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Towards Greener Skies: Past Achievements and Future Horizons of Sustainable Aviation Fuels

Nowadays industries worldwide are transforming to become more climate and environment aware, hence there is a radiant shift of focus and demand toward more green and sustainable solutions which can be easily spotted in various inventions and developments. Aviation is no stranger to these demands if not the most pressurised sector to reduce its environmental footprint, while accommodating the growing demand for air travel. The increased number of funded research in the field of creating new generation and greener aircraft (electrical, hybrid, hydrogen) is the proof of that quest. Pursuing those goals is very important, however, it is safe to say that the industry still has a long way to go. The proposed solutions, while very innovative, lack the resources to provide safe and economical operational flights due to immature technological tools. Therefore, a quick and alternative way was sought after in the meantime, which is what made sustainable aviation fuels (SAF) emerge as a viable option for reducing greenhouse gas emissions and promoting environmental sustainability in aviation. This paper presents a detailed review of SAF's previous accomplishments and future possibilities and aspects.

Keywords: *sustainability, reduce greenhouse effects, reduce exhaust gas emissions, green aviation, sustainable aviation fuel, SAF*

1. Introduction

In the past years, various fields and sectors of different industries have been focusing and investigating their negative imprint on the global climate and environment. However, since transportation is regarded as one of the major contributors to today's pollution, it is notable that transportation fields are making a huge effort to limit their negative impact.

Air travel plays a fundamental role in global connectivity and economic growth, it has unquestionably transformed human mobility, allowing for fast travel across enormous distances and connecting diverse parts of the world. However, this contemporary marvel has a high environmental cost, with aviation becoming a major producer of greenhouse gas emissions and air pollution. In the past years, aviation represented 2% of the worldwide energy-related CO_2 emissions, which shows that it had increased more rapidly in recent decades than railway transport, road, or even shipping. As worldwide travel demand rebounds after the Covid–19 pandemic, in 2022 aircraft emissions were estimated to have reached approximately 800 Mt CO_2 which is equivalent to 80% of pre-pandemic levels according to the International Energy Agency (IEA) [1].

Taking into consideration the relatively high percentage of CO_2 emission, it became crucial to understand how to reduce this percentage to an acceptable rate. Of course, this emission comes from the combustion of fossil jet fuels, which are primarily derived from petroleum, by combustion they can produce approximately 70% of carbon dioxide (CO_2) from the total gas exhaust, and water vapour (H_2O), which is equal to 30%. Less than 1% of the total combustion exhaust gases are made of pollutants like nitrogen oxides (NO_x), oxides of sulphur (SO_x), carbon monoxide (CO), partially combusted or unburned hydrocarbons (HC), particulate matter (PM), and other trace compounds [2].

By taking a more in-depth investigation of the emissions, the results show that the air travel impact on climate change is more complicated, it depends on multiple parameters and factors such as altitude and power of the engines. The jet aircraft's impact on the climate is explained clearly in Figure 1, the data collected in this figure was taken from the United Nations Intergovernmental Panel on Climate Change (IPCC). The cloud behind the airplane contains the different gases and particles produced by jet fuel combustion (kerosene). The warming or cooling effect of these gases is explained in detail below the cloud in the "Climate Impact" line, and the blue and red coded bar gives a clear idea of a comparison of each exhaust product to the warming effect of CO_2, where red indicates to a warming impact and blue indicates to a cooling effect [3].

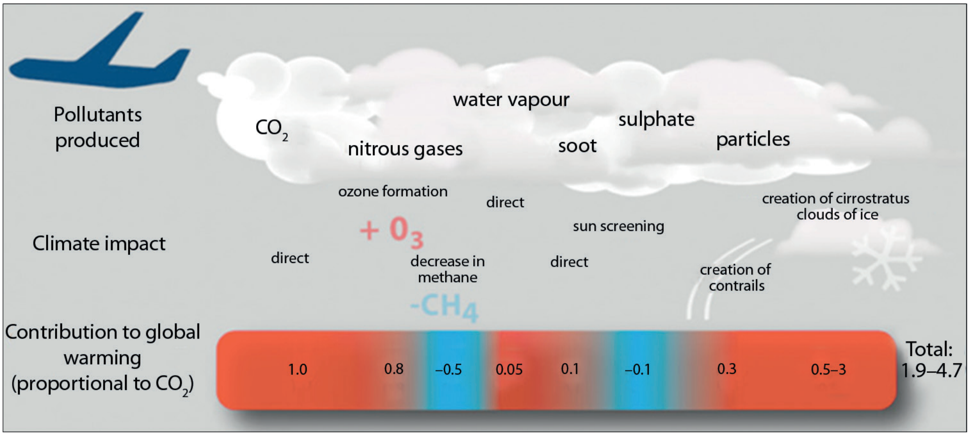

Figure 1.
Effect of aviation on the global climate [3]

