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PROSPECTS OF NOVEL TECHNOLOGIES FOR SAF PRODUCTION

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Summary. For very large aircraft and very long distances, low-carbon alternative fuels are at present the only viable replacement for fossil fuels, contributing towards sustainability targets before electric and hydrogen technologies will become mature. Since the interest on Sustainable Aviation Fuels (SAF) is growing, more pathways will be introduced and approved.

The scientific research is mainly focusing on the production of advanced biofuels and e-fuels. For the advanced biofuels, beyond existing modern technologies for SAF production, novel pathways are proposed, mainly related to the conversion and fermentation of feedstocks to alcohol and then biofuels.

E-fuels are produced using renewable energy for fuel synthesis. New technologies for e-fuels production, like power-to-liquid process are promising for reducing greenhouse gas emissions in aviation. They are not yet available on the market, but there is a growing interest from various

companies in establishing production facilities. Moreover, a growing enthusiasm for the electrochemical route has potential to improve e-kerosene production.
In this work the characteristics together with pro and cons of the different SAFs will be discussed in order to understand the possibilities of their usage in the near future.

1 INTRODUCTION

The aviation industry is focusing on the reaching of net-zero carbon emissions target within 2050, as required by European Green Deal [1, 2]. Research involves the use of new propulsion systems like battery and turbo-electric technologies, as well as hydrogen combustion in turbines and fuel cells that power electric motors. These solutions ensure no emissions during flight, although for very large aircraft and very long distances, are not a solution. Sustainable Aviation Fuels (SAF), are low-carbon alternative fuels and are at present the only viable replacement in near term for fossil fuels. They have reduced particulates, nitrogen, sulphur and critical greenhouse gases and have the advantage of being “drop-in fuels” that do not require changes in aircraft, neither for the engines nor for the fuel tanks, and fuel infrastructure or airport facilities [3, 4].

SAF are not equally sustainable, and their sustainability mainly depends on the type of feedstocks used to produce the fuels and on the source of energy used in the production process.

ReFuelEU is a European regulation adopted in 2023 that mandates jet fuel suppliers to blend a growing share of SAF into the fuel they provide to EU airports.

The European Union (EU) Council in October 2023 has adopted the ReFuelEU Aviation initiative, as part of the ‘Fit for 55’ package, with the main objective to increase both demand for and supply of SAF, while ensuring a level playing field across the EU air transport market [5]. According to ReFuelEU, SAF are defined as drop-in aviation fuels that are either biofuels produced from feedstocks listed in Annex IX of the Renewable Energy Directive (RED II) recycled carbon fuels, produced from fossil wastes that cannot be prevented, reused, or recycled, or synthetic fuels made from renewable hydrogen and a source of carbon, which comply with the sustainability and greenhouse gas (GHG) emissions reductions criteria in Article 29 of the RED. ReFuelEU defined the different kind of SAF as:

- Aviation biofuels
- Synthetic Aviation Fuels/Electrofuels
- Recycled carbon aviation fuels

Aviation biofuels are divided into:

- biofuels, produced from feedstocks listed in Annex IX, Part B of the RED (cooking oils, fats):
- advanced biofuels, produced from the feedstocks listed in Annex IX, Part A of the RED (municipal solid waste, straw, animal manure and sewage sludge, forest residue, biomass, algae)
- other biofuels with exceptions, like animal fats category 3

Synthetic aviation fuels (e-kerosene, electrofuels, e-fuels) are synthesized from green hydrogen and carbon (from biogenic or industrial point sources, or directly captured from the air). **Recycled carbon aviation fuels** are from non-recyclable plastic or industrial gases.

ReFuelEU Aviation also gives advices in selecting the right types of SAF, starting from the feedstock sustainability (**Figure 1**). Crop-based biofuels, and other problematic feedstocks such as non-Annex IX intermediate crops, Palm Fatty Acid Distillate (PFAD) and palm- and soy-derived materials, and soap stock and its derivatives are considered not sustainable.

