RECENT ADVANCES IN THE SUSTAINABLE AVIATION INDUSTRY

Currently, global aviation accounts for approximately 2.5% of all human-induced greenhouse gas emissions [1]. A report claims that air traffic doubles every fifteen years, with an 80% increase in the number of flights between the years 1990 and 2014 [2]. In fact, greenhouse gas emissions due to aviation are projected to grow by approximately 300-700% compared to data from 2005 [3]. This drives the urgency to implement more environmentally sustainable technologies into the aviation system. Increased interest in this effort is motivated by the impact of burning fossil fuels which includes natural resource depletion as well as climate change. In addition, the aviation sector is concerned by rising oil prices and dependence on suppliers [2]. Thus, researchers all over the world are scrambling to figure out a more secure way to fuel aviation and mitigate its carbon footprint.

Despite, the increased productivity of the aviation industry and a 130% improvement in efficiency of U.S. airlines since 1978, the aviation industry has only managed to reduce carbon emissions by less than 15% [4,5]. Advancements to turbofan engines are possible; however, it is clear to many experts that reducing carbon emissions will require the implementation of aviation fuel which is not derived from petroleum [6, 7]. Jet engine design evolution generally takes 14-19 years to complete and is extremely expensive, costing hundreds of millions of dollars, in comparison to the process of fuel certification, which generally takes 3-5 years and costs $5-15 million. While, non-liquid fuel technologies like electrification or fuel cells do not currently have the sufficient energy density for commercial aircraft [4, 5]. Therefore, a more feasible approach to this issue will be to implement drop-in sustainable aviation fuel (SAF) into the current aircraft infrastructure.

According to the International Civil Aviation Organization's (ICAO) Resolution A40-18, SAFs are defined as alternative aviation fuels which achieve net greenhouse gas emission reduction throughout the fuel's life cycle, respect areas of importance due to biodiversity or other benefits of conservation, and contribute to social and economic development. Research into alternative aviation fuels began following the increase in fuel price in the 1970s, which was caused by concern regarding security of supply [7], and the first flight fueled by blended biofuel took place in 2008 [8]. With airlines committed to reducing their carbon footprint by 50% before 2050 [1, 4], there is a clear need to begin the process of implementation. That is why United Airlines began using alternative fuels in 2016, and Delta Airlines currently plans for 10% of its fuel to be SAF by the end of 2030 [9]. According to studies, the use of SAFs as a replacement for conventional fuel has the potential to reduce greenhouse gas emissions by 55-92% compared to 2005 levels [10]. Thus, this approach is more promising in the near term than any other, and it is already in the works of being executed.

In October 2016, the ICAO announced the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), which aims at offsetting 80% of harmful emissions above 2020 levels. The plan involves a proposed timeline for implementation and transition. There will be three phases: Phase I will take place during the years 2021-2023, Phase II will be during the years 2024-2027, and Phase III will be from 2028-2035. Phases I and II are known as the voluntary phases, in which airlines may choose to participate, whereas Phase III will involve obligatory mandates which will be enforced by requiring extra payment for producing excess carbon emissions above 2020 levels for all international flights [5]. In order to meet the ICAO goals, over 30% of the global jet fuel consumption will need to be SAF by 2040 [4].

Property	Units, (qualitative), (quantitative)	Description/Relevance
Specific energy	(Energy/mass), (MJ/kg)	Enables fuel efficiency by lowering takeoff weight, critical for mass-limited missions
Energy density ^{a}	(Energy/volume), (MJ/L)	Most important metric for volume-limited missions or military operations involving refueling
ThermalsStability	Variable	Limits ability of fuel to sustain elevated temperatures in the engine and fuel injector
Emissions/sooting ^{a}	Variable	Particulate emissions

Table 1. Key performance properties of jet fuels. [4]

Jet fuels consist of four families of hydrocarbons: n-alkanes, iso-alkanes, cycloalkanes, and aromatics. Other molecular families such as oxygenated molecules, heteroatom-containing molecules, unsaturated hydrocarbons (olefins), and metals are unsuitable. This may be due to varying reasons which include poor thermal stability, freeze point, and specific energy. The bulk properties of jet fuel are mainly determined by the hydrocarbon class composition. Important performance properties include specific energy, energy density, emissions, and thermal stability. Safety and operability limits are primarily shaped by the viscosity, density, surface tension, flash point, and reactivity (DCN) of a fuel. Additionally, low freeze point is a key property among jet fuels, for it allows long-range flights to use more optimum flight profiles. These properties essentially determine the range, payload, and cycle efficiency of a jet fuel in use. Table 1 describes the necessary performance properties of jet fuels. Improvements to the specific energy can enable more passengers and cargo by reducing the weight of the aircraft during flight. Therefore, when formulating alternative jet fuels, there is an opportunity to not only substitute but out-perform traditional fuels by producing a hydrocarbon mixture of maximum desirability while maintaining drop-in compatibility [4].

