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An Overview of SAF and its Implementation in the Current and Future Aviation Industry

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[Abstract]

Sustainable Aviation Fuel (SAF) has recently shown exciting growth in the aviation industry. It can provide a short and long term solution to reducing net carbon emissions, an inherently difficult target for air transportation. This report reveals the composition of SAFs, how it differs from current aviation fuels, its implementation along with potential improvements, production methods, certification requirements, limitations and short and long term objectives and challenges, exploring an example where reduction in the fuel content of aromatics reduces pollutant emissions. This report also gives an insight into these production methods, current production rates of associated fuels, their input resources (feedstock), future feedstock forecasts and explores a specific avenue exploiting algae, which could significantly contribute towards the long-term production of SAF.

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Nomenclature

AJF	Alternative Jet Fuel
BTU	British Thermal Unit
CJF	Conventional Jet Fuel
CO_2e	CO_2-equivalent
EU	European Union
FAME	Fatty Acid Methyl Esters
GHG	Greenhouse Gases
LCE	Lifecycle Emissions
Mbbl	Thousand Barrels
R&D	Research and Development
SAF	Sustainable Aviation Fuel
SPK	Synthesized Paraffinic Kerosene
TBtu	Trillion BTU

Word Count

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1 Introduction

1.1 The Current Aviation Industry Issue

In the current aviation industry, environmental effects are of ultimate importance. Before the COVID-19 Pandemic, Air Transport was growing at an almost exponential rate, reaching approximately 4.5 billion passengers being transported by aircraft in 2019, with 2023 seeing 29% increases in passenger traffic year-on-year [1]. As a result, the aviation industry generates approximately 2.1% of CO_2-equivalent (CO_2e) emissions (914 million tonnes) caused by human behaviour worldwide (43 gigatonnes) in 2019, with the U.S. consuming 1.71 million barrels of jet fuel per day in 2023 [2, 3]. With current engines nearing maximum efficiency, efforts are being directed elsewhere to further reduce lifecycle emissions (LCE) associated with aviation.

Worldwide, investment within the aviation industry is being directed towards greater efficiency, reducing emissions and pollutions by other means. Increasing investment is channelling into research and development (R&D) to understand the potential of alternative power sources such as electrically powered engines. High specific energy and energy density are key properties for aviation fuel, allowing for reduced flight emissions or extended operational ranges. Hydrogen and Jet Fuel have a specific energy of 120 MJ/kg and 43 MJ/kg respectively, which incentivised hydrogen combustion and hydrogen fuel cell powered engines to be researched as a potential fuel source [4, 5].

Efforts to reduce the industries emissions are driven to meet Net-Zero Carbon emissions by 2050, which is a waypoint incorporated by governments to decarbonise all industries within the half-century. As governments are interested in solutions to adhere to this initiative, policy is also a factor in industry regulation to lower emissions within the designated timelines. The UK Government has issued a policy paper outlining their proposed strategies and policies, including on the aviation sector, mentioned in 4.1 [6].

One potential solution that has recently arisen is for the use of SAF, a solution opposing electric or hydrogen powered engines. In this report, a breakdown what SAF is will be discussed, exploring the viability of this technology as an emission-reducing solution compared to other strategies within the aviation industry, both in the short and long term.

2 Sustainable Aviation Fuel (SAF)

2.1 What is SAF?

Sustainable Aviation Fuel (SAF) is a group of alternative jet fuels (AJF) that are produced from renewable sources, unlike fossil-derived conventional jet fuels (CJF). These renewable sources can be from waste products such as oils and food, alcohols, agricultural byproducts, and algae. The fuel must meet sustainability requirements to be classed as a SAF. Therefore, the aviation industry can obtain fuel from the biomass industry as its feedstock.

