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Refuelling the future: Progress towards testing drop-in biofuels in replacing conventional fuel for commercial flights

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Abstract. Due to different motivations, including the interest in reducing the dependency on fossil fuel and environmental implications, drop-in biofuels are a reality in today's commercial aviation. This paper summarizes the state-of-the-art of biomass-origin kerosene certification and provides references to the commercial flights performed so far by all airlines around the world. Results prove that the normal operation of the flights using the drop-in biofuel do not experience any repercussion in the performance in both engine and maintenance.

1. Introduction

Air transport is one of the most rapidly grown transport sectors. Forecasts give future air traffic yearly growth rates of 4 % [1, 2, 3, 4, 5]. Despite of the benefits from that growth, there are concerns about the increase in aviation greenhouse gas emissions (GHG). The significant growth suggests aviation could become a significant factor over the coming decades [6, 7, 8, 9]. Carbon Oxide (CO2) is considered the most important greenhouse gas emitted by aircraft, responsible for 3% of global fossil fuel consumption and 12% of transportation-related CO2 emissions [10]. Recent studies suggest that if the global economic growth continues, aviation CO2 emissions are likely to experience a greater than three-fold increase between 2000 and 2050 [11, 12, 13].

In response to concerns over the global environmental impacts of aviation, stakeholders have committed to strategies of mitigation related to efficiency improvement (fleet replacement, use of larger aircraft, increased density seating inside aircraft, improvements in Air Traffic Control (ATC) and navigation procedures). The calculation of the practical consequences of all those elements is rather complicated, but according to International Air Transportation (IATA) the results show an average improvement in efficiency, measuring in ton of fuel per (Revenue Ton per Kilometers) RTK, around 1.9% yearly [14] for the IATA members, although other studies indicate lower fuel per RTK [15]. The International Civil Aviation Organization (ICAO) Council, in its climate change mitigation program, has set an aspirational target for the World Air Transport sector of 2.0% yearly CO2 improvement until 2020.

Sustainable, advanced-generation aviation biofuels will play a large role in reducing CO2 emissions [6, 16]. The European (Emission Trading Scheme) ETS Directive [17]considers a zero emission factor for aviation biofuels, although assessments of life-cycle CO2 emissions typically show a potential reduction compared to fossil jet fuel in the order of 30-90%, depending on feedstock and production processes [18]. As for the biofuel usage in aviation, most of the specification and operational questions have already been answered and no technological show-stopper is seen thus far. However, the economic viability is still far from being made secured [19, 20, 21].

In 2009, data gathered suggest that the proportion of biofuels in total fuel consumption by commercial aviation was 0.5% and will rise to 15.5% in 2024 in a "moderate" scenario, and to 30.5% in an "ambitious" scenario [22]. In the European Union, the European Commission has launched the "European Advanced Biofuels Flightpath", an industry-wide initiative to speed up the market uptake of aviation biofuels in Europe. It provides a roadmap to achieve an annual production of two million tonnes of sustainably produced biofuel for aviation by 2020 [23] This research paper investigates the state-of-the-art of the biojet fuel usage considering biofuel certification and the utilization of drop in biofuels for commercial aviation around the world.

2. Drop-in Biofules Tests on Commercial Flights

In 2008, a ground test was performed on a CFM 56-7B with a new alternative energy using biomass algae and jatropha for the biojet fuel in a 50% mix with the current jet fuel [24, 25]. In September 2009, alternative fuel was produced using the Fischer Tropsh (F-T) process and was certified for aviation usage by American Standard Testing Material (ASTM) International Standard D7566 [26] A 50% blend of F-T synthetic fuel with conventional fuels is currently used by some biojet fuel flight tests in commercial aviation [27]. On July 1st 2011, ASTM approved the jet fuel product slate of Hydroprocessed Esters and Fatty Acids (HEFA) under alternative fuel specification ASTM D7566 [28]. HEFA fuel that meets this specification can be mixed with conventional jet fuel, up to a blend ratio of 50%. [29]. HEFA is currently the leading process for producing renewable jet fuel [27, 30, and 31]. A summary of biofuel tests performed on commercial flights can be seen in the figure 1 below:

