AVIATION FUEL EVOLUTION: A REVIEW

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ABSTRACT

Aviation covers a significant role in environmental impacts, as it accounts for 2% of global carbon dioxide (CO_2) equal to more than 33 Gt emissions. Due to the progressive increase in air traffic, aviation polluting emissions are growing by approximately 5% by year and double each 15 years. The road map of aviation sustainable development program is ambitious; the objective is to stabilize CO_2 emissions by 2020 and afterwards to reduce them by 50% in 2050 compared to 2005 quota. Governments, manufacturers, airlines and international transport organization to ensure aviation greater sustainability, largely are aware the promotion of bio-jet fuel use.

This paper aims to describe aviation fuel evolution particularly with regard to bio-jet fuel, based on data related to civil and military flight tests from 2006 up today and on national and international references and technical reports of international organizations such as IPCC, (Intergovernmental Panel on Climate Change), ICAO (International Civil Aviation Organization), IEA (International Energy Agency) and IATA (International Air Transport Association). The study identifies typologies and features of bio-jet fuel available on the market, focusing on feedstock used and conversion processes applied to their production, reporting related environmental impacts and issues. The final purpose is to highlight strengths and weaknesses related to bio-jet fuel production and use, in terms of market and environmental implications.

Keywords: *sustainability, air transportation, biofuels, air pollution, renewable resources*
JEL Classification: *Q56, L93, Q16, Q53, Q20.*

1. Introduction

Aircraft engines emit various pollutants, of which CO2 influences climate change (European Aviation Safety Agency, European Environment Agency, Eurocontrol, 2016) and aircraft transport has a direct impact on the depletion of the Earth's ozone layer (Kisska-Schulze & Tapis, 2012). The world's airlines carry over three billion passengers a year and 50 million tonnes of freight (Air Transport Action Group, n.d.-e). Future scenario for aviation industry estimates a growth of 5% per year doubling the traffic within 15 years based on 2012 year (Nygren et al.,

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2009; Chiaramonti et al., 2014). Due to these "fugures" aviation, since the last decade, is investing, researching and testing sustainable alternative fuels.In 2009, Air Transport Action Group (ATAG) Board agreed on three environmental targets, which included improving fuel efficiency by an average of 1.5% per year from 2009 to 2020, stabilizing emissions from 2020 with carbon-neutral growth and reducing net emissions from aviation by 50% by 2050 compared to 2005 levels (Air Transport Action Group, n.d.). During the same year, the first International Conference on Aviation and Alternative Fuels (CAAF), organized by International Civil Aviation Organization (ICAO), encouraged Member States to establish policies that support the use of sustainable alternative aviation fuels (International Air Transport Association, 2016). Aviation has considered its activities and the related increase of environmental impacts and in the last decade it has invested in the research and testing of sustainable alternative fuels. Given the above, this paper aims to describe aviation fuel evolution particularly with regard to bio-jet fuel, based on data related to civil and military flight tests from 2006 up today, national and international references and technical reports of international organizations such as IPCC, (Intergovernmental Panel on Climate Change), ICAO (International Civil Aviation Organization), IEA (International Energy Agency) and IATA (International Air Transport Association). The study identifies typologies, properties and costs of bio-jet fuel available on the market, focusing on feedstock used and conversion processes applied to their production, reporting related environmental impacts and issues. The final purpose is to highlight strengths and weaknesses related to bio-jet fuel production and use, in terms of market and environmental implications.

2. Biofuel generation

The continuous evolution of research on sustainable fuel has led to identifying four generations of biofuel. The first generation is based mainly on oleaginous plants, such as corn, soybean, rapeseed, sunflower and palm, which is in competition with food industry. The second generation uses inedible energy crops, in particular camelina, jatropha and switchgrass as well as feedstocks resulting from lignocellulosic biomass (woody and agricultural residues), used cooking oil, animal fat, industrial and municipal wastes. The second one is receiving growing attention on large-scale market. The third generation includes microalgae and halophytes, often genetically modified. The interest in these microorganisms is due to the fact that they can be cultivated on arid and/or marginal land and also in salt water, they have a very high growth rate and they have lower carbon output compared with other feedstock (Schmitigal & Tebbe, 2011). The last generation considers bacteria, microbes and yeasts but this option is still at laboratory stage.

