Chapter

Recent Application of Bio-Alcohol: Bio-Jet Fuel

Gi Bo Han, Jung Hee Jang, Min Hwei Ahn and Byung Hun Jung

Abstract

Recently, the biomass-based energy production has been actively studied as a research and development area for reducing carbon emissions as a solution to global warming caused by the increase of carbon dioxide emissions. Especially, as the energy consumption in the air transportation field increases, the carbon dioxide emissions increase simultaneously. Therefore, the bio-jet fuel production technology is being actively developed to solve this problem. The bio-jet fuel manufacturing process is a process of manufacturing biomass-derived jet fuel that can replace the existing petroleum-based jet fuel. It includes an alcohol-to-jet (ATJ) process using bio-alcohol such as bio-butanol and bio-ethanol, oil-to-jet (OTJ) process using vegetable oil, and an F-T process using syngas obtained from gasification of biomass-based raw materials.

Keywords: bio-alcohol, bio-ethanol, bio-jet fuel, manufacturing technology, greenhouse gas reduction, alcohol-to-jet (ATJ) process

1. Introduction

Bio-alcohol is an environment-friendly clean fuel for transportation application and convertible to various other fuel compounds. It is also a means of reducing greenhouse gas and fossil fuel consumption. Bio-alcohol includes various formulas such as bio-ethanol and bio-butanol. R & D for commercialization of bio-butanol is currently active which can replace existing petroleum fuel or can be converted to other forms of fuel. Bio-ethanol is collectively called as bio-alcohol in view of worldwide total production volume and quantity in use. Bio-ethanol among other bio-alcohols is mainly considered in the present survey, especially related to its current trend of conversion technology to other fuel formulas. Korean domestic bio-alcohol technology boasts of its long history in alcohol liquor industries. However, its food-based raw material casts a negative perspective, and technical solution for diversion to nonfood-based raw material is to be sought after. As an example, bio-alcohol production from cellulosic biomass as raw material involves the introduction of breaking method for the strong chemical bonding of cellulosic biomass to improve conversion efficiency, which was made possible by pre-treatment technology. However, high production cost incurred from pre-treatment process technology and high enzyme cost for bio-treatment process are another technical barrier, and it has to be overcome by overall process and energy cost reduction.

About 100 billion liters (5 million TOE) of bio-ethanol is produced worldwide in 2014. The USA consumes 14.4 billion gallons of bio-ethanol per annum, the most significant quantity in the world. This is also manifested in **Figure 1** where most of the bio-ethanol production is consumed in North and South America with comparatively similar amount consumed in Europe and China. As for bio-ethanol production, the USA and South America, especially Brazil, are well known for bio-ethanol production. Brazil was ranked first as a bio-ethanol exporter before 2010, but the USA surpassed Brazil as a prime exporter of bio-ethanol thereafter (**Figure 2**). This is attributed to significant growth in number of bio-ethanol producers such as

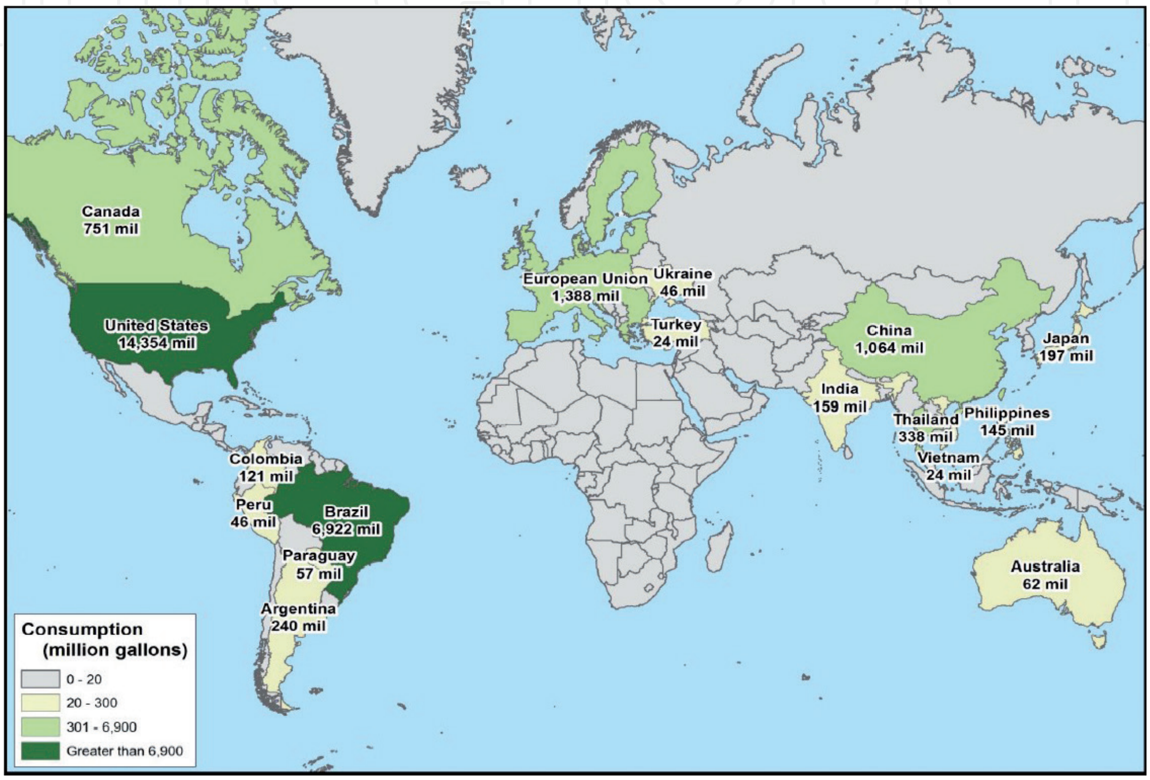

Figure 1.
Global ethanol consumption for transportation fuel in 2016 [1].