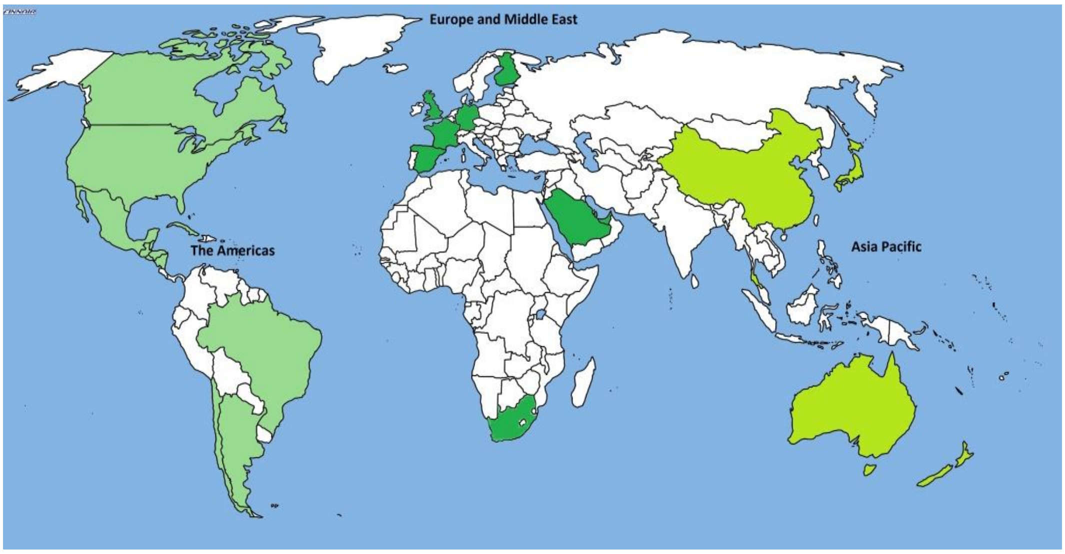

Figure 1. The world biojet fuel map for Commercial Aviation flight

2.1 Asia Pacific

Policy and regulations initiatives on the aviation biofuels and renewable energy are crucial when considering the ICAO global and international policy and strategy. Continuous development and improvement will be needed to accelerate the utilisation of national potential resources, investment and implementation. Table 1 presents the flight test and scheduled flight in Asia Pacific region using biojet fuel.

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Table 1. Asia Pacific Flights

CARRIER	AIRCRAFT	PARTNERS	DATE	BIO-FUEL	BLEND	DESTINATION
Virgin Atlantic	B747-400	Boeing, GE Aviation	23.02.2008	Coconut Babassu	20% one engine	Amsterdam- London
Air New Zealand	B747-400	Boeing, Roll Royce	30.12.2008	Jatropha	50% one engine	Two hour flight test
JAL	B 747-300	Boeing, P&W, Honeywell UOP	30.01.2009	Camelina, Jatropha, Alage blend	50% one engine	Demo flight
Air China	B747-400	Boeing, Petro China, Honeywell UOP	June 2011	Jatropha	50% of one engine	Test Beijing airspace
Thai Airways	B777-200	SkyNRG, Roll Royce Boeing	21.12.2011	Castor seed	One engine	Bangkok- Chiang Ma
QANTAS	A330	Airbus	April 2012	Cooking Oil	50%	Sydney- Adelaide
ANA	B787	Boeing	April 2012	Cooking Oil	10% Blend	Evert's Paine Field(KPAE to Haned (HND)
Jetstar	A320	Airbus	April 2013	Cooking Oil	50% Blend	Melbourne -Hobart
Hainan Airline	B737-800	Boeing, Sinopec	21.03.2015	Cooking Oil	50% Blend	Shanghai – Beijing
Singapore Airlines	A350-900	AltAir, Fuels, SkyNRG, NAFCO, CAO	3.5.2017	Cooking Oil	50% Blend	San Francisco- Singapore

Thailand, Singapore and Indonesia are working in ensuring the contribution towards the refueling the future with biojet fuel. This can be seen when Thai Airways becomes one of the earliest to conduct the Biojet fuel flight test back in the year 2011. The details are as below:

- Thai Airlines (22.1.2011): B777-200
- Engine: Roll Royce 877
- Partner: Rolls Royce, Boeing, SkyNRG
- Biofuel use: Castor Seed
- Destination: Bangkok to Chiang Mai

Singapore is committed to the global effort to reduce international aviation Emissions in partnership with the Civil Aviation Authority of Singapore (CAAS). In May 2017, Singapore Airlines conducted biojet fuel flight test , SQ31, where details information as below;

- Singapore Airlines (3 May 2017): (3-month projects A350-900 Engine Rolls-Royce Trent XWB-84.
- Partner: AltAir Fuels, SkyNRG and American Fuel Corporation (NAFCO), China Aviation Oil (Singapore)
- Biofuel use: cooking oils and conventional jet fuel
- Destination: San Francisco to Singapore

2.2 Europe and Middle East

European Countries' contribution cannot be questioned in terms of using biojet fuel in their projects, research and development. Most of the biojet fuel producers and providers were European companies and the details of carrier, aircraft type and biofuel types can be seen in table 2 below.

KLM carrier from Netherland, is the most Airlines that participate in Biojet fuel flight (test schedule flight). This can be seen starting from the early years of Biojet fuel projects in 2009 until 2016. In the eyar 2014, KLM participated in 26 total flights from Amsterdam (AMS) to New York (JFK). Currently KLM is an active Airlines which have the highest collaboration with biojet fuel producer's SkyNRG and Neste which base in Netherland.

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Table 2. Europe and Middle East Flights

CARRIER	AIRCRAFT	PARTNERS	DATE	BIO-FUEL	BLEND	DESTINATION
QATAR Airline	A340-600	Airbus , Shell	12.10.2009	Gas to Liquid (Not biofuel)	50% four engi	London - Doha
KLM	B747-400	GE, Honeywell UOP	23.11.2009	Camelina	50% one engi	1.5 hours flight test
Iberia	A320	Airbus, Iberia, SkyNF		Camelina	25% of one engine	Madrid- Barcelona
KLM	B737-800	KLM, SyNRG	29.06.2011	Cooking oil	50% of one engine	Amsterdam - Paris
Finnair	A319	Airbus, SkyNRG	July 2011	Cooking Oil	50% Blend	Amsterdam- Helsinki
Air France	A321	Airbus, SkyNRG	October 2011	Used Cooking Oil	50% blend	Toulouse- Paris
Etihad	B777-300ER	Boeing	Jan 2012	Vegetable cooking o	Fuel blend	Abu Dhabi – Seattle
Lufthansa	A321	Airbus, Lufthansa Technik (LHT) and MTU Aero Engines	15 July – 27 December 2011	Jatrohpa, Camelina, Animal fat	50% of one engine	Frankfurt-Hamburg
KLM	B777-200ER	Boeing, SkyNRG	March 2013	Cooking Oil	50% blend	JFK, New York Weekly flight to Amsterdam (Total 26 flights)
KLM	A330-200	Airbus, SkyNRG, ITAKA	May 2014	Cooking Oil	20% Blend	Amsterdam – Carribean Island (Aruba & Bonaire)
Finnair	A330	Airbus, SkyNRG, Statoil Aviation	Sept 2014	Cooking Oil	Fuel blend	Helsinki- New York
Lufthansa	A320	Amyris Total	September 2014	Renewable Farsane-Sugarcane	10% blend (Max)	Frankfurt- Berlin
Scandinavian Airlines	B737-800	SkyNRG Nordic	07.10.2014	Cooking Oil	10% Blend	Stockholm - Oslo
Scandinavian Airlines	B737-800	SkyNRg Nordic	11.11.2014	Cooking Oil	48% Blend	Trondheim – Oslo
Norwegian	B737-800	SkyNRG Nordic	11.11.2014	Cooking OIl	50% Blend	Bergen – Oslo
KLM	Embraer 190	Neste, Renewable Jet Fuel	31.06.2016	Camelina	50% Blend	Oslo – Amsterdam
Mango Airlines	B737-800	SkyNRg, Boeing	15.07.2016	Nicotine-free tobacc plant Solaris		Johannesburg – Cape Town

2.3 The Americas

The Americas on the other hand, contributes more than 14 flight tests mostly from United States and Brazil. Many of the flight tests have been conducted using biofuel but more to military purposes. Details of the flight test is shown in Table 3.The blend of biojet fuel being used is up to 50%, and most common types being used such Algae, Camelina Jathropa and used cooking oil. In July 2014, when the World cup was held in Brazil, all flight inbound and outbound from Orlando to Brazil were using Biojet fuel produce by Amryis and Total fuel producer.