2.2 CJF Composition

CJF collates the traditional jet fuels that arise from coal or fossil fuels. Jet fuels consist of four hydrocarbons: n-alkanes, iso-alkanes, cycloalkanes, and aromatics. Different jet fuels contain different compositions of these hydrocarbons (as well as additives). The most common commercial fuel used is JET A-1, which currently constitutes the majority of total aviation fuel used. JET A-1 is a kerosene-derived fuel consisting of C9 to C16 hydrocarbons. Its composition consists, on average, of 78.82 weight percent (w.%) paraffins + naphthene's and 21.18 w.% aromatics, has a flashpoint temperature of 38°C and a minimum freezing point of -47°C [7]. JET-A, a fuel similar to JET-A1, has a minimum freezing point of -40°C. JET-A1 is refined to optimise this property to gain superior performance for use on international flights through colder climates in winter, at a trade-off of less fuel obtained for the same amount of crude oil [8]. The typical procedure for processing crude oil into CJF in shown in FIG. 1.

Fuels must be certified to be acceptable for use in aircraft, so that engines can be certified to operate for a particular fuel. This means declaring a specification for the composition of the fuel type, resulting in different fuels having different chemical properties.

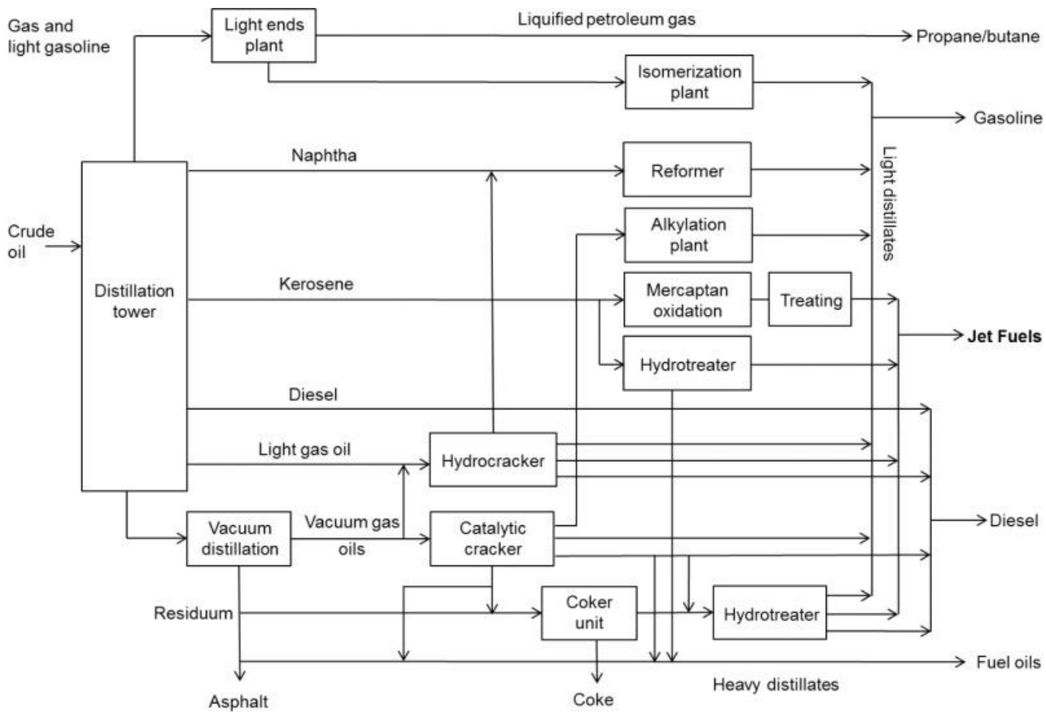

FIG. 1 Kerosene/Jet Fuel Processing Diagram. Figure taken from [7].

2.3 Method Certification

To become an aviation fuel, a candidate fuel must meet several specifications. These are set by the global standards body, ASTM International, that outline all regulatory information for fuels. This includes certified methods for creating these fuels, called a pathway. A fuel must be produced by a pathway adhering to these specifications. Just as for certifying a new fuel, a pathway also has to undergo certification to be an approved production method. Some specifications are of particular emphasis.

2.3.1 ASTM Specification's D1655 & D7566

ASTM D1655 is a standard for all aviation turbine fuels, that outlines the necessary properties a fuel blend requires, in particular for Jet-A and Jet-A1 [9]. This standard is for conventional, fossil-derived kerosene.