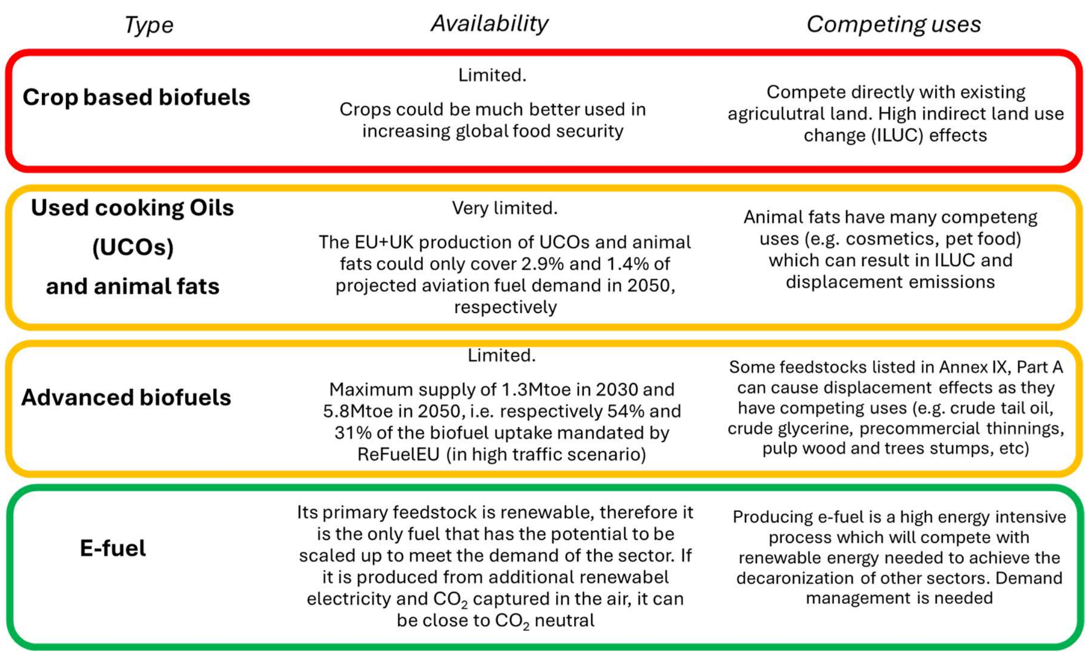

Figure 1: SAF sustainability per type of feedstock. Red: unsustainable, yellow: questionably sustainable, green: sustainable (with demand management)

Considering the actual situation and developments, in this work we will analyse the perspectives of SAF in the near future.

2 • AVIATION BIOFUELS

New fuels can be used in commercial flights after the approval by the ASTM D7566 standard [6]. In the last 5 years there has been a large increase of approved pathways for biofuels/advanced biofuels production: 5 pathways were approved from 2009 to 2018, whereas 14 pathways have been approved from 2020 to 2023 (**Table 1**), and at the moment 6 routes are under approval process (**Table 2**).

Table 1: Recent approved pathways for SAF production [6]

Pathways Processes	Feedstock	Date of Approval	Blending ratio by Volume	Commercialization Proposals
Hydroprocessed Esters and Fatty Acids Plus (HEFA +)	Oil-bearing biomass, e.g., algae, jatropha, camelina, carinata	2021	50%	Boeing
Catalytic Hydro thermolysis Synthesized Kerosene (CH-SK, or CHJ)	fatty acids and fatty acid esters, lipids that come from plant and animal fats, oils and greases (FOGs)	2020	50%	ARA
Hydro processed Hydrocarbons (HH-SPK, or HC-HEFA)	bio-derived hydrocarbons, directly from oils (triterpenes) produced by the Botryococcus braunii algae	2020	10%	IHI Corporation
Alcohol to Jet Synthetic Kerosene with Aromatics (ATJ-SKA)	Fermentation of starches/sugars, from feedstocks (e.g. field corn, sweet sorghum, cane, sugar beets, tubers) or derived from cellulosic biomass (e.g. via hydrolysis from lignocellulose)	2023	50%	

