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The future of sustainable aviation fuels

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Presented work has an overview character and is focused on perspectives of sustainable aviation fuels application in civil aviation sector. The mean role of SAF application is to ensure reduction of greenhouse gas emissions and aviation footprint on environment. Paper describe the combustion proces of hydrocarbon fuels and problem related to the emission of carbon dioxide to the atmosphere. Fuel consumption, CO_2 emission and SAF production data was presented on the graphs. The sustainalbe aviation fuel has been characterized. Certified conversion technologies with potential feedstock used for SAF production was described. Literature studies indicate that sustainable aviation fuel is successfully used in air transport.

Key words: *sustainable aviation fuel, kerosene, emissions, carbon dioxide, renewable feedstock*

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1. Introduction

Civil aviation is a dynamically developing sector, that is responsible for approximately 2.5% of global greenhouse gas emissions and before pandemic, their amount were constantly grow. Modern aircrafts used nowadays, emit about 80% less carbon dioxide per seat kilometer than they did 50 years ago [6]. Over the years, significant development took place in most areas of aviation sector. New lighter materials were implemented in aircraft and engine construction, aircraft aerodynamics was significantly improved, as well as attention has been paid on optimization of flight routes. More fuel-efficient turbofan or turboprop engines were introduced to the aviation fleet [42]. All taken activities lead to the one main goal – to reduction of anthropogenic CO_2 emissions [20]. Despite numerous actions, the main feature that still remain unchangeable is aviation fuel based on fossil feedstock. Generated by the aircraft engines emissions are directly related to the fuel burn process [42]. From this reason the type of applied fuel exert a direct impact on emissions level. The amount of fuel burned in aircraft engines is another important factor, because each kilogram of fuel that is not used, allow to reduce the emission of carbon dioxide by 3.16 kilograms [42].

An entire aircraft participation in CO_2 emission is about 2% in comparison to total global emissions [61]. This numbers indicate for relatively small contribution to global anthropogenic CO_2 emissions, however in case of aviation it should be taken into account that this emissions took place in upper layers of atmosphere (troposphere and lower stratosphere).

Aviation decarbonization is an unavoidable procedure that lead to development and implementation of new type of fuel, that ensure sustainability. For aviation industry, alternative fuels present opportunity to minimalize harmful emissions. A good near-term options are sustainable aviation fuels (SAF), which are non-fossil fuels, produced from variable feedstock [17]. Sustainability means that raw material used for SAF production cannot compete with food production or water resources and cannot degrade the natural environment [26].

The main properties of sustainable aviation fuel are ability to reduction of greenhouse gas emissions, compatibility with conventional aviation fuel, sustainability, clean burning process and renewable resources [23]. The amount of carbon dioxide absorbed by plants during photosynthesis is roughly equivalent to the amount of CO_2 produced by fuel burning in combustion engine. This feature allow SAF to be specified as carbon neutral over the life cycle [31].

The SAF production process (Fig.1) is also a source of contamination, therefore researches are carried out on development new conversion technologies, allowing for the CO_2 reduction at the production level and to meet the costs targets. Properties of SAF caused that it has the ability to significantly reduction of CO_2 emissions over the whole fuel life cycle. Application of such kind of fuel enable the reduction of carbon dioxide emission by 80% (over the fuel life cycle) compared to kerosene [2, 31].

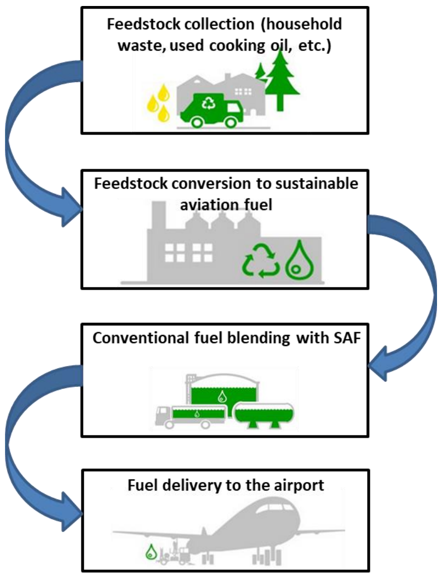

Fig. 1. Sustainable fuel production process [15]

The other advantage of sustainable aviation fuel is the low aromatic content which cause the reduction of soot formation and aerosol emission by 50 to 70% [24]. Taking into account that airlines industry and other transport sectors are dependent on the fossil fuels sources and changing prices of crude oil, SAF production would contribute to increasing the world-wide energy security.

In a recent years a lot of attention has been paid to reduction of carbon dioxide emission, due to its harmful effect on environment, local air quality and human health. Due to the fact that aviation industry work towards the systematical reduction of CO_2 emissions, two key goals have been formulated to achieve [7]:

– carbon-neutral growth: from 2020 net carbon emission, what means that the grow of flights will don't cause the grow in greenhouse gas emissions,
– 50% reduction in CO_2 emissions up to 2050 year from the level in 2005 year. In accordance with this target, 915 million tons of CO_2 emitted in 2019 year (Fig. 3) should be reduced to 325 million tons in 2050.

Commercial aircrafts release about 750 million tons of pollutants every year [9].

Presented on Fig. 2 statistical data [29] show the continuous growth of fuel consumption by commercial airlines. In 2019 the fuel consumption reach the level of 436 billion liters. Forecast for 2020 year expected further growth of fuel consumption however due to the COVID-19 pandemic, the fuel consumption drastically dropped to 236 billion liters due to the suspension of significant number of flights. Forecast for 2021 show a slight increase in fuel consumption compared to the previous year.

