toward sustainable aviation fuels

Climate Solutions
PRACTICAL SOLUTIONS TO GLOBAL WARMING
www.climatesolutions.org

a primer and state of the industry

october 2015

Climate Solutions is a Northwest-based clean energy economy nonprofit whose mission is to accelerate practical and profitable solutions to global warming by galvanizing leadership, growing investment, and bridging divides. We pioneered the vision and cultivated the political leadership in the Northwest for the proposition that clean energy and broadly shared economic prosperity can go hand-in-hand. For 17 years, we have led successful initiatives to deliver climate and clean energy policies, models, and partnerships that accelerate the transition from fossil fuels to a clean energy economy.

The **Strategic Innovation Team** at Climate Solutions focuses on developing solutions to reduce greenhouse gas emissions and remove carbon pollution from the atmosphere at the scale required to address the climate crisis. We identify the pathways to a low carbon future and create replicable models for emission reduction and carbon storage that provide economic as well as climate benefits, through the following programs:

- **Pathways Project** identifies, analyzes, and publicizes the pathways to transition from a fossil fuel-based economy to a low carbon, clean energy economy, focusing on the technically and economically viable solutions that will move the states of Washington and Oregon off of oil and coal.
- **New Energy Cities** partners with small- and medium-sized communities to achieve significant greenhouse gas reductions by 2030. We are catalyzing replicable models of city-led clean energy innovation by working with communities to set and attain quantifiable carbon reduction targets for buildings, transportation, and energy supply.
- **Sustainable Advanced Fuels** accelerates low carbon alternatives to petroleum fuels in the Northwest. By supporting state clean fuels policies, driving awareness of advanced fuel technologies, and helping to build a viable advanced fuels market, we aim to achieve significant reduction in carbon emissions from transportation fuels.

toward sustainable aviation fuels

a primer and state of the industry

october 2015

Primary Author:	**Seth Zuckerman**, Senior Writer & Research Analyst, Climate Solutions
Editor:	**Eileen V. Quigley**, Director of Strategic Innovation, Climate Solutions
Contributor:	**Ross Macfarlane,** Senior Advisor, Business Partnerships, Climate Solutions
Reviewers:	**Barbara Bramble**, Senior Advisor for International Affairs, National Wildlife Federation **Ralph Cavalieri, PhD**, Professor of Biological Systems Engineering, Washington State University **John C. Gardner, PhD**, Vice President for Development (Note: also CEO, WSU Foundation), Washington State University **Michael Lakeman**, Associate Technical Fellow, The Boeing Company **Elizabeth Leavitt,** Director, Aviation Planning and Environmental Services, Port of Seattle **Stephanie Meyn**, Climate Protection Program Manager, Port of Seattle **Darrin Morgan**¸ Director of Biofuels Strategy, The Boeing Company **Peter Moulton,** Emerging Tech Team/Bioenergy Coordinator, Washington State Department of Commerce **John Plaza,** President and CEO, Imperium Renewables, Inc. **Carol Sim**, Director, Environmental Affairs, Alaska Airlines/Horizon Air **Misha Valk,** Business Development, SkyNRG
Design:	**Jonathan Lawson,** Digital Communications Manager, Climate Solutions, **Shew Design**
Cover Photos:	**Eileen V. Quigley** (*airplane*); **Marcus Kauffman** (*hybrid poplar chips grown in Jefferson, OR as feedstock for liquid biofuels*); **Sebastian Vandrey** (*rapeseed*). All photos licensed under Creative Commons.

Contents

toward sustainable aviation fuels

a primer and state of the industry

I. Executive Summary

Commercial aviation accounts for 2 percent of global carbon pollution, a figure projected to grow to between 3 and 4.7 percent by 2050 without concerted action to curb emissions. Accordingly, a comprehensive solution to the world's climate predicament requires a strategy to reduce aviation's carbon footprint. Industry leaders recognize this imperative and accordingly have set a goal of reducing the sector's carbon emissions 50 percent by 2050.

Major projects are underway in Oregon, California, Nevada, the US Midwest, and Britain to manufacture sustainable aviation fuels from feedstocks as varied as vegetable oils, municipal solid waste, and forestry by-products.

Sustainable aviation fuels (SAF) are integral to that strategy. More efficient aircraft and engine design, streamlined flight operations, and improvements to air traffic management systems can slow the growth in aviation's climate pollution, but it will take substituting fuels with a lower carbon footprint to actually reduce the industry's greenhouse impact in coming decades. Because commercial planes have long useful lifetimes and new models have long design and production timelines, liquid hydrocarbon fuels that can be used in existing planes and fueling infrastructure—"drop-in biofuels"—are necessary.

Interest in SAF has accelerated in the past decade. Individual flights of commercial airliners powered by SAF began in 2008; in 2011, both Lufthansa and Alaska Airlines embarked on a series of flights using fuel made from plant and animal oils. These fuels must meet essential physical and performance specifications set by the engineering testing body American Society for Testing and Materials (ASTM). Three kinds of biofuel received this approval in 2009, 2011, and 2014, and three more varieties are on track to receive it in the coming year. The three approved varieties of SAF must be blended with fossil jet fuel in order to ensure that the fuel performs properly in flight, but other types would make it possible to fly using fuel derived entirely from biological materials. Research and development continues on promising new SAF production processes, using feedstocks such as industrial waste gases and brine-raised algae.

SAF development continues apace despite the slide in petroleum prices that began in 2014, although no SAF facilities operate yet at commercial scale. Major projects are underway in Oregon, California, Nevada, the US Midwest, and Britain to manufacture SAF from feedstocks as varied as vegetable oils, municipal solid waste, and forestry by-products. The pending approval of green diesel for blending into jet fuel at ratios of up to 10 percent will create an immediate opportunity for large-scale SAF use, since that fuel is already in commercial production for ground transport.

The lack of consistent and reliably supportive government policies has been the most significant factor holding back SAF growth. Clean fuels mandates at the state and federal level, as well as financing mechanisms that reduce the risks for SAF investors, and infrastructure projects to facilitate the introduction of SAF to the jet fuel supply would all accelerate the adoption of SAF.

***photo:* Helge F.**

II. Introduction

In our increasingly interconnected world, commercial aviation represents a growing challenge to humanity's climate predicament. Its emissions already account for 2 percent of global carbon pollution,[1] and air traffic is projected to increase by 2.5 times over the next 20 years,[2] an increase fostered by the expansion of the middle class in the world's developing economies. Aviation is apt to take on even larger climate importance as energy efficiency improvements and renewable electric generation from wind and solar power shrink the carbon pollution attributable to other sectors. Reducing the climate cost of aviation will therefore require airlines to increase fuel efficiency and substitute fuels with a low carbon footprint for the petroleum-based jet fuel that is now the lifeblood of flight.