Table 2: Pathways actively pursuing certification at various stages in the process [6]

ASTM Progress	Pathway	Feedstock	Task Force Lead
Phase 2 Testing	Hydro-deoxygenation Synthetic Kerosene (HDO-SK)	Sugars and cellulosics	Virent (inactive)
	Hydro-deoxygenation Synthetic Aromatic Kerosene (HDO-SAK)	Sugars and cellulosics	Virent
Phase 1 OEM Review	High Freeze Point Hydroprocessed Esters and Fatty Acids Synthetic Kerosene (HFP HEFA-SK)	Renewable FOG	Boeing
	Integrated Hydropyrolysis and Hydroconversion (IH^2)	Lignocellulosics	Shell
Phase 1 Testing	Alcohol-to-Jet Synthetic Kerosene with Aromatics (ATJ-SKA)	Sugars and lignocellulosics	Swedish Biofuels, Byogy
	Alcohol-to-Jet (ATJ)	Sugars	Global Bioenergies

Furthermore, 15 routes are listed to enter the process, among them several novel pathways are related to alcohol based processes:

- L-ETH-Jet (Biochemical conversion of lignocellulose to Ethanol)
- SYN-FER-J (Gasification, Syngas Fermentation to Ethanol)
- S-ETH-J (Sugarcane Juice to Ethanol by Sucrose Fermentation)

These technologies foresee the use of renewable feedstock (lignocellulose, alcohols) for fuel production [7]. In L-ETH-Jet a biological conversion mechanism turns sugars generated by the hydrolysis reaction into microbial lipids, which are then converted by the HEFA process. In SYN-FER-J bio-methane is used as substrate for fermentation and is transformed into hydrocarbons using catalysts as transition metal oxides, zeolite, and heteropoly acid, followed by distillation. In S-ETH-J advanced methods are used to convert sugar from can by acidic chemicals, paraffin compounds, oxygenated hydrocarbons, and furans.

The obtained alcohols are then converted to jet fuel by several steps:

- Dehydration of the alcohol to obtain olefins
- Oligomerization of olefins
- Hydrogenation of the oligomerized olefins to obtain alkanes

Oligomerization is realized over various heterogenic or homogenous catalytic processes. Certain catalysts may cause isomerization and cracking and create some number of cyclic olefins, or even aromatics, therefore they have to be accurately selected. The advantage of this kind of approach is that the production of aromatic substances, important for the compatibility of the SAF with the engines, can be performed as an integrated flow in the overall production process.

The properties of the fuels based on alcohol feedstocks have interesting properties and are suitable for use as SAF if blended with kerosene. In particular, the new approved Alcohol To Jet Synthesized Paraffinic Kerosene (AtJ-SPK) and Synthesized Kerosene with Aromatics (AtJ-SKA) routes have properties and quality satisfying the specification requirements of Jet-Fuels (JF) [8]. Despite the content of aromatics in conventional jet fuel is strictly limited, still at least minimum recommended value (about 8 % vol.) should be maintained to provided good compatibility of fuel with rubber materials. To maintain this recommendation the AtJ-SPK route was adopted to AtJ-SKA route. The properties of the AtJ-SKA component are more similar to conventional JF, therefore the change of properties of blended JFs is not so intense as for the AtJ-SPK component. Primarily, this is due to the content of aromatic hydrocarbons in fuel component. AtJ-SKA fuel causes a minimal change in the density of blended JFs. A slight reduction of kinematic viscosity is observed. Blending AtJ-SKA provides fewer changes in fractional composition compared to AtJ-SPK and the distillation profile of blended JF is closer to conventional JF. And similarly to AtJ-SPK, AtJ-SKA component positively influences on low-temperature and safety properties of blended JFs.