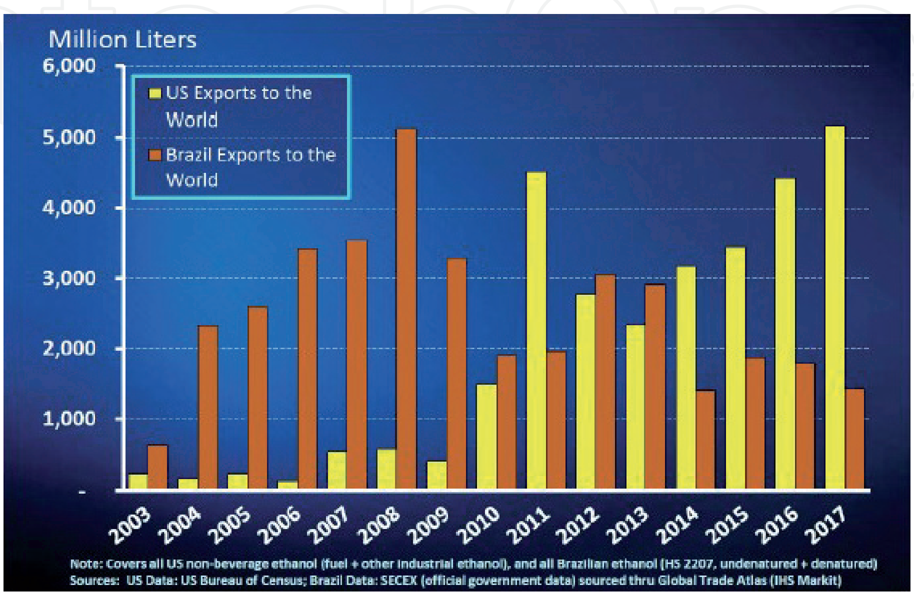

Figure 2.
Yearly variation in export of US and Brazilian bio-ethanol based on nonfood-based ethanol [2].

Producers	Production quantities
Archer Daniels Midland Co. (ADM)	6.44 billion liters
POET Ltd	6.06 billion liters
Green Plains	5.68 billion liters
Valero	5.3 billion liters
Flint Hills	3.03 billion liters
Others	33.31 billion liters

Table 1.
Bio-ethanol production by major US domestic producers.

ADM, POET Ltd., and Green Plains. **Table 1** shows production scale of US bio-ethanol production companies.

Bio-ethanol is well known for its direct application for transportation fuel as well as for various other fuels after conversion. The use of bio-ethanol is currently sought after as a fuel source for renewable energy such as hydrogen production and bio-jet fuel production. Worldwide attention is directed to efficient conversion of bio-ethanol to environment-friendly hydrogen and bio-jet fuel. Conversion of bio-ethanol to hydrogen and bio-jet fuel is surveyed.

2. Necessity for bio-jet fuel

Recent fuel consumption survey shows that 12% of transportation fuel is accounted for by aviation industry and it contributes 2% of greenhouse gas to environment pollution and global warming. To comply with 2015 Paris Climate Change Accord, improved energy efficiency and increased low-carbon bio-energy and fuel utilization (rate) in aviation industries are expected, and such efforts are in progress in various related fields. As examples of such efforts, airlines and aircraft manufacturers voluntarily set goals for carbon-neutral growth, and 50% reduction of greenhouse gases by 2050 with respect to 2005 criteria and various concrete ways are implemented. Ordinarily, electricity, solar energy, and hydrogen fuel are mentioned as means of low-carbon energy utilization in transportation fields [3]. As for aviation industries, the only technically viable means is limited to bio-jet fuel and its utilization. Therefore, long-term carbon reduction is only made possible by increased utilization of bio-jet fuel. **Figure 3** shows IRENA's future prospect for carbon emission by aviation industries. As shown in **Figure 3**, it was known that the 1.5% reduction of greenhouse gas is reportedly possible by both the utilization of bio-jet fuel and the increase in the energy efficiency resulting from aircraft design improvement, optimization of airport facility, and flight paths.