For SAF, additional specifications must be adhered to. ASTM D7566 specifies these properties for aviation turbine fuels containing a mixture of CJF and synthetic components, alongside outlining the specifications that define the testing methods which must be performed to confirm these fuel properties obey the standard, described in 2.4 [10]. A key section within this standard is that if the fuel meets the requirements of Specification D7566, this fuel can be reclassified as Specification D1655 turbine fuel. This means that SAF fuel that meets this specification can be treated and named as an equivalent fossil-derived fuel, such as Jet-A1. Currently, SAFs must be blended with CJF, up to a maximum 50% blend. This combined blend must meet D1655 Specification.

2.3.2 Drop-In v Non-Drop-In Fuels

Drop-in fuels are SAFs which can be interchangeable with CJF. This means that a fuel and its current infrastructure, for fuelling, transportation, storage, certification and use on aircraft, can all be used with the SAF without requiring different systems. This will be because the chemical properties of the two fuels are similar, and so the resulting infrastructure supporting the initial fuel is unimpacted with the incorporation of the new fuel.

Conversely, a non-drop-in SAF means all the infrastructure from production to aircraft needs to be added or replaced. At an airport, this requires building an entirely new, independent fuel storage and pumping system, supplying each terminal with either fuel. On the aircraft, this results in replacement of piping and fuel tanks; engines would require either modification and recertification for the new SAF, or replacement.

2.3.3 The improvement boundary of SAF due to CJF

The production of a non-drop-in SAF has clear implications on the current technology used in the aviation industry. Changing worldwide infrastructures currently used would incur excessive costs in airport architecture and aircraft maintenance. Consequently, current research has expanded on the production of drop-in SAF. However, due to drop-in SAF being inherently similar in properties to current CJFs, there is a limit on the potential benefits achievable with SAF fuels.

For example, current JET-A1, as mentioned in 2.2, consists of (on average) 21.18 w.% aromatics. The aromatic content of a jet fuel burns slower than the other hydrocarbons, resulting in higher particulate emissions, as they burn less cleanly. Aromatics have a low specific energy and so lower the jet fuels specific energy [5]. Aromatics are the most significant contributors to sooting [5]. As well as for having a high energy density (helping the fuel meet D1655 specifications), aromatics are present in jet fuel to promote swelling of seals, such as O-Rings, throughout fuel systems in aircraft. Studies show the correlation between increased aromatic content and sealant swelling, showing a potential of seals to shrink when using too low of an aromatic content, resulting in fuel leaks [11]. However, recent understandings show that this is only the case with seals that have previously been in contact with fuels containing high aromatic content [5]. Research has found a process using a combination of cycloalkanes and iso-alkanes that could provide the energy density and swelling benefits of aromatics, removing the need to use the significantly pollutant aromatics [5].

From this information, a fuel with no aromatic content seems beneficial as a superior option to CJF. However, this fuel would be a non-drop-in fuel, as current fuel systems onboard all aircraft with JET A-1 would require new sealant systems, as these have been exposed to high aromatic content fuel. New aircraft would be compliant with this fuel, however any airport infrastructure would not. The trade-off between the fuels benefits and the consequences of being a non-drop-in fuel renders such fuel a less viable solution.

For a SAF to be classed a drop-in fuel, the ASTM D7566 Specification contains a minimum aromatic concentration, currently set at 8% [10]. Therefore, SAF can provide a reduction in aromatic content, from 21% to 8%, and consequentially pollutant emissions. This reduction is limited due to the economic feasibility of non-drop-in fuels.

2.3.4 ASTM Specification D4054

D4054 specification shows the process to evaluate whether a new or modified fuel can be used in current aviation infrastructure, thus a drop-in fuel. Currently, certification of a new fuel production method is an expensive and time-consuming process. The approval process for a new or modified fuel is shown in FIG. 2.