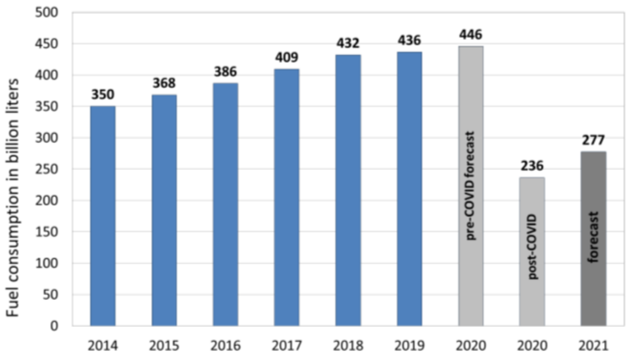

Fig. 2. Total fuel consumption of global commercial airlines [29, 57]

An increase in fuel consumption is accompanied by an increase in CO_2 emission, which is presented on Fig. 2. For 2019 the CO_2 emission reach the value of 915 million tones. The prediction made for 2020 year indicate the grow of emission up to 936 million tones, however the suspension of flights significantly reduce this value to 495 million tones.

Covid-19 pandemic drastically reduce the number of flights and at the same time emission of carbon dioxide (see Fig. 3). It is estimated that fuel consumption and CO_2 emissions will increase in coming decades as the demand for air transport. This trend will not be stopped by the decline in CO_2 per revenue passenger kilometer (RPK), caused by technological improvement [36].

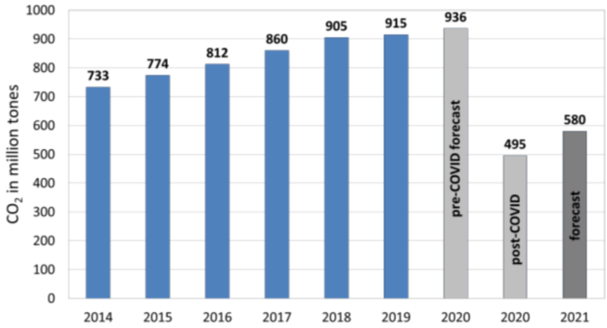

Fig. 3. CO_2 emission generated by the global commercial airlines [29, 56]

2. Combustion of hydrocarbon fuels and emission problem

A typical civil aviation fuel, used globally in turbines engines, is a JetA-1 (also called JP-1A) fuel, based on kerosene for which the mean C/H ratio is $C_{12}H_{23}$ [38]. At 20°C and under the pressure 1013 hPa, the JetA-1 appearance in liquid state, is transparent and characterized by low-viscosity. The flash point of JetA-1 is higher than 38°C and the freezing point below –47°C [50].

Aviation fuel is blended with a small amount of additives. Additives pay a different role, for example are used to prevent fuel igniting in uncontrolled manner or prevent fuel freezing. Jet fuels are subject to demanding international quality standards [50].

2.1. Hydrocarbon fuels burning process

Complete combustion of hydrocarbon fuel require sufficient amount of air to convert the fuel completely to carbon dioxide (CO_2) and water vapor (H_2O). The stoichiometric air-fuel-ratio can be calculated from the reaction equation (1) which for general hydrocarbon fuel of average molecular composition C_aH_b, takes the form [19]:

$$C_aH_b + \left(a + \frac{b}{4}\right)(O_2 + 3.773N_2) = aCO_2 + \frac{b}{2}H_2O + \\ +3.773\left(a + \frac{b}{4}\right)N_2 \quad (1)$$

The stoichiometric air-fuel-ratio [19]:

$$AFR = \frac{\left(a+\frac{b}{4}\right)(O_2+3.773N_2)}{C_aH_b} \quad (2)$$

The aviation fuel is a mixture of hydrocarbons. For Jet A-1 fuel based on kerosene, the number of carbon range between 8 to 16 [40]. For kerosene described by $C_{12}H_{23}$ chemical formula [39], relation (1) takes forms:

$$C_{12}H_{23} + 17.75\,O_2 + 66.97\,N_2 = \\ = 12\,CO_2 + 11.5\,H_2O + 66.97\,N_2 \quad (3)$$

The stoichiometric air fuel ratio (AFR) depends on the fuel composition [19] and for analyzed case, based on the equation (2) is 14.63. For each type of fuel the AFR will have a different value.

In modern turbine engines, during the combustion of 1 kg of aviation kerosene in 3.4 kg of oxygen are generated compounds such as [58]:

– 3.16 kg of CO_2,
– 1.29 kg of H_2O,
– less than 0.6 g of CO,

- less than 15 g of NO_x,
- less than 0.8 g of SO_2,
- less than 0.01 g of UHC,
- 0.01 to 0.03 g of soot.

The amount of carbon dioxide in exhaust gases can be calculated from stoichiometric relationship (3). The combustion reaction can be write as follows:

$$167 \text{ kg } C_{12}H_{23} + 568 \text{ kg } O_2 + 1875.16 \text{ kg } N_2 = \\ = 528 \text{ kg } CO_2 + 207 \text{ kg } H_2O + 1875.16 \text{ kg } N_2 \quad (4)$$

Assuming that 167 kg of $C_{12}H_{23}$ fuel produces 528 kg of CO_2, it can be written that:

$$1 \text{ kg } C_{12}H_{23} = 528/167 \text{ kg } CO_2 \quad (5)$$

Summarizing the above calculations, 1 kg of burned fuel produces about 3.16 kg of carbon dioxide.

Stoichiometric mixture contain sufficient amount of oxygen for complete combustion but the combustion process can also take place when there is excess (fuel rich) or deficiency of the oxygen (fuel lean). The deficiency of the oxygen result in incomplete combustion because there is insufficient amount of oxygen to fully oxidize the fuel ingredients carbon (C) and hydrogen (H) to CO_2 and H_2O. During incomplete combustion are formed such components as carbon monoxide (CO) and unburned hydrocarbons (UHC) [53]. In general the combustion process in gas turbines continues with the excess of air, thus the exhaust gases consist primarily of such combustion product as CO_2, H_2O, O_2 and N_2 [52].

