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The Flight Paths for Biojet Fuel

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Introduction

Jet fuel is a 22-billion-gallon per year market in the United States and about 80 billion gallons per year worldwide.[1] Biofuels have made inroads into gasoline and diesel fuel supplies, but are only beginning to enter the jet fuel market. "Biojet" is a term that describes fuel made from renewable, biologically-derived raw materials and, once blended with petroleum jet fuel, is suitable for use in an unmodified jet engine. "Alternative jet fuel" is a more general term that describes jet fuel blending components made from biogenic and fossil (e.g. coal, natural gas, industrial waste gases, or the non-biogenic portion of municipal solid waste) feedstocks. There are several reasons for interest in biojet. Airlines and the U.S. Department of Defense are looking to biojet to diversify fuel supplies and lower fuel costs in the long run. As with other transportation modes, greenhouse gases are a concern for aviation. The International Civil Aviation Organization (ICAO), the United Nations body that sets standards and recommended practices for international aviation, has set a goal for international aviation to achieve carbon-neutral growth from 2020.[2]

Despite the keen interest in biojet fuels, wide-scale deployment of biofuels into the jet fuel market has significant barriers to overcome:

- Aircraft and airport fuel storage and delivery systems are designed to last for decades; new fuels must be compatible with existing systems. Non-petroleum jet fuels such as biojet must consist entirely of hydrocarbon compounds that are already found in petroleum jet fuel. In other words, biojet must be a drop-in biofuel.

- The approval process for new formulations of jet fuel is very involved, due to the range of conditions under which jet fuel must perform. A plane may take off from a scorching Arizona desert, climb to a freezing 30,000 feet, and land in a humid Louisiana swamp. Under all these varied conditions, the fuel can't freeze, boil, or absorb water.

- Biojet producers will need to compete with biodiesel and ethanol producers for raw material, and biojet purchasers must pay a sufficiently high price to keep the biojet from being sold into distillate fuel markets.

- Many of the tax and other incentive programs for blending of biofuels into highway fuels have traditionally not been available for biojet.

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[1] EIA International Energy Statistics, 2010, http://www.eia.gov/cfapps/ipdbproject/iedindex3.cfm?tid=5&pid=63&aid=2&cid=ww,US,&syid=1990&eyid=2012&unit=TBPD.

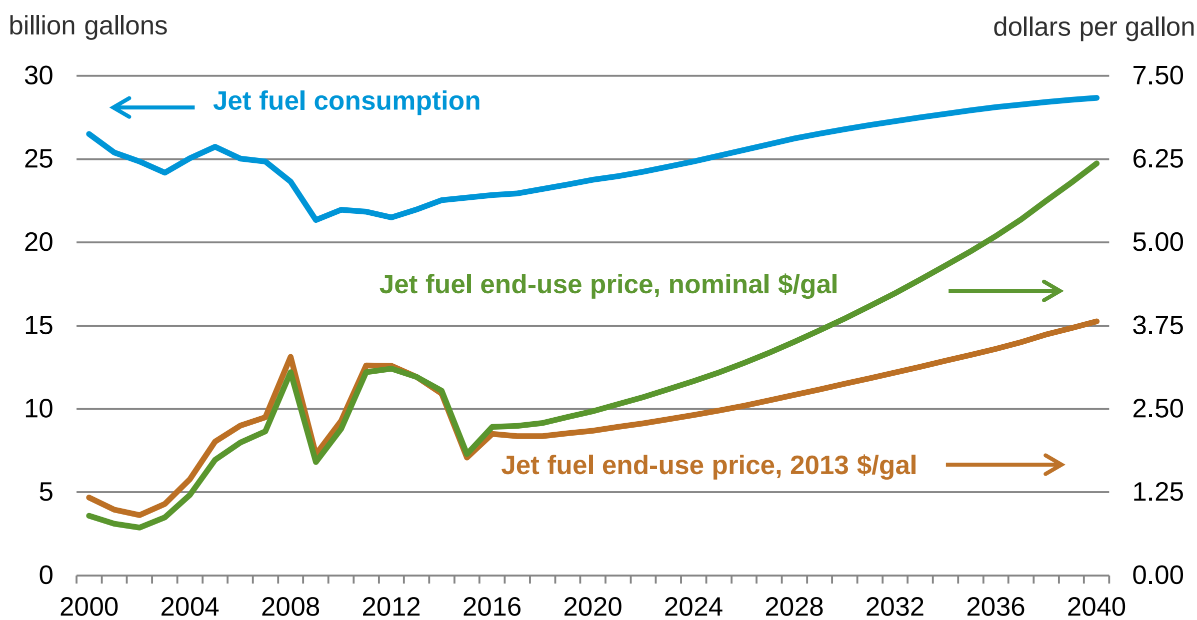
[2] International Air Transport Association press release, "Historic Agreement on Carbon-Neutral Growth," June 3, 2013, http://www.iata.org/pressroom/pr/Pages/2013-06-03-05.aspx. The Air Transport Action Group (ATAG) is a global aviation coalition of airlines, airframe and engine manufacturers, airports and air navigation service providers. Its goals include annual average fuel efficiency improvements through 2020, carbon neutral growth from 2020 and an aspirational goal to achieve a 50% net reduction in carbon dioxide emissions in 2050 relative to 2005 levels, http://aviationbenefits.org/environmental-efficiency/aviation-and-climate-change/our-climate-plan/. The U.S. airlines are part of this coalition. See also Airlines for America's Climate Change Commitment, http://airlines.org/a4as-climate-change-commitment/.

Despite these challenges, biojet technology and deployment is progressing. Alaska Airlines, KLM, and United Airlines deployed biojet fuel on commercial flights in 2011 to demonstrate how the fuels could be integrated in regular service. Further, in 2012, the first airline purchase agreement for regular supply was inked with a prospective biojet producer. In 2014, the first volumes of biojet from a commercial biojet plant in Brazil were used in commercial service and KLM launched a six-month series of transatlantic commercial flights using biojet that year.[3] Also in 2014, the U.S. Department of Defense announced that it would purchase biojet blends for general use if available at competitive prices and various U.S. airlines have now entered commercial agreements for biojet supply.

EIA jet fuel projections

Despite continued improvements in aircraft efficiency and rising fuel prices, EIA projects growing domestic jet fuel demand (see Figure 1). By 2040, jet fuel consumption is projected to be 27% higher than 2014 levels. Jet fuel prices, driven primarily by crude oil prices, are projected to increase quickly. By 2040, the jet fuel price paid by airlines is projected to be 40% higher than the price in 2014 in real terms and 123% higher in nominal terms.