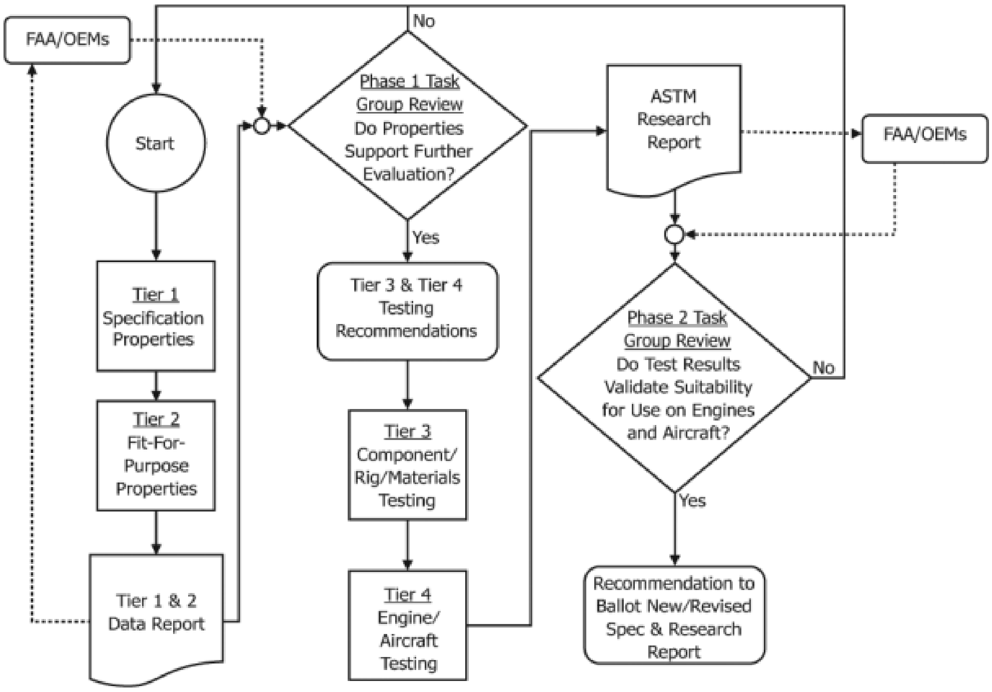

FIG. 2 Aviation Fuel Approval Process. Figure taken from [12].

During Tier 1, about 38L of the test fuel is required. Tier 2, 3 and 4 then required approximately 303L, 37,850L and 852,000L respectively, initially testing small samples for specification confirmation, up to in flight testing and fuel system material compatibility [12]. These large expenses fall on the production company, in building the necessary facilities and equipment to expand production of the new fuel for the large batch testing, as well as approximately $5.5 million in testing costs spanning up to 5 years [5].

ASTM have acknowledged these issues. Their solution to this is a fast-track approval process, based on the knowledge and experience gained up to the present day. A fast tracked fuel will skip to the ASTM Research Report stage, shown in FIG. 2. This process is only available for new fuels that have properties similar to already approved fuel blends, and limits the fuel to a 10% blend with CJF [12].

2.4 SAF Production Pathways

Currently, there are eight approved pathways, as well as three further co-processing methods (currently limited to 5% blends). These are outlined in the latest ASTM D7566 Specification. Another eleven conversion processes are under the evaluation stage. The first approved fuel, Annex A1, was approved in June 2009. The largest estimated production pathway, said to produce 82.1% of SAFs by 2029 (52 million tonnes), is HEFA (Annex A2) [1]. The current approved pathways, their feedstock and conversion processes are outlined in Table 1.

