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

H Mohd Noh¹, M N Mahamad Taher¹, G A Rodrigo², N A Abdul Rahman¹, S Ismail¹, M Mat Rani¹, I Mohd Salleh¹, Y Dahdi¹, W N S Wan Abdul Razak¹, M S Mat Ghani¹, M R Yusoff¹ and A Benito²

¹Mechanical Department, Universiti Kuala Lumpur – MIAT, Lot 2891, Jalan Jenderam Hulu, 43900, Dengkil, Selangor
²Air Transport Department, ETSIAE, Universidad Politecnica De Madrid, Pz Cardenal Cisneros, 28040, Madrid, Spain

Corresponding email: hazariah@unikl.edu.my

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 Biofuels 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 Tropsch (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](image_url)

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.
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 Mai    |
| 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 Haneda (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- Beijing |

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.
## Table 2. Europe and Middle East Flights

| CARRIER          | AIRCRAFT | PARTNERS                     | DATE       | BIO-FUEL               | BLEND | DESTINATION               |
|------------------|----------|------------------------------|------------|------------------------|-------|---------------------------|
| QATAR Airlines   | A340-600 | Airbus, Shell                | 12.10.2009 | Gas to Liquid          | 50%   | London - Doha             |
| KLM              | B747-400 | GE, Honeywell UOP           | 23.11.2009 | Camelina               | 50%   | 1.5 hours flight test     |
| Iberia           | A320     | Airbus, Iberia, SkyNRG       | 26.11.2009 | Camelina               | 25%   | Madrid - Barcelona        |
| KLM              | B737-800 | KLM, SyNRG                  | 29.06.2011 | Cooking oil            | 50%   | Amsterdam - Paris         |
| Finnair          | A319     | Airbus, SkyNRG               | July 2011  | Cooking Oil            | 50%   | Amsterdam - Helsinki      |
| Air France       | A321     | Airbus, SkyNRG               | October 2011| Used Cooking Oil       | 50%   | Toulouse - Paris          |
| Etihad           | B777-300ER| Boeing                      | Jan 2012   | Vegetable cooking oil  | Fuel blend | Abu Dhabi – Seattle        |
| Lufthansa        | A321     | Airbus, Lufthansa Technik (LHT) and MTU Aero Engines | 15 July – 27 December 2011 | Jatropha, Camelina, Animal fat | 50% of one engine | Frankfurt-Hamburg |
| KLM              | B777-200ER| Boeing, SkyNRG              | March 2013 | Cooking Oil            | 50%   | JFK, New York Weekly flight to Amsterdam (Total 26 flights) |
| KLM              | A330-200 | Airbus, SkyNRG, I1KA        | May 2014   | Cooking Oil            | 20%   | Amsterdam – Carribean Island (Aruba & Bonaire) |
| Finnair          | A330     | Airbus, SkyNRG, StatOil Aviation | Sept 2014 | Cooking Oil            | Fuel blend | Helsinki - New York       |
| Lufthansa        | A320     | Amryis Total                | September 2014 | Renewable Farsane-Sugarcane | 10% blend (Max) | Frankfurt - Berlin         |
| Scandinavian Airlines | B737-800 | SkyNRG Nordic               | 07.10.2014 | Cooking Oil            | 10%   | Stockholm - Oslo          |
| Scandinavian Airlines | B737-800 | SkyNRG Nordic               | 11.11.2014 | Cooking Oil            | 48%   | Trondheim – Oslo          |
| Norwegian        | B737-800 | SkyNRG Nordic               | 11.11.2014 | Cooking Oil            | 50%   | Bergen – Oslo             |
| KLM              | Embraer 190 | Neste, Renewable Jet Fuel | 31.06.2016 | Camelina               | 50%   | Oslo – Amsterdam           |
| Mango Airlines   | B737-800 | SkyNRg, Boeing              | 15.07.2016 | Nicotine-free tobacco 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  | Fuel blend           | Santiago – Concepcion Chile                           |
| Aero-        | B777           | Boeing, Honeywell Green Jet,           | June 2012    | Jatropha, Camelina| 50% blend            | Mexico city- Sao Paul Rio + 20                        |
| Mexico       | B737           | Boeing, Honeywell Green Jet,           | June 2012    | Cooking oil, Inedible Corn Oil | 50% blend          | Sao Paulo – Rio Janeiro Rio + 20                      |
| GOL          | A319           | SkyNRG                                 | June 2012    | Used cooking oil  | (SkyNRG)             | Toronto - Mexico City                                  |
| Air Canada   | LAN            | Airbus, LATAM Airlines, Terpel         | August 2013  | Camelina          | 20% Blend            | Bagota- Calli                                         |
| GOL          | B737 Fleet     | Boeing, Inter Americ; 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 Jatropa (9 flights), Camelina (8 Flights) and Algae(3 Flight). This will not included the mixture of one or two of biomass.

![Type of biojet fuel](image)

**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.

![Biojet fuel Flight blending percentage](image)

**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
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 strengthened in ensuring the projection of the usage of biofuel for commercial aviation can be adapted worldwide.

Acknowledgment
The researchers would like to thank you MOHE for the research funding under the Fundamental Research Grant Scheme FRGS/1/2015/TK10/UNIKL/03/1.