Figure 1. U.S. jet fuel consumption and prices, 2000-2040



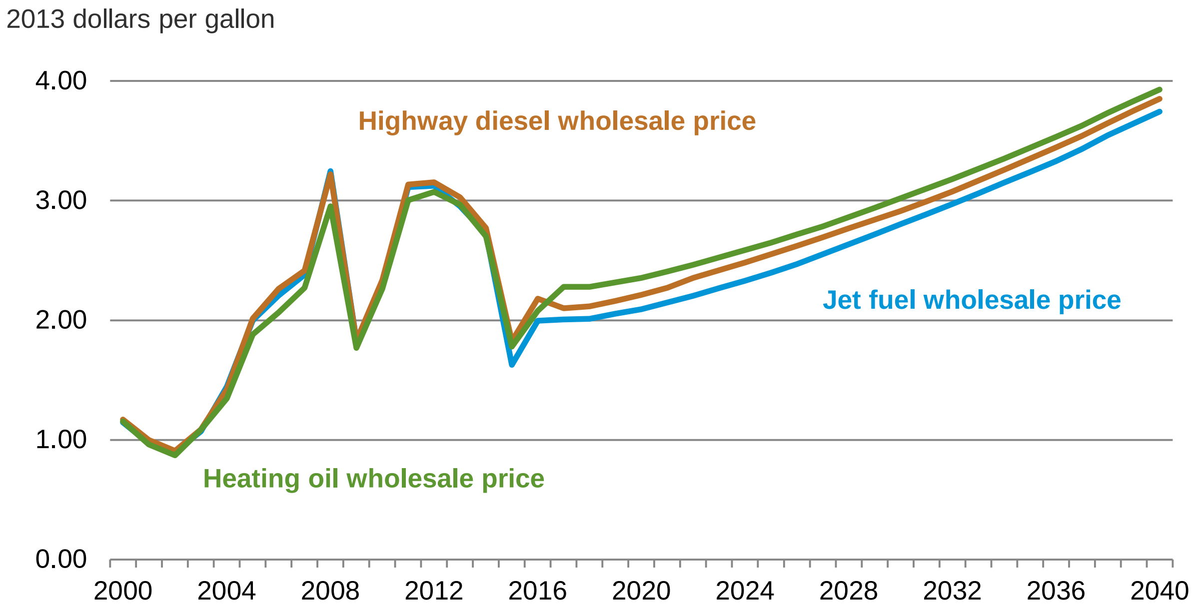
Sources for all figures and tables are found in the appendix.

Rising jet fuel prices are an obvious incentive for civilian and military users of jet fuel to seek substitutes. Firms interested in supplying alternative jet fuel, however, face one less-obvious economic challenge illustrated in Figure 2. Jet fuel is fairly close to diesel fuel and heating oil in composition. Non-petroleum hydrocarbons that can go into jet fuel can also be blended into diesel fuel or heating oil, both

[3] KLM press release, "KLM launches transatlantic biofuel flights from Amsterdam to Aruba and Bonaire," May 16, 2014. http://news.klm.com/klm-biofuelflight-aua-bon.

of which are projected to sell for higher prices than jet fuel in the future. The projected price differentials are caused by the tighter limits on sulfur in diesel fuel and, increasingly, heating oil relative to jet fuel. High-sulfur blending components that in the past could have gone into diesel fuel or heating oil are now restricted to jet fuel blending, which reduces the refiner wholesale price of jet fuel relative to diesel fuel or heating oil. Biojet fuel blending components have zero sulfur content, making them attractive for both ultra-low sulfur diesel fuel and ultra-low sulfur heating oil. Further, biodiesel and renewable diesel have benefitted from state and federal tax incentives and consumption requirements to encourage blending into diesel fuel and heating oil, most of which did not apply to biojet.[4]

Figure 2. U.S. jet fuel and distillate fuel prices, 2000-2040



Sources for all figures and tables are found in the appendix.

Current and near-term alternative jet fuels

The best-known processes for producing biofuels do not produce hydrocarbons. The first commercially successful biofuels were fuel ethanol for use in gasoline, and fatty acid methyl ester (biodiesel) for use in diesel fuel. Neither fuel is a drop-in, as both are chemically distinct from the hydrocarbons into which they are blended and require special infrastructure to handle. Fischer-Tropsch (FT), Hydrotreated Esters of Fatty Acids (HEFA), and Synthesized Iso-Paraffins (SIP) are all approved technologies for the production of biojet fuel. It remains to be seen whether these technologies will achieve wide commercial deployment. The first drop-in biojet fuel to achieve commercial production was fuel produced by the HEFA pathway, in up to a 50% blend with traditional jet fuel, as described below.

[4] Biojet can earn credit under the Renewable Fuels Standard, but no credits have been generated as September 2015. See EPA's 2015 RFS2 data by fuel type, http://www.epa.gov/otaq/fuels/rfsdata/2015emts.htm

The alphabet soup

These are widely-used acronyms for various processes that produce non-petroleum jet fuel blending components.

ATJ	Alcohol-To-Jet
CH	Catalytic Hydrothermolysis
FT	Fischer-Tropsch
FT-SPK	Fischer-Tropsch Synthetic Paraffinic Kerosene
FT-SKA	Fischer-Tropsch Synthetic Kerosene with Aromatics
HDCJ	Hydrotreated Depolymerized Cellulosic Jet
HDO-SK	Hydro-Deoxygenated Synthesized Kerosene
HDO-SAK	Hydro-Deoxygenated Synthesized Aromatic Kerosene
HEFA	Hydrotreated Esters of Fatty Acids
SIP	Synthesized Iso-Paraffins

South African refiner Sasol was the first firm to market jet fuel from non-petroleum sources, although these raw materials were not biobased. The company has lengthy experience with FT synthesis of fuels and chemicals from coal. Sasol operates a coal-to-liquids plant with capacity of 160,000 barrels per day (bbl/d) in Secunda, South Africa. In 1999, after receiving regulatory approval in the United Kingdom,[5] the company started selling a semi-synthetic jet fuel that contained 50% synthetic kerosene from coal. For the next decade, this was the only alternative jet fuel in commercial use. In 2008, Sasol received UK approval for a fully synthetic jet fuel formulation, which has been commercially available since 2010. Two more blending components for Sasol's semi-synthetic jet fuel – FT heavy naphtha and FT kerosene with aromatics – were approved by the UK in 2010 and 2011, respectively.[6] The approval of heavy naphtha allows more of the FT product slate to be blended into jet fuel, and the aromatic kerosene is a potential solution to the aromatics deficiency of most alternative jet fuel formulations.

ASTM International is a non-government entity that sets the specification for jet fuel that is used in the United States; the organization is integrated with the U.S. Federal Aviation Administration's regulatory and oversight authority (see the text box on page 8). Several other countries recognize the ASTM International jet fuel specification as well. The first alternative jet fuel pathway approved by ASTM was synthetic paraffinic kerosene produced via FT synthesis (FT-SPK).[7] Sasol's semi-synthetic jet fuel is an FT-SPK fuel. Unlike the earlier UK regulation, the ASTM approval was not conditioned on a particular raw material. FT synthesis can use coal, natural gas, or biomass as its feedstock. The raw material is converted to synthesis gas, which is a mixture of carbon monoxide and hydrogen. The synthesis gas can then be converted using catalysts to liquid hydrocarbons such as diesel fuel or jet fuel. Since FT-SPK is low in aromatic compounds, it is required to be blended with at least 50% petroleum jet fuel.[8] Sasol,

[5] Sasol's semi-synthetic jet fuel was added to UK Ministry of Defence Standard 91-91 in 1999, and their fully synthetic jet fuel was added in 2008. Only material from the Secunda facility could be used to blend either fuel.