The most representative way to reduce carbon emissions is to develop the biomass-based fuels such as bio-aviation oil with low carbon emission and their production technologies. Also, many international airlines have launched pilot projects for their application feasibility. However, it is difficult to secure economic feasibility in various cost aspects. In order to overcome these problems such as securing economic feasibility, developing bio-air fuels as well as setting international standards and providing incentives for the use of bio-fuels, which can be the basis for establishing carbon emission goals and policies of international airlines. In order to overcome such problems as securing economic feasibility, the international standards that can be the basis for establishing carbon emissions goals and

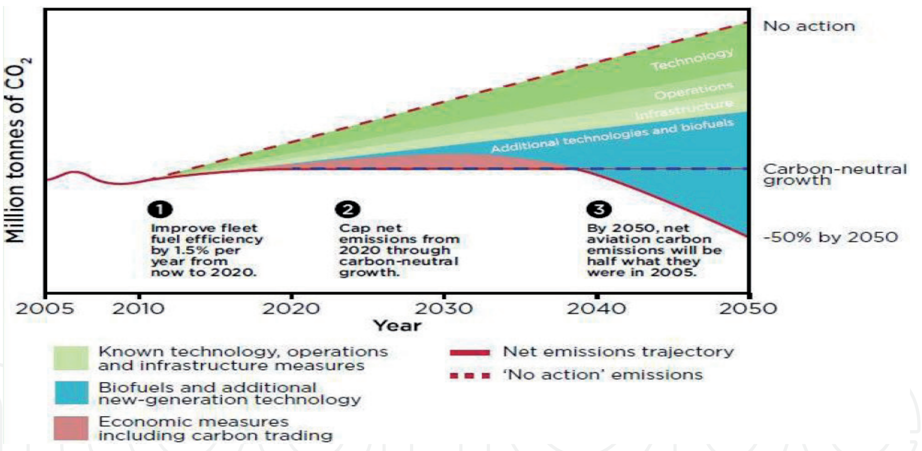

Figure 3.
Future prospect for carbon emission from aviation industries (unit: million tons of CO_2) [4].

policies for international airlines should be established, and the bio-jet fuel market should be activated by securing technologies for developing bio-jet fuel fuels in addition to providing incentives for the use of bio-jet fuels. In order to achieve this goal, the ICAO established the Commission for Aviation Environment Protection (CAEP), and efforts to reduce aviation greenhouse gas emissions have been increasing, especially for ICAO. Developments are emerging, and countries and international organizations are stepping up their aviation bio-fuel development policies. The 38th ICAO General Assembly resolution approved the importance of aviation biofuels as a medium-to-long term GHG reduction measure, established a global framework, the possibility of sustainable drop-in aviation biofuel technology, and emphasis is placed on the need to introduce policies and incentives from a perspective of accelerating wide utilization. The IATA announces continued use of renewable energy as the most reliable way to meet its greenhouse gas reduction targets and requires by 2020 to replace 6% of aviation fuel demand with renewables. The various bio-fuel support policies are being promoted by spreading awareness that bio-fuels can contribute to greenhouse gas emission reduction, energy security enhancement, rural income, and new market development. These support policies include tax exemptions for bio-fuels in most countries, including budgetary support (tax exemption or direct subsidies to bio-fuel producers, sellers, and users), minimum mix ratios, and import tariffs on imported bio-fuels. In addition, subsidies are being used to support bio-fuel dissemination, resulting in $ 20 billion in grants from governments around the world in 2009, mostly in the US and EU countries. The Korean government subsidies are expected to increase to US$ 37.5 million annually from 2010 to 2020 and to US$ 70.8 million annually from 2021 to 2035.

3. Production technologies for bio-jet fuel

Representative production technologies for bio-jet fuel include alcohol-to-jet (ATJ), oil-to-jet (OTJ), gas-to-jet (GTJ), and sugar-to-jet (STJ) process. OTJ process produces bio-jet fuel from animal or plant tallow such as waste vegetable oil, beef tallow, and microalgae. More specifically, hydrotreated esters and fatty acid (HEFA) technology, a kind of OTJ process, encompasses hydrotreated renewable jet (HRJ) process among HEFA technologies, catalytic hydro-thermolysis (CH), and rapid thermal decomposition process (HDCJ). STJ process involves catalytic upgrading and conversion of glucose- or starch-based raw material to hydrocarbons or biological conversion to bio-jet fuel via direct sugar to hydrocarbons (DSHC) and catalytic upgrading. ATJ process involves production of bio-jet fuel via hydrolysis of wooden fiber biomass or glucose into intermediate alcohols (methanol, ethanol, butanol, and fatty acid alcohols) and their dehydration and oligomerization. It is divided into ethanol-to-jet or butanol-to-jet technologies, depending on alcohol involved. GTJ process involves biogas, natural gas, or syngas from wood fiber biomass to bio-jet fuel via bio-chemical or thermos-chemical routes such as gas fermentation and Fischer-Tropsch processes. **Table 2** shows the production technologies for bio-jet fuel.

Figure 4 shows the production process-wise raw material and technology overview for bio-jet fuel. Among many classification methods, bio-jet fuel is divided via production pathways: fermentation, deoxidation, or thermal decomposition. As of 2016, ASTM 7566 dictates five production processes (Fischer-Tropsch Synthetic Kerosene with Aromatics (FT-SPK), HEFA, Synthesized Iso-Paraffins (SIP), ATJ) as means to produce commercially viable bio-jet fuels. It simultaneously regulates product quality criteria as per 100% assay as well as mixing proportion in existing

Technologies	Production processes
Alcohol to jet	Ethanol to jet
	N-butanol to jet
	Iso-butanol to jet
	Methanol to jet
Oil to jet	Hydro-processed renewable jet
	Catalytic hydro-thermolysis
	Hydrotreated depolymerized cellulosic jet
Gas to jet	Fischer-Tropsch synthesis
	Gas fermentation
Sugar to jet	Direct sugar to hydrocarbons
	Catalytic upgrading

Table 2.
Production technologies for bio-jet fuel [5].