The n- and iso-alkane classes generally compose about 55-60% of conventional jet fuel. These molecules tend to have high specific energy, low energy density, and high thermal stability in relation to others. However, despite having the highest DCN among similar hydrocarbons, n-alkanes are known to have poor jet fuel characteristics, for larger versions have high freeze points while smaller versions do not meet the required flash point. Therefore, the blend potentials of n-alkanes are limited. In contrast, iso-alkanes have low freeze points and demonstrate desirable jet fuel properties, though they are expensive and require continued research and development toward reducing their cost. [4]

The hydrocarbon family of cycloalkanes includes a diverse spectrum of molecules. Average Jet A fuel is composed of monocyclic and fused bicyclic molecules. Monocyclic alkanes can portray a density, specific energy, freeze point, and flash point which exceeds the necessary requirements. Different subclasses of cycloalkane molecules have varying properties and remain an area of exploration within this field. [4]

The aromatics present in conventional jet fuel are mostly alkyl aromatics with low amounts of multi-ring variations. Collectively, aromatics demonstrate low specific energy, high energy density, and poor emission reports. These molecules are necessary in jet fuel to ensure the swelling of seals in order to prevent fuel leaks (this only applies to seals which have previously been exposed to fuel). However, aromatics have been labeled as the most significant contributor toward soot and particulate matter emissions, being responsible for up to 90%. Owing to the fact that these molecules do not burn cleanly, environmental benefits have been realized with fuels containing a low aromatic content [4]. SAFs with low aromatic content have been reported to reduce soot formation and other emissions by 50-70% [1]. Since drop-in SAFs are blended with petroleum fuel containing adequate amounts of aromatics for swelling, there is little need for renewable fuels to continue to contain these molecules [4].

Putting things into perspective, out of the four hydrocarbon groups, the two most important hydrocarbon families for researchers to look into are iso-alkanes and cycloalkanes, as iso-alkanes are necessary for the specific energy of a jet fuel and cycloalkanes provide sufficient energy density for the fuel. Aromatics show the least desirable characteristics and are therefore limited to 20% capacity. Research has shown opportunities to produce an attractive fuel in which aromatics are diluted with renewable iso-alkanes initially, to then be fully replaced by cycloalkanes. Notably, a SAF containing a blend of cycloalkanes and iso-alkanes could increase energy density and specific energy of the fuel while maintaining the necessary performance and characteristic requirements such as freeze point, flash point, swelling demands, and low emissions [4].

SAFs refer to a wide range of alternative aviation fuel types which can be made using a variety of methods from different feedstocks and waste products. Common feedstocks include municipal solid waste, cellulosic waste, used cooking oil, or plants such as camelina, jatropha, halophytes, or algae. There are also non-biological alternative fuels such as what is known as power-to-liquid jet fuel [11]. However in the end all SAFs must comply to the standards and specifications for aviation fuels such as ASTM D7566.

ASTM D7566 is the Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons. Any fuel intended to be put to commercial use must be certified by ASTM International first, undergoing a long process of testing. As of 2020, there have been eight pathways approved by ASTM for the production of SAFs. There are currently seven annexes to D7566:

1. Fischer-Tropsch Synthetic Paraffinic Kerosene (FT-SPK)
2. FT-SPK with aromatics (FT-SPK/A)
3. Hydroprocessed Esters and Fatty Acids (HEFA-SPK)
4. Hydroprocessed Fermented Sugars to Synthetic Isoparaffins (HFS-SIP)
5. Alcohol-to-jet Synthetic Paraffinic Kerosene (ATJ-SPK)
6. Catalytic Hydrothermolysis Synthesized Kerosene (CH-SK or CHJ)
7. Hydroprocessed Hydrocarbons, Esters, and Fatty Acids Paraffinic Kerosene (HHC-SPK or HC-HEFA-SPK)

In addition, ASTM D1655-20b (as of 2020) permits co-processing as a means of converting fats, oils, and greases from petroleum refining into jet fuel for a blending limit of up to 5% [4].