Reducing the climate cost of aviation will require airlines to increase fuel efficiency and substitute fuels with a low carbon footprint for the petroleum-based jet fuel that is now the lifeblood of flight.

Key international aviation bodies have recognized these imperatives. The Air Transport Action Group (ATAG), an international coalition of firms and trade associations in the sector, has committed to 1.5 percent annual reduction in carbon emissions up to 2020, carbon-neutral growth beyond 2020, and a 50 percent reduction in carbon emissions by 2050 compared to a 2005 baseline—goals that can only be met by using fuels that have much lower climate impacts than those made from crude oil. At a pivotal UN meeting in 2013, the International Civil Aviation Organization (ICAO) reported that its member states were taking "concrete steps for coordinated and comprehensive actions to address CO_2 emissions from international aviation" and developing policies, standards, and tools to enable carbon emission reduction for 80 percent of global air traffic.[3]

This year, aviation's climate impacts gained new urgency in the United States with a finding that foreshadows the possibility of future regulation. In June 2015, the US EPA's Office of Transportation and Air Quality issued proposed findings under Clean Air Act section 231(a) that GHG emissions from aircraft engines "contribute to the pollution that causes climate change thus endangering public health and welfare." The EPA also gave notice of proposed rule-making that could lead to U.S. adoption of international carbon dioxide emissions standards for aircraft that the ICAO has been developing since 2010.[4]

The Pacific Northwest has been ahead of the curve in considering and responding to these issues. Four years ago, Climate Solutions collaborated with a wide range of stakeholders in an initiative called Sustainable Aviation Fuels Northwest (SAFN), which resulted in a landmark report on the opportunities available to our region in the realm of clean power for flight.[5] Participants in the 2011 SAFN process and report included members of the aviation industry from airplane manufacturers to airlines, airports to research universities. SAFN articulated the need for aviation fuels not made from crude oil, and developed a roadmap for the transition away from petroleum—with its climate-altering emissions of carbon dioxide—as the source of power for commercial aviation.

The overall need and physical dimensions of that challenge remain unchanged, but significant progress—some halting, some rapid—has occurred over the past four years. ***Toward Sustainable Aviation Fuels: A Primer and State of the Industry*** offers a concise introduction to aviation biofuels and describes sustainable advanced fuel initiatives underway in the Pacific Northwest and around the world to provide a snapshot of the state of play in the sustainable aviation fuels arena.

III. The Need for Sustainable Aviation Fuels

Reducing air travel's carbon footprint must be part of any comprehensive plan to solve the problem of climate change. Globally, commercial air travel and freight account for the consumption of 4.7 million barrels of jet fuel per day,[6] representing about 6 percent of global petroleum demand,[7] leading to the emission of roughly 700 million tons of carbon dioxide annually[8] (2 percent of the anthropogenic total)—about the same emissions as Italy and Spain combined.[9] Unlike ground transportation, for which alternatives such as hydrogen fuel cells and battery electric drive are in advanced development, aviation will depend on liquid hydrocarbon fuels for the foreseeable future. Accordingly, its success at curbing its climate impact will depend on reducing the emissions of greenhouse gases from those fuels over their cycle of production and use.

Algae of the future
photo: Liloh

In coming decades, air travel is predicted to grow, while other sectors are projected to become less dependent on fossil fuels. Without concerted action, air travel's share of anthropogenic (human-caused) emissions will swell to between 3 and 4.7 percent of the world's total by 2050 (see Figure 1). A projected increase of 4 to 5 percent per year in passenger-miles flown drives this trajectory of increasing emissions under a business-as-usual scenario, which will result in a tripling of air travel over the course of 30 years (2010–2040).[10]

Aviation leaders recognize that the sector's contribution to climate change is significant not only for the global environment, but also for the industry's public image and economic health. "We're trying to insure we retain our license to grow as an industry, that we do not get too heavily regulated, by others, that we set those aggressive goals and targets for ourselves," said Julie Felgar, managing director of environmental strategy and integration for Boeing Commercial Airplanes, in June 2015. "The risk of doing nothing is risk to our market growth down the road."[11]

With these considerations in mind, ATAG has pledged to cut aviation's net emissions of CO_2 in half by 2050 compared with 2005 emission levels. As initial steps toward this goal, the industry can use three strategies to reduce fuel consumption, as represented by the three green wedges at the top of Figure 1.

1. Plane manufacturers can reduce fuel consumption per mile, through more efficient engines and aeronautical design improvements that reduce drag, such as improved wing tips. The metric that the ICAO has established for measuring CO_2 emissions from aircraft[12]—with performance standards in development that member states could enact—is part of these efforts.

2. Airlines can change flight operations to save fuel, using strategies such as routing changes and gliding; and
3. Governments can adapt their Air Traffic Management practices to expedite planes' passage to their destination and reduce wasteful circling and holding patterns.

The aviation industry has made tremendous progress in improving efficiency and reducing fuel usage. However, by themselves, those three strategies won't be adequate to achieve the industry's greenhouse-gas reduction goals; they would slow the growth in emissions, but not reverse it. A fourth strategy—depicted as the blue wedge in Figure 1—is needed to actually reduce emissions to half of their 2005 levels by the middle of the century.

4. Reducing the life-cycle greenhouse-gas emissions of the fuel used in aviation.

One other factor affecting aviation-related emissions is passengers' propensity to travel. It is possible to reduce the demand for business travel by using digital technologies to replace physical presence with virtual presence, or by building high speed rail lines in heavily used corridors. However, these trends are likely to be outweighed by the upward pressure on demand from the rise of a more affluent and mobile global middle class. Countries such as China, India, and Brazil are expecting very significant increases in air travel as their economies grow.[14] Consequently, all four of the above strategies will be needed to decrease aviation's carbon emissions.

Reducing the overall carbon pollution from aviation fuel requires a thoughtful understanding of the entire life cycle of fuel production and combustion. It means including not just the emission of carbon dioxide when the fuel is burned (net of the carbon absorbed in growing the crops from which the fuel is made), but also any climate pollution released in the course of producing the feedstocks from which the fuel is made. Causes of these emissions can include clearing of new cropland, impacts of fertilization on the emissions of other greenhouse gases such as nitrous oxides, and the fossil fuel inputs required for cultivation and subsequent processing of the crops.