Annex in ASTM D7566	**Name**	**Date Approved**	**Feedstock**	**Process**	**Max Blend**
Annex A1	Fischer-Tropsch Hydroprocessed Synthesized Paraffinic Kerosene (FT-SPK)	June 2009	Coal, Natural Gas, Biomass	Feedstock processed into syngas. FT process applied to syngas.	50%
Annex A2	Synthesized paraffinic kerosene from hydroprocessed esters and fatty acids (HEFA-SPK)	July 2011	Vegetable Oils, Animal Fats, used cooking oils	Hydrotreated, via hydroprocessing and hydrocracking.	50%
Annex A3	Synthesized iso-paraffins from hydroprocessed fermented sugars (SIP)	June 2014	Biomass used for sugar production	Fermentation of sugar cane juice	10%
Annex A4	Synthesized kerosene with aromatics derived by alkylation of light aromatics from non-petroleum sources (FT-SKA)	November 2015	Coal, Natural Gas, Biomass	Hydroprocessing, fractionation.	50%
Annex A5	Alcohol to Jet synthetic paraffinic kerosene (ATJ-SPK)	April 2016	Ethanol, isobutanol, isobutene from biomass	Dehydration (to alcohol), oligomerization, hydrogenation and fractionation.	50%
Annex A6	Catalytic hydrothermolysis jet fuel (CHJ)	January 2020	Vegetable Oils, Animal Fats, used cooking oils	Hydrothermal conversion of fatty acid esters & free fatty acids. Combination of hydrotreating, hydrocracking or hydroisomerization, fractionation.	50%
Annex A7 (Approved through Fast Track process)	Synthesized paraffinic kerosene from hydroprocessed hydrocarbons, esters and fatty acids (HC-HEFA)	2020	Algae	Hydrogenation and deoxygenation of bio-derived hydrocarbons, fatty acid esters and free fatty acids.	10%
Annex A8	Alcohol to Jet Synthetic Paraffinic Kerosene with Aromatics (ATJ-SKA)	2023	C2 – C5 alcohols from biomass	Dehydration, aromatization, hydrogenation and fractionation.	50%

Table 1 Approved pathways to obtain SAFs, written in ASTM D7566 Specification. Data collated from [5, 10, 13].

3 Current and Future SAF Production

3.1 Current Biofuel Production

As of 2023, SAF production is in its relative infancy. SAF contributed to 0.2% of global jet fuel consumed (600million litres) in 2022, double that of the previous year [14]. This number is growing exponentially due to the approval of more pathways and the progress in building SAF facilities to increase the scale of production.

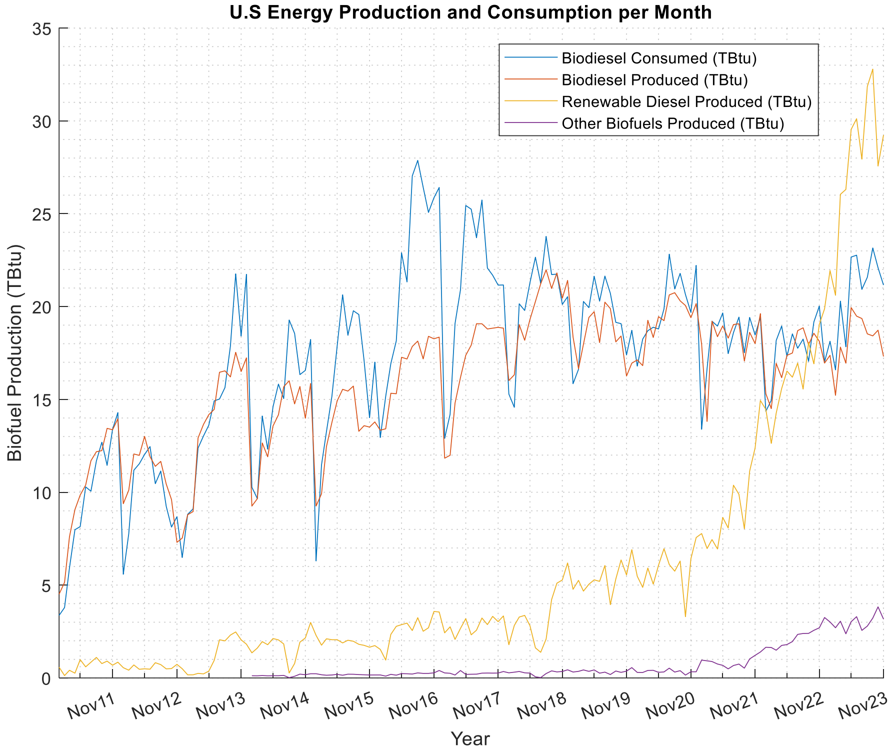

FIG. 3 Energy production and consumption in the U.S., between January 2011 and November 2023. Units are in Trillion British Thermal Units (TBtu). Data collated from [2].