Based on the feed-stocks used, bio-jet fuels can be classified in four main categories: Alcohol-To-Jet (ATJ), Oil-To-Jet (OTJ), Gas-To-Jet (GTJ) and Sugar-To-Jet (STJ). Different technology pathways are used to obtain them. Table 1 summarizes different categories and technology pathways both approved than in the course of approval. Up to date, only five (bold style) have been approved by American Society for Testing and Materials (ASTM) International and, among them, HEFA technology using vegetable and waste oils represents the only conversion pathways that are ready for large-scale production. For each different pathway, considering the limitations imposed by feedstock composition, pre-treatment and conversion steps, the conversion efficiency rate (from feedstock to liquid hydrocarbon fuel) ranges from less than 20% up to more than 80% (Wormslev et al., 2016).

Table 1. Bio-jet fuel conversion processes

Category	Tecnology pathway	Feedstock
Alcohol to Jet (ATJ)	Alcohol to Jet Synthetic Paraffinic Kerosene (**ATJ-SPK**) or Isobutanol to Jet (ITJ)	Cellulosic biomass, starch, sugar
Gas to Jet (GTJ)	Fisher-Tropsch-Synthetic Paraffinic Kerosene (**FT-SPK**)	Agricultural waste, coal, biomass, municipal waste, natural gas
	Fischer-Tropsch Synthetic Kerosene with Aromatics (**FT-SKA**)	Agricultural waste, coal, biomass, municipal waste, natural gas
Oil to Jet (OTJ)	Catalytic Hydrothermolysis (CH)	Animal fat, recycled oil, vegetable oil and any other bio-oil containing tri-glycerides
	Hydroprocessed Esters and Fatty Acids (**HEFA**) or Hydroprocessed Renewable Jet (HRJ) or Bio-Synthetic Paraffinic Kerosene (Bio-SPK)	Algal oil, animal fat, recycled oil, vegetable oil and any other bio-oil containing tri-glycerides
	Hytdrotreated Depolymerized Cellulosic Jet (HDCJ) or Hydrogenated Pyrolysis Oil (HPO)	Agricultural waste, lignocellulosic biomass, municipal waste
Sugar to Jet (STJ)	Direct Sugar to Hydrocarbons (DSHC) or Synthetic Iso-Paraffin (**SIP**)	Any fermentable sugar
	Hydro-Deoxygenated Synthesized Kerosene (HDO-SK) [Catalytic Upgrading]	Starch, sugar, cellulosic biomass
	Hydro-Deoxygenated Synthesized Aromatic Kerosene (HDO-SAK) [Catalytic Upgrading]	Starch, sugar, cellulosic biomass

Sources: Lang & Elhaj, 2014; Radich, 2015; Toop et al., 2014; Wang et al., 2016; Wormslev et al., 2016.

Jet fuel (conventional or bio) has to meet many specifications and basic qualities in order to ensure safety and efficiency of flight. They have to comply with standards and specifications established by national and international institutions or organizations such as: ASTMInternational and United Kingdom Defence Standard (DEF STAN) of United Kingdom Ministry of Defence. ASTM International standard specification D1655, for instance, fixes two types of jet fuels for civil use: Jet A and Jet A-1 (Zhang et al, 2016). The ideal bio-jet fuels must meet the technical official standard and in the same time has to be available and suitable to be used in existing engine technology. Researches and studies in this field are aimed by the same and common interest, that is to develop the so-defined "drop-in" fuels intending a bio-jet fuel "… *that is completely interchangeable and compatible (can be mixed over a range of percentages) with a particular conventional (typically petroleum-derived) fuel, it does not require adaptation of the fuel distribution network or the vehicle or equipment engine fuel systems"* (Blakey et. al, 2011). In September 2009, a "bio-standard" for bio-jet fuels, the ASTM D7566, was approved as drop-in fuel specification. Table 2 compares civil conventional ASTM D1655 standard with bio-one ASTM D7566. Data recorded in table 2 shows that bio-jet fuels certified by ASTM D7566 standard meets ASTM D1655 one allowing them to be seamlessly integrated into the current aircraft and infrastructures (Zhang et al., 2016).