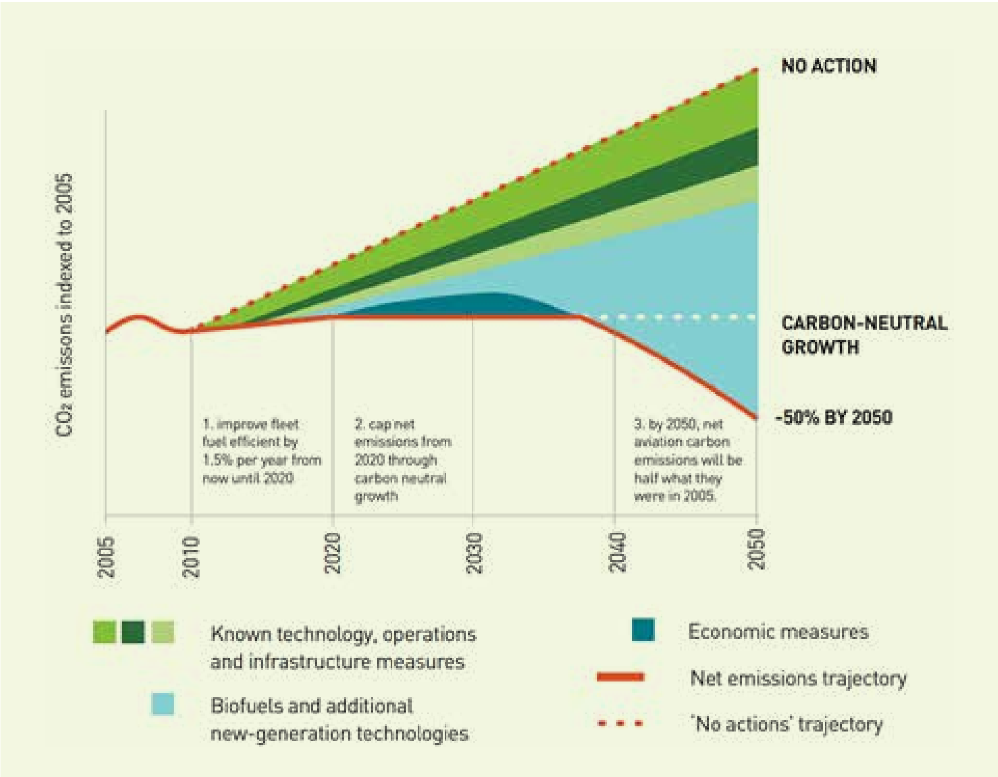

Figure 1: Projected growth in CO_2 emissions from aviation and how to reduce it[13]

Fuels made from biologically derived ingredients (biofuels) that survive this closer scrutiny will be essential to curbing the significant climate impacts of commercial aviation. Biofuels which can be used to power airplanes and which meet these criteria are known as "sustainable aviation fuels," or SAF, and are also referred to in this paper as "biojet" to distinguish them from fossil or petroleum-derived jet fuel. Considering all of those factors, World Wildlife Fund International and Ecofys found in a 2011 *Energy Report* that it would be possible to power the aviation sector entirely with sustainably produced biofuels by 2045,[15] radically shrinking the sector's carbon footprint.

In addition, biofuels for aviation can provide other advantages. Because they can be produced from a variety of feedstocks, they can be sourced locally, thereby reducing the aviation industry's reliance on oil imports and freeing it from dependence on the tenuous geopolitical stability of petroleum-producing regions. Using a mix of fuels and feedstocks reduces the industry's exposure to fuel price volatility, since the cost of production is more predictable and doesn't depend on the price of petroleum, which is prone to wide swings on international commodity markets. Although SAF is currently priced at a premium to petroleum, many observers believe that, with development of new conversion technologies and economies of scale, biojet fuel could become cost-competitive with petroleum.

"Green Hornet" F/A-18D in flight. ***photo: Paul Farley***

This is a significant benefit to airlines, for whom fuel represented one-third of operating costs in the early part of this decade.[16] In the developing world, where petroleum imports can represent a large drain on foreign currency reserves, the local production of biofuel could replace that drain with a gain. Finally, the regional production of aviation fuel would keep more money circulating within the region than the refining of imported petroleum, so any region that imports petroleum or jet fuel could realize an economic multiplier effect associated with a shift to biofuels.

IV. A Brief History of Sustainable Aviation Fuels

In 2006, several U.S. commercial airlines, aircraft manufacturers, and the U.S. government established the Commercial Aviation Alternative Fuels Initiative (CAAFI) to develop alternatives to petroleum-based jet fuel. Other initiatives sprang up in other parts of the world, as well. Virgin Atlantic made the first test run of a commercial airliner on biofuel in 2008, flying a Boeing 747 from London to Amsterdam using a blend of 80 percent petro-jet and 20 percent biofuel made from tropical oils. As interest grew, interested airlines in 2008 established the Sustainable Aviation Fuel Users Group (SAFUG) to accelerate the development and commercialization of SAF. The following year, KLM used biofuel for the first time to carry passengers, using a blend made with camelina, an oilseed in the mustard family.

In 2010, United States Navy F/A-18 "Green Hornet" aircraft flew on camelina-based biojet fuel in the first flight to demonstrate how a 50/50 blend of petroleum and biofuel would perform at supersonic speeds. This test flight was a major milestone in the certification and use of camelina fuels in military aircraft.[17]

In 2011, Lufthansa embarked[18] on a series of more than 1,000 flights between Hamburg and Frankfurt, using a blend that included fuel made of jatropha, camelina, and tallow.[19] In the Pacific Northwest, Alaska Airlines undertook a series of 75 flights that same year between Seattle and Portland and between Seattle and Washington, DC. Its planes used a blend of 80 percent petroleum kerosene mixed with 20 percent biofuel from used cooking oil.[20] Other trials and pilot programs continue; to date, about two dozen carriers have flown more than 2,000 commercial flights using biojet fuel.

In these test flights and pilot programs, as in any larger-scale adoption of biofuel that may follow, the fuel must first and foremost meet essential chemical, physical, and performance standards to ensure the safety of the aircraft using them. These standards are attested to by certification bodies such as the American Society for Testing and Materials (ASTM) and, in Europe, DEFSTAN. Three different kinds of biofuels have been approved, in 2009, 2011, and 2014. Fuels cannot be used in commercial flight until they gain this approval.

The sustainability of a fuel is assessed through a separate process, such as the one administered by the Roundtable on Sustainable Biomaterials (RSB), which vouches for the sustainability of a fuel produced in a particular way from a specific feedstock. These certification systems are discussed in greater detail below.