The content of carbon dioxide in the exhaust gases generated by the aircraft engines comprises about 70% while the water vapor about 30%. Less than 1% of exhaust fumes consist of nitrogen oxides (NO_x), oxides of sulfur oxide (SO_x), carbon monoxide (CO), partially burned or unburned hydrocarbons (UHC), particulate matter (PM) generally called soot and other trace compounds. The source of 'aviation emissions' are not only aircrafts but also ground support equipment (GSE), auxiliary power units (APU) and other included in the airport service [20].

Emissions from aircraft engines exert the impact on the climate and local air quality, which in turn translates into people's health. The main emitted greenhouse gases (GHG) are CO_2 and H_2O.

The soot is an aerosol whereas SO_x, NO_x and hydrocarbons contributes to aerosol production after emission. Emission of water vapor in connection with aerosol lead to condensation trail formation [36].

NO_x from turbine engines operate like a catalyst in the oxidation process of CO, CH_4 and other hydrocarbon compounds. NO_x is not classified as a greenhouse gas but it change the concentration of two main GHG's, ozone (O_3) and methane (CH_4), through complex photochemical processes. Ozone increase at cruise altitude conduct to a positive Radiative Forcing (RF). Nitrogen oxide cause also increase of hydroxyl radical (OH), which react with CH_4 and in this way reduce its concentration and result in negative RF [36].

Carbon dioxide is long-lived greenhouse gas. Its atmospheric residence time is about 100 years [16]. The value of emission index (EI) for CO_2 is defined as 3160 ±60 g of CO_2 per 1 kg of jet fuel for complete combustion [38]. The residence time for N_2O is about 114 years while for H_2O about 9 days [16].

3. Sustainable aviation fuel

The SAF term describe the nonconventional aviation fuel [16]. Its chemical and physical properties are similar to the properties of conventional jet fuel (fossil fuel) used in turbine engines. This type of fuel can be directly added to regular jet fuel and safely mixed with them to varying proportions (Table 1). Application of such kind of non-conventional fuel do not require engines or airport infrastructure modification. Fuels with such properties are also named drop-in fuels. This feature of drop-in-fuel is very important for aviation industry, because do not require new infrastructure implementation which is associated with additional costs. In addition new fuel implementation require developing new safety and operational procedures [31].

3.1. Feedstock

Sustainable aviation fuel can be produce from a wide range of available feedstocks.

As the most common and cheapest feedstock for SAF production are considered waste oils (used cooking oil, animal fats, other fatty acids) [49]. Based on this feedstock the sustainable fuel is produced through the HEFA conversion process and can be blend with traditional aviation fuel up to 50% by volume (Table 1). Neste company is able to process about approximately 1 million tonnes of waste oils per year.

The production cost for HEFA fuel was set at €0.88 per liter, which is twice the cost of production of conventional aviation fuel based on kerosene [49].

Used cooking oil (UCO) can be received from commercial sources like restaurants and some households. In the European Union (EU) almost all recovered UCO is used for biofuel production [49]. Actually, 62% of UCO used for biofuel production in EU is imported. Three quarters of imported feedstock come from Asia. It has been estimated that collection of UCO from household would contribute to increase the availability to this raw material by 11% [49].

The animals fats (beef tallow, pork lard, chicken fat) are obtained from rendering plants and have application in food product, animal feed and soap processing. Costs of this feedstock are lower than for vegetable oil. Due to the fact that animals fats are used outside the biofuels sector, there is not expected the significant increase in demand of this raw material for SAF production within a decade [49].

The other example of raw material for sustainable fuel production are forestry residues, which with the excess wood can be processed into synthetic fuel through the Fischer-Tropsch process [49]. This feedstock can be also converted into renewable isobutanol and next through the ATJ process to jet fuel [49, 59].

Due to the large supply the municipal solid waste from households and industries can be used as sustainable feedstock for fuel production. This would reduce the emission of carbon dioxide and other gases that are released into atmosphere by municipal waste collected in landfills [10]. As examples can be mentioned products packing, food scraps, paper from newspapers or other articles, cardboard, bottles as well as clothing and furniture [10, 49]. Municipal waste of organic origin generate methane as a results of anaerobic decomposition [49].

Another group as an potential feedstock for SAF production are energy crops, like camelina, jatropha, algae and halophytes.

Camelina belongs to the group of non-food energy crops and is characterized by high lipid oil content (Fig. 4). The average oil content is about 30–40%. Camelina can grow on the infertile soil and is less susceptible to disease as other plants and can be cultivated as rotational crop for wheat and cereals [23]. After oil extraction remains the meal which can be used as animal feed. Energy crops used for sustainable fuel production should not compete with food production. They also should not have a negative impact on the environment and do not contribute to deforestation [23].

Fig. 4. Camelina [10]

The another example of energy crops is Jatropha (Fig. 5), which is inedible plant. This plant that can grow in marginal land which cause that is not compete with food production. Jatropha is characterized by rapid growth even in unfavorable conditions, is resistant to drought and pests. With a small amount of moisture the plant can yield for 40 years [23]. The meal left after oil extraction process is toxic, but due to the fact that contain nitrogen (N), potassium (K) and phosphorus (P), it can be used as organic fertilizer [23].

Fig. 5. Jatropha [10]

Algae (Fig. 6) are attractive raw material for SAF production due to several positive attributes. Algae are characterized by high lipid content, capacity to high absorption of CO_2 and quick growth. Algae do not require soil and water to growth, therefore do not affect the food cultivation [23]. Algae have ability to product large amount of lipids and carbohydrate by using sunlight, waste water and CO_2. The residue of the algae oil extraction is biomass, that can be used as animal feed, for bio-plastic preparing or further processed for energy production (dry biomass). Algae can produce 30 times more harvests per acre than other energy crops [23].