Table 2. Civil conventional ASTM D1655 and bio jet fuel ASTM D7566 main peculiarities and properties.

	ASTM D1655	ASTM D7566 (Bio-jet fuel)
Composition		
Acidity, total (mg KOH/g)	0.1, max	0.1, max
Aromatics (vol %)	25, max	25, max
Sulfur, total (wt %)	0.3, max	0.3, max
Volatility		
Distillation temperature:		
10% Recovery (°C)	205, max	205, max
Final BP (°C)	300, max	300, max
Flash point (°C)	38, min	38, min
Density @ 15 °C (kg/m^3)	775-840	775-840
Fluidity		
Freezing point (°C), max	-40 Jet A; -47 Jet A-1	-47
Viscosity @ -20 °C (cSt)	8, max	8, max

	ASTM D1655	ASTM D7566 (Bio-jet fuel)
Combustion		
Net heat of comb. (MJ/kg)	42.8, min	42.8, min
Smoke point (mm)	25, min	25, min
Smoke point and naphthalenes (vol %)	18 (min), 3 (max)	18 (min), 3 (max)
Thermal stability		
JFTOT Delta P @ 260 °C (mm Hg)	25, max	25, max
Tube deposit rating (Visual)	< 3	< 3
Conductivity		
Conductivity (pS/m)	50-600	50-600
Lubricity		
BOCLE wear scar diameter (mm)	0,85, max	0.85, max

Sources: Iakovlieva et al., 2013; Wang & Tao, 2016

Starting from bio-standard (ASTM D7566) approval, FT bio-jet fuels production become compliant to ASTM D7566. Subsequently, other four bio-jet fuels obtained by other feedstock and technology pathways were qualified to be used and blended in different percentage with conventional jet fuels. Approval data and blend percentage of five bio-jet fuels are describes in table 3.

Table 3. Data of bio-jet fuel standard

	ASTM D7566 (Bio-jet fuel)				
	FT-SPK	HEFA	SIP	FT-SKA	ATJ-SPK
Approved	September 2009	July 2011	June 2014	November 2015	April 2016
Blend Percentage	up to 50%	up to 50%	up to 10%	up to 50%	up to 30%

Sources: Bi et al., 2015; Federal Aviation Administration, 2016; Greenair Online, 2016; Holladay et al., 2014; International Civil Aviation Organization, 2011

3. Environmental impact

Bioenergy is often considered carbon neutral, because is assumed that the CO_2 absorbed during plant growth compensates emissions released during combustion phase. First generation biofuels, such as corn-based ethanol, tend to emit more greenhouse gas (GHG) emissions than second and third generation ones, as corn cropping requires higher use in fertilizer and pesticide. The United States Department of Energy claims that use of sustainably produced biofuel reduces life-cycle CO_2 emissions by 50 to 80% compared to conventional petroleum fuel (International Air Transport Association, 2016). Several studies and researches have been carried on life cycle assessment GHG emissions related to production of bio-jet fuel,

The GHG emissions of jet fuels derived from various categories are illustrated in Fig. 1, using $kgCO_2/GJ$ basis.

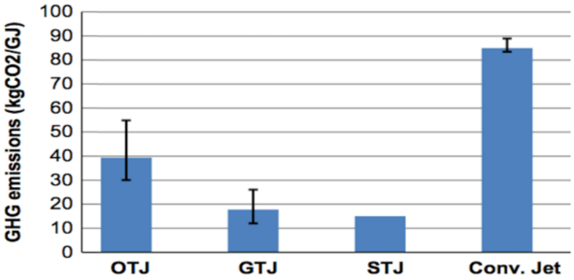

Fig. 1 Greenhouse gas emissions (GHG) of jet fuel from various pathways

Note: For OTJ pathway, the higher and lower end uncertainties represents GHG emissions of rapeseed and palm oils, respectively. For the GHG emissions of OTJ and GTJ pathways, without land use change is considered. For GTJ pathways, switch-grass is selected as the feedstock; without soil carbon sequestration is considered.