By 2015, more than two dozen international carriers had joined SAFUG, between them accounting for 33 percent of global commercial aviation fuel demand. SAFUG's partnership also includes the three largest passenger plane manufacturers in the world (Boeing, Airbus, and Embraer), environmental NGOs, and representatives of the fuel industry. [21] It has developed a pledge of sustainability to which all of its members commit, and adopted sustainability criteria that call for fuel manufacture to be consistent with RSB guidelines or "other emerging internationally recognized standards."[22]

V. What is Sustainable Aviation Fuel?

Engineering Requirements

A basic premise of biojet fuel is that it needs to be fully compatible with existing planes and fueling infrastructure. This criterion is reflected in the term "drop-in fuel"—it can be "dropped into" current planes and fueling systems, where it will be fully interchangeable with petroleum-based fuels and meet the same standards of safety and reliability.

Here's why that is essential: Planes are such a long-lived capital investment that it would be economically infeasible to retire them early to accommodate a new fuel. The average age of commercial aircraft in service in the U.S. is about 15 years, with some planes having stayed in the fleet for as long as four decades.[23] Similarly, airports have made substantial investments in fueling infrastructure, with fuel typically pumped from central tanks through underground pipes to refuel planes while they are parked at the gates. As a consequence, aviation biofuels must be able to be used interchangeably with petroleum-derived jet fuel, particularly while the supply of biofuels is still growing to scale.

ASTM is the primary stakeholder process used in aviation to define the standard for jet fuel's physical properties and combustion performance. Although there are other standards, such as DEFSTAN, in practice, the ASTM process sets the agenda on fuels approval because of its global and participatory approach. The various global standards are all similar in terms of criteria and performance requirements, making them largely (though not entirely) interchangeable, and almost all commercial and military aircraft are certified to fly on fuel that is compliant with these standards. The basic requirements are summarized in Table 1 (p. 15) with a brief explanation of why they matter to airplane performance and safety.

Argonne biophysicist Philip Laible oversees the growth of new variants of photosynthetic bacteria designed to produce target biofuel molecules. In this culture mode, it is easy to extract cells during all phases of growth for analysis, and add chemicals (shown here) to speed growth or induce the production of target fuels.
photo: Argonne National Laboratory

Biofuels that have been created for other applications, such as ground transportation, do not meet the stringent criteria for jet fuel. For example, fatty-acid methyl esters that constitute automotive biodiesel freeze at too high a temperature[24] to be used in jet engines; ethanol distills at a lower temperature, has a lower flash point, and a lower energy density.[25] Biofuel used in jet aircraft needs to be synthesized for this specific application.

To accommodate those purpose-made biofuels, the ASTM devised a standard for synthetic jet fuels, known as D7566 that sets the specifications and requirements to ensure a biofuel can be used in commercial aviation. The individual conversion processes (described in greater detail in the next section) are certified separately, with specific requirements described in an "annex" to the overarching D7566 standard.

The first annex, adopted in 2009, approved fuel made using the Fischer-Tropsch process (F-T), which can use as its raw material any kind of biomass, municipal solid waste, or even coal or natural gas. The second, passed in 2011, approved hydrotreated fatty acid esters and free fatty acids (HEFA), which are made from natural oils and fats. The third annex, finalized in 2014, approved fuels made using the direct fermentation of sugar to hydrocarbons (DSHC). A fourth annex is expected to be approved by mid-2016, allowing the use of "green diesel" (also known as Hydro-treated Renewable Diesel), which is already in production for surface transportation. Several other conversion processes are at various stages of the fuel approval process.

The biofuels approved to date may only be used in a blend with petroleum-based jet fuel. A central reason for this blending requirement is that jet fuel must have a minimum level of aromatic hydrocarbons[26] to maintain the integrity of seals in the fuel system,[27] and most biofuels either lack aromatic compounds entirely, or do not have a predictable minimum percentage of aromatics. The first two certifications (F-T and HEFA) were approved for blends of up to 50 percent biofuel, while the certification of DSHC allows for blends of up to 10 percent biofuel. Green diesel is expected to be allowed at a ratio of up to 10 percent as well.

Testing is underway to determine the minimum aromatic content required in fuel blends. In addition, some biofuels under development do include aromatic compounds, offering the hope that jets could eventually fly on 100 percent biomass-derived fuels.

Sustainability Requirements

Sustainable aviation fuels are developing during an era when the notion of a triple bottom line—assessing economic, environmental, and social gain—is fundamental to the idea of sustainability. Accordingly, the definitions of sustainability guiding the industry have been broad and far-reaching. This section explores the ramifications of biofuel production that enter into the certification of biofuels as sustainable, with particular focus on two especially thorny issues.

The economic element of the triple bottom line requires that biojet become cost-competitive with petroleum-based fuels. Airlines will not be able to make extensive use of biofuels unless they can obtain them at a similar price to petrojet, and government incentive programs cannot be counted on to continue indefinitely. In jurisdictions where a carbon price or carbon cap has been enacted, the resulting market premium for low-carbon fuels would be a reasonable component of biofuel's economic viability.

The Air Transport Action Group committed the aviation industry to reductions in its carbon footprint by improving fleet fuel efficiency 1.5 percent per year between now and 2020; capping net carbon emissions by 2020; and cutting net emissions from 2005 levels in half by 2050. Bringing a triple bottom line approach to realizing these goals, the Sustainable Aviation Fuels Users Group (SAFUG) developed a set of commitments about how sustainable aviation fuel should be produced. The Users Group said[28] that biofuels:

- should not compete with food production,
- should not degrade biodiversity,
- should not require the clearing of high-conservation-value areas and native ecosystems,
- should not endanger supplies of drinking water,

Table 1: Key engineering specifications for jet fuel

Property	Value	Significance
Specific energy, net	min. 42.8 MJ/kg	Provide enough engine power for the weight carried into the air
Smoke point	min 25 mm	A measure of how easy it is to fully combust the fuel—longer smoke points (measured in millimeters) are better.[29]
Density at 15˚C	775 to 840 kg/m^3	Fit enough fuel in volume-limited tanks
Adequate volatility	Distillation temp between 200 and 300˚C	Fuel must vaporize at correct temperature to burn well in engines
Flash point	min 38˚C	Fuel must not catch fire too easily for safety
Freezing point	max –47˚C (–40˚C for Jet A)	Fuel must remain liquid even in cold temperatures found at high altitude
Viscosity at –20˚C	max 8 mm^2/s (cSt)	Fuel must flow readily even at low temperatures

These standards are spelled out in ASTM Standard D1655, and in a similar specification issued by the UK Ministry of Defense, DEFSTAN 91-91.