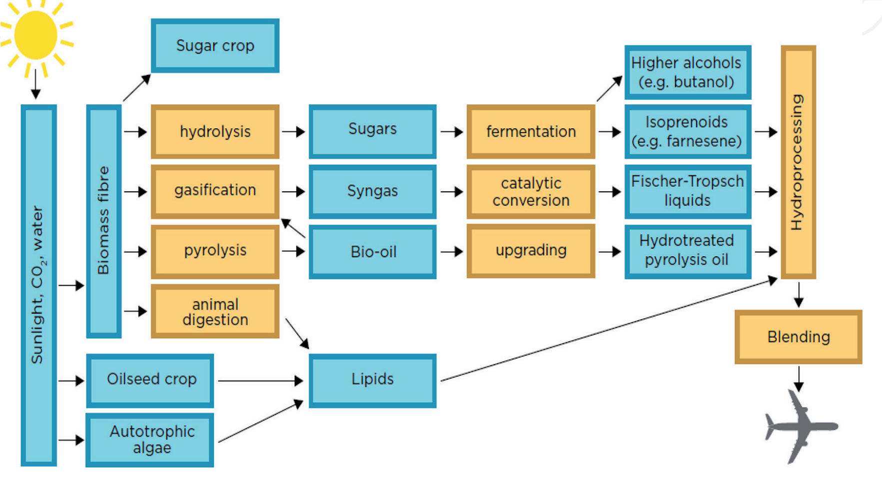

Figure 4.
Production process-wise raw material and technology overview for bio-jet fuel [6].

Production process	Developer/manufacturer	Raw materials	Aromatic content	ASTM review stage and max. Mixing proportions
FT-SPK	Sasol, Shell, Syntroleum	Coal, natural gas, biomass	Low	(2009)-50% Approved
HEFA	Honeywell UOP, Neste Oil, Dynamic Fuels, EERC	Vegetable oil, animal fat, recycled vegetable oil	Low	(2011)-50% Approved
SIP	Amyris, Total	Sugar	Low	(2014)-10% Approved
ATJ-SPK	Gevo, Cobalt, Honeywell UOP, LanzaTech, Swedish Biofuels, Byogy	Starch, sugar, cellulose-based biomass	Low	(2016)-30% Approved
FT-SKA	Sasol	Coal, natural gas, biomass	High	Under review by committee
HDO-SK	Virent	Starch, sugar, cellulose-based biomass	Low	Investigation report submitted
HDO-SAK	Virent	Starch, sugar, cellulose-based biomass	High	Investigation report under review
HDCJ	Honeywell UOP, Licella, KiOR	Cellulose-based biomass	High	Supplement to investigation report received
CH	Chevron Lummus Global, Applied Research Associates, Blue Sun Energy	Vegetable oil, animal fat, recycled vegetable oil	Low	Investigation report under review

Table 3.
Production process-wise classification of bio-jet fuel production process [7].

petroleum-based aviation fuel. Many other production processes are also used to produce bio-jet fuel, and the following technologies are under review by ASTM for approval. **Table 3** shows production process-wise classification of bio-jet fuel production process.

4. Bio-alcohol-based bio-jet fuel production technologies

Figure 5 shows current worldwide production and consumption trend of bio-jet fuel. Bio-ethanol is widely commercialized as sustainable source of energy for use in transportation with worldwide production of 104 million m^3 and 80% of its utilization as transportation fuel. The USA and Brazil accounted for 51.8 and 2.77 million m^3 production, respectively. Worldwide bio-jet fuel amounted to 30 billion m^3. On the other hand, Korean domestic petroleum-based aviation fuel products totaled 13% (20.66 million m^3) in 2013, which is similar to gasoline products (13.5%) and 44% of light oil products (29.7%).

Possible raw material for ATJ process includes methanol, ethanol, and butanol. Such alcohol-based raw material is converted to bio-jet fuel via polymerization and upgrading technology. Among these alcohols, bio-ethanol utilization is promising in view of its current production and consumption and worldwide use. At present,