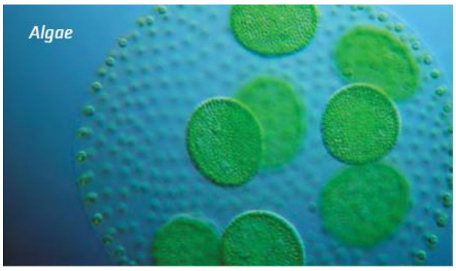

Fig. 6. Algae [10]

Halophytes (Fig. 7) are species of grasses that grow in salty water. Can grow in marshes, lakes, seashores, desert areas and in the sea. Due to the possibility of cultivation in difficult conditions, halophytes will not compete with food production [23].

Fig. 7. Halophytes [10]

3.2. SAF production

The diagram with SAF production data was presented on Fig. 8. The graph present information about SAF production from 2011 to 2019 as well as forecast for 2020 and 2021 year [25]. In present year, the production of SAF should achieve about 80 million litres. The estimated upper limit of production, that indicate the full production possibilities, get approximately 120 million of litres.

The forecast for 2025 year [25] indicate that SAF production will be on the level 3 billion of litres, however it is estimated that the upper production limit may reach approximately 4.5 billion litres [25].

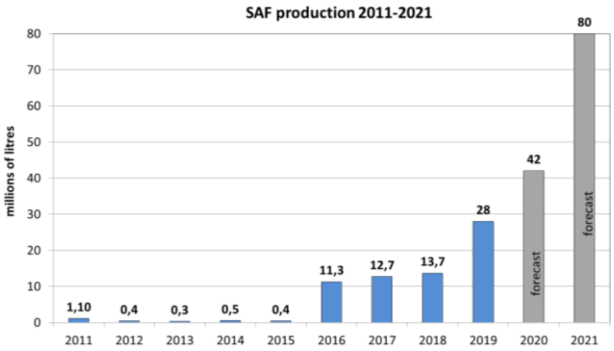

Fig. 8. SAF production data [25]

The quantity of sustainable fuel used by commercial aircraft increase by 65% between 2019 and 2020, despite of the financial losses suffered by the airlines caused by pandemic. The another increase in SAF consumption by 70% is expected in 2021 [8].

Actually there are eight certified SAF conversion technologies [18, 34,41]:

- Fischer-Tropsch hydroprocessed synthesized paraffinic kerosene (FT),
- Synthesized paraffinic kerosene from hydroprocessed esters and fatty acids (HEFA),
- Synthesized iso-paraffins from hydroprocessed fermented sugars (SIP),
- Synthesized kerosene with aromatics derived by alkylation of light aromatic from nonpetroleum sources (FT-SKA),
- Alcohol to jet synthetic paraffinic kerosene (ATJ-SPK),
- Catalytic hydrothermolysis jet fuel (CHJ),
- Synthesized paraffinic kerosene from hydrocarbon-hydroprocessed esters and fatty acids (HC-HEFA-SPK),
- Co-processing Synthetic Crude Oil in Petroleum Refinery.

In progress are three other conversion technologies such as [51]:

- High Freeze Point Hydroprocessed Esters and Fatty Acids Synthetic Kerosene (HFP HEFA-SK or HEFA+),
- Hydro-Deoxidation Synthetic Aromatic Kerosene (HDO-SAK),
- Alcohol-to-Jet Synthetic Kerosene with Aromatics (ATJ-SKA).

The information about the blending ratio (based on the technology pathway) and potential feedstock that can be used in a particular conversion process are listed in the Table 1.

Table 1. SAF conversion processes [34]

Reference documentation	Technology	Blending ratio	Feedstock
ASTM D7566 Annex 1	FT	50%	coal, natural gas, biomass
ASTM D7566 Annex 2	HEFA	50%	bio-oils, animal fat, recycled oils
ASTM D7566 Annex 3	SIP	10%	biomass used for sugar production
ASTM D7566 Annex 4	FT-SKA	50%	coal, natural gas, sawdust, biomass
ASTM D7566 Annex 5	ATJ-SPK	50%	biomass from ethanol or isobutanol production
ASTM D7566 Annex 6	CHJ	50%	triglicerydes such as soybean oil, jatropha oil, camelina oil, carinata oil, tung oil
ASTM D7566 Annex 7	HC-HEFA-SPK	10%	algae
ASTM D1655	Co-processing	5%	fats, oils, greases from petroleum refining

Coal and natural gas presented in Table 1 as a possible feedstock for FT and FT-SKA process, are non-renewable sources of raw material, therefore are not suitable for sustainable fuel production [35].

Fischer-Tropsch Synthetic Paraffinic Kerosene (FT-SPK) process was approved by ASTM in 2009 [52]. The FT conversion technology consists of steps such as biomass gasification, cleaning and conditioning of the produced synthesis gas. The synthesis gas is catalytically converted by the FT process into hydrocarbons such as jet fuel or diesel [18, 35]. Gasification is partial oxidation process that take place at high temperature (700–1500°C). During this process biomass and gasifying medium such as air, oxygen or steam is converted into synthesis gas, primarily consisting of CO, CH_4 and H_2 (hydrogen). After gasification syngas is prepared for catalytic conversion by cleaning and conditioning. Syngas consist also of CO_2, a range of higher hydrocarbon chains (tars) and other pollutants as hydrogen sulfide (H_2S) and particulate matter. The main objective of syngas cleaning is removal of tar, particular matter and chemical element such as S (sulfur), N (nitrogen), Cl (chlorine) [18].

The gas conditioning process is carried out to optimize gas quality before the catalytic synthesis of the syngas, which lead to the desired final product. In FT synthesis process, the CO and H_2 gases react in the attendance of the catalyst to create liquid hydrocarbons [18].