- should significantly reduce the life-cycle emissions of greenhouse gases compared with fossil jet fuel, and
- should improve socioeconomic conditions without displacing local populations involuntarily.

SAFUG works with the Roundtable on Sustainable Biomaterials (RSB) on the implementation of these commitments. RSB is an international certification body founded in 2007[30] and made up of more than 100 organizations drawn from seven different chambers or interest groups:[31] farmers; biofuel producers; retailers, blenders, and users of biofuels; trade unions and other rights-based organizations; rural development and indigenous people's groups; NGOs focused on environment, climate, and conservation; and government, academic, and research institutions.

Sustainable aviation fuels are developing during an era when the notion of a triple bottom line—assessing economic, environmental, and social gain—is fundamental to the idea of sustainability.

Each chamber sends two or three representatives to the RSB's Assembly of Delegates, which is responsible for adopting certification standards.[32] This ensures that any standard promulgated will have broad support among stakeholders. The RSB has garnered praise from the environmental community for its thoroughness and credibility, winning high marks from the Natural Resources Defense Council,[33] International Union for the Conservation of Nature,[34] the World Wildlife Fund.[35] Besides establishing standards, the RSB also accredits third-party certifiers who inspect the operations of firms that claim to follow RSB standards, ensuring that biofuels suppliers are actually living up to the principles they espouse.

SAFUG uses RSB standards as a benchmark. "[Sustainability] criteria should be consistent with, and complementary to emerging internationally-recognized standards such as those being developed by the Roundtable on Sustainable Biomaterials," says the SAFUG pledge.

Table 2 (p. 17) lists the indicators adopted by the RSB for the principal arenas of sustainability, all of which must be considered when evaluating the sustainability of potential fuels.

Among the many sustainability concerns, two have been especially debated and are examined here in greater detail: the life-cycle greenhouse gas emissions resulting from biofuels use, and the impacts on food security.

LIFE-CYCLE GREENHOUSE GAS EMISSIONS

The expected climate benefit of biofuels stems from the fact that the CO_2 emitted when they are burned had been recently removed from the atmosphere by photosynthesis when the feedstocks were raised, and that a comparable amount of CO_2 can be removed again when a new crop is grown. (In contrast, fossil jet fuel releases carbon into the atmosphere that had been sequestered underground for millions of years.)

However, substantial amounts of fossil fuels may be used in growing, harvesting, and transporting biofuel feedstocks, and in making, processing, and delivering biofuels. In addition, agriculture may release other greenhouse gases, such as nitrogen oxides and methane. As a result, understanding the impact of a particular biofuel requires that we examine the entire ***supply chain*** leading from the origin

Table 2: Summary of RSB Standards for biofuels

Carbon life-cycle balance	At least 50% GHG reduction Emissions from indirect land use changes (those caused by the displacement of agricultural uses onto other lands as a result of the increased cultivation of biofuel feedstocks) do not have to be accounted for, but can be tracked using an optional module[36] approved by the Assembly of Delegates in June 2015[37]
Land and labor rights	Slave, forced, and child labor is barred Laborers have the right to organize and be free of discrimination
Rural and social development	Promote permanent and local labor, cooperatives, micro-credit facilities, local ownership, and creation of institutions
Food security	Participating operators should conduct a food security assessment and mitigate any impacts on food security that biofuel operations are expected to have
Habitat conservation and biodiversity	Identified "no-go" areas Ecological services and natural buffers/corridors must be maintained Migration of invasive species should be prevented
Soil conservation	Soil erosion is to be minimized and soil organic matter enhanced
Water quality and quantity	Efficient water use and maintenance of water quality is required Depletion of surface or groundwater is forbidden
Air pollution	Best available technology should be used, respecting local context, operational scale, and intensity
Use of technologies	Use of genetically modified organisms (GMO) must follow local laws GMO must stay within the operational area

of the feedstock to the delivery and use of the final product.

Besides carbon emissions resulting from crop cultivation and processing, additional emissions may arise from changes in land use, when heightened demand for feedstocks prompts the clearing of land with a higher standing stock of carbon, such as forest. These impacts may be direct (DLUC–direct land-use change), when new lands are cleared specifically for biofuels, or indirect (ILUC—indirect land-use change), when demand for biofuel feedstocks causes land clearing elsewhere to meet other needs for food, feed, and fiber.

Estimates of GHG emissions for different biojet supply chains can vary widely. One recent study from the Argonne National Laboratory in the United States found 55 to 85 percent life-cycle emissions reductions compared to petroleum-derived jet fuel for several different SAF supply chains,[38] with the variability resulting from differences in the sustainability of feedstock production. Other studies have shown, however, that some biojet supply chains can have greater GHG emissions than fossil fuels.

In a worst-case scenario, producing jet fuel from palm oil using the Hydrogenated Esters and Fatty Acids (HEFA) process has been estimated in one study to result in a 687 percent increase in life-cycle GHG emissions above fossil jet A-1, in large part because of the carbon emitted when converting tropical rainforest to palm plantations. No type of biomass is sustainable or unsustainable as such.

Sustainability depends upon the local conditions and how the crop is grown, not the crop itself. Hence the impact of feedstock production on social and environmental issues may be positive or negative depending on local conditions and the design and implementation of specific projects.

At the other extreme, the same study estimated that when jet fuel is produced from used cooking oil via the same HEFA process, life-cycle GHG emissions can be reduced by 84 percent compared to fossil jet A-1.[39] This variability illustrates the critical importance of looking closely at life-cycle GHG emissions in the design and development of any SAF supply chain.

FOOD SECURITY

First-generation biofuels are made from feedstocks, such as corn for ethanol and soybeans or canola for biodiesel, that also supply food for humans and livestock. As a result, policy-makers and advocates have expressed concern that they might adversely affect food security for the less affluent, particularly since increasing production of biofuels has coincided with record-high global food prices. The impacts need to be evaluated on a case-by-case basis, as it isn't uniformly true that use of food crops reduces the supply of human food. The use of these feedstocks can yield a by-product—soy meal, in the case of soy-based diesel, or distiller's dried grain in the case of corn ethanol—that is useful as animal feed.