[6] "An Overview of Sasol's Jet Fuel Journey," Paul Morgan, 20th World Petroleum Congress, December 2011. http://www.sasol.com/sites/default/files/presentations/downloads/The_synthetic_jet_fuel_journey_WPC_PMorgan_Sasol_1323236837470.pdf, pages 8/21 and 9/21.

[7] ASTM D7566 Annex A1, in 2009. See "New ASTM Specification Approves Use of Up to 50% Synthetic Hydrocarbons in Aviation Fuel Blends," Green Car Congress, September 29, 2009, http://www.greencarcongress.com/2009/09/d7566-20090929.html.

[8] Jet fuel with too-low levels of aromatic compounds can cause problems with aircraft fuel system seals. See "Alternative seals for alternative fuels," *Aerospace Engineering*, June 8, 2011, http://www.sae.org/works/committeeResources.do?resourceID=236915.

Shell, and Syntroleum contributed to the U.S. development effort.[9, 10] The existing commercial production of FT fuels is based on coal and natural gas, not biomass. Thus, FT fuels from existing sources help meet the goal of diversifying jet fuel supply to include non-petroleum sources but do not reduce the carbon intensity of air travel. There are, however, two FT jet fuel facilities that are planned to use municipal solid waste and one that is planned to use forestry residue.[11]

The second pathway to receive U.S. approval was HEFA.[12] Honeywell UOP, Dynamics Fuels, Neste Oil, and the Environment and Energy Research Center (EERC) contributed to this development effort.[13] Vegetable oil or animal fat is reacted with hydrogen in the presence of a catalyst to yield jet fuel and other hydrocarbons. A very similar process is used to produce renewable diesel fuel. Like FT-SPK, HEFA jet fuel is also a low-aromatics product and is subject to the same 50% blend limit. Honeywell UOP licenses two HEFA processes, Green Diesel and Green Jet, which are targeted for the diesel fuel and jet fuel markets, respectively. Neste Oil markets HEFA-based renewable diesel fuel and plans to market renewable jet fuel.

Most fuel suppliers, engine manufacturers, and airplane builders view the production of biojet as a separate process from renewable diesel. Boeing, on the other hand, believes that the renewable diesel currently in the market can be used as-is in jet fuel at low blend levels; up to 10% is under consideration. They analyzed renewable diesel from existing producers and concluded that the product currently marketed as renewable diesel fuel has very similar properties to jet fuel, which means that small percentages of renewable diesel could be blended into jet fuel with no additional processing. In 2014, Boeing announced its intention to qualify renewable diesel as a jet fuel blendstock through a revision or addition to the HEFA section of the ASTM jet fuel specification.[14] In December 2014, Boeing flew a 787 using a blend of 15% renewable diesel and 85% jet fuel for one of the plane's two engines and found no degradation of performance.[15] If successful, the approval of renewable diesel could result in considerably lower costs and expanded production of biojet blends.

[9] "FAA Alternative Jet Fuel Activities," presentation by Nate Brown to the CLEEN Consortium, November 20, 2013, http://www.faa.gov/about/office_org/headquarters_offices/apl/research/aircraft_technology/cleen/2013_consortium/media/FAA_Alternative_Fuels_Activities_Nov_2013.pdf, pages 9/13 and 10/13.

[10] Syntroleum agreed to sell all its assets to Renewable Energy Group in December 2013. See "Renewable Energy Group to Acquire Syntroleum Corp," *OPIS Biofuels Updates*, December 17, 2013.

[11] They are Solena, Fulcrum BioEnergy, and Red Rock Biofuels. See the "Commercial and military use of biojet" section of this report.

[12] ASTM D7566 Annex A2, in 2011. See "ASTM aviation fuel standard now specifies bio-derived components," *Green Car Congress*, July 1, 2011, http://www.greencarcongress.com/2011/07/astm-20110701.html.

[13] See note 7.

[14] "Boeing seeks approval for green diesel as new aviation biofuel," *Flightglobal*, January 14, 2014, http://www.flightglobal.com/news/articles/boeing-seeks-approval-for-green-diesel-as-new-aviation-394821/.

[15] "Boeing Conducts World's First Flight with 'Green Diesel' as Aviation Biofuel," *PR Newswire*, December 3, 2014. http://www.prnewswire.com/news-releases/boeing-conducts-worlds-first-flight-with-green-diesel-as-aviation-biofuel-300004140.html

The most recent biojet pathway to receive U.S. approval, in June 2014, was SIP.[16] Unlike FT or HEFA blending components, SIP is only approved at up to 10% blend levels. This fuel is produced using novel strains of yeast to ferment sugar to farnesene, a 15-carbon molecule of carbon and hydrogen that is not found in petroleum but is of similar density to some of the petroleum hydrocarbons used in diesel fuel or jet fuel. The farnesene then undergoes further processing with hydrogen to yield diesel and jet fuel blending components. French oil refiner Total and American biotechnology company Amyris developed the SIP process. Amyris built a plant in Brazil to utilize cane sugar as its raw material, but sugars obtained from beets, corn, or cellulosic materials can also be converted to SIP. [17] The extraction of sugar from the raw material for SIP conversion is exactly the same as it would be for ethanol production.

Biojet pathways under development

There are six processes currently under development (and not approved by ASTM) to produce renewable jet fuel blending components, in addition to the first three pathways in Table 1 that were already approved by ASTM. One process is intended to increase jet fuel yields from an FT facility. Four processes are aimed at using a feedstock that is less expensive than the vegetable oils and animal fats needed for HEFA while avoiding the capital costs of an FT process. The remaining process would use vegetable-oil based but is intended to reduce operating costs compared to HEFA.

Sasol continues to develop FT technology for aviation fuels using two pathways, including FT synthesized kerosene with aromatics (FT-SKA), which is distinct from FT-SPK discussed above. FT-SKA is intended to supply additional aromatics compounds to alternative jet fuels blends. Most of the other pathways, including FT-SPK, yield products that are too low in aromatic content to be used on their own.

Alternative jet fuel components such as FT-SKA that are high in aromatics compounds may be a route to 100% alternative jet fuel blends. The product can be produced by direct FT synthesis, by hydrocracking wax obtained from FT synthesis, or by alkylation of benzene. Sasol developed FT-SKA using coal and employs the technology to blend its fully synthetic jet fuel. FT-SKA has been successfully evaluated under ASTM D4054, but a proposed D7566 annex has yet to be accepted due to insufficient detail about each of the three production processes. Though Sasol is working with coal as the raw material, cellulosic biomass can also be used for FT synthesis.