The increase in fossil fuel consumption enhanced Greenhouse Gas emissions (GHG), which led to prominent changes to the climate. These changes were manifested in the form of increased temperatures and global warming [4]. Hence, trying to mitigate the bad impact of fossil fuels has become crucial to the continuity and strength of air travel. Within this context, sustainable aviation fuels (SAF) rose to be a potential and promising solution for reducing the aviation footprint on the atmosphere. Additionally, it will give the means to energy security and help transition the industry to more sustainable and green developments.

In this paper, the focus will be shed on the historical overview of sustainable aviation fuels (SAF), the economic and environmental benefits of the SAF, the current state, and the future prospects.

2. Overview of aviation fuels

Standard jet fuel is unique in the form that it is made in a way to meet the strict and international standards. The specifications of regular jet fuels are developed to be usable at low temperatures and offer the high power needed for the engines, these fuels are characterised to have heavier density in comparison with other fuel types, or, in other words, "heavier" than normal gasoline, they have a higher flash point and lower freezing point [5].

However, since regular jet fuel is a form of fossil fuel, it has consequently a high carbon emission. Although there is a lot of research in the pipeline for greener engine solutions such as hydrogen or electrical engines, it is safe to state that these technologies are not ripe yet and the industry still needs to go a long way to arrive at that point.

Sustainable fuels though offered a great alternative and a great opportunity for airliners to cut down on the bad impact of flying to the environment. Reducing emissions is the key factor of focus today to achieve the net-zero carbon goal by the year 2050 which is a common objective for all international aviation industries [6].

2.1. Conventional fossil jet fuel

Conventional fossil jet fuel or in another word kerosene is produced through a complex combination of processes for crude oil, where the various fuel types are separated based on their boiling point, kerosene has a boiling point range of 130–300 °C [7].

Kerosene is a complex mixture of hydrocarbons that can be categorised into 4 main groups, which are illustrated in Figure 2.

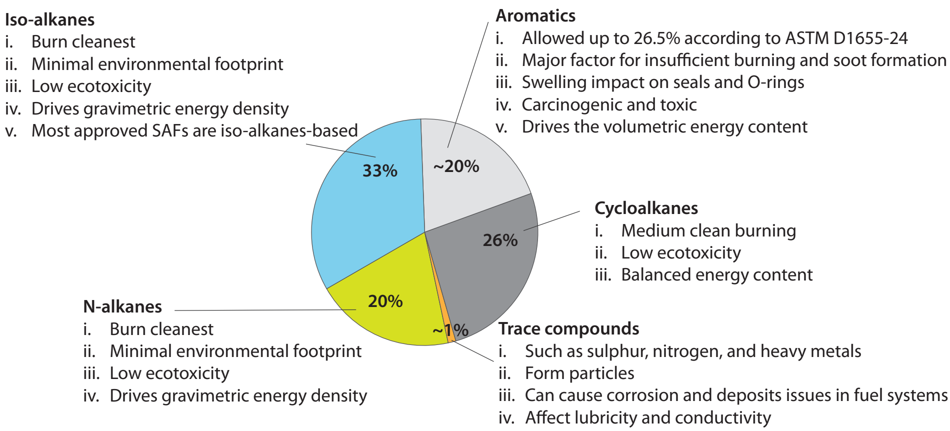

Figure 2.
Volumetric share of compounds in kerosene [the authors]

N-alkanes have a straight-chain structure with no branches, while iso-alkanes are branched-chain alkanes, they have the same molecular formula as n-alkanes but are different in the arrangement of carbon atoms, featuring at least one branch, as shown in Figure 3. Both n-alkanes and iso-alkanes have the same formula described by Equation 1.

$$C_n H_{2n+2}$$

In cycloalkanes, the carbon atoms are connected in a ring or cyclic structure as shown in Figure 3, with the general formula Equation 2.

$$C_n H_{2n}$$

Aromatic compounds feature a ring of carbon atoms with alternating double and single bonds, as shown in Figure 3, which can be described by the general Equation 3 [8].

$$C_n H_{2n-6}$$

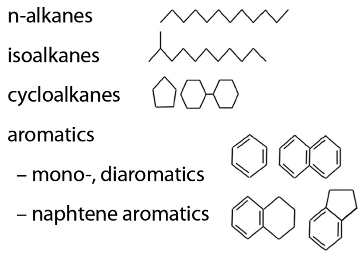

Figure 3.
Main compounds in kerosene [9]

These hydrocarbons can be grouped together based on their carbon numbers which are normally allocated as shown in Figure 4, the majority of compounds have carbons in the range of C8 to C16, however, compounds up to C19 might be found [8].