3. Biojet Fuel Flight

From the total biojet fuel flight test conducted from 2008 until 2017, the type of aircraft that is widely used for flight test is the B737 series which is 11 flights. As B737 series is among the simplest type of fleet to be monitor without creating any conflict with the system itself. Meanwhile, the second higher types of aircraft used in six flight tests are from A320 and the least type used from A340,A 350, Embraer 190, B787, and B757 with only one flight test. See figure 2. As a logical opinion, Airbus and Boeing determined in supporting this biojet fuel flight along together with the biojet fuel producers.

Table 3. The Americas Flights

CARRIER	AIRCRAFT	PARTNERS	DATE	BIO-FUEL	BLEND	DESTINATION
Continental	B 737-800	Boeing, GE Aviation, CFM, Honeywell UOP	7.01.2009	Algae and Jatropha	50% one engine	Houston- over Gulf of Mexico
United	A319	Rentech	30.04.2010	GTL	40% two engine	90 minute flight test
TAM	A320	Airbus , CFM	23.11.2010	Jatropha	50%	45 minutes flight test
Interjet	A320	CFM, Safran, EADS,	1.04.2011	Jatropha,	50%	Mexico City- Tuxtla Gutierrez
BOEING	747-8F	Boeing new model aircraft	June 2011	Camelina	15% mix all four engines	Paris Airshow
Aeromexico	B777-200	Boeing, ASA	August 2011	Jatropha	30% blend	Mexico- Madrid
Thompson Airways	B757-200	Boeing, SkyNRG	October 2011	Used Cooking Oil	50% blend	Birmingham Airport
Continental	B737-800	Boeing, Solazyme	November 2011	Algae	40% blend	George Bush Intercontinental Airpo t- O'Hare Chicago Airport
Alaska Airlines		Boeing, Bombardier, SkyNRG	November 2011	Used Cooking Oil	20% blend	Seattle - Washington
LAN	A320	SkyNRG, Air BP Copec	March 2012	Used cooking oil (SkyNRG)	Fuel blend	Santiago – Concepcio Chile
Aero-mexico	B777	Boeing, Honeywell Green Jet,	June 2012	Jatropha , Camelina	50% blend	Mexico city- Sao Paul Rio + 20
GOL	B737	Boeing, Honeywell Green Jet,	June 2012	Cooking oil, Inedibl Corn Oil	50% blend	Sao Paulo – Rio Janei Rio + 20
Air Canada	A319	SkyNRG	June 2012	Used cooking oil (SkyNRG)	50% blend	Toronto - Mexico City
LAN	A320	Airbus, LATAM Airlines, Terpel	August 2013	Camelina	20% Blend	Bagota- Calli
GOL	B737 Fleet	Boeing, Inter Americ Bank, Amyris, Total	July 2014	Renewable Farsane-Derived Sugarcane	10% Blend	Orlando- Sao Paulo (World Cup carrier)