Several innovative technologies for the implementation of SAF pathways have been considered for the development of start-ups for the commercialization of different SAF types. The National Renewable Energy Laboratory (NREL) of the U.S. Department of Energy is facilitating several start-ups and incumbents to use their facilities to pilot refinery technology, drawing a clear direction for the future use and diffusion of SAF (**Figure 2**) [9].

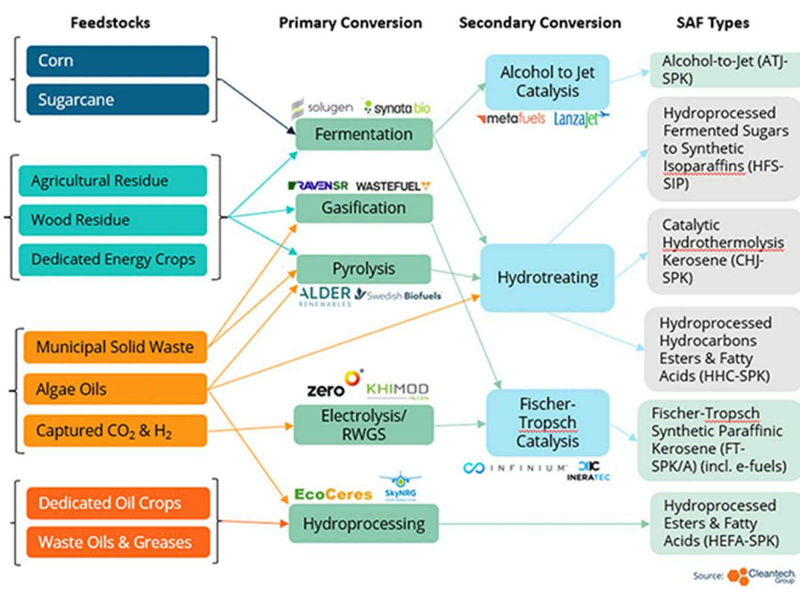

Figure 2: SAF pathways with innovation technologies and start-up. SAF in grey are approved by ASTM but not in production [9]

3 SYNTHETIC AVIATION FUELS

Synthetic Aviation Fuels technologies, more commonly known as electrofuels or e-fuels, have had a significant advancement in the last years. E-fuels result from the combination of 'green or e-hydrogen', produced by electrolysis of water with renewable electricity, and CO_2, which can be captured from several sources including biomass combustion, industrial processes (e.g., fuel gases from fossil oil combustion), biogenic CO_2, and CO_2 captured directly from the air. E-fuels, using renewable energy for fuel synthesis, are carbon-neutral with respect to GHG (Green House Gas) emission [10].

Different conversion routes are developed according to the final desired e-fuel such as the methanization route for e-methane; methanol synthesis for e-methanol, e-dimethyl ether, e-oxymethylene ether; or the reverse water–gas shift (RWGS) reaction to produce syngas + FT synthesis. The last process is also used to produce other e-liquid hydrocarbons, such as e-gasoline and e-diesel [11].

The main appeal of e-fuels is that most of them are compatible with existing aircraft and with the existing liquid fuel storage and distribution systems. However, e-fuels have still some drawbacks, that are the low energy conversion efficiencies from electricity to energy at the wheels and the high production costs compared to fossil and biomass-based counterparts.

Several projects related to e-fuels in the EU confirm the interest in this approach to obtain SAF. In Denmark seven new projects with commissioning after 2022, including the biggest power-to-ammonia project in Europe, are planned. Countries like Denmark and Germany have a broader approach to projects looking into methane, methanol, e-kerosene and ammonia, whereas other countries are more focused on one specific fuel output. The Netherlands has a strong focus on e-kerosene in their airport hubs in Rotterdam and Amsterdam and Norway has announced only e-kerosene projects for the aviation sector. Finally, in Germany in October 2022 world's first commercial PtL e-kerosene plant was inaugurated. It converts CO_2 captured from the air and from a biogas plant with electrolytic hydrogen (1.25 MW) to aviation fuel.