The fuels produced through the Fischer Tropsch pathway, named FT fuels, are characterized by non-toxicity, lack of nitrogen oxide emission, high cetane number which characterized the fuel ability to self-ignition of compressed fuel-air mixture. The other advantages of Fischer Tropsch fuels are low sulfur and aromatic content, reduced particulate matter emission and fuel combustion of such compounds as carbon dioxide and hydrocarbons [23]. In accordance with [23], the efficiency of FT conversion process ranges from 25 to 50%.

The fuels obtained by this production process are similar to Jet A-1 fuel. They are composed of hydrocarbons which amount and length may differ in comparison to conventional jet fuel. Also the number of H/C ratio may be different [16].

Hydroprocessed Esters and Fatty Acids (HEFA) process was approved in 2011. The HEFA pathway consist of catalytic reactions of various mechanism in hydrogen attendance. The first step in this conversion process is the hydrogenation, which consist in saturation of double bonds of the lipid chain by the catalytic addition of hydrogen. Hydrogen addition allow to remove the carbonyl group after hydrogenation and to brake the glycerol compound creating propane and chains of free fatty acid (FFA). The carboxyl group attached to the FFA can be removed to form straight paraffin chains by three ways: hydro-deoxygenation (HDO), decarboxylation (DCOX) or decarbonylation (DCO). To improve biofuel properties other processes are required: isomerization, cracking or cyclization [18]. The properties of final product are influenced by such factor as feedstock type and operating conditions (used catalyst, reaction pressure and temperature) [18].

Synthesized iso-paraffins (SIP) process was approved in 2014. This method is a biochemical conversion technology which allow for sustainable fuel production through the sugar fermentation [18]. As a feedstock can be used sugar cane or other sugar plants, for example sugar beets, sweet sorghum, cellulosic sugars or halophytes [18]. Direct sugar to hydrocarbon process (DHSC) include hydrolysis of biomass, carbohydrate fermentation, purification and hydroprocessing.

Alcohol-to-Jet Synthetic Paraffinic Kerosene (ATJ-SPK) technology was approved in 2016 [52]. This is biochemical conversion process for SAF production from alcohols such as methanol, ethanol, butanol and long-chain fatty alcohols [59]. First step in this technology pathway is biomass pretreatment and conditioning. After this activity alcohol can be produced through fermentation process. Further process of alcohol conversion to jet fuel include alcohol dehydration, oligomerization and hydrogenation [18].

Catalytic hydrothermolysis jet fuel (CHJ) receive certification in 2020 [37]. CHJ process consist of a reaction such as cracking, hydrolysis, decarboxylation, isomerization and cyclization. During the production pathway the triglycerides are change into the composition of straight chain, branched and cyclic hydrocarbons [59]. The reaction progress at presence of water and with/without a catalyst. The reaction process takes place at temperature 450–475°C and pressure of 210 bar [59]. The reaction products are processed to decarboxylation and hydrotreating for saturation and oxygen removal. The final step is fractionation for separation to naphtha, jet fuel and diesel [59].

Synthesized paraffinic kerosene from hydrocarbon-hydroprocessed esters and fatty acids (HC-HEFA-SPK) certified in 2020 [37]. In this process, the processed hydrocarbons are of biological origin. Their comes from oils found in *botryococcus braunii* algae [27].

Co-processing is the last approved SAF conversion pathway that contain co-processing of fats, oils and greases in conventional petroleum refinery, for supplying petroleum refining process [18]. This process was approved in 2018 and was include as an update (Annex A1) to ASTM D-1655 documentation [52].

The selected properties of neat fuels obtained by FT-SPK, HEFA, SIP and ATJ-SPK conversion technologies in relation to Jet A-1 fuel are presented in Table 2.

Table 2. Properties of selected fuels [32, 41, 43, 55, 60, 63, 64]

	Limits ASTM D1655 and D7566	Jet A-1	FT-SPK	HEFA	SIP	ATJ-SPK
Density 15°C kg/m^3	775–840	803.30	744.50	756.70	773.10	757.10
Kinematic Viscosity −20°C mm^2/s	max. 8.0	4.04	3.80	4.80	14.13	4.80
Heat of combustion MJ/kg	min. 42.80	43.25	44.10	44.15	44.10	43.20
Freezing point °C	–47	–49.60	–42.90	–54.40	< –80	< –80
Flash point °C	min. 38	40.50	51.50	42.00	107.50	47.50

3.3. SAF certification and quality control

Like all fuels used in aviation, sustainable aviation fuels need meets technical and certification requirements, allowing to use in commercial aircraft.

The standard specification for Jet A (commonly used in US) and Jet A-1 fuel (commonly used of the rest of the world) is ASTM 1655 'Standard Specification for Aviation Turbine Fuels'[28]. The other commonly used quality standard, confirmed by United Kingdom Ministry of Defence, is UK Defence Standard 91-91'Turbine Fuel, Aviation Kerosene Type, Jet A-1' (Def Stan 91-91) [41]. The differences between these two specifications are related to test limits for acidity level and naphthalene content [41].

The technical certification of SAF is regulated by the ASTM D7566 'Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons'[41]. This is the first specification that SAF need to meet. After that it can be blended with traditional fuel up to the allowable certified limit outlined in D7566. After blending process prepared fuel mixture is certified with ASTM D1655 [28].

Specifications allow to control the physical and chemical properties of fuel as well as allow for periodic checking for compliance. The deviations from standards included in the specifications are not permitted [28].

In many cases fuel have to travel many kilometers from the production facility to the direct recipient by various means of transport. From this reason the supply chain also require quality control. In situation when tested fuel does not meet the standards presented in ASTM (at the refinery or along the supply chain), the batch must be separate from other fuel and retested [41].

To the most common examples of quality documentations related to the sustainable aviation fuel are:
– Refinery Certificate of Quality (RCQ),
– Certificate of Analysis (COA),
– Recertification Test Certificate (RTC).