***photo:* Dennis Pennington**

In addition, decisions about the cultivation of agricultural land occur against a heterogeneous background of competing opportunities, resource availability, and land tenure arrangements, which make it hard to speak categorically about the impact of fuel production on the food supply. Nevertheless, there is enough overlap—mediated in part through the link between fluctuating food prices and the costs of first-generation biofuel feedstocks—that interest has grown in biofuels that do not compete with sources of human food.

However, because impacts arise from specific local conditions, it would be incorrect to assume that a specific feedstock meets or fails sustainability criteria wherever it is grown. Each feedstock source and supply chain must be evaluated on its own merits. Further, adhering to the RSB criteria for SAF development should result in biofuels that do not cause food insecurity because RSB states that in food-insecure regions, potential impacts need to be mitigated through measures such as helping farmers increase yields, setting aside land for food production, and providing for biofuel feedstock workers to be able to cultivate household subsistence crops as well.

The next section of this report describes how to produce biojet fuels, addressing both the feedstocks that can provide the raw materials and the processes that can be used to convert them into liquid fuel.

VI. How is Sustainable Aviation Fuel Produced?

This section focuses on the processes that can be used to produce sustainable aviation fuels and addresses the critical challenge of moving beyond laboratory scale to yield fuel in commercial quantities. To understand these, it will be helpful to first step back and consider the entire supply chain, from feedstock to airline customer. (In this report, we use "supply chain" to encompass the fuel's entire journey from feedstock procurement through combustion in the jet engine, and "pathway" to refer to a combination of feedstock and conversion process. See Figure 2, next page)

Feedstocks

The supply chain begins with a feedstock from one of four broad categories: oils; sugars and starches; woody materials; and industrial byproducts. Most production processes can only work with one feedstock category, while some can make use of a variety of different feedstocks.

The oil category includes some food crops (such as palm, soy, corn, and canola oil) as well as food byproducts (inedible corn oil, tallow, and used cooking oil) and crops raised exclusively for fuel (jatropha, algae oil, carinata, camelina, and field pennycress). Sugars and starches mostly include familiar food crops such as sugar cane, sugar beets, sweet sorghum, maize, and other grains.

Woody materials and some crop residues and organic waste are also known as "lignocellulosic" for their two main organic compounds, lignin and cellulose. They include wood plantations and varieties of grass and sorghum raised specifically as fuel feedstocks. Finally, industrial byproducts include municipal solid waste; agricultural wastes, such as corn stover, rice husks, and bagasse; and residues from logging and milling operations.

Another promising process proposes to use bacteria to ferment industrial waste gases from industrial processes, such as steelmaking, into fuel.[40] Many developers are also focusing on producing fuels from oil extracted from algae.

Conversion

The bridge between feedstock and fuel is the conversion process—the technology to convert and refine the biomass into fuels with the same engineering characteristics as fossil jet fuel. These technologies rely on a number of different chemical processes, described in more detail below. At the end of this step, the feedstocks have been transformed into biofuel, which is tested to ensure it conforms to ASTM specifications. Additional marketable products often result from feedstock conversion processes. These co-product streams add additional revenue to the overall biorefinery balance sheet and make it possible to keep the price of biofuel more competitive.

Downstream Logistics

The biojet fuel is then blended with fossil jet and re-tested to make certain that the finished product meets ASTM specifications. (In some localities, this process would have to happen upstream of the airport, since there is no infrastructure to support fuel blending on-site.) Once it has passed this hurdle, the process depends on the delivery infrastructure of each site.

Outside the U.S., an international aviation fueling standards forum known as the Joint Inspection Group (JIG) developed a set of standards that embodies the most