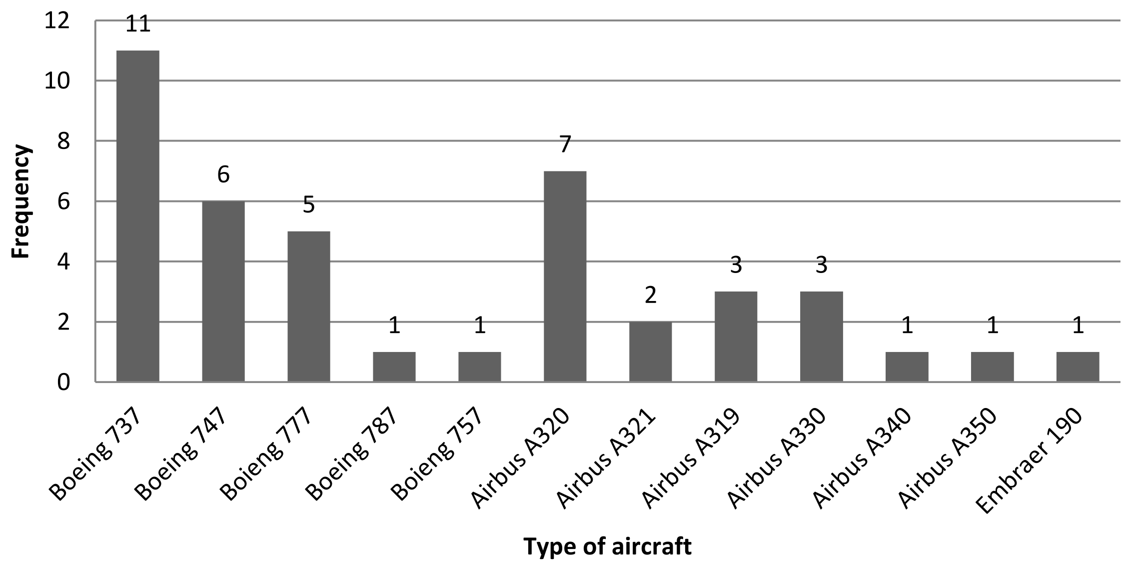

Figure 2. Biojet fuel Flight and aircraft type

In figure 3 below, highlights indicate the types of biofuel frequently used in the test flights. Cooking oil is shown to be most frequently used in 20 flights, followed by, Jathropa (9 flights) , Camelina (8 Flights) and Algae(3 Flight). This will not included the mixture of one or two of biomass.

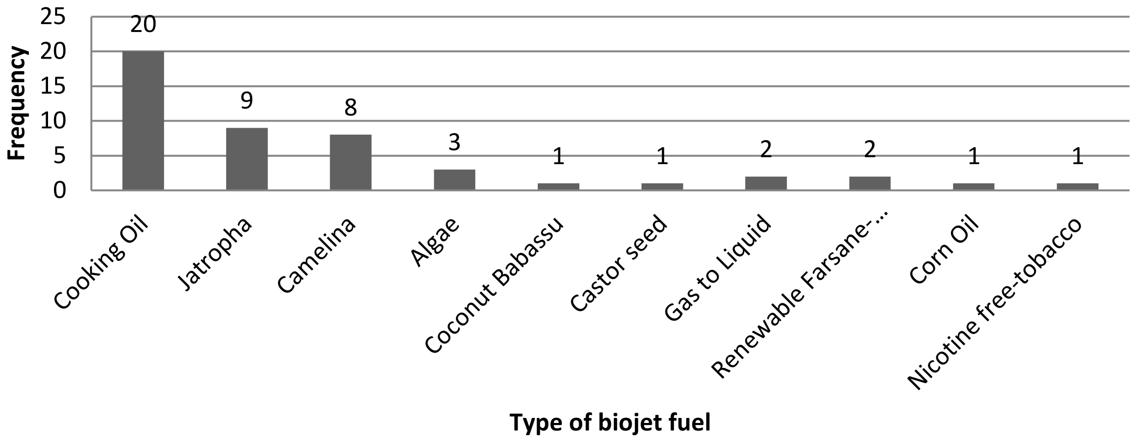

Figure 3. Biojet fuel flight with alternative fuel type

Whereas in Figure 4, the highest fuel blend used for biojet fuel flight is 60.61% with a 50 % blend. The mixture consists of fuel from jatropha, algae, camelina, GTL- Gas to liquid, cooking oil, Brassica, and carnita. Meanwhile, the second higher fuel blend is 18.18% with a 20 % blend which uses alternative fuel from coconut, babassu, jatropha, cooking oil and camelina. The least percentage of fuel blend used is 3.03% with a 30 % blend which is from alternative fuel type, Jatropha. Due to direct conversion from used cooking oil, compares with other types of biomass its contributes more to the flight test without any restriction in high conversion cost.