The next alternative jet fuel pathway likely to be approved in the United States is Alcohol-to-Jet (ATJ). ATJ begins with an alcohol such as ethanol or biobutanol, both of which can be produced by fermentation of sugars from multiple sources, including corn, sugarcane, and cellulosic biomass. The alcohols are then dehydrated and oligomerized to hydrocarbons with varying carbon numbers. Gevo, Cobalt, Lanzatech, Swedish Biofuels, and Byogy are all pursuing some version of this pathway. Gevo's process begins with the production of isobutanol from corn; Cobalt's process begins with normal

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[16] ASTM D7566 Annex A3, in 2014. See "Revised ASTM Aviation Fuel Standard Paves the Way for International Use of Synthesized Iso-Paraffinic Fuel in Airliners," *ASTM International news release*, June 19, 2014, http://www.astmnewsroom.org/default.aspx?pageid=3463.

[17] "Amyris/Total renewable jet fuel gets ASTM green light as SIP fuels are approved for commercial aviation use," *Green Air Online*, June 20, 2014. http://www.greenaironline.com/news.php?viewStory=1937.

butanol produced from cellulosic sugars.[18] Byogy, on the other hand, is developing a process that converts ethanol to jet fuel, avoiding the technology risk associated with novel fermentation organisms needed to produce biobutanol.[19] One significant advantage of ATJ over other processes is that it can tap into U.S. supplies of corn.

Table 1. Biojet pathway summary

Pathway	Technology Developer	Feedstock	Aromatics content	ASTM Status
FT-SPK	Sasol, Shell, Syntroleum	Coal, natural gas, biomass	Low	Approved 2009
HEFA	Honeywell UOP, Neste Oil, Dynamic Fuels, EERC	Vegetable oil, animal fat, recycled oils	Low	Approved 2011
SIP	Amyris, Total	Sugar	Low	Approved 2014
FT-SKA	Sasol	Coal, natural gas, biomass	High	Ballotted to ASTM in May 2015, in process of resolving one remaining negative vote
ATJ	Gevo, Cobalt, Honeywell UOP, Lanzatech, Swedish Biofuels, Byogy	Starch, sugar, cellulosic biomass	Low	Research report in final stages of OEM review, expect to ballot to ASTM in late-2015
HDO-SK	Virent	Starch, sugar, cellulosic biomass	Low	Research report submitted for Initial OEM Review in May 2015
HDO-SAK	Virent	Starch, sugar, cellulosic biomass	High	Initial manufacturer review of research report late in 2015
HDCJ	Honeywell UOP, Licella, KiOR	Cellulosic biomass	High	Awaiting additional test results to update research report
CH	Chevron Lummus Global, Applied Research Associates, Blue Sun Energy	Vegetable oil, animal fat, recycled oils	Low	Initial manufacturer review of research report late in 2015

Sources for all figures and tables are found in the appendix.

[18] "Albemarle lands Navy alcohol-to-jet contract using Cobalt butanol," *Ethanol Producer Magazine*, March 22, 2012, http://ethanolproducer.com/articles/8659/albemarle-lands-navy-alcohol-to-jet-contract-using-cobalt-butanol.

[19] "Avianca and Lufthansa team up with US next-gen biofuel companies to support alcohol-to-jet fuel approval," *GreenAir Online*, May 9, 2014. http://www.greenaironline.com/news.php?viewStory=1854

Jet fuel approval process

ASTM International is a non-government entity that is recognized as the U.S. authority on the basic characteristics of liquid fuels, including motor gasoline, diesel fuel, and jet fuel. Nearly all of the jet fuel used in the United States is kerosene-based and is known as Jet-A or Jet-A1. ASTM specification D1655 establishes the characteristics of Jet-A and Jet-A1, which are traditionally petroleum-based fuels with no allowance for any non-petroleum component.[1] In 2009, ASTM released specification D7566 for jet fuel containing synthesized hydrocarbons. When released, D7566 covered blends of traditional jet fuel and hydrocarbons produced by FT synthesis. But D7566 was written in a way to facilitate future expansion as new methods to produce alternative jet fuel are proven. The HEFA annex was added in 2011, and the SIP annex was added in 2014.[2]

The Federal Aviation Administration (FAA) oversees the operation of aircraft in U.S. airspace. The development of ASTM standards for alternative jet fuel is crucial for engine manufacturers, airplane builders, and owners. If ASTM decides that an alternative jet fuel formulation meets either D7566 or D1655, FAA requires no further certification for aircraft operators wishing to use that particular fuel.

The aviation sector is so cautious about new fuels that ASTM actually has a standard on how to develop new standards for jet fuel. ASTM D4054, Standard Practice for Qualification and Approval of New Aviation Turbine Fuels and Fuel Additives, establishes a four-tiered process for the testing of new aviation fuels:

1. Specification of the new fuel
2. Establish “fitness for purpose”
3. Component testing
4. Engine and auxiliary power unit testing

Once the D4054 tests are complete, the D7566 approval process begins:

1. Draft research report by fuel producer
2. Engine and airplane manufacturer review of research report
3. Finalize research report incorporating manufacturer feedback
4. ASTM vote on final research report
5. ASTM vote on specification to be added to D7566

Another significant world authority on the characteristics of jet fuel is the British Ministry of Defence, whose Standard (DEF STAN) 91-91 covers jet fuel for military use but has been widely adopted by civilian users of jet fuel as well. (China and Russia also have comparable jet fuel standards).

Bringing a new jet fuel blending component into general use requires years of effort by engine manufacturers, airplane builders, and regulators. The regulatory burden of proof on new jet fuels is high enough that no party can effectively go it alone. To address this issue, and to otherwise promote the development and deployment of alternative aviation fuels, airlines, engine manufacturers, regulators, airports, and renewable fuels producers formed the Commercial Aviation Alternative Fuels Initiative (CAAFI) in 2006.[3]

[1] ASTM Standard D1655, http://www.astm.org/Standards/D1655.htm.
[2] ASTM Standard D7566, http://www.astm.org/Standards/D7566.htm.
[3] CAAFI, http://www.caafi.org/about/functionnfocus.html.

U.S. corn growers and ethanol producers have reached a demand threshold of nearly 10% ethanol in every gallon of domestic gasoline and are looking for new uses of corn. Gevo's isobutanol technology can be used to convert all or part of an existing ethanol plant to isobutanol production. ATJ is intended as a biojet pathway, but the alcohols that are the building blocks of the process can also be obtained from fossil sources.

Hydro-deoxygenated synthesized kerosene (HDO-SK) and hydro-deoxygenated synthesized aromatic kerosene (HDO-SAK) are two related pathways being developed by Virent.

Both processes utilize catalytic conversion of carbohydrates in a water solution, which Virent calls BioForming, to remove oxygen from the carbohydrates to yield hydrocarbons and are analogous to the fermentation step in ethanol production.

Some examples of the carbohydrates that can be processed are cane sugar, corn starch, or sugars from cellulosic biomass. Virent's process still requires preprocessing of raw material to extract starch or sugar, which is especially difficult with cellulosic feedstocks.