RCQ is the final document, created in the refinery for each part of product, that describe the quality of the product. It contains the results of measurements made in laboratory as well as information about the type and amount of additives that can be implemented to the fuel. This document contain also information about refinery name, batch number, date, as well as information that fuel meets ASTM D1655 [41].

COA can be issued by laboratories or by certified inspectors. This documentation include information about refinery name, batch number, date, information that fuel meets ASTM D1655 or D7655 [41]. COA does not contain detailed information about additives added previously but usually contain the results from ATA Specification 103: Standard for Jet Fuel Quality Control at Airports [41]. The Refinery Certificate of Quality and Certificate of Analysis are similar documents [41].

RTC confirms that recertification tests has been carried out. This process is implemented to check whether the fuel quality has not changed and meets specification requirements after transportation. Recertification is also necessary while the aviation product (fuel) is transfer to installation under conditions which may result in contamination, for example when fuel travel by the multiproduct pipeline [28, 41].

Quality process for conventional fuel begins with creation of RCQ in accordance to proper specification (ASTM D1655 or Def Stan 91-91). After leaving refinery, fuel start the transportation process to its destination, by variable means of transport (tanks, pipelines, trucks, etc.). At each transition point the fuel is re-inspected and COA certificate is issued. For neat SAF this process is similar but some additional steps occurred. In this case in refinery will be create RCQ in accordance with ASTM D7566 [28].

Blending process may occur directly at the refinery or at the suitable point along the supply chain (storage facility, airport). The choice of blending point depends on the access to conventional fuel [28]. Another important point is the fact, that conventional fuel composition is not constant and may vary within the range indicated by the specification. As an example can be used the density and aromatic content which are the key parameters for blending process, therefore at firs the composition of fuel should be known, to make sure that the final product meet the ASTM D7566 [28].

3.4. SAF producers

Actually, there are two main SAF producers: World Energy and Neste. World Energy (Fig. 9) start production in 2016 in their facility located in Paramount in California. Initially they supply United Airlines and later their expanded collaboration to KLM. Besides the SAF, the company also has in their offer biodiesel, renewable diesel, RINs and glycerin and fatty acids [62].

Fig. 9. World Energy in Paramount [14]

Neste (Fig. 10) is the world's largest SAF and renewable diesel producer. Their deliver SAF to San Francisco International Airport from refinery plant located in Rotterdam (Netherlands) by using existing multi-product pipeline infrastructure. Neste MY Renewable Jet Fuel TM, the brand name of produced SAF, is made from renewable waste and residue materials, like used cooking oil or animal fats [46].

Fig.10. Neste refinery plant in Rotterdam [47]

They manufacture renewable products in Finland, Netherlands and Singapore. The company plan increase its renewable annual production capacity from actual 3.2 to 4.5 million tons in the first quarter of 2023. 1.3 million tons will be provided by Singapore facility. The facility located in Rotterdam and Singapore are the biggest and the most advanced renewable fuels refineries in the world [45].

There are also other companies interested in SAF production. Fulcrum Bioenergy, is produce the low-carbon and low-cost transportation fuel from household garbage [21]. In this year the company finish the construction of the Sierra BioFuels factory located east of Reno in Nevada. They plan to convert 175 thousand tons of municipal solid waste into approximately 11 million gallons of synthetic crude [21].

Received product will be then upgraded to transportation fuels like sustainable aviation fuel, renewable diesel and renewable gasoline (Fulcrum FuelTM). The fuel production will begin during at fourth quarter of 2021 year. Fulcrum strategic partners include BP, United Airlines, Cathay Pacific, Japan Airlines and World Fuel Servicesand Marubeni [21].

Another example of company interested in SAF production is Red Rock Biofuels, which used a waste woody biomass as a feedstock. This company plans to convert 136 thousand tons of wood waste into 15 million gallons of SAF and renewable diesel [41].

The number of airports that distributing sustainable aviation fuel in the continuously manner or in batch is gradually increasing. Detailed information are contain in Table 3.

3.5. SAF application

Sustainable aviation fuels are an alternative option to conventional fuels and they properties may help to achieve the goals of aviation sector decarbonisation. Airbus, considered as a pioneer in SAF introduction, willingly supports all initiatives that contribute to sustainable fuel development and application in commercial flights. Today sustainable fuel can be applied in amount up to 50% without any modification of engine fuel system. Researches are carried out on the possibility of using larger amounts of alternative fuels. This will allow in the future for complete kerosene replacement by SAF.

On 29th June 2011, took place the first commercial Air-France KLM flight on sustainable jet fuel, using Boeing 737-800 [54]. Aircraft engines were operated on conventional jet fuel blended in 50% with sustainable fuel. The flight numbered KL1233 took place between Amsterdam Schiphol Airport and Paris Charles de Gaulle Airport carrying 171 passengers [54].

In 2012 took place the first flight of Air Canada (AC991), from Toronto to Mexico City, on airbus A319 aircraft powered by 50% blend of sustainable alternative fuel. Applied sustainable aviation fuel was produced from used cooking oil provided by SkyNRG. This flight was named "Perfect Flight" due to the fact that the routs and altitude were optimized, which finally help to decrease fuel consumption and reduce the noise generated by the aircraft [3].