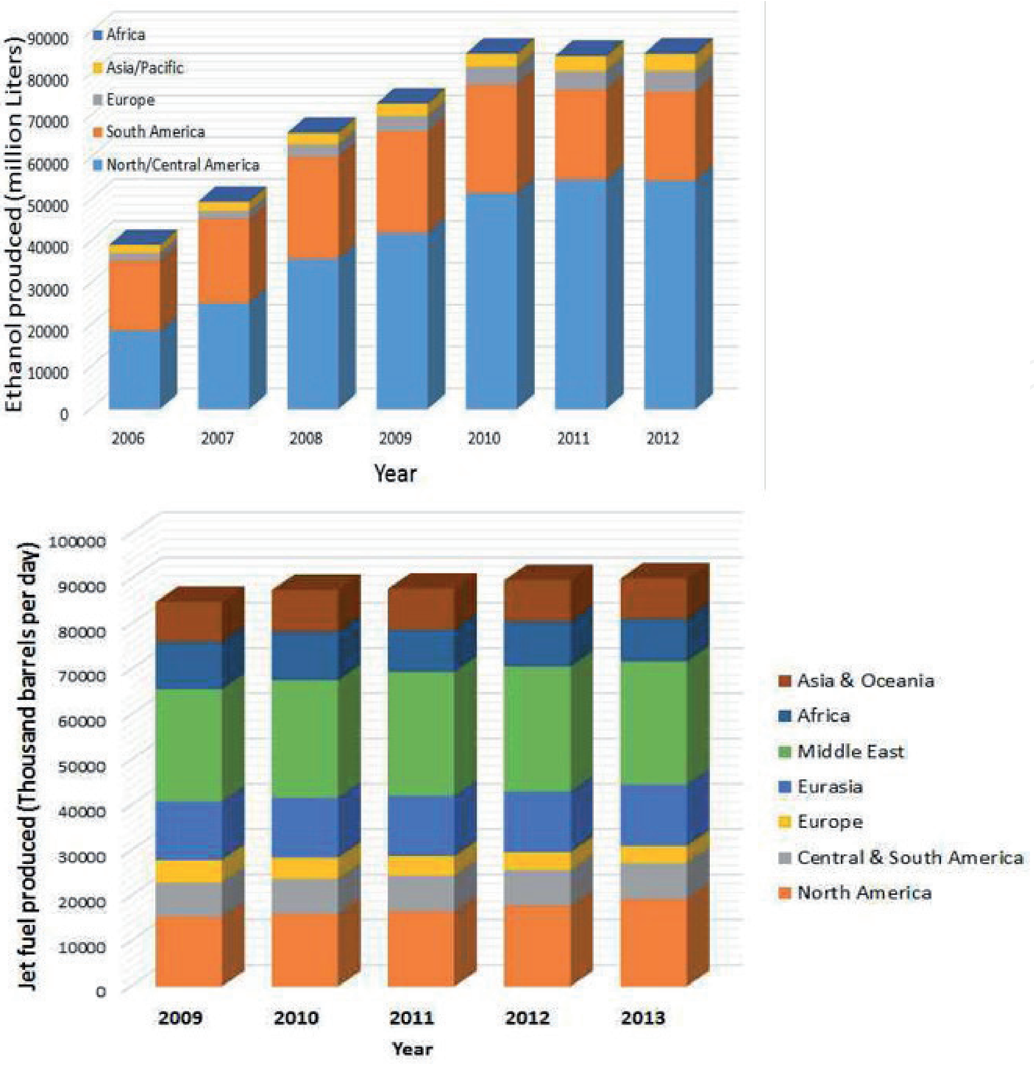

Figure 5.
Worldwide bio-ethanol production and consumption of aviation fuel.

bio-ethanol is mixed to maximum 10~15% with gasoline. Although potential market of ethanol for mixing with gasoline seems limited for expansion, conversion to bio-jet fuel via bio-ethanol upgrading shows possibility of replacing existing petroleum-based aviation fuel.

For conversion of bio-ethanol to bio-jet fuel, physicochemical properties of bio-ethanol should be compatible with petroleum-based aviation fuel. The USA is utilizing advanced ATJ technology to make physicochemical properties of bio-ethanol compatible with those of existing petroleum-based fuel. More specifically, 99.5~99.9% of anhydrous ethanol is mixed with existing fuel or converted to bio-jet fuel. High purity ethanol is used as raw material in the process for upgrading physicochemical properties of bio-jet fuel. Such ATJ process is based on bio-ethanol for production of bio-jet fuel, and oxygen contents of bio-ethanol is removed by dehydration, polymerization for access of carbon atoms from existing petroleum-based aviation fuel, and hydrogenation reaction for optimization of physicochemical properties. **Figure 6** shows technical overview of ATJ process for production of bio-jet fuel from bio-ethanol [8].

The most efficient method of reducing carbon emission is low carbon bio-jet fuel, relevant technology to produce it and its commercialization. Many international airlines initiated small-scale projects, but so far economic viability has not been demonstrated, and possible remedy is under consideration. To accomplish such economic viability, international standards for carbon emission objective and related policy on the part of airlines have to be established as well as monetary

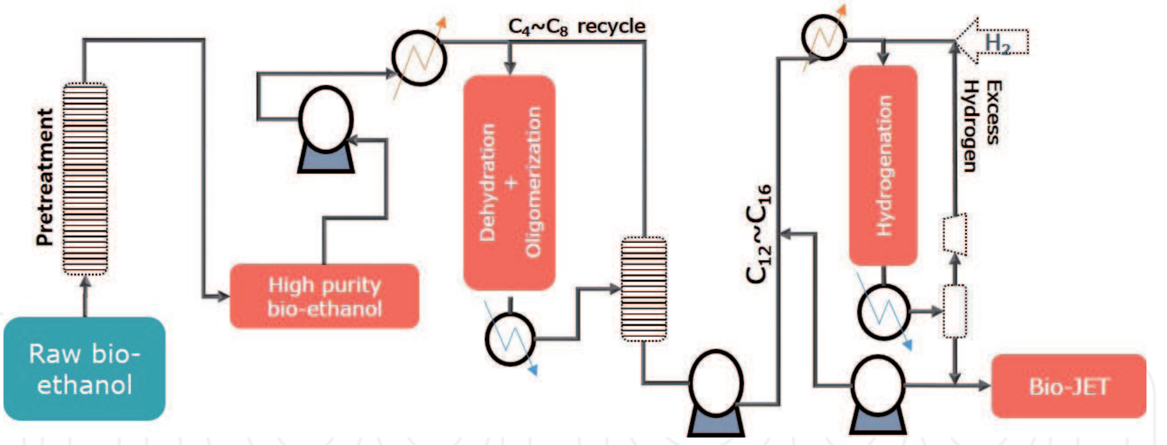

Figure 6.
Technical overview of ATJ process for production of bio-jet fuel from bio-ethanol.