The HDO-SK process produces a distillate stream suitable for blending into diesel fuel or jet fuel. The HDO-SAK process produces an aromatic stream suitable for blending into jet fuel or gasoline.[20]

Easily-converted carbohydrate feedstock such as cane sugar and corn starch are the most likely candidates for the ATJ, DSHC, HDO-SK, and HDO-SAK processes and tend to be relatively high in cost. Cellulosic biomass may be low in cost but is a hard-to-convert carbohydrate. Liquid fuels produced by pyrolysis of cellulosic biomass hold promise for meeting the RFS cellulosic biofuels obligation, and developers are looking to adapt the technology to produce jet fuel blending components. (See the adjacent text box for more detail on biojet in relation to the RFS.) As with similar processes aimed at the production of gasoline, diesel, or renewable fuel oil,

Biojet and the Renewable Fuels Standard

The U.S. Environmental Protection Agency (EPA) has authority over emissions from aircraft engines under the Clean Air Act, in consultation with the Federal Aviation Administration (FAA). The FAA has lead regulatory authority over the use of particular fuels in aircraft. EPA began to regulate jet engine emissions in 1974 and last revised its engine standards in 2012.[1,2]

In addition to regulating emissions, EPA administers the Renewable Fuels Standard (RFS), which requires certain quantities of renewable fuels to be blended into motor gasoline and diesel fuel.

Compliance with the RFS is demonstrated through the use of Renewable Identification Numbers (RINs). RINs are generated when renewable fuel is produced and are transferred along with the physical product until the renewable fuel is blended, when the RINs can be separated from the physical volume of renewable fuel.

The volume of jet fuel marketed does not contribute to a fuel marketer's renewable volume obligation, but production of biojet can generate RINs, which are then separated upon blending biojet into jet fuel. The reason is that some of the petroleum blendstocks used to produce jet fuel can also be used to produce diesel fuel or heating oil. Displacement of a gallon of petroleum-based jet fuel is therefore equivalent to the displacement of a gallon of petroleum-based diesel fuel.

[1] http://www.epa.gov/otaq/regs/nonroad/aviation/420f05015.pdf, page 2/3.
[2] http://www.epa.gov/otaq/regs/nonroad/aviation/420f12027.pdf.

[20] Advanced Biofuels Association member page, http://advancedbiofuelsassociation.com/member.php?id=29.

hydrotreated depolymerized cellulosic jet (HDCJ) begins with a thermal reaction to convert cellulosic raw materials into a liquid that is high in oxygen. Subsequent hydrotreatment removes the oxygen to yield hydrocarbons, from which jet fuel blending components are distilled. Compared to alternative jet fuel from most of the other processes, HDCJ is relatively high in aromatics compounds. Jet fuel requires a minimum level of aromatic compounds to enable elastomer parts in aircraft fuel systems to seal properly.[21] HDCJ may therefore complement low-aromatics alternative jet fuels produced by other pathways. Honeywell UOP, Licella, and KiOR are all working on versions of HDCJ technology.

Catalytic hydrothermolysis (CH) is a process by which vegetable oil or animal fat is reacted with water to obtain a product that is similar to a light crude oil. The crude-like product is then hydroprocessed to obtain a blend of diesel, jet fuel, naphtha, and liquefied petroleum gases. The final step is the distillation of individual products out of the blend. The CH jet fuel product, unlike some of the others under consideration, can be used without blending into petroleum jet fuel. Chevron Lummus Global and Applied Research Associates are the developers of the CH process, which they call the Biofuels ISOCONVERSION Process. The two developers, in conjunction with Blue Sun Energy, started up a 100 bbl/d demonstration plant located in St. Joseph, Missouri, in March 2014.[22]

Commercial and military use of biojet

Alaska Airlines, KLM, and United Airlines deployed biojet fuel on commercial flights in 2011 to demonstrate how the fuels could be integrated in regular service. Further, in 2012, the years of development work on biojet fuel began to pay off with the first airline offtake agreement. In 2014, the first volumes of biojet from a commercial biojet plant in Brazil were used in revenue service and two more offtake agreements were signed. Also in 2014, the U.S. Department of Defense (DoD) announced that it would purchase biojet blends for general use if available at competitive prices.

Commercial airlines and the U.S. military are eager for alternatives to 100% petroleum jet fuel. Both civilian and military users are concerned about petroleum supply disruptions and see biofuels as a means of reducing the impact of a sharp contraction in petroleum supply. Even in the absence of supply disruption, increasing demand for petroleum means rising jet fuel prices. Jet fuel represents as much as 40% of the cost of flying a commercial airliner.[23] Civilian jet operators also want to be prepared for future limitations on carbon dioxide emissions.

Airline offtake agreements and/or ownership of biojet producers are potential solutions to keep biojet blending components from being diverted to higher-priced diesel or heating oil. An offtake agreement is a contract between an airline and a biojet producer for biojet supply. Such agreements may be negotiated before the producer invests in capacity to produce the fuel. In such cases, the airline agrees to purchase the fuel if it can be made available within a specified price range at a future date and the

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[21] "New Options Emerge for Aviation Fuel," ASME web article, August 2011, https://www.asme.org/engineering-topics/articles/aerospace-defense/new-options-emerge-for-aviation-fuel.

[22] "100% drop-in aviation fuels are 'closer' as Blue Sun demo plant goes 24/7 in Missouri," *Biofuels Digest*, March 24, 2014, http://www.biofuelsdigest.com/bdigest/2014/03/24/100-drop-in-aviation-fuels-are-closer-as-isoconversion-demo-plant-opening-in-missouri/.

[23] Michael Huerta, Federal Aviation Administration speech at the CAAFI General Meeting, January 28, 2014, http://www.faa.gov/news/speeches/news_story.cfm?newsId=15654.