Table 3. List of airports distributing SAF [33]

Date	Airport	State	Status	Fuel producer
06.10.2021	Toronto-Pearson Airport	Canada	Ongoing deliveres (offtake agreement)	Canada's Biojet Supply Chain Initiative (CBSCI)
14.09.2021	Boeing Field/King County Intl Airport	USA		–
23.08.2021	Le Bourget Airport	France		TotalEnergies
13.08.2021	Melbourne Orlando International Airport	Australia		Neste
14.07.2021	Farnborough Airport	United Kingdom		Neste
12.07.2021	Zurich Airport	Switzerland		Neste
28.06.2021	Cologne Airport	Germany		Neste
06.05.2021	Munich Airport	Germany		N/A
26.04.2021	Aspen Airport	USA		Neste
26.04.2021	Clemont-Ferrand Airport France	France		Air BP
06.04.2021	Biggin Hill Airport, London	United Kingdom		Air BP
23.03.2021	Van Nuys Airport	USA		World Energy
23.03.2021	John Wayne Orange County Airport	USA		World Energy
04.03.2021	Piedmont triad international airport	USA	Batch delivery	Neste
01.03.2021	Bristol Airport	United Kingdom	Batch delivery	BP
26.02.2021	Monterey Regional Airport	USA	Ongoing deliveres (offtake agreement)	Neste
26.02.2021	Oakland International Airport	USA		Neste
12.02.2021	Camarillo Airport	USA		N/A
08.12.2020	London Luton Airport	United Kingdom		Neste
03.02.2020	Fort Lauderdale Executive Airport	USA	Batch delivery	Gevo
07.09.2019	Bob Hope Burbank airport	USA	Ongoing deliveres (offtake agreement)	Neste
23.08.2019	Jackson Hole Airport	USA	Batch delivery	Gevo
01.06.2019	Umeå Airport	Sweden	Batch delivery	Air BP
01.06.2019	Malmö Airport	Sweden	Batch delivery	Air BP
02.05.2019	New York's Republic Airport	USA	Batch delivery	Gevo
17.01.2019	Van Nuys Airport	USA	Batch delivery	Gevo
19.12.2018	Stockholm Bromma Airport	Sweden	Ongoing deliveres (offtake agreement)	Air BP
19.12.2018	Åre Östersund Airport	Sweden	Batch delivery	World Energy
19.12.2018	Göteborg Landvetter Airport	Sweden	Batch delivery	World Energy
19.12.2018	Visby Airport	Sweden	Batch delivery	World Energy
19.12.2018	Luleå Airport	Sweden	Batch delivery	World Energy
06.12.2018	San Francisco Airport	USA	Ongoing deliveres (offtake agreement)	World Energy
12.11.2018	Kalmar Öland Airport	Sweden		World Energy
14.05.2018	Vaxjo Smaland Airport	Sweden		World Energy
19.04.2018	Toronto-Pearson Airport	Canada	Batch delivery	Canada's Biojet Supply Chain Initiative (CBSCI)
08.11.2017	Chicago O'Hare Airport	USA	Batch delivery	Gevo
03.10.2017	Brisbane Airport	Australia	Batch delivery	Gevo
21.08.2017	Bergen Airport	Norway	Ongoing deliveres (offtake agreement)	World Energy
26.07.2017	Halmstad City Airport	Sweden		World Energy
05.01.2017	Stockholm Arlanda Airport	Sweden		World Energy
24.05.2016	Montreal Trudeau Airport	Canada	Batch delivery	Canada's Biojet Supply Chain Initiative (CBSCI)
01.03.2016	Los Angeles Airport	USA	Ongoing deliveres (offtake agreement)	World Energy
22.01.2016	Oslo Airport	Norway		World Energy
26.01.2014	Karlstad Airport	Sweden	Batch delivery	Statoil

Between 2011 and 2015, 22 airlines accomplish over 2500 passenger flights on fuel containing up to 50% of bio-jet fuel. The bio-jet feedstock included used cooking oil, camelina, jatropha, algae and sugarcane [30].

On 18th of March 2021 took place the first test flight of Airbus A350 (Fig. 11) supplied by 100% Sustainable Aviation Fuel. Tests were conducted on Blagnac airport located in Toulouse, in France [2].

Nowadays all Airbus aircrafts are certified to fly on jet fuel blended with SAF up to 50%. An Airbus-led project named 'Emission and Climate Impact of Alternative Fuel' (ECLIF3) in collaboration with Rolls Royce, DLR (German Aerospace Research Center) and Neste (SAF producent) [2, 44]. The goal of the project is looking into the effect of 100% SAF application on engine emission and performance. Test are conducted on Airbus A350-900 powered by Trent XWB – three-shaft turbofan engine [2].

Fig.11. Airbus A350 flight on 100% SAF (2021) [2]

The emissions generated by 100% SAF fuel, measured during ground and flight tests were used for comparison with emissions emitted during kerosene burning and kerosene with low sulfur content [2]. Conducted researches will also include the control of particulate-matter emissions [2]. The first flight of aircraft fueled by 100% SAF went well, without noticeable difference in engine behavior.

On 18th of May 2021 at 15:40 took place the first long-haul flight on the aircraft supplied by SAF produced entirely in France. Air France Flight 342 was from Paris-Charles de Gaulle Airport (CDG) to Montreal in Canada. Fuel was made from waste and residue source that come from the circular economy. It was produced from used cooking oil by Total company in La Mede bio-refinery and Qudalle factory. Developed sustainable fuel received ISCC-EU certification from International Sustainability & Carbon Certification System. Prepared fuel mixture contained 16% of SAF and allow for CO_2 emission reduction by 20 tonnes. The Air France KLM conducted their first flight on SAF in 2009 year. Between 2014 and 2016 they made 78 flights on aircrafts powered by fuel with 10% of SAF blend [1].

On 17th June 2021 took place first commercial flight of Japan Airlines (JAL), numbered JL515, using two types domestically produced SAF, blend with the jet fuel. The flight on Airbus 350 aircraft, was from Tokyo Haneda to Sapporo (Chin-Chitose) [13]. The 3,132 liters of SAF was blended with conventional jet fuel at 9.1% blending ratio. The first type of used SAF was produced from wood chips by Mitsubishi Power, Toyo Engineering and JERA and the second from algae by IHI Corporation. The JAL Group plan permanently introduce 10% of SAF to conventional aviation fuel by 2030 [12, 13, 22].