incentive for bio-jet fuel utilization. To initiate economic drive for bio-jet fuel market, mass production-capable technology for bio-jet fuel production has to be developed. For carbon-neutral growth by 2050, international carbon emission reduction objective has been set by the ICAO with respect to greenhouse gas emission of 2005. For this, the CAEP has been established within the ICAO, and the ICAO is playing a central role to reduce aviation-induced greenhouse gas emission by intensive efforts. Development of aviation bio-jet fuel is taken as a pivotal means for greenhouse gas reduction, and many nations and international organizations are actively initiating aviation bio-jet fuel development. The ICAO 38th general meeting resolution approved aviation bio-jet fuel as vitally important intermediate to long-term means of greenhouse gas reduction, thus establishing fundamental frame of reference. More specifically, possibility of sustainable drop-in bio-jet fuel technology and related long-term policy as well as monetary incentive is also emphasized. Furthermore, IATA announced that sustainable and renewable energy utilization is the most reliable means to achieve established objective of greenhouse gas reduction and requested 6% replacement of aviation fuel with renewable energy by 2020. Bio-fuel is regarded as efficient and economical means of greenhouse gas reduction, energy security, new source of income, and market development for farm products in rural areas. Therefore, bio-fuel drive is supported as a national policy. Bio-fuel is supported by national policy in many nations via budget support (bio-fuel producers, vendors, and users are exempt from taxation or subsidy is given), minimum mixing proportion regulation, and import duty levied on foreign bio-fuel for wide distribution of bio-fuel. Altogether, worldwide monetary subsidy for bio-fuel totaled 20 billion US dollars in 2009 which was supported by US and EU nations. The Korean government subsidy will increase by 4.5 billion KRW every year during 2010~2020. This will be augmented by 8.5 billion KRW during 2021~2035.

To convert ordinary alcohol to fundamental aviation fuel element of hydrocarbon, oxygen contents have to be removed by dehydration via catalytic upgrading process. Alumina, transition metal oxides, and zeolite derivatives of SAPO, H-ZSM-5, and heterogeneous acid catalyst 0.5%La-2%P/H-ZSM-5 with acid sites [9]. Conversion rate was close to 100% at 250°C. Selectivity of ethylene was nearly 99.9% which was obtained by removal of oxygen via dehydration [10]. Such ethylene is converted to another reaction intermediate of alpha-olefin by polymerization called oligomerization. This is approximately equivalent to existing aviation fuel compound and intended to increase distribution of carbons. Candidate catalysts include Ziegler-Natta-based, homogeneous chromium-diphosphine-based, and heterogeneous zeolite-based catalysts. Oligomerization reaction took place at 90~110°C and 89 bar, where alpha-olefin with C4~C20 carbon numbers was synthesized with 96~97% of yield. Commercial oligomerization reaction involves 200°C and 250 bar with relatively wide range of carbon distribution of 5% C4, 50% C6~C10, 30% C12~C14, and 12% C16~C18 [11]. Such wide range of carbon numbers enables separation by selective distillation to light oil and aviation fuel. Hydrocarbons with low carbon numbers of C4~C8 separated by selective distillation process are reintroduced into oligomerization process and further synthesized into hydrocarbons with relatively high carbon numbers. Existing petroleum-based aviation fuel consists of hydrocarbons with C6~C16 range of high carbon numbers which require upgrading process. Such upgrading process necessitates hydrogenation reaction under hydrogen atmosphere and 370°C, WHSV of 3 h^{-1}, using 5% Pd/C or 5% Pt/C catalysts [12, 13].

5. Technological overview of bio-jet fuel based on bio-alcohol

Bio-jet fuel is currently being developed and commercialized with various degrees of technology development readiness with various production processes