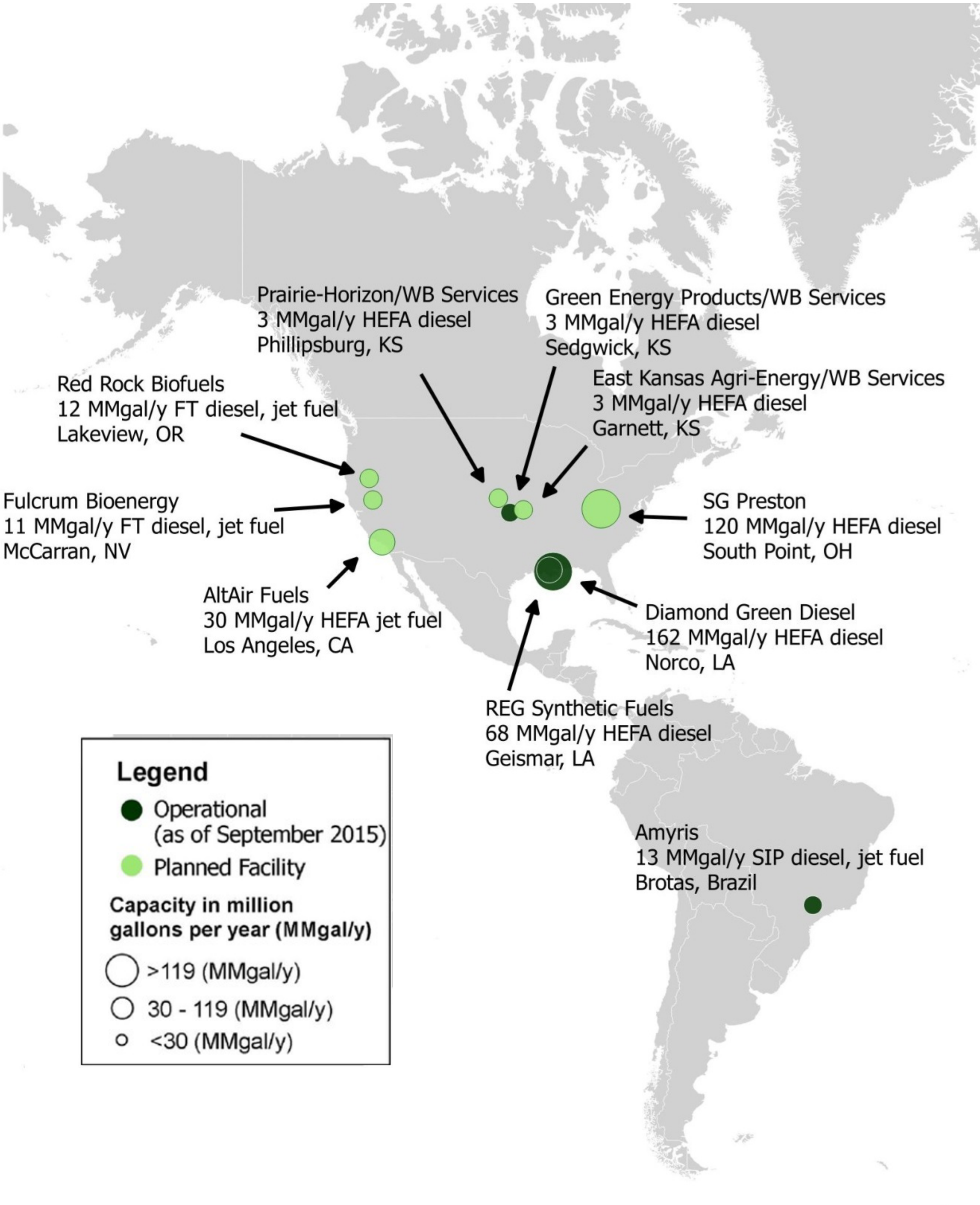
producer can use the agreement to obtain financing for the project on more favorable terms. United Airlines announced in 2013 that it had reached an agreement with AltAir fuels to purchase up to 5 million gallons of biojet per year starting in 2014 and continuing through 2016. AltAir is the developer of the Los Angeles production facility shown in Figure 3. The company is retrofitting idled capacity in an operating petroleum refinery to run Honeywell's Ecofining technology, optimized for renewable jet production in this application. Altair's capacity will be 30 million gallons per year of renewable jet fuel and renewable diesel fuel.[24] In July of 2013, Alaska Airlines entered an agreement for the future purchase of biojet from Hawai`i BioEnergy LLC. The feedstock for the biofuel, which is slated for delivery beginning in 2018, is anticipated to be woody biomass.[25]

In 2012, British Airways committed to purchase biojet from Solena Fuels over an 11-year period to begin in 2017. In March 2014, Solena selected a former petroleum refinery about 20 miles east of London to site for the facility that will supply British Airways (Figure 4). The fuel is to be FT-SPK produced from biomass separated from municipal solid waste. British Airways is also a regular consumer of Sasol's coal-based FT-SPK.[26]

KLM cofounded SkyNRG to supply sustainable jet fuel to itself and other aircraft operators following a successful biojet test flight in 2009.[27] Beginning in 2011, KLM has undertaken a series of transatlantic commercial flights using SkyNRG biojet.[28] Brazilian airline GOL made its first flight on a 10% blend of Amyris's SIP jet fuel on July 30, 2014.[29] GOL intends to use the blended SIP fuel in all of its Boeing 737s, the only type of aircraft that GOL operates.[30] The biojet component of the fuel that GOL plans to use is produced at the Brotas, Brazil facility.

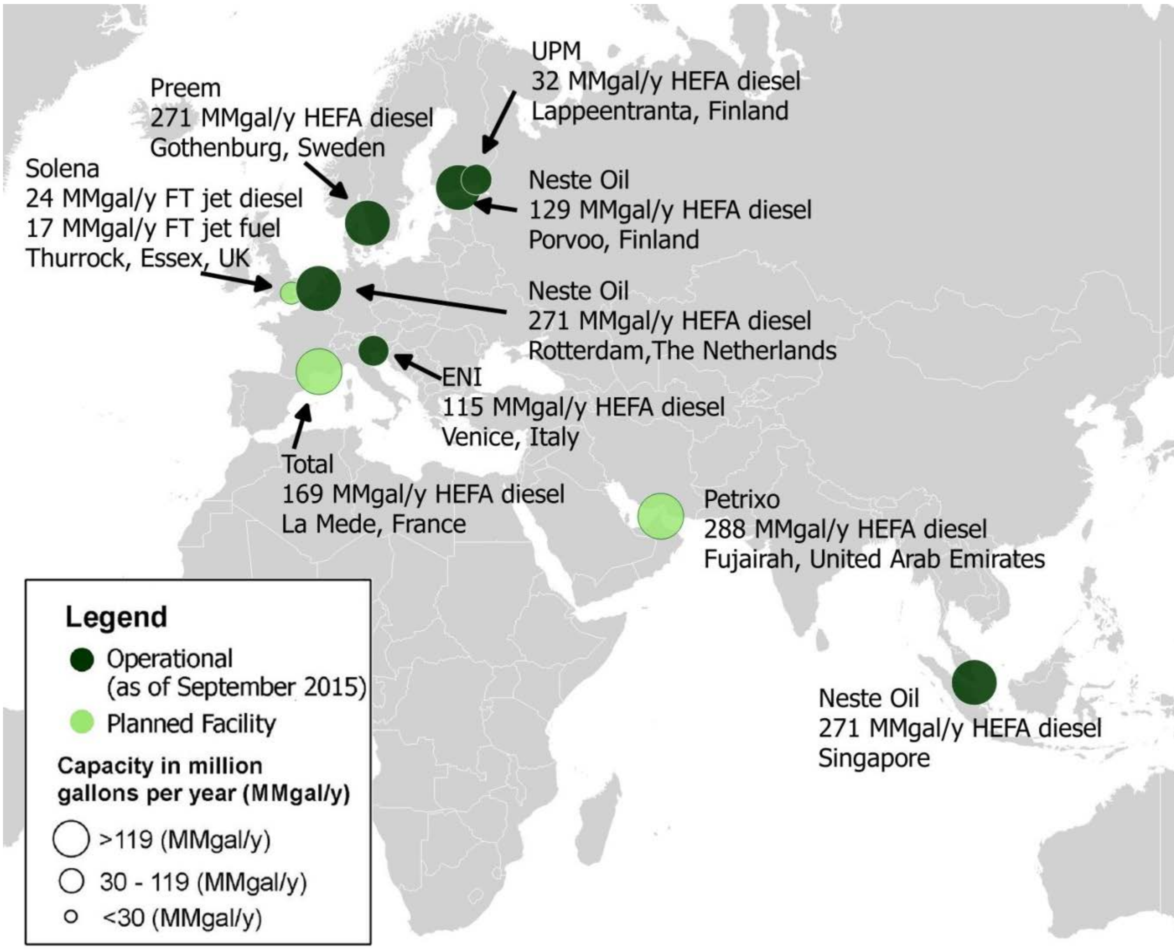
[24] "United Airlines Buys Big into Biofuels," *Wired*, June 5, 2013, http://www.wired.com/2013/06/united-airlines-biofuel/.
[25] Hawai'i Bioenergy press release, "Alaska Airlines and Hawai`i BioEnergy Sign Agreement for the Carrier to Purchase Sustainable Fuel," July 24, 3013, http://www.hawaiibioenergy.com/alaska-airlines-and-hawaii-bioenergy-sign-agreement-purchase-sustainable-fuel
[26] "Making jet fuel out of garbage -- a first," *E&E ClimateWire*, April 25, 2014, http://www.eenews.net/climatewire/stories/1059998443.
[27] See SkyNRG's main website at http://skynrg.com/ and its list of founders at http://skynrg.com/founding-partners/
[28] A description of SkyNRG's role in providing KLM with biojet is found at http://skynrg.com/klmcorporatebiofuelprogramme/#track-record
[29] "GOL Airlines completes flight with Amyris-Total aviation biofuel," *Biomass Magazine*, July 31, 2014, http://biomassmagazine.com/articles/10731/gol-airlines-completes-flight-with-amyris-total-aviation-biofuel.
[30] GOL Airlines fleet page, accessed on September 18, 2014, http://www.voegol.com.br/en-us/a-gol/nossa-frota/paginas/default.aspx.