FIG. 3 shows the growth of biofuel and biodiesel production in the U.S. Renewable diesel production has also increased significantly in recent years, producing a record 32.788 Trillion British Thermal Units (TBtu) in September 2023 ($1\text{TBtu} = 1.055 * 10^9\text{MJ}$ energy) [2]. As seen in FIG. 4, there is an overlap in the boiling point ranges of jet fuel and diesel, resulting in refineries having the option of picking the fuel to produce. FIG. 3 shows the clear contrast in production between renewable diesel and SAF, which contributes to only 0.25 TBtu of ‘Other biofuels Produced’ [5].

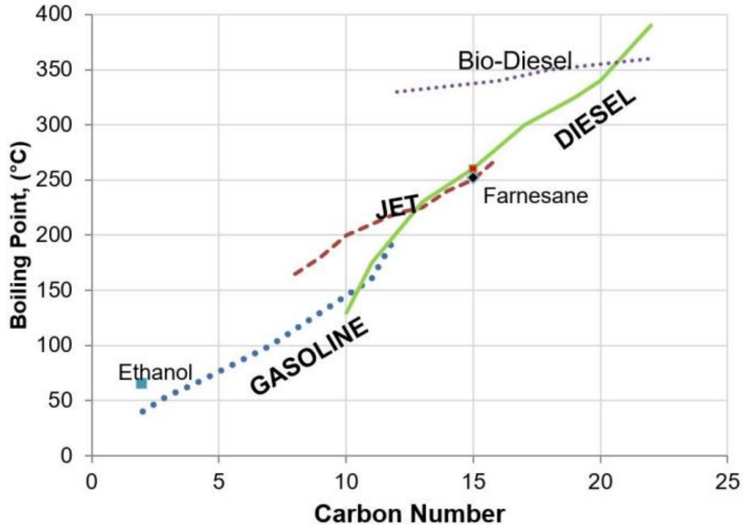

FIG. 4 Carbon numbers and boiling points for Gasoline, Jet Fuel and Diesel. Graph taken from [5].

3.2 Future Feedstock Availability

To escalate the production of SAFs, the supply of biomass feedstock has to be capable of meeting the high demands presented in 1.1.

As increasing numbers of pathways become approved, a wider variety of feedstocks become available for consumption to produce SAFs. This alleviates the dependence on each pathway, increasing the scalability of biomass consumption whilst reducing the likelihood of bottlenecking progression due to a limited supply of feedstock type. Using current pathways and assuming several pathways currently under evaluation are approved, global SAF production needs to be capable of reaching approximately 125 billion gallons by 2050 [5].

The production of biodiesel will be important to the aviation industry, as it is primarily made of Fatty Acid Methyl Esters (FAME). Its production growth can be seen in FIG. 3. It becomes relevant as HC-HEFA, Annex A7 in the ASTM D7566 Specification, is an approved pathway that includes the use of FAME to be processed into SAF [10]. FAME can be sourced from a species of algae (Botryococcus braunii), which can be hydrocracked in a refinery to produce 97% transport fuels and 3% residual oils [15]. Conclusions by [16] state that the potential for sea algae as a feedstock for biofuel into 2050 are high, with the potential of 1 billion tonnes per year, although forecasts are uncertain due to the low amount of current information in this topic. Nonetheless, the potential to increase the growth of algae to be processed into SAF is present, with the necessary supply being capable and the pathway already approved.

This process of expanding the supply of feedstocks which pathways can exploit is essential to fulfil the potential of SAF.

4 Ambitions for SAF

4.1 Short-Term Difficulties and Resulting Mitigation Strategies

As mentioned in 2.4, interests in pathway qualification are high. However, current SAF production is much lower. As of 2022, only a handful of refineries produce commercial SAF [17]. As seen in 3.1, the potential for current SAF production is available, but a large reason refineries choose to refine renewable diesel instead is due to current policy, and as SAF is not currently economically viable both during production and consumption [5]. Therefore, increasing supply and lowering prices of SAF require addressing. It has been studied that, due to the low and poor marketing, the population's 'willingness to pay' for increased airline ticket prices due to SAF is low, as little is understood on the benefits and risks of its implementation [18].

To combat this, policy has been set to mandate SAF implementation to meet the long-term decarbonisation goals. ReFuelEU is an approved proposal within "Fit for 55" legislation by the European Commission to reduce EU GHG emissions by at least 55% by 2030. It initially sets a 2% minimum SAF volume for all EU aircraft operators at EU airport, starting in 2025 [19].