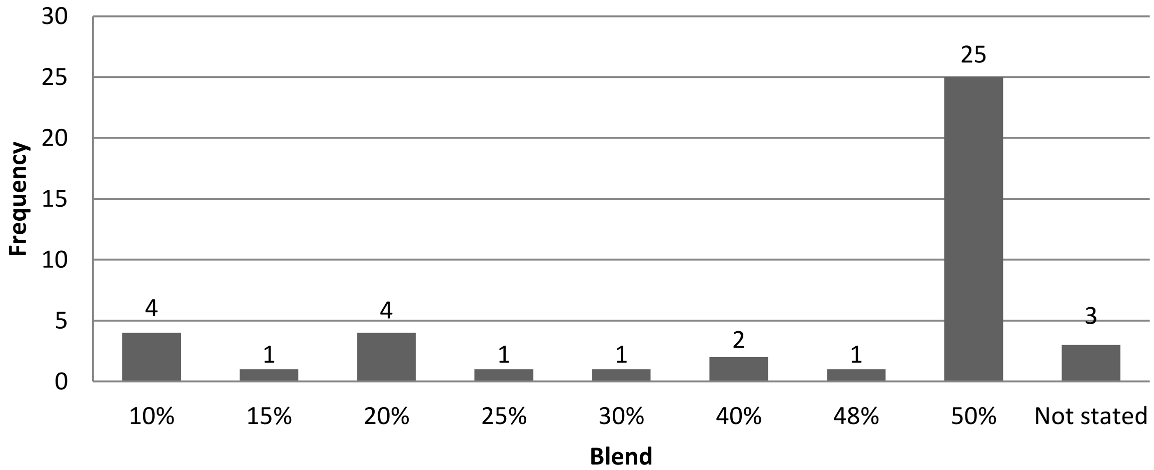

Figure 4. Biojet fuel Flight blending percentage.

4. Global Demand on Biojet Fuel

The longest experience so far using biofuel was the Lufthansa BurnFAIR Project. One engine (V2533) of a Lufthansa Airbus A321 was refueled with a biofuel blend from 15.07.11 until 27.12.11 and performed 1,187 scheduled flights between Hamburg and Frankfurt. The biofuel blend was supplied by Nestle Oil and contained a mix of 50% biosynthetic kerosene and 50% conventional kerosene. Observation of the

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engine trend analysis showed a reduction in fuel flow of 1.2% which was due to the result of higher fuel heating value of the bio fuel blend [32]. In addition, all components were reported to be in good condition: fuel tanks with no microbial growth, fuel line and fitting with normal conditions, fuel filter with no sediments or unusual material.

The used of Biofuel on flight tests so far has proven that it can be a drop-in fuel without any major modification to the engine [33]. The aromatics (molecule with a carbon ring of unsaturated bonds) remain an impediment [34, 35, 36]. Undergoing research in creating biojet fuel – Fischer Trop (F-T) with aromatics is currently under the (ASTM) D4060 [31]. The main problem encountered about land availability in harvesting biomass for biojet fuel and sustainability means that it is not prudent at this time to assume that in 2050 biofuels could account for more than 10% of global aviation fuel [37]. At the same time, the growing global demand for air travel has led to collective motivated research to obtain more sustainable alternative fuels [38, 39]. The incentives in promoting the biojet fuel throughout the globe need to be measured as an indication to project much more sustainable flight to be conducted [40, 41].

5. Conclusion
The implementation on Biojet Fuel in the aviation industry will need to be measured through Fuel Readiness Level and Technology Readiness Level. As this will contribute to ensure further development on refuelling the future for the commercial aviation using the new alternative fuels. What is more, future collaboration from fuel manufacturer, Airlines and Engine manufacturer around the world such as Shell, GE Company, Airbus and Boeing will strengthen the path for forthcoming progress. The sharing platform from government bodies, policy makers, engine manufacturer, aircraft manufacturer and biofuel manufacturer need to be strengthend in ensuring the projection of the usage of biofuel for commercial aviation can be adapted worldwide.

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