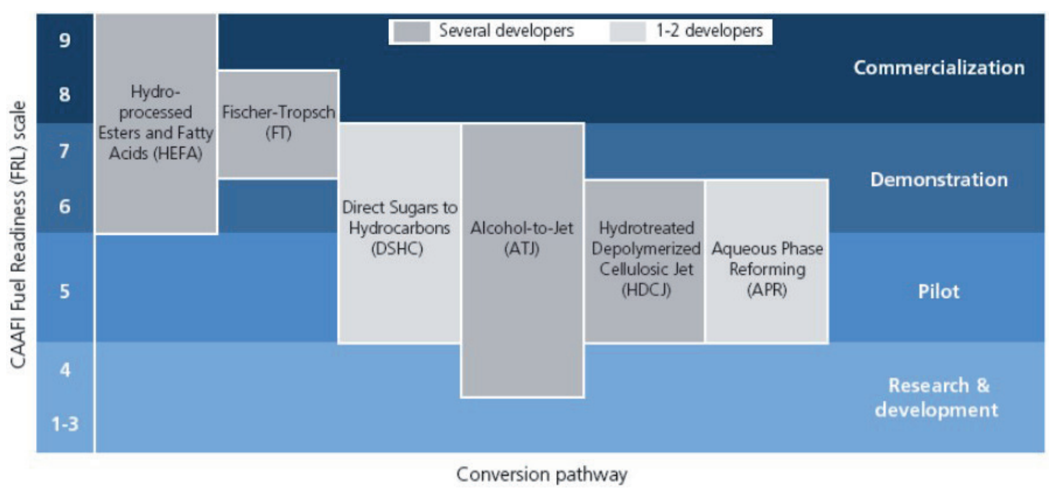

Figure 7.
Process technology-wise fuel readiness level (FRL) for bio-jet fuel [14].

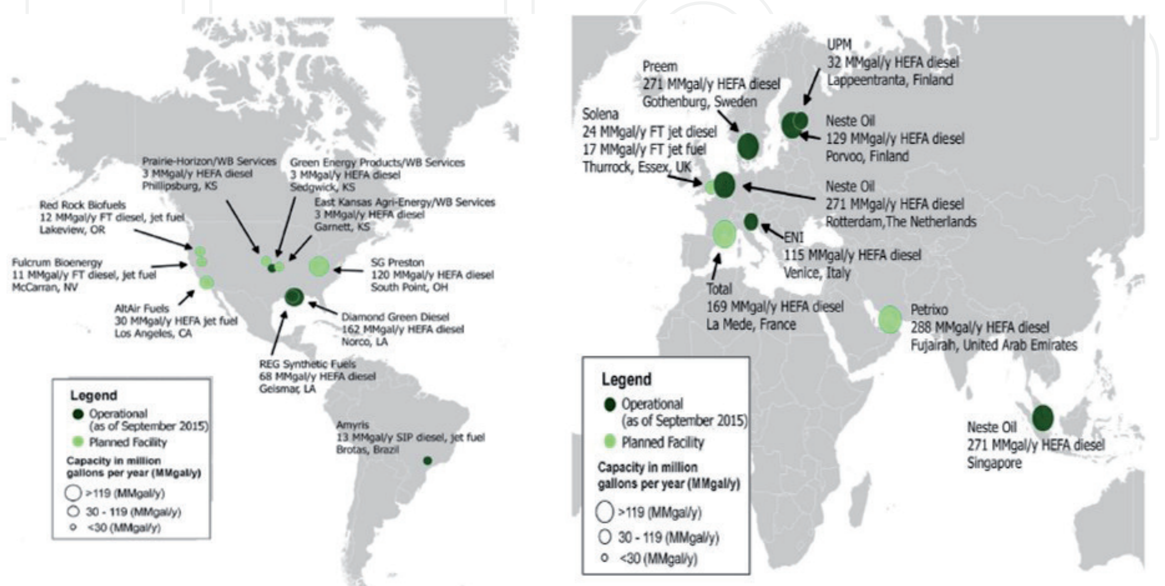

Figure 8.
Worldwide bio-jet fuel production facility and scale [15].

Airlines	**United**	**Cathay**	**FedEx/ Southwest**	**United**	**JetBlue**	**GE Aviation**	**Gulf Stream**	**KLM**	**Lufthansa**
Providers	Altair	Fulcrum	Red Rock	Fulcrum	SG Preston	D' Arcinoff	World Fuel Services (Altair)	Altair	Gevo
(t/yr)Supply	17,000	100,000	10,000	270,000+	33,500	17,000	—	—	270,000+
Major raw material	Waste fat oil	Waste	Forest residue	Waste	Vegetable oil	Cellulosic biomass	Waste fatty oil	Waste vegetable oil	Wood waste
Duration	3 years	10 years	8 years	10 years	10 years	10 years	3 years	3 years	5 years
Introduced	2016	2019	2017	2019	2019	—	2016	—	—
Contract year	2013	2014	2014	2015	2016	2013	2015	2016	2016

Table 4.
Current status of bio-jet fuel production and utilization [16].

employed for different raw materials. **Figure 7** shows the process technology-wise fuel readiness level (FRL) for bio-jet fuel. In view of the fuel readiness level (FRL), the bio-jet fuel production process close to technology development completion is HEFA process which was commercialized by UOP, AltAir, and Neste Oil companies as a kind of OJT process. On the other hand, FT, DSHC, and ATJ processes involving gasification of biomass, fermentation of glucose and catalytic conversion, and alcohol conversion, respectively, are also actively studied, but they are not as economically viable as HEFA/HRJ process from practical standpoint. As for major bio-ethanol upgrading companies, Terrabon and ZeaChem produce organic acid-derived hydrocarbon fuels, and Gevo and Vertimass produce alcohol-derived hydrocarbon fuels, the latter company utilizing ORNL technology. However, none of these companies have accomplished commercialization capability.