Fig. 12. First Beluga flight with SAF [5]

The other example of SAF application is Airbus Beluga first flight in December 2019 (Fig. 12). Beluga aircrafts named also Super Transporter are used for transportation huge loads such as fuselage fragments or wings. Beluga fleet operating from Broughton in Wales, will be supply by 35% blend of non-fossil derived fuel. The sustainable feedstock is used to produce the SAF for Beluga fleet, such as cooking oil. The fuel is supplied to Airbus in Broughton and Hamburg by Air bp [4].

Since first passenger flight on SAF blend fuel in 2011 year until now, there was more than 375 thousand of commercial flights operated on this kind of fuel [11].

In previous year, the SAF production was about 190 thousand tones, which is less than 0.1% of the total fuel consumption. The main reason of such low production is SAF prices, which are two up to three times higher in accordance to fossil fuels [6].

It is worth to mentioned that Swiss International Air Lines (SWISS) create the first complex logistic chain for importing Neste MY Sustainable Aviation Fuel™ to Switzerland in collaboration with different business partners [51]. At the same time it does makes SWISS the first airline which use the SAF in its regular operation from Switzerland. In addition Swiss airlines collaborate with Lufthansa Group on SAF researches and adoption.

Lufthansa Group conducted in 2011 the first long-term test of biofuels in their scheduled flight operations in cooperation with Neste [48].

3.6. Infrastructure

Commercial airports have an extensive airport infrastructure for fuel management – fuel receive, storage and transmition to the fuel tanks located on the aircraft. Fuel infrastructure consist of fuel tanks, pipelines, fuel pumps, flow meters to control the flow of the fuel, filters to remove contaminants, safety system to detect and prevent fuel leakage. Fuel is delivered to the fuel tanks located in the aircraft wings by hydrant systems or fuel truck [41]. There are several means of transport used for fuel transition from manufacturer to the destination place. Commonly used in aviation Jet-A fuel is mostly transfer by pipes [41]. SAF can be transport by pipelines only in case when it is co-processing in refinery and meet ASTM standards. For example Neste company transport SAF to the West Coast where is blended with conventional jet fuel. Prepared fuel is delivered by pipes to the San Francisco International Airport [41].

The World Energy use different delivery schedule. The Jet-A fuel is delivered to the production facility by trucks and there blended with SAF. Then sustainable fuel is delivered to Los Angeles International Airport by truck. The delivery schedule depends on many factors. In case of methods used by World Energy decided mostly the neighborhood of airport, availability of Jet-A fuel nearby and low fuel volumes [41]. Different delivered methods will be used for low volume SAF production and for higher volumes.

There are two options of SAF blending in the terminal:

- In the first case (Fig. 13) both SAF and Jet-A are storage in separate tank. Individual tank is used to blending process. If the sample of blended fuel meet the requirements from ASTM D7655, is denote as ASTM D1655 and is ready to delivery,

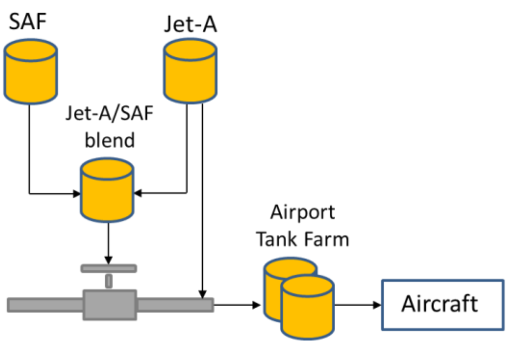

Fig. 13. First option of Jet-A and SAF blending at the terminal [41]

– In the second option (Fig. 14) SAF is deliver to the tank with Jet-A fuel. This option will require carefully control to identify the amount of added SAF.

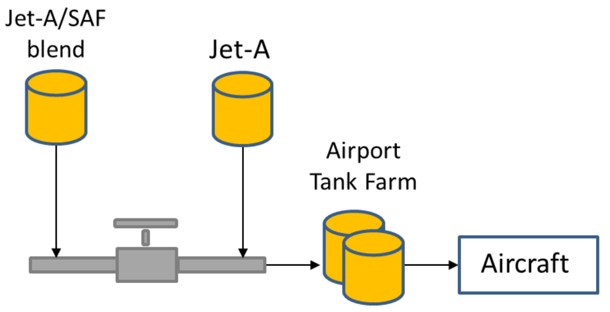

Fig. 14. Second option of Jet-A and SAF blending at the terminal [41]

Due to the fact that SAF meet the same standards as conventional jet fuel, specified by ASTM, therefore the problems with compatibility are not excepted [41].

4. Conclusions

Zero emission aircrafts are actually not available. SAF application don't require aircraft, engines, storage and distribution infrastructure modification. This feature of alternative fuel is very important and facilitate the introduction of alternative fuel to the aviation. Due to the fact that aviation sector has no near-term alternative to liquid hydrocarbon fuels, the SAF produced from variable renewable feedstock seems to be the best option for modern aviation fleet. The gradual SAF introduction in aircraft sector should result in reduction of CO_2 emission. The results of conducted literature studies indicate that the use of sustainable aviation fuels is of great interest. The number of flights on sustainable fuel increase very quickly, which also indicate high operational safety and reliable operation of turbine engines. New, more efficient SAF conversion technologies are still develop. The fuels obtained through different processes are characterized by different properties. For this reason, the blending process is a key stage in the production pathway that allows to obtain the final products with desired properties and compliant with the required standards.

Nomenclature

APU	auxiliary power unit
ASTM	American Society for testing and Materials
GHG	greenhouse gas
GSE	ground support equipment
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
IRENA	International Renewable Energy Agency
SAF	sustainable aviation fuel

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