Fischer-Tropsch Synthetic Paraffinic Kerosene (FT-SPK) is the earliest SAF to be approved by ASTM. This fuel is a mixture of iso- and n-alkanes resulting from the Fischer-Tropsch synthesis of syngas which is produced from the gasification of feedstock, which transforms either lignocellulosic biomass or solid waste into fuels [7]. The main feedstocks are different types of biomass, including wood waste, grass, or municipal solid waste [4]. Key steps include feedstock pretreatment, gasification, syngas conditioning, Fischer-Tropsch catalysis, distillation, and hydrocracking, with the possible addition of isomerization and catalytic reforming [7]. FT-SPK can be applied to turbofan engines when blended with traditional petroleum fuel in concentrations of up to 50% [4]. Additionally, FT-SPK can also be produced via a power-to-liquid (PtL) process combining carbon and hydrogen via electrolysis, requiring electricity, water, and a concentrated source of CO_2. Costs for the PtL process can be highly dependent on the electrical cost; however, PtL is attracting widespread interest due to its ability to produce fuels with low greenhouse gas emissions without the involvement of biomass feedstock constraints [7].

FT-SPK with aromatics (FT-SPK / A) is essentially the same as the first approved SAF, with the addition of aromatics in the molecular composition. The feedstocks are the same as well, that being renewable biomass such as municipal solid waste, and agricultural and wood waste. This fuel can be blended up to 50% for direct application. [4]

Hydroprocessed Esters and Fatty Acids (HEFA-SPK) is the most commercially mature SAF production method [7]. While HEFA-SPK has a similar molecular composition to FT-SPK, consisting of iso- and n-alkanes, it is produced by the hydrotreating of esters and fatty acids from fats, oils, or greases derived from feedstocks such as algae, jatropha, and camelina [4]. To produce HEFA-SPK hydrogen is utilized to convert unsaturated compounds like alkenes and aromatics into more stable cycloalkanes and paraffins. The energy conversion efficiency of SAF production route is approximately 76%, the highest efficiency among approved SAF production technologies. Yet, to obtain the lowest alternative fuel costs the hydroprocessing requires utilization of already used cooking oils or animal fats rather than vegetable oils derived from food crops and fuel crops [7]. Similar to FT-SPK, HEFA-SPK can be applied in aviation fuel blends in concentrations of up to 50% [4].

Unlike the previously mentioned SAFs, Hydroprocessed Fermented Sugars to Synthetic Isoparaffins (HFS-SIP) fuel is made up of a single 15-carbon hydrotreated sesquiterpene molecule known as farnesane. Farnesane is produced by the fermentation of sugars, often derived from sugar cane juice. However, this fuel is limited to blends of up to 10% in aviation fuels [4]. The process involved in converting lignocellulosic sugars into fuels causes this to be the most expensive alternative fuel pathway due to its complexity and low efficiency [7].

Alcohol-to-jet Synthetic Paraffinic Kerosene (ATJ-SPK) is currently approved for use in SAFs with iso-butanol concentrations of up to 30% in fuel blends and ethanol concentrations of up to 50% in fuel blends. This fuel consists of iso-alkanes of 8, 12, or 16 carbons when starting from iso-butanol. When starting from ethanol, the carbon number can be broadened and the branching level can be reduced. Feedstocks for the necessary alcohol to produce ATJ-SPK include agricultural waste like corn shoots, grass, straw, or other cellulosic biomasses [4]. The alcohols are then turned into jet fuel through the processes of dehydration, oligomerization, hydrogenation, isomerization, and distillation [7]. The highest reduction in greenhouse gas emissions from the ATJ route can be achieved by using iso-butanol derived from forest residues, yielding a promising 74% reduction [2].

Catalytic Hydrothermolysis Synthesized Kerosene (CH-SK or CHJ) contains all four hydrocarbon families, including n-, iso-, and cyclo-alkanes, as well as aromatics and is produced from lipids derived from vegetable or animal fats. The lipids are converted into jet fuel using a supercritical hydrothermal process which is then blended with aviation fuel in concentrations up to 50% [4].

Hydroprocessed Hydrocarbons, Esters and Fatty Acids Synthetic Paraffinic Kerosene (HHC-SPK or HC-HEFA-SPK) is made from lipids derived specifically from Botryococcus braunia, a species of algae, via a hydrocracking/hydroisomerization process in order to remove oxygen and saturate double bonds. The product of this process is rich in iso-alkanes. HHC-SPK was the first drop-in SAF to be approved through the ASTM D7566 "fast track" process but is currently limited to 10% concentration in aviation fuel blends [4].

Another important specification standard with regards to SAFs is ASTM D1655-20b the Standard Specification for Aviation Turbine Fuels. This standard allows for the coprocessing of mono-, di-, and triglycerides, as well as free fatty acids and fatty acid esters of up to 5% FT hydrocarbons and requires hydrocracking/hydrotreating and fractionation are required for this process. However, coprocessing in refineries has not been permitted for jet fuel besides this singular pathway [4].