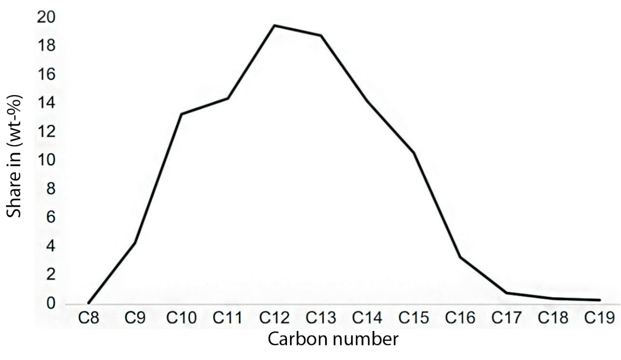

Figure 4.
Distribution of carbon numbers in kerosene [8]

2.2. SAF introduction

Sustainable aviation fuels (SAF) or as alternately known as the next generation fuels have already been used today in many countries and by many consumers or airlines. SAF is a combination of traditional fossil fuels and synthetic components derived from a variety of renewable resources for example used cooking oils, animal fats, plant oils, and municipal, agricultural, and forestry waste.

So far aircraft manufacturers have only certified their aircraft to fly with a maximum of 50% combination of SAF with other standard jet fuels [10], with a forecasted vision that this rate will reach 100% by 2030.

The reason for this enormous focus on SAF and related research is that the aircraft already produced and operated cannot be scrapped if new generation aircraft (electric/hydrogen) get invented due to obvious economic reasons.

According to the International Civil Aviation Organization (ICAO) [11], the American Society for Testing and Materials (ASTM) has certified and approved the use of seven pathways to produce synthesised (non-petroleum) jet fuel blending components [12]. However, according to Airbus, the most used blending pathways are Hydrotreated Esters and Fatty Acids (HEFA), Alcohol to Jet (AtJ) and e-fuels [10]. The timeline of the certification of different SAF pathways is illustrated in Figure 5.

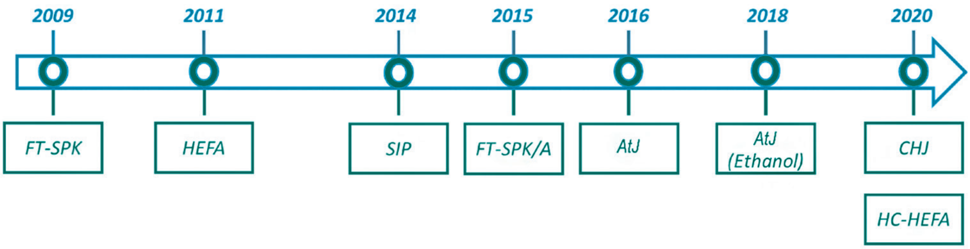

Figure 5.
Time stamp of SAF [13]

2.3. Most common SAF pathways

2.3.1. Hydrotreated esters and fatty acids (HEFA)

HEFA pathway was approved back in 2011, with a blending limitation ratio with fossil fuel of 50%, the chemical process includes the conversion of woody biomass to syngas by utilising the process of gasification, then a synthesis reaction called Fischer–Tropsch converts the syngas to jet fuel [14]. Feedstocks include different types of renewable biomass, primarily woody biomass such as municipal solid waste, agricultural wastes, forest wastes, wood, and energy crops [15]. As illustrated in Figure 6, HEFA from palm oil and used cooking oil (UCO) are the most cost-effective [16], making HEFA one of the feasible future solutions in the mid-and long-term taking into consideration the limited feedstock availability, which still represents a major challenge [17].

2.3.2. Alcohol-to-Jet (AtJ)

Alcohol-to-jet synthetic paraffinic kerosene was certified for use by commercial aircraft in 2016 for isobutanol and in 2018 for ethanol at a 50% mixing ratio. It is primarily manufactured by turning cellulosic or starchy alcohol (isobutanol and ethanol) into a drop-in fuel by a sequence of chemical events such as dehydration, hydrogenation, oligomerisation, and hydrotreatment. Alcohols are produced from cellulosic or starchy feedstock via fermentation or gasification processes. Ethanol and isobutanol generated from lignocellulosic biomass (such as corn stover) are regarded as suitable feedstocks [13].