Figure 3. Fuel production facilities in North and South America with capability to produce biojet



Sources for all figures and tables are found in the appendix.

Figure 4. Fuel production facilities in Europe and Asia with capability to produce biojet



Sources for all figures and tables are found in the appendix.

After initial work by the U.S. Air Force, the U.S. Navy took over the lead on the development of biofuels that are suitable for military use, particularly jet fuel. In June 2014, the DoD released its annual procurement[31] for bulk fuels to be delivered to facilities in the eastern and inland United States and Gulf Coast. For the first time, this procurement specifically requested military-grade diesel fuel and jet fuel that are blended with biofuels. The biofuels components, however, were optional and would only be accepted if certain cost and performance requirements are met. The DoD sought 1.18 billion gallons of jet fuel and 138 million gallons of marine diesel fuel for delivery to all service branches in the East, Inland, and Gulf Coast regions starting on April 1, 2015. For jet fuel, only the portion known as JP-5 (about 255 million gallons) was eligible for blending with biofuels, while the entire portion of marine diesel fuel was eligible. These fuels may contain no less than 10% and no more than 50% drop-in biofuels by volume. A similar procurement for the Rocky Mountain and West Coast regions was

[31] Federal Business Opportunities, solicitation number SP060014R0061, June 9, 2014, https://www.fbo.gov/index?s=opportunity&mode=form&id=e806a983245d4bf72dfaffd965f5c7f9&tab=core&_cview=1.

announced in April 2015[32] and the bulk fuel procurement for the Western Pacific and Middle East Regions was announced in May 2015.[33]

Drop-in biofuels, however, tend to be more costly than petroleum fuels. The DoD's expenditures on its biofuels trial programs, as high as $26 per gallon for test quantities of algae-based jet fuel, have come under Congressional scrutiny. The 2014 National Defense Authorization Act[34] prohibits the DoD from paying prices for alternative fuels that are higher than it would pay for traditional fuels. To address these economic problems, the Navy and the U.S. Department of Agriculture (USDA) announced the formation of the Farm-to-Fleet program in December 2013.[35] The program, which was fashioned on commercial aviation's "Farm to Fly" initiative,[36] aims to incentivize the production of drop-in biofuels in the short term to allow producers to improve yields and feedstock costs through experience, and achieve economic competitiveness by 2020.

Fulcrum Bioenergy is one of the Navy's commercial partners in the effort to develop biojet fuel. In September 2014, Fulcrum received the first USDA loan guarantee for a renewable jet project. The loan will help fund construction of a plant in McCarran, Nevada, to produce FT-SPK diesel and jet fuel from municipal solid waste. Capacity will be 11 million gallons per year, and first production is expected late in 2016.[37] In August 2014, Cathay Pacific Group took an equity stake in Fulcrum Bioenergy and agreed to purchase 375 million gallons of biojet over a 10-year period. Fulcrum also agreed to establish additional production facilities to supply this quantity of fuel.[38] In June 2015, United Airlines announced a $30 million equity investment in Fulcrum BioEnergy. In addition to the equity investment, United and Fulcrum have entered into an agreement that contemplates the joint development of up to five projects located near United's hubs expected to have the potential to produce up to 180 million gallons of fuel per year.[39]

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[32] Federal Business Opportunities, solicitation number SPE600-15-R-0711, April 9, 2015, https://www.fbo.gov/index?s=opportunity&mode=form&id=cdb3ebc02d977ca6ce6f34416243f2d1&tab=core&tabmode=list&=

[33] Federal Business Opportunities, solicitation number SPE600-15-R-0715, May 27, 2015, https://www.fbo.gov/index?s=opportunity&mode=form&id=e1e42c067d6fa9b5a60863e123981c79&tab=core&_cview=0

[34] H.R. 3304 Public Law 113–66, December 2013, http://www.gpo.gov/fdsys/pkg/CPRT-113HPRT86280/pdf/CPRT-113HPRT86280.pdf.

[35] USDA News Release No. 0237.13, Dec. 11, 2013, http://www.usda.gov/wps/portal/usda/usdamediafb?contentid=2013/12/0237.xml&printable=true&contentidonly=true.

[36] See "Agriculture and Aviation: Partners in Prosperity," published by USDA in conjunction with Airlines for America and the Boeing Company, January, 2012, http://www.airlines.org/Documents/usda-farm-to-fly-report-jan-2012.pdf. See also USDA Press Release, "Agriculture Secretary Vilsack and Transportation Secretary LaHood Renew Agreement to Promote Renewable Fuels in the Aviation Industry," April 15, 0213, http://www.usda.gov/wps/portal/usda/usdahome?contentid=2013/04/0070.xml&navid=NEWS_RELEASE&navtype=RT&parentnav=LATEST_RELEASES&edeployment_action=retrievecontent

[37] "USDA Provides $105 Million Loan Guarantee to Fulcrum BioEnergy," *OPIS Biofuels Updates*, September 4, 2014.

[38] Cathay Pacific Group press release, "Cathay Pacific invests in sustainable biojet fuel developer," August 7, 2014, https://www.cathaypacific.com/cx/en_HK/about-us/press-room/press-release/2014/Cathay-Pacific-invests-in-sustainable-biojet-fuel-developer.html.