Sources: Authors personal elaboration on data: Wang et al., 2016; Wang & Tao, 2016

GHG emissions are reduced when using the bio-jet fuels and STJ pathway has the highest reduction and depending primarily by the farm input, land use change and biorefinery processes. Life Cycle Assessment (LCA) is a useful tool to evaluate environmental impacts associated to each bio-jet fuel. LCA of aviation sector, also known as well-to-wake (WTW) analysis, has two phases: well-to-tank (WTT) and tank-to-wake (TTW). In the first phase, kind of feedstock, land use change and conversion pathways influence GHG emissions, while in the second one the emissions derived fromburning jet fuels are the most significant issue. The WTW GHG emissions from conventional jet fuel are reported to be approximately equal to 87.5 gCO_2e/MJ, of which 14.3 gCO_2e/MJ are linked to WTT steps and 73.2 gCO_2e/MJ to TTW ones (Wang & Tao, 2016).Alternative jet fuels based on fossil fuels emits more GHG emissions than sustainable ones.Actually the data related to bio-jet fuel derived from biomass does not consider the additional emissions caused by land use change and these are direct (DLUC) or indirect (ILUC).According to Blakey et al. (2011), some researches demonstrated that land use change linked to the cultivation of biomass has the potential to release significant emissions, as the GHG emissions resulting from biomass cultivation is largely dependent on previous land use.Consequently, indirect land use change reduces or cancels any greenhouse gas savings from biofuel production based on energy crops (Popp et al., 2014).GHG emissions could increase of 40–800% compared with conventional jet fuel when accounting for land use change (Wang & Tao, 2016).HRJ fuel has GHG emissions 62–92% higher than FT Biomass to Liquid, due to fertilizer and chemical use. GHG emissions from the FT BTL process are 92–95% less than those of conventional jet fuel, also because 48% of the energy consumed for the conversion processes is obtained by the biomass itself (Wang et al., 2016; Wang & Tao, 2016).

4. Bio-jet flight evolution

The first flight with biofuel was realized near Edwards Air Force Base - California by United States Air Force (USAF) in September 2006 with a B52 Stratofortress bomber. The flight test involved running two of the bomber's engines on a synthetic fuel, made from a 50-50 blend of traditional crude oil-based fuel and a FTfuel derived from natural gas, while the jet's other six engines ran on traditional JP-8 jet fuel (Unites States Air Force, 2006). Table 3 illustrates the flight trials according to the type of bio-jet fuels, and their feedstock. Most of the flight tests were carried out with various blend percentages of bio-jet fuel and conventional aviation fuel. In few cases aviation has carried out flight tests with 100% biofuel. To date bio-jet fuels certified are blended with conventional jet fuel up to 50%.

Table 4. First biofuel flight tests

Feedstocks	First Fly in	Percentage (%)	Aviation	
			Civil	Military
Natural gas	September 2006	50		x
Used cooking oil	October 2007	100	x	
Coconut oil and babassu oil	February 2008	20	x	
Soy and animal fat	November 2008	100	x	
Jatropha	December 2008	50	x	
Algae and Jatropha	January 2009	50	x	
Camelina, jatropha and algae	January 2009	50	x	
Camelina	November 2009	50	x	
Animal fat	April 2010	50		x
Algae	June 2010	100	x	
Used cooking oil and algae	June 2010	50		x
Animal fat and natural gas	August 2010	50		x
Chicken tallow and beef tallow	March 2011	50	x	
Camelina, jatropha and animal fat	July 2011	50	x	
Jatropha and halophytes	July 2011	30	x	
Camelina and brassica carinata	April 2012	50	x	
Cellulose	June 2012	50		x
Corn oil and used cooking oil	June 2012	50	x	
Sugarcane	June 2012	50	x	
Used cooking oil, jatropha and camelina	June 2012	50	x	
Brassica carinata	October 2012	100	x	
Palm oil and used cooking oil	April 2013	n.d.	x	
Isobutanol	December 2013	50		x
Green diesel (vegetable oil, used cooking oil, waste animal fat)	December 2014	15	x	
Tobacco without nicotine	July 2016	30	x	
ReadiJet (yellow grease, used cooking oil, brown grease)	September 2016	100		x