Figure 8 shows the worldwide bio-jet fuel production facility and scale. According to published data of ATAG and EIA in 2017 and 2015, annual US consumption of jet fuel and production of bio-jet fuel amounted to 8 billion and 200 million gallons, respectively. Approximately 190 million gallons of the bio-jet fuel was commercially produced by HEFA process, which is attributed to similarity to green diesel or hydrotreated vegetable oil (HVO) facility which produces automobile light oil using biomass. Sweden, the Netherlands, Singapore, and UAE are in possession of 50% of the production facility, while the USA produced 20% of them in eight regions. Representative bio-jet fuel producers include AltAir Fuels Refinery which was established in 2013 and introduced Honeywell UOP technology. Neste oil is operating production facility in Finland, Singapore, and the Netherlands, totaling 2 million gallons per annum. Other bio-jet fuel producers and airline consumers are listed in **Table 4**.

Apart from this, short-term test flight using bio-jet fuel is also actively performed by major airlines. Japan Airlines was tested by supplying 50% bio-jet fuel mixture to one of the four jet engines in January, 2009. Singapore Airlines also

Airlines	Aircraft	Manufacturer/partners	Year	Raw material	Mixing proportion of bio-jet fuel
Virgin Atlantic	B747–400	Boeing, GE Aviation	2008	Coconut babassu	20%
Air New Zealand	B747–400	Boeing Rolls-Royce, UOP	2008	*Jatropha*	50%
Continental Airlines	B737–800	Boeing, GE Aviation, CFM, Honeywell UOP	2009	2.5% Algae, 47.5% *Jatropha*	50%
JAL	B747–400	Boeing, Pratt & Whitney, Honeywell UOP, Nikki-Universal	2009	42% *Camelina*, 8% *Jatropha*, <0.5% algae	50%
KLM	B747–400	GE, Honeywell UOP	2009	*Camelina*	50%
KLM	B737–800	SkyNRG, Dynamic Fuels	2011	Waste cooking oil	50%
TAM Airlines	A-320	Airbus, CFM	2010	*Jatropha*	50%

Boeing	B747-8F		2011	*Camelina*	15%
Air France	A-321	SkyNRG	2011	Waste cooking oil	50%
Gulfstream Aerospace	Gulfstream G450	Honeywell, NBAA	2012	*Camelina*	50%
Air China	B747–400	Boeing, PetroChina	2012	*Jatropha*	50%
Alaska Airlines	B737, Bombardier Q400	Dynamic fuels, Horizon air	2011	Algae and waste cooking oil	20%
Paramus Flying Club	Cessna 182	SkyNRG	2013	Waste cooking oil	50%
LAN	A-320	Honeywell	2013	*Camelina*	30%
Thai Airways	Boeing-777	SkyNRG	2012	Waste cooking oil	50%
NRC Canada	Falcon 20, T-33	Aemetis, AFRL, Rolls-Royce, FAA-CLEEN, Agrisoma Biosciences, Applied Research Assoc., Chevron Lummus Global	2012	Carinata	100%
Military aircraft	**Aircraft**	**Manufacturer/partners**	**Year**	**Raw materials**	**Mixing proportion of bio-jet fuel**
US Navy	F/A-18	Honeywell UOP	2010	*Camelina*	50%
US Air Force	A-10c	Honeywell UOP	2010	*Camelina*, waste cooking oil	50%
US Air Force	F-22	Honeywell UOP	2011	*Camelina*	50%
US Navy	MH60S Seahawk Helicopter	Honeywell UOP, Bozeman	2010	*Camelina*	50%
US Navy	MH60S Seahawk Helicopter	Solazyme	2011	Algae	50%
Netherlands Air Force	AH-64D Apache Helicopter	Honeywell UOP	2010	Waste cooking oil and algae	50%
US Army	Sikorsky UH-60 Black Hawk helicopter	Gevo	2013	Cellulose-derived alcohol	50%
US Air Force	B-52	Syntroleum	2006	Natural gas	50%

Table 5.
Representative civil and military test flights using bio-jet fuel [17].

performed 12 test flights for 3 months from May, 2017, using bio-jet fuel mixture from waste vegetable oil. According to the ICAO, 40,000 or more flights were successfully performed by using bio-jet fuel, and US Air Force and Navy aircraft were also separately tested for possibility of using bio-jet fuel as a contingency plan for replacement fuel. Representative test flight data for civil and military aircraft are listed in **Table 5**.

6. Summary

Recently the Brisbane Airport of Australia made a partnership with Virgin Australia and the US fuel company of Gevo for a 2-year supply of bio-jet fuel produced by ATJ process to Virgin Australia and other Brisbane Airport-departing airlines, which approximately reached commercialization-capable level. However, economical feasibility is a prime concern before commercialization of bio-jet fuel and unit production cost is a major such index. For this, unit production cost of bio-alcohol is very important for its subsequent utilization as raw material of bio-jet fuel. As of 2011, unit retail price of ethanol produced by bio-chemical process from biomass was \$4.18/GGE (gallon for gasoline equivalent). On the other hand, minimum unit retail price for ethanol produced by thermochemical process was \$3.8 GGE. Butanol's unit retail price was \$0.34/kg produced by ABE fermentation process from corn of \$79.23/ton, while cellulosic raw material resulted in \$4.1/GGE. For proper assessment of economic feasibility for ATJ conversion process, commercial production facility, upgrading process, and product distribution are primary considerations, which require intensive efforts for process upgrading.

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