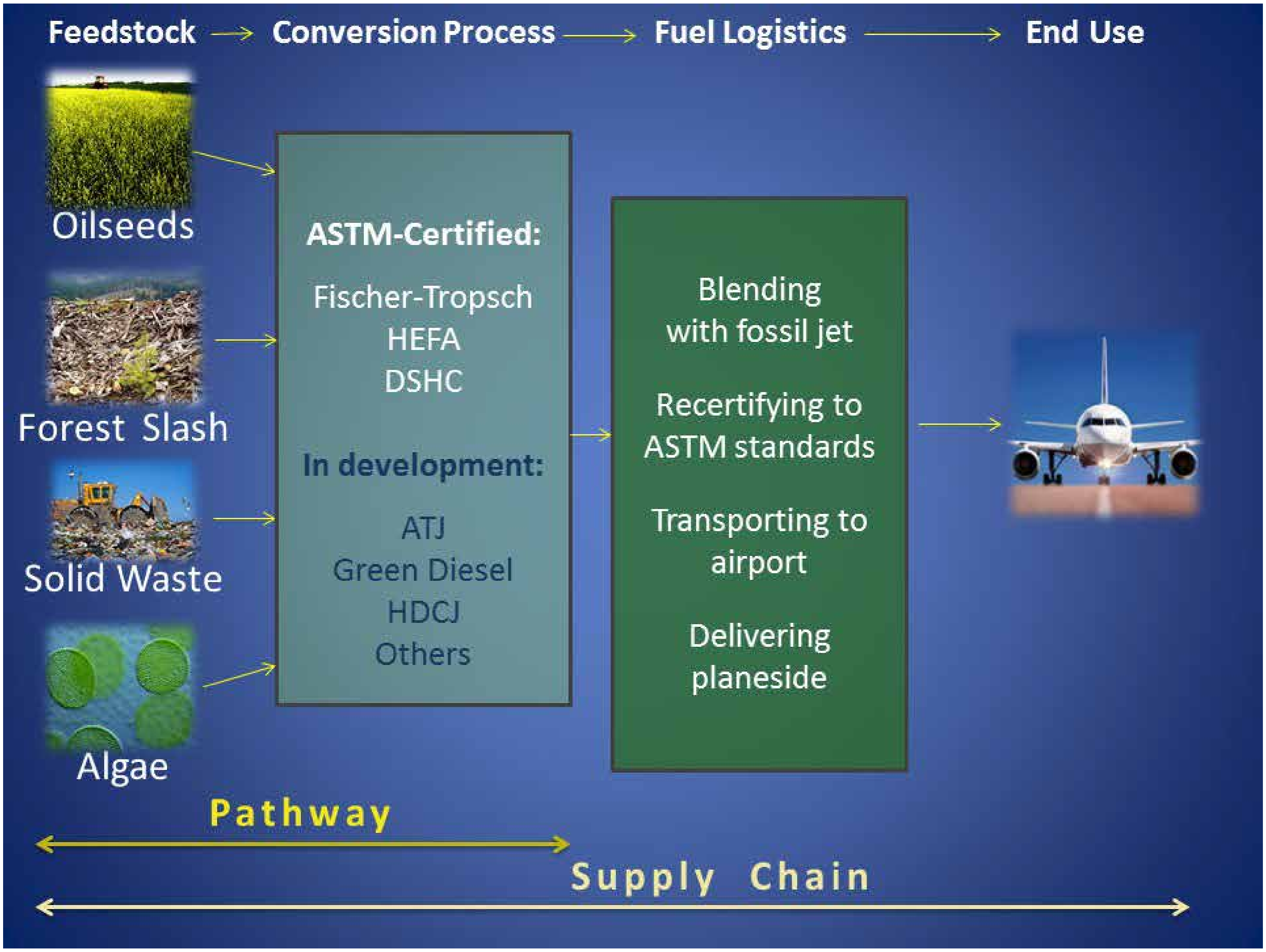

Figure 2: The supply chain, from feedstock to end use

stringent requirements of DEFSTAN 91-91 and ASTM D1655, thereby adopting a slightly more restrictive standard, but one that will be sure to satisfy both of the parent standards. JIG's fuel rules provide that the blended biofuel can be introduced into the same fueling network of tanks, pipelines, and hydrants that carry fuel through the airport, a practice followed in Mexico, for example.

In the United States, the use of biojet blends in the airport fuel infrastructure requires the agreement of all airlines fueling at the airport, as well as the airport management itself.

To date, the modest quantities of biojet consumed in U. S. commercial aviation have been delivered to airplanes via a completely segregated system of trucks, barges or railcars, and then transferred to refueling trucks that bring the product to the plane. In part, this is likely because the airlines purchasing the fuel wanted to know (and to be able to tell the world) that they were flying on biofuels, and also to check whether there was any change in performance or maintenance needs as a result of using biofuels. However, in the long term, the feasibility of SAF will depend on its integration into the supply stream of jet fuel in order to keep costs down.

End Use

Because of the significant capital expenditure required to build an advanced biorefinery that can produce these drop-in fuels, long-term fuel purchase contracts (known in the fuel business as "off-take agreements") are essential to the budding sustainable aviation fuels industry. If airlines are to buy significant quantities of biofuel, they have indicated that they can't afford to pay a premium for the product. So the price to airlines must be competitive with fossil jet for the industry to take flight. Another critical factor involves available markets for co-products, such as fuels for other sectors or chemicals, which may improve the economics for production facilities. Only in rare cases would scale-level production be developed for a single product, such as aviation fuels.

A modified harvester cuts, chips, and blows hybrid poplar biomass into a truck that will haul it to a biofuel processor
***photo:* Marcus Kauffman**

Conversion Processes

This section describes several of the most developed conversion processes.

FISCHER-TROPSCH

The Fischer-Tropsch process (F-T) can turn any carbon-rich feedstock into fuel. First, a synthetic gas, or syngas, is made by heating the feedstock and reacting it with steam. The resulting mixture of hydrogen and carbon monoxide is then reacted with a catalyst to yield a mixture of hydrocarbons. This mixture, typically in the form of a wax, is then refined (or "cracked," in refinery parlance) into a variety of end products.

The F-T process was first developed in Germany between the world wars as a way of turning coal into liquid motor fuel, and its largest-scale current operations convert coal and natural gas into liquid fuels in South Africa, Qatar, and Malaysia. In 2009, the F-T process became the first to earn ASTM certification for its biojet fuel product, which can be blended at ratios of up to 50 percent with fossil jet. Although none of the F-T fuel that has been used thus far in commercial aviation has been derived from biomass feedstocks, several biofuel projects are underway to transform municipal solid waste and forest residues into sustainable aviation fuel using the F-T process.

While F-T has the advantage of being able to make use of many feedstocks, its development has been held back by its high capital cost.

HYDROGENATED ESTERS OF FATTY ACIDS (HEFA)

The HEFA process—also known as Hydrotreated Renewable Jet (HRJ) and Hydrotreated Vegetable Oil (HVO)—starts with an oily feedstock, such as tallow, palm or canola oil, or used cooking oil. The oil is then "hydrotreated," meaning that elemental hydrogen is reacted with the feedstock to remove oxygen atoms from the organic molecules and split the triglycerides (fat molecules) into individual long-chain hydrocarbons.

Those hydrocarbon molecules are then "cracked"—reacted at high temperature with a catalyst to shorten them, a process also used in petroleum refining. The resulting mix of hydrocarbons is distilled to separate different products: renewable diesel, jet fuel, and naphtha. With proper tuning of the cracking process, renewable jet fuel (known as HEFA-Synthetic Paraffinic Kerosene or HEFA-SPK) can be the majority product.

In 2011, ASTM approved HEFA-SPK for use in commercial aircraft at ratios of up to 50 percent. To date, it represents the lion's share of the global supply of SAF and has powered more than 90 percent of the world's biofueled test and commercial flights.

Rapeseed
photo: Mark Fletcher

Although HEFA has been approved by ASTM and is produced today in modest quantities, many observers believe that its potential to scale up is limited. Virgin oil feedstocks are cost-prohibitive, because their price is tied to food commodity markets. Supplies of used cooking oil, which do not have that competing alternative use, are available only in limited quantities. For this pathway to become a significant source of biojet fuel, new, oilseed crops that are not used as foods (such as camelina or carinata[41]) would have to be grown at larger scales.

DIRECT SUGAR TO HYDROCARBON (DSHC)

The DSHC process relies on a strain of yeast that has been genetically engineered to produce hydrocarbons instead of alcohol as the by-product of its metabolism. The yeast digests a feedstock such as sugar cane syrup to yield a 15-carbon molecule called farnesene.

In further chemical processing, hydrogen is added to yield a saturated 15-carbon hydrocarbon known as farnesane, which can be blended into jet fuel.[42] Research and development is underway worldwide to explore this pathway further, but only one firm is using this process to produce fuel on a commercial scale: Amyris, whose facility is located in Brazil.

In 2014, ASTM approved this fuel—also known as Synthetic Iso-Paraffin, or SIP—for use at a ratio of up to 10 percent in jet aircraft.[43] The low ratio, compared with the 50 percent maximum allowed for fuel from the HEFA and F-T processes, is due to the molecule's location at the large end of the spectrum for jet fuel. (The typical range for jet fuel is nine to 16 carbon atoms per molecule.) In too high a concentration, farnesane makes the fuel too viscous. In addition, fuel performance requires a "smooth distillation curve," meaning that not too much of the fuel vaporizes at any one boiling point, limiting the amount that any single compound can comprise.