Source: Personal elaboration by authors

The first 100% biofuel flight was carried out by old military trainer aircraft, L-29 Delfin. The Green Flight International-owned L-29 took place on October 2007 from Nevada's Reno-Stead airport and the biodiesel supplied for testing was made from recycled vegetable-derived cooking oil (Coppinger, 2007). During February 2008, Virgin Atlantic, one of the world's leading long-haul airlines, flew a GE-powered 747 jumbo jet on biofuel from London Heathrow to Amsterdam, becoming the first airline in the world to fly on renewable fuel, composed of babassu oil and coconut oil (GE Aviation, 2008). Honeywell made history in Paris Air Show in June 2011, landing its Gulfstream G450 jet at Le Bourget after the first transatlantic flight using biofuel (camelina) from the New York-area Morristown Airport, burned a 50/50 blend of "Honeywell Green Jet Fuel" (Harrison, 2011). It was also the first intercontinental bio-jet fuel flight. In 2011, KLM Royal Dutch Airlines was the first airline in the world to carry passengers, using bio-jet fuel. The Boeing 737-800 carried 171 passengers on June 29, burning a 50/50 blend of used cooking oil from Amsterdam to Paris (Paur, 2011). Actually, already in November 2009 KLM had made a demonstration flight with guest passengers. The U.S. Navy successfully flew an EA-18G Growler on 100% renewable jet fuel on September 1, 2016,flying out of Naval Station Patuxent River – Maryland and completed the first of nine test flights as part of the military specification certification for the ReadiJet® fuel's operational use (Oldham, 2016).

5. Conclusion

TheIntergovernmental Panel on Climate Change (IPCC) has concluded that, in the absence of fully committed and urgent action, climate change will have severe and irreversible impacts across the world (International Energy Agency, 2015). The use of biofuels could play an important role limiting the consumption of fossil fuels, reducing greenhouse gas emissions and environment protection; developing new policies aiming at sustainability and preservation of biodiversity. Moreover, fuel is one of the biggest operating costs for the aviation industry estimated in 2012 and for all airlines, in approximately $47 billion (Wang & Tao, 2016).Forecasts on bio-jet fuel use highlights a progressive growth and, as a matter of the fact, International Air Transport Association (IATA) expects 30% contribution of bio-jet fuel for the jet fuel use by 2030 and European Union (EU) has been set the target of 2 Mt of aviation alternative fuels by 2020 (corresponding to 4% of annual aviation fuel consumption) (Chiaramonti et al., 2014; Hari et al., 2105).Worldwide, aviation can have a significant influence in fostering the promotion of sustainable biofuels. Now all aviation actors are aware that there is the need to implement new actions and solutions to achieve the ambitious goals that Governments and Organizations have fixed by to improve climate change. Current efforts are dedicated in trying a bio-jet fuel production based on sustainable and feedstcks, no competition with food production, more environmentally friendly and with minimal effects related to the direct and indirect land-use change. Feedstock has to be also cheap, it is estimated that it is the largest cost item of bio-jet fuels production ranging from 45% to 90%. Considering the different technologies, its influence is highest for HEFA pathway, lowest in FT (waste residues) and medium in ATJ and SIP (International Air Transport Association, 2015). The technology and policy play a key role improving respectively process efficiency and increase in bio-jet fuel commercialization. Aviation industry members are encouraging to produce and use cleaner technologies and bio-jet fuels, thanks to the agreements that are signed at international level. Also the passengers, choosing "bio-jet fuels flights", confirm their interest in environmental issues and make much more "active" the market of "green fly".

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