References
[1] EUROCONTROL 2010 Long Term Forecast – Flight movements 2010-2030.
[2] IATA, 2012 Airline Industry Forecast 2012-2016.
[3] Airport Council International 2013 Global Traffic Forecast 2012-2031.
[4] Airbus 2012 Global Market Forecast 2012-2031 Airbus, Blagnac Cedex.
[5] Boeing 2012 Current Market Outlook 2012, Boeing Commercial Airplanes, Seattle.
[6] ATAG (Air Transport Action Group) 2012 Aviation Benefits Beyond Borders (EU), October 2012
[7] European Commission, COM 697.
[8] Kurniawan, J., S., Khardi, S. 2011 Environmental Impact Assessment Review 31 240
[9] Macintosh, A., Wallace, L., 2009 Energy Policy 37 264
[10] Simone, N., Stettler, M., Barrett, S., 2013. Transportation Research Part D: Transport and Environment 25 33
[11] ICAO Information Paper 2009 Global Aviation CO2 Emissions Projections to 2050.
[12] Lee, D. S., Fahey, D. W., Forster, P. M., Newton, P. J., Wit, R. C. N., Lim, L. L., Sausen, R. 2009. Atmospheric Environment, 43(22-23), 3520
[13] Alonso, G., Benito, A., Lonza, L., & Kousoulidou, M. 2014 Journal of Air Transport Management 36 85
[14] IATA 2013 Aviation and the environment, ITDI, Montreal.
[15] Peeters, P., 2013 ICAO CAEP WG3 Information Paper, Madrid.
[16] Krammer, P., Dray, L., Köhler, M. 2013 Transportation Research Part D: Transport and Environment 23 64
[17] European Commission 2008 Directive 2008/101/EC of 19 November 2008 amending Directive
2003/87/EC so as to include aviation activities in the scheme for greenhouse gas emission allowance trading within the Community.

[18] Stratton, R. W., Wong, H. M. Hileman, J. I. 2010 Life Cycle Greenhouse Gas Emissions from Alternative Jet Fuels, PARTNER Project 28 report

[19] Gorter, H. De, & Just, D. R. 2010 Energy and Agricultural Policy 32(1), 4

[20] Halog, A., & Manik, Y. 2011 Sustainability 3(12) 469

[21] Demirbas, A. 2009 Applied Energy, 86 (1) 108

[22] S. Sgouridis, P. A. Bonnefoy, and R. J. Hansman 2011 Transp. Res. Part A Policy Pract. 45, no. 10 1077, 2011.

[23] James D. Kinder and Timothy Rahmes 2009 Evaluation of Bio-Derived Synthetic Paraffinic Kerosenes (Bio-SPK)

[24] Jain, S., & Sharma, M. P. 2011 Renewable and Sustainable Energy Reviews 15(1) 438

[25] ASTMD 1655. 2006 Standard specification for aviation Turbine fuels, American Society for Testing and Materials, [Online] http://www.astm.org/Standards/D1655.htm (Accessed: 15May 2013).

[26] IATA 2009 Alternative Fuels Foreword 2009 (pp. 1–92). [online] http://www.iata.org/publications/Documents/2009-report-alternative-fuels.pdf (Accessed: 10 April 2010).

[27] IATA fact fuel sheet 2013 FACT SHEET: Fuel The global airline industry’s, (December 2012),[Online] http://www.iata.org/pressroom/facts_figures/fact_sheets/pages/index.aspx (Accessed: 10 January 2013)

[28] Liu, G., Yan, B., & Chen, G. 2013 Renewable and Sustainable Energy Reviews 25 59

[29] IATA 2013 IATA ANNUAL REPORT 2009. [Online] http://www.iata.org/pressroom/Documents/IATAAnnualReport2009.pdf (Assessed: 15th January 2011)

[30] IATA 2013 IATA 2013 Report on Alternative Fuels 8th edition Dec 2013. [Online] http://www.iata.org/publications/documents/2013-report-alternative-fuels.pdf; (Accessed: 29 April 2014).

[31] MTU Aero Engine. Report on Technical Memorandum Project FAIR (2012). [Online] http://www.puresky.de/en#/results-of-the-six-month-long-term-trial/at-a-glance/ (Accessed: 13 March 2013)

[32] Law, C. K. 2012 AIAA Journal 50(1) 19

[33] Agusdinata, D. B., Zhao, F., & Delaurentis, D. A. 2012 Environmental science technology Journal 27

[34] Daggett, D. L., Hendricks, R. C., Walther, R., & Corporan, E. 2007 Alternate Fuels for use in Commercial Aircraft. Most, (April), 1–8. [Online]. http://gltrs.grc.nasa.gov/reports/2008/TM-2008-214833.pdf (accessed date; 15th April 2012)

[35] Dufferwiel, S. 2011 Alternative Aviation Fuels – Aromatics & Thermal Stability, The University of Sheffield-Research Council UK for Low carbon Report-(May 2011).

[36] Rosillo-calle, F., Teelucksingh, S., & Seiffert, M. 2012 The potential and Role of Biofuels in Commercial Air Transport- Biojetfuel IEA UK Task Force 40 http://www.bioenergytrade.org/downloads/T40-Biojetfuel_Report-Sept2012.pdf (Accessed: 2 September 2013)

[37] Gegg, P., Budd, L., & Ison, S. 2014 The market development of aviation biofuel: Drivers and constraints. Journal of Air transport Management, 39, 34

[38] Nair, S., & Paulose, H. 2014 Energy Policy, 65, 175

[39] Blakey, S., Rye, L., & Wilson, C. W. 2011 Proceedings of the Combustion Institute, 33(2), 2863

[40] H M. Noh, A. Benito, and G. Alonso 2016 Transp. Res. Part D Transp. Environ. 46 298

[41] H. Mohd Noh, M. N. Mohd Tahir, Y. Nur Halimatun Radhiah, N. A. Abdul Rahman, G. A. Rodrigo, and J. Othman 2017 Sci. Int. 29 1