[39] United Airlines press release, "United Airlines Purchases Stake in Fulcrum BioEnergy with $30 Million Investment," June 30, 2015, http://newsroom.united.com/2015-06-30-United-Airlines-Purchases-Stake-in-Fulcrum-BioEnergy-with-30-Million-Investment. The additional production sites have not been identified and so do not appear in Figures 3.

Red Rock Biofuels, another Navy partner, announced in September 2014 an offtake agreement with Southwest Airlines and received a Defense Production Act grant to build an FT plant in Lakeview, Oregon. Red Rock's feedstock will be forestry residue, and its capacity will be 12 million gallons of diesel and jet fuel per year. Delivery of 3 million gallons of fuel per year to Southwest Airlines is projected to begin in 2016.[40] In July 2015, FedEx and Red Rock announced that FedEx has also contracted to buy 3 million gallons of jet biofuel a year from the refinery.[41]

The plants being built specifically to produce biojet fuel are generally smaller than the renewable diesel plants. Amyris, with 13 million gallons of capacity, is currently the only commercial biojet producer. Altair is expected to come online in late 2015; FT biojet producers Fulcrum and Red Rock are expected to begin production in 2016; and FT biojet producer Solena is expected in 2017.[42] The total capacity of these 5 entities, once complete, will be 83 million gallons of jet fuel per year.[43] Figure 3 and figure 4 display producer locations and capacities in a map format.

The effort to qualify renewable diesel as a jet fuel blending component, either as a revision to the ASTM HEFA jet fuel specification or under a new annex to the ASTM jet fuel specification, could expand the world's capacity to produce biojet considerably. There are currently 1.3 billion gallons of HEFA diesel capacity divided among four large producers, two mid-size producers, and one small producer. The large producers are Neste Oil, with plants in Finland, Denmark, and Singapore; Preem, of Sweden; Diamond Green Diesel in Louisiana, and ENI, of Italy. REG Synthetic Fuel, also in Louisiana, and UPM, of Finland, are midsize producers. Green Energy Products, of Kansas, is the small producer. Two more 3 million gallon-per-year plants, also in Kansas, are being built by East Kansas Agri-Energy and Prairie Horizon Energy to start in 2016. In 2017, SG Preston's 120 million gallon-per-year plant is expected to come online in Ohio, and Total's 169 million gallon-per-year plant is expected to start in France. Finally, Petrixo is planning a 288 million gallon-per-year plant in the United Arab Emirates with an unspecified starting date. Total HEFA diesel capacity will be 1.9 billion gallons per year once these 5 projects are complete.

Since biojet is just coming into commercial use, there is no production history on which to base a forecast. In recognition of the growth in drop-in diesel fuel and the potential for biojet, EIA has proposed adding data collection on biojet, biokerosene, and renewable diesel production to the next iteration of its monthly biodiesel survey.[44]

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[40] "Red Rock Biofuels lands contracts with Southwest Airlines, feds," *Denver Business Journal*, September 24, 2014. http://www.bizjournals.com/denver/blog/earth_to_power/2014/09/red-rock-biofuels-lands-contracts-with-southwest.html

[41] "Red Rock Biofuels to power FedEx jets under new contract," *The Denver Post*, July 21, 2015, http://www.denverpost.com/business/ci_28513304/red-rock-biofuels-power-fedex-jets-under-new

[42] "Look, up in the sky! The best of aviation biofuels slides from ABLC 2015," *Biofuels Digest*, March 29, 2015. http://www.biofuelsdigest.com/bdigest/2015/03/29/look-up-in-the-sky-the-best-of-the-aviation-biofuels-slides-from-ablc-2015/

[43] This total excludes Solena's 24 million gallons of FT diesel capacity and assumes that the entire output of the other producers will be usable as jet fuel.

[44] The Federal Register notice of the proposed changes is found at http://www.eia.gov/survey/frn/petroleum/FRN-60-Day-Supply-July-9-2015.pdf. The proposed survey form is found at http://www.eia.gov/survey/form/eia_22m/proposed/form.pdf.

Appendix: Sources for figures and tables

Figure 1: For years 2000-2016, nominal $ were converted to 2013 $ using the GDP deflator as reported in the EIA STEO, April 2015. For 2017-2040, the EIA AEO 2015 presents both nominal and 2013 $ prices. *Sources: 2000-2014: EIA Petroleum Supply Monthly; 2015-2016: EIA STEO, April 2015, http://www.eia.gov/forecasts/steo/index.cfm; and 2017-2040: EIA AEO 2015, Tables 11 and 12, http://www.eia.gov/forecasts/aeo/data.cfm, select Summary Case Tables.*

Figure 2: For years 2000-2016, nominal $ were converted to 2013 $ using the GDP deflator as reported in the EIA STEO, April 2015. *Sources: 2000-2014: EIA Petroleum Supply Monthly; 2015-2016 highway diesel and heating oil wholesale prices: EIA STEO, April 2015, http://www.eia.gov/forecasts/steo/index.cfm;* 2015-2016 jet fuel wholesale price: *EIA AEO 2015, Table 59; 2017-2040: EIA AEO 2015, Table 59. http://www.eia.gov/forecasts/aeo/data.cfm, select Petroleum, Natural Gas, Coal, Macroeconomic, International Data.*

Table 1: *Sources: CAAFI General Meeting, Certification-Qualification Breakout Session, January 28, 2014. http://www.caafi.org/information/pdf/CQ_Breakout_Session.pdf. FT-SKA: page 29/38. HDO-SK: page 27/38. HDO-SAK: page 28/38. HDCJ: page 27/38. CH: page 25/38. ATJ: page 22/38; see also the abstract of ASTM research report "Evaluation of Alcohol to Jet Synthetic Paraffinic Kerosenes (ATJ-SPKs.)" http://www.astm.org/DATABASE.CART/WORKITEMS/WK41378.htm* ASTM status was provided by Mark Rumizen of the Federal Aviation Administration via email on April 8, 2015 and on September 15, 2015.

Figures 3 and 4: Capacities stated in metric tons per year were converted assuming densities of 338.7 gallons per metric ton (780 kilograms per cubic meter) for HEFA diesel and HEFA jet fuel and 343.1 gallons per metric ton (770 kilograms per cubic meter) for FT diesel and FT jet fuel. These conversion factors were obtained from: Tom N Kalnes and Terry Marker (UOP), David R Shonnard and Ken P Koers (Michigan Technological University), "Green diesel production by hydrorefining renewable feedstocks", p. 8. http://www.uop.com/?document=uop-hydrorefining-green-diesel-tech-paper&download=1 Diamond Green's stated capacity of 11,000 barrels per day converted assuming 350 operating days per year. ENI and Petrixo's nameplate capacities represent all biofuel output, not just renewable diesel and biojet. Renewable diesel and jet capacity were obtained by applying a factor of 85% to ENI and Petrixo's respective capacities.

Sources: "Neste Oil reports more renewable diesel capacity in Q1 results," Biomass Magazine, April 29, 2015. http://biomassmagazine.com/articles/11875/neste-oil-reports-more-renewable-diesel-capacity-in-q1-results

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WB Services website. http://www.wbservicesllc.com/projects/green-energy-products-llc-2/