand stimulus oriented we should strive for.

6.2. The Technological Breakthroughs in SAF

The bottle necks for technical level are concentrating on the synthesis process. Fortunately, a series of new techniques may account for manufacturing approaches in the future.

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6.2.1. The Breakthrough in SAF Synthesis

Fischer-Tropsch Synthetic Paraffinic Kerosene (FT-SPK) is the earliest SAF conversion pathway [18]. This method is the key to reducing the ecological impact of remote airports due to the long-range transportation of kerosene. FT-SPK can allow decentralized on-site production of synthetic paraffinic kerosene [18], which is the pursuit of the producers. So, this synthesis approach can eliminate the risks of contamination during the kerosene conveying.

6.2.2. Potential Technologies

The materials and technical issues of SAF have been linked to the American Society of Testing Materials (ASTM). Fortunately, several new techniques that are not authenticated by this institute have been presented. Two practical solutions are proposed in Figure 5: Converting Lignocellulosic feedstocks and wet algae to Liquid Jet Fuel, or carbohydrate to hydrogen by photo fermentation [19].

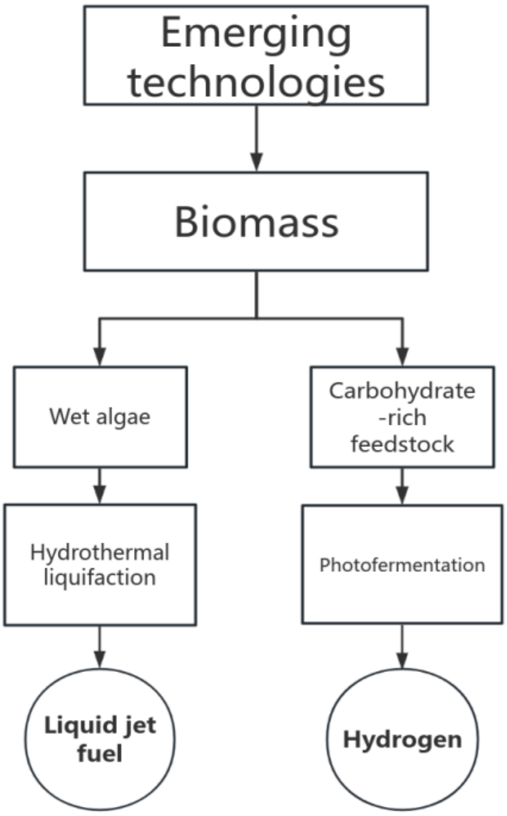

Figure 5: Two methods that produce SAF from biomass [19].

Algae Hydrogen aircraft are less expensive to operate than kerosene-powered aircraft, but the production and maintenance costs dramatically increased by about 25% [19]. Equally important, Hydrogen's low volume density indicates that we need larger fuel tanks. These tanks have to be deposited in the main body of airplanes, thus the space for passengers will be contracted, which can become a fatal drawback for narrow-body aircraft due to their single aisle. Nevertheless, Hydrogen fuels still ranked as one of the potential scenarios for SAF.

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6.3. The Outlooks of SAF

The Virgin Boeing 787-9 flight, which took off on 28 November 2023 from London Heathrow (LHR) to New York John F Kennedy Airport (JFK), is the first to showcase the feasibility of flying on 100% SAF over such a long distance [20]. This can demonstrate the feasibility of using SAF to accomplish the targets deployed by the Paris Agreement. This kind of exorbitant cost fuel, which is seemingly not on scale, will provide non-carbon travel by introducing concrete actions. Developed countries arrange to build large-scale edible oil (biofuel) refineries and gradually exploit pure renewable energy sources (such as hydrogen energy). Great progress in SAF has also occurred in developing countries: China has erected two commercialization companies; the production regime is the Hydrotreated Esters and Fatty Acids (HEFA) process with waste oil as raw materials [21]. With the multiple explorations in different types of SAF, it can come into vogue in the aviation industry.

7. Conclusion

For more than ten years of experimentation, SAF has been proven to be a suitable aviation fuel in the long term, which can significantly reduce the carbon emissions of the aviation industry. Although commercialization, technology refining and competition for alternative products are the suppressive factors of SAF, the spur of the Paris Agreement and the policies espoused can let people to divide the emissions cuts into several periodical targets. First, upgrade the existing airplanes, which can raise the fuel efficiency as much as possible without struggling for the SAF. Consequently, gradually increase the proportion of SAF in the fuel by searching suitable raw materials and making SAF synthesis in terms of technique. The blending of incentive and compulsory policies has to regulate the whole process. If we are reducing emissions in civic aviation industry successfully, people can set a benchmark for other industries that are in a dilemma with carbon reduction and lead the world to take a key step toward carbon neutrality.

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