Before reaching the D7566 standard, fuels must make it past the ASTM D4054 approval process. Currently, several fuels are caught in the D4054 approval pipeline, waiting to be streamed into D7566 approval. This includes SPK (n- and iso-alkanes), cycloalkanes, aromatics, and mixtures of all four hydrocarbon families. [4]

Although society is set on the objective of implementing SAFs, the endeavor will not be that easy. A significant bottleneck within this field is the fact that the jet fuel market size is large and growing. The 106-billion-gallon global market is projected to reach over 230 billion gallons by 2050. With biomass as the main SAF feedstock, there is currently about 340 million tons of biomass available in the U.S. This could amount to roughly 21 billion gallons of jet fuel, which just about matches the domestic market size [4]. However, the aviation fuel industry has to compete with other feedstock-demanding markets such as ethanol and biodiesel [5]. In 2014, there were about 1.2 billion vehicles on roads compared to 26,000 commercial aircrafts in flight; thus, current policies focus renewable fuels toward diesel and the much larger, more demanding motor-vehicle industry [4]. However, this also means that integrating alternative fuels into the aviation industry could potentially be a lot easier due to comparatively limited scope [13]. To prevent biodiesel and ethanol production from limiting the biomass supply, appropriate policies should be placed so as to equally distribute biomass among the necessary industrial sectors [4].

Another notable barrier in the widespread application SAFs is the increased economic costs of SAFs, costing 2-5 times the price of traditional jet fuel [7]. Airlines are already expected to pay 40% more for jet fuel by 2040 compared to jet fuel costs in 2014 [5]. Also of note, fuel makes up approximately 20-30% of aviation operating costs; thus, with the current costs of SAFs the aviation industry must decide between the increased cost or the reduced carbon emissions [4]. Ultimately, for SAFs to gain popularity, SAF prices need to be reduced through continued research and development.

Considering that the processes used to generate fossil kerosene and alternative fuels are very similar, the main factor driving the high cost of SAF is feedstock. The simplest way to mitigate this cost is to utilize less expensive materials such as waste biomass. Using feedstocks like used cooking oil or municipal solid wastes puts something potentially harmful to the environment to good use at a lower cost, thus "killing two birds with one stone" [4]. Additionally, since this approach does not require land to produce the feedstock, there are less sustainability concerns [12]. For instance, the land use in the production of biomass feedstock, the development of cultivable land, as well as the hydrogen and other inputs necessary during the conversion processes of biojet fuel generates carbon emissions which need to be taken into consideration [5]. Fortunately, these concerns can partially be diminished when taking into account the lifecycle basis in which excess carbon is recycled via biomass photosynthesis. The amount of CO2 absorbed by plants is similar to the amount emitted during the combustion of biofuel. In this way, , maintaining a carbon neutral to carbon negative lifecycle in terms of greenhouse gas emissions is much easier in comparison to the use of conventional jet fuel with lifecycle emission reduction of up to 20-95%, illustrating waste material and raw biomass are both attractive feedstocks despite the cost [2, 12].

Although research needs to focus on reducing the price of SAF, there is hope for its current economic viability. Since these fuels are admissible under CORSIA, the upscaling of this technology will be aided. While in June 2021, the Alliance for Aviation Across America held a meeting with local government officials to discuss commitments and investments in emerging technologies. Of note, discussion of SAFs elucidated current SAFS are primed for use but there is a need for federal and local support to accomplish current sustainability goals present within the aviation community [14]. With government and investors' aid, various projects will continue to scale up, allowing costs to decrease. Thus, SAF production will inevitably overcome the restrictions associated with cost.

As air travel is projected to increase by a factor of 2.75 by the year 2050 and aviation emissions are expected to more than triple the urgency to improve sustainability is mounting [10, 15]. This further emphasizes the need to transition our current system to one of more sustainability as soon as possible. In order to prevent global warming from getting out of control, we must begin to implement sustainable alternative energy such as SAF at a large scale immediately. In order for any future SAFs to be feasible, it must meet the required conditions of performance, operability, and drop-in compatibility such as those of ASTM [4]. In the next few years, research on SAFs has the opportunity to focus on enhancing fuel properties and lowering emissions. The future of improving specific fuel consumption exists in the manipulation of hydrocarbon composition in upcoming alternative fuel technologies. Thus, the aviation industry has started to incorporate this new technology and, with favorable policy and legislation, will continue to do so until the transition away from petroleum fuels is complete. Society has its mind set on reversing the effects of global warming, and SAFs are a solid first step towards this goal.

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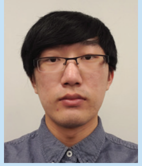
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