The UK Government are committing £180 million towards supporting SAF development (after already committing £15 million), aiming to achieve 10% SAF production by 2030. This is alongside co-investments (£150 million annually) and support for R&D towards Zero Emission Infrastructures (£15 million) [6].

In 2023, an estimated 500,000 tonnes of SAF were consumed by the aviation industry, equating to a $756 million increase in fuel costs and a unit cost 2.8x higher than CJF. With production growth, this figure is estimated to rise to $2.4 billion for 2024 [1]. Despite profit reducing costs, the aviation industry is strongly in favour of increasing SAF usage. Between 2021-23, 75 offtake agreements were signed, contracting future SAF production from producers to an airlines [1].

The Sustainable Skies Act, introduced into law by U.S Congress, amended the Internal Revenue Code of 1986 to incorporate tax credits for each gallon of commercial SAF to the producer. This credit is $1.50 per gallon, plus $0.01 per gallon for every percent above 50% lifecycle GHG emissions reduction compared to CJF, meeting D7566 Specification or produced via FT-SPK (Annex A1) [20]. Also, the U.S proposed a $1 billion grant, spanning five years, to increase SAF production refineries [19].

4.2 Long-Term Aspirations

ASTM Specifications limit the use of SAF to a 50% blend with CJFs. For the short term, due to low production volumes, there is no encouragement for this to change. However, this is an arbitrary value and, as SAF production increases towards 2050, this limit can increase towards 100% [5]. ICAO has begun work to ensure SAF can reach 100% fuel use, also increasing co-processing pathways from 5%, up to 30% [13]. ReFuelEU are to mandate increments every five-years, from 2% minimum SAF blend in 2025 to 70% in 2050 [14, 19].

It has been suggested that SAF production via algae feedstocks, alongside other technologies currently in early development, may be the long term solution to provide the required volume needed [5]. Low-cost feedstocks need to be sourced, so that is more economically feasible to produce SAF and incentivise refineries to produce SAF instead of renewable diesel. This incentive may be helped further with the electrification shift of ground transportation, vastly lowering demand of renewable diesel. Economies of scale may help towards lowering SAF costs as the industry grows.

With the increasing use of SAF, jet fuel quality is likely to improve, as highlighted in 2.3.3. Existing engines can still be used with fuel 15% more energy dense than current fuel, which can be exploited with further SAF implementation, such as replacing aromatic contents as mentioned earlier, or with potential prospect 'high-performance molecules' [5].

4.3 Competing Technologies

Currently, other technologies are not at a Technology Readiness Level (TRL) matching SAF. R&D into electrifications technological feasibility is taking place, however the short-term forecasts are only for light aircraft, with potential to assist large commercial aircraft are at least, even optimistically, decades away. Issues that also arise, similar to implementation of non-drop-in fuels, occur for both electrification and hydrogen systems in terms of complete systems replacement [5].

5 Conclusion

Although relatively unheard of in the general population in comparison to electrification solutions, it appears imperative that SAF production continues to grow, as it is the only feasible short-term solution to limiting net GHG emissions in the aviation industry. Drop-in SAFs can improve fuel performance and reduce pollutant emissions whilst mitigating industry disturbance during transition from CJF, unlike other potential solutions. This technology is new and, with policy and recent mandates being adopted worldwide, shows the urgency required to ensure that this technology grows fast enough to cope with the forecasted growth of the aviation industry. Recent offtake agreements prove airliners' understanding of this too. It is clear that further research needs to be done to find more low-cost feedstocks that can be exploited by the industry. Government involvement to expand SAF production facilities and refineries is hopeful, as development solely from companies would always be limited due to the high costs involved with SAF implementation. However, the growth required to replace CFJs is extreme, and it is currently unsure what the feasibility of this is given the infancy of these solutions and how many factors there are towards achieving the long-term goals. Currently undeveloped feedstock markets, such as algae, require expansion to become significant contributors to SAF production. Overall, the current initial growth in the technology is portraying optimistic trends towards further implementation that achieves decarbonisation in the aviation industry.

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