As shown in Figure 2, aromatics have a toxic and carcinogenic effect which means SAF with free aromatics is beneficial for air quality and the environment but unfortunately, aromatics play a very important role in the engine fuel system (e.g. rubber seals), since the experimental results show that the relationship between the rate of seal swelling and total aromatic content and fuel type is in fact linear [18], which means SAF with low aromatics content causes leakages in the fuel system leading to airworthiness consequences, from this point of view, AtJ is an option for future 100% SAF because it is possible to produce SAF that contains aromatics [15].

2.3.3. Fischer–Tropsch synthesised kerosene (FT-SPK)

FT-SPK pathway was approved back in 2006, it is liquid hydrocarbons that are created by the conversion of syngas's catalytic which is a mixture of CO and H2 via gasification from a variety of biogenic feedstock like biomass, wood, agricultural, forest wastes, and municipal solid waste. These compounds are characterised of being non-toxic, sulphur-free, and include few aromatics content, which in the results leads to lower emissions. The Fischer–Tropsch synthesised kerosene with aromatics (FT-SPK/A) pathway was approved back in 2009, it is similar to FT-SPK but with the addition of aromatic components [13], [19].

2.3.4. E-fuels

The e-fuels are made by absorbing carbon dioxide from CO_2 available in the atmosphere from factories' exhaust or any transportation sources and producing synthetic fuels using green hydrogen and renewable power. This form of SAF is also called e-fuels or Power-to-Liquid (PtL) [20]. PtL attracted significant interest in the past decades since it was made possible to produce SAF with very low GHG emissions avoiding feedstock constraints and sustainability issues in comparison to other bio-based SAF [21].

In general, most of the current articles and research have reached the same conclusion which can be described that pathways HEFA, FT-SPK, AtJ, and PtL are cutting-edge technologies and will lead the aviation industry towards the targeted fuel transition [13]. These pathways are the most efficient solutions for the near future due to their high technological readiness [22]. The ideal option for commercialisation is HEFA, but FT-SPK and AtJ procedures can also be efficient routes to improve their cost-effectiveness [23].

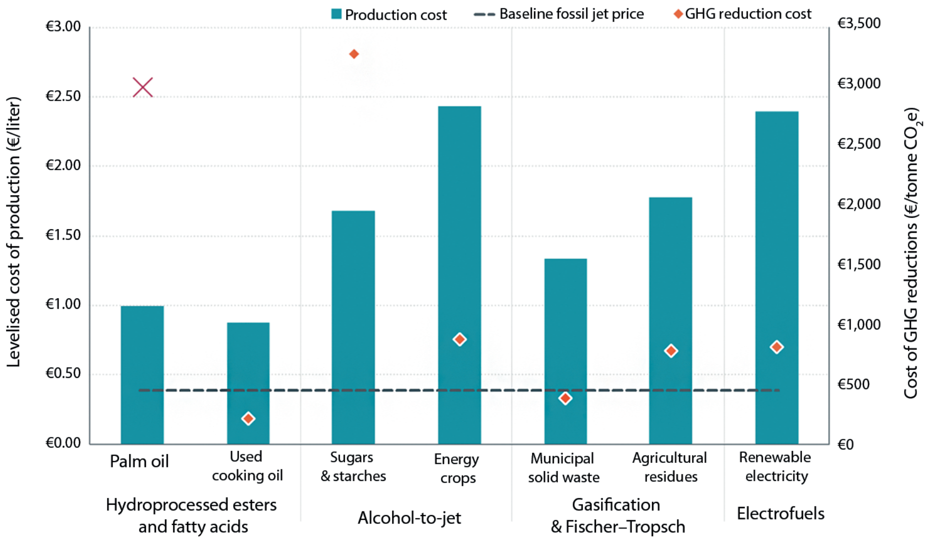

Figure 6.
HEFA, AtJ, FT-SPK, and e-fuels estimated costs compared with kerosene price [16]

3. Future milestones and vision

Based on the above chapters it is clear that the research is quite intense about different mixing ratios and combinations of fuels. The future improvements and visions can be categorised into two main topics, the first topic is dealing with increasing the SAF share in the final mixture (considering ASTM D7566 requirements) and the second topic is finding new solutions to make the current engines (which are already in service) capable to be fed with higher SAF content. The importance of the last topic lies in the fact that most engines and aircraft manufacturers confirmed that all their productions will be compatible with 100% SAF by 2030. However, according to the EASA environment report, aircraft can remain in service for about 30 years [24], meaning that current aircraft/engines which are manufactured in 2024 (and compatible with 50% SAF) may stay in service until 2054, which will be the majority of fleets in the mid-future.