The conversion process still faces elevated capital and operational expenses because the technology is under development and there is a significant cost associated with electricity. The growing enthusiasm for the electrochemical route will give a significative contribution for the diffusion of e-fuels [12].

4 RE-CYCLED CARBON AVIATION FUELS

Re-cycled carbon fuels have been defined in the revised Renewable Energy Directive (REDII) [13] and include fuels produced from utilization of waste processing gas and exhaust gas of non-renewable origin. They are produced from the fossil fraction of liquid and solid wastes using thermochemical conversion technologies such as, e.g., gasification, pyrolysis and liquefaction. These kind of fuels, although derived from waste fossil carbon, are included in RED II because of their potential contribution to the reduction of GHG. Though, there is some concerning on the use of recycled carbon fuels produced using unsustainable carbon in the long-term, which could entail a continued use of non-sustainable fuels and the related emissions [14]. Therefore, at the moment, there is no significant development in techniques related to re-cycled aviation fuels.

5 NEW PERSPECTIVES

An interesting approach for the production of e-fuel is the Solar-to-synfuel energy conversion. This technique is based on the production of syngas via solar thermochemical splitting of CO_2 and water, the syngas is then used for Fischer-Tropsch (FT) and methanol synthesis of the gas-to-liquid (GTL) fuel pathway [15, 16]. The two main ingredients of this pathway, H_2O and CO_2, are obtained by the DAC (direct air capture) process. This process, based on an adsorption-desorption cyclic process at low-temperature, integrates well with a solar thermochemical redox cycle driven by concentrated solar heat. The solar concentrating system consists of a field of sun-tracking heliostats that reflect and concentrate sun light onto an array of solar receivers on the top of a tower.

The solar receivers convert concentrated solar radiation into high-temperature process heat that is delivered to a redox reactor, wherein H_2O and CO_2 are split to H_2 and CO. Next, they are supplied for the FT and methanol synthesis. The use of the full solar spectrum during DAC allows to reach high energy conversion efficiencies.

The Heliogen CSP (Concentrated Solar Power) demonstration facility in Lancaster (northern Los Angeles County) is carrying the project for SAF production, with an initial target to produce one barrel per day, with a broader objective of developing a fuel pipeline equivalent to approximately 3 million barrels over the next decade. Existing commercial CSP plants operate on the Rankine Cycle, utilizing steam turbines to convert solar thermal energy into electrical energy. The operational temperature of these steam turbines is 565°C, resulting in a net design point efficiency ranging from 42% to 45%.

6 CONCLUSIONS

HEFA is currently the only commercially deployed pathway, for SAF production, but it has scaling up limitations due to its inherent dependence on feedstock availability, therefore new technologies are developed. Alcohol-to-jet pathways and Fischer-Tropsch processes are in commercial pilot stages and show promise in scaling up.

The physical-chemical properties of JFs blended with AtJ-SKA component are very close to conventional JFs and fuels containing AtJ-SKA component satisfy the requirements of specifications. Considering these results, it is expected that AtJ-SKA component may be successfully used for blending with conventional JF and the maximal limit of AtJ-SKA fuel in blends may be increased compared to AtJ-SPK component.

Synthetic fuels are the most promising ones as long as DAC processes are adopted, and the electricity needed comes from renewable sources. The main drawbacks for e-fuels are the low energy conversion efficiencies from electricity to energy at the wheels and the high production costs.

In 2019 SAF accounted for just 0.1% of all JF used worldwide, now over 450,000 flights have taken off using a mix of SAF and traditional fuels and more than 50 airlines around the world have at least some experience with SAF, this encourage the research in the direction of finding solutions with a better economic impact to reach the net-zero target within 2050.

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