The new ReFuelEU Aviation regulations help to provide a high, standard level of environmental protection in the aviation industry as shown in Figure 7. The goal of 2050 is for 70% of all the fuel supplied in to EU airports to be SAF, of which 35% would be synthetic SAF, providing grater potential for reducing CO_2 emissions. EASA has a special role, which is to monitor and report on the use of SAF and fossil fuels by airlines at EASA Member States' principal airports [25], [26].

Another strategy known as CORSIA developed by ICAO, which stands for the Carbon Offsetting and Reduction Scheme for International Aviation, includes methodologies and policies aiming to mitigate greenhouse gas emissions from the aviation industry and stabilise their levels [27].

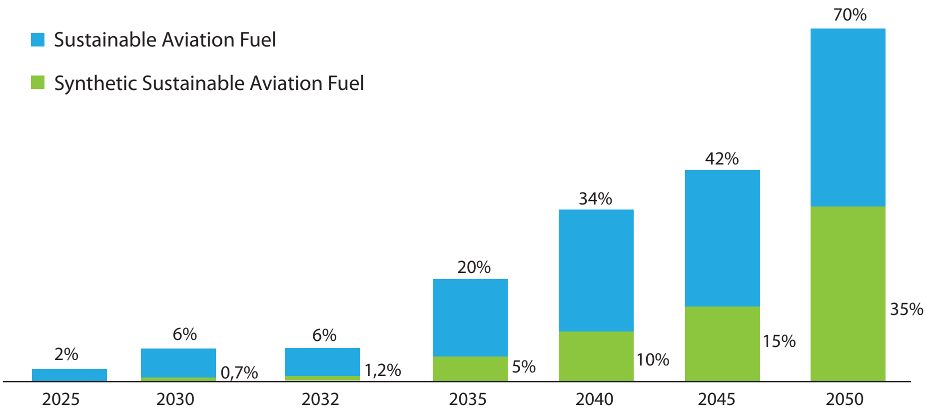

Figure 7.
The mandatory minimum proportion of SAF in the future [25]

4. Conclusion

SAF has made significant progress towards their goal of reducing emissions and improving air quality. Over the last few years, significant advances have been made in the development and implementation of SAF, demonstrating their potential to lower carbon emissions and decrease reliance on fossil fuels. Despite these accomplishments, challenges remain, such as scaling up production, lowering costs, and ensuring compatibility with aircraft, engines, and infrastructure. The future of SAFs looks promising as one can clearly see a continuing investment in this field of research. Furthermore, it is predicted that this way will be supported by regulatory policies and various collaboration efforts in between different aeronautical and aviation industries. As HEFA, FT-SPK, and AtJ are becoming more common nowadays, they will play an important role in establishing a more sustainable and environmentally friendly aviation industry, which shows the importance of investigating and researching these pathways.

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Cél a zöldebb égbolt – a fenntartható repülési üzemanyagok jelene és a bennük rejlő lehetőségek jövője

Napjainkban az iparágak világszerte átalakulnak, egyre inkább klíma- és környezetbarátabbak lesznek. A hangsúly és a kereslet a zöld és fenntarthatóbb megoldások felé tolódik, ami könnyen észrevehető a különböző találmányokban és fejlesztésekben. A légi közlekedés sem idegen ezektől az igényektől, ha nem is a legnagyobb hatással rendelkező ágazat, amely a növekvő kereslet kielégítése mellett a környezet terhelésének csökkentésére törekszik. Az új generációs és környezetbarátabb repülőgépek (elektromos, hibrid, hidrogén) létrehozására irányuló kutatások számának növekedése a legnagyobb bizonyíték erre a törekvésre. Ezeknek az irányoknak a követése nagyon fontos, azonban kijelenthető, hogy még hosszú út áll előttünk. A javasolt megoldások, bár nagyon innovatívak, a kiforratlan technológiai eszközök miatt nem rendelkeznek a biztonságos és gazdaságos üzemszerű repülésekhez szükséges erőforrásokkal. Ezért időközben gyors és alternatív megoldásokat kerestek, és ez az, ami miatt a fenntartható repülőgép-üzemanyagok (SAF) az üvegházhatású gázok kibocsátásának csökkentésére és a légi közlekedés környezeti fenntarthatóságának előmozdítására szolgáló életképes lehetőségként jelentek meg. Ez a tanulmány részletesen áttekinti a SAF eddigi eredményeit, valamint a jövőbeli lehetőségeket és szempontokat.

Kulcsszavak: *fenntarthatóság, üvegházhatás csökkentése, kipufogógáz-kibocsátás csökkentése, zöld repülés, fenntartható repülőgép-üzemanyag, SAF*

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