GREEN DIESEL FOR AVIATION

Green diesel (sometimes known Hydrotreated Renewable Diesel (HRD) is produced using the same initial steps as the HEFA process, drawing on a similar range of oily feedstocks. Instead of the final cracking steps that shorten the hydrocarbon chains to produce the lighter, lower freezing-point mix of compounds characteristic of jet fuel, the process leaves the hydrocarbon chains longer, the freezing point higher, and the product usable as either diesel motor fuel or for blending at low concentrations with fossil jet. This strategy has two advantages: it requires less hydrogen, which saves on cost and improves the carbon footprint of the complete fuel production cycle, and it yields a product (diesel) with a wider potential market.

In addition to this operational cost saving, there is also a capital expenditure cost saving in that there is no need to build a distillation column. Those cost savings pale, however, in comparison to green diesel's major advantage: its production capacity. Worldwide, biorefineries already in production can produce 1 billion gallons of renewable diesel per year.[44]

ASTM approval of green diesel as a blending ingredient in jet fuel is expected by mid-2016. The Boeing Company has been a strong advocate for its approval, and successfully tested a blend of 15 percent renewable diesel in one engine of a 787 in late 2014.[45] A Boeing 757 flew cross-country on a green diesel fuel blend from Seattle, WA to Langley, VA in June 2015.[46] Even if it is certified only for a very low percentage (10 percent or less) of the finished fuel, green diesel is already being produced at scale and at competitive prices (inclusive of applicable governmental incentives), which would make it possible to introduce large quantities of biofuel into the jet fuel supply chain in relatively short order.

The world's largest producer of green diesel is Neste Oil, with refineries in Rotterdam, Singapore, and Finland whose combined capacity exceeds 650 million gallons per year.[47] According to Bloomberg New Energy Finance, Neste will add another 220 million gallons per year in capacity at existing facilities by 2017, while its competitors are on track to add another half-billion gallons per year in production over the same period, which will bring worldwide capacity to 1.7 billion gallons annually.[48]

ALCOHOL TO JET (ATJ)

The ATJ process builds on humanity's long record of converting sugars and starches into alcohol. The alcohol is dehydrated (removing the OH group from the molecule), and goes through the process of oligomerization, which combines a few molecules together into one. The resulting mixture of hydrocarbons is then distilled into separate fractions with different boiling points, and the remaining double bonds and oxygen atoms are removed through hydrogenation.

The possible feedstocks for this process are as diverse as the raw materials for fermented spirits and industrial alcohols; in addition to sugars and starches, substantial R&D is underway to break down lignocellulosic (woody) feedstocks into compounds that can be fermented by yeast. Besides the most widely produced alcohol (ethanol, with two carbon atoms per molecule), the ATJ process can also start with slightly larger alcohol molecules (the three-carbon propanol or the four-carbon butanol), which can also be produced from biomass.

Two task forces within ASTM are pursuing certification for ATJ fuels. One is focused on Synthetic Paraffinic Kerosene (SPK), a straight-chain alkane mixture that is expected to be approved in 2015 when produced from n-isobutanol at a blend of up to 50 percent with fossil jet. A separate task force is focused on the production of Synthetic Aromatic Kerosene, which would include the aromatic compounds[49] that are essential to the proper functioning of seals in the fuel

Table 3: State of play for certification of biojet fuels

Process	Certification date	Blend ratio
Certification approved		
Fischer-Tropsch-derived Synthetic Paraffinic Kerosene (SPK)	Approved 2009	Maximum 50%
Hydroprocessed esters and fatty acids (HEFA)-derived SPK	Approved 2011	Maximum 50%
Direct Sugars to Hydrocarbons-derived SPK	Approved 2014	Maximum 10%
In the approval process		
Alcohol-to-jet SPK	Expected 2015	Probably max 50%
Green diesel	Expected June 2016	Probably around 10%
Fischer-Tropsch-derived Synthetic Kerosene with Aromatics (SKA)	Expected December 2015	Likely 100%
Alcohol-to-jet-derived SKA	Expected in 2016 or later	Likely 100%
Hydroprocessed depolymerized cellulose-derived SKA	Unknown	Probably max 25%
In development		
Hydrothermal cracking and cyclization-derived SKA	Most likely not before 2018	Probably max 50%
Catalysis, oligomerized and hydrotreated SPK	Most likely not before 2018	Probably max 50%
Hydroprocessed esters and fatty acids-derived SKA	Most likely not before 2018	Probably max 25%
Catalysis to SKA	Most likely not before 2018	Probably max 25%

system of jet aircraft. Accordingly, this process could be a key ingredient in biofuel that could be used at 100 percent concentration in jet aircraft. Approval of this pathway by ASTM is not expected before 2016.

While ATJ is expected to require less capital investment than the F-T or HEFA processes, its viability depends on the availability of alcohol as an input. Currently in the U.S., mandates to blend renewable fuels into motor gasoline are soaking up the supply of ethanol, but if the supply of alcohol exceeds the 10 percent cap on ethanol content in motor fuel, an ethanol surplus may develop that could be channeled into ATJ. Until then, ATJ's development is handicapped by the fact that ethanol as a raw material is worth more than the jet fuel that can be produced with it. The development of pathways that rely on propanol or butanol as an intermediate input would also circumvent this obstacle.

HYDROTREATED DEPOLYMERIZED CELLULOSIC JET (HDCJ)

HDCJ is fuel made from cellulosic feedstocks such as forestry wastes and agricultural residues. They are depolymerized, meaning that the complex organic compounds that make up the woody materials are broken into their smaller organic building blocks. This mixture is hydrotreated, meaning that it is reacted with hydrogen to remove double bonds and oxygen atoms, leaving pure hydrocarbons.

The process begins by grinding up the feedstock and then heating it rapidly to about 500˚C, sometimes with a catalyst on the heating medium. This liquefies the biomass through the process of pyrolysis (literally, heat-splitting), yielding a bio-crude oil. The remaining two steps—hydrogenation and distillation—are similar to those used in a petroleum refinery, making it possible to re-purpose oil refineries to carry out these final processes.

This process yields a high percentage of aromatic compounds when ligno-cellulosic materials are used as a feedstock; as a result, blending of this fuel will be limited because the proportion of aromatics in jet fuel is capped at 25 percent.

Table 3 (page 24) summarizes the state of play for each of the conversion processes used to manufacture sustainable aviation fuel. In addition to the six processes described above, four others are in more speculative stages of development, and are listed here for the sake of completeness but not explained.

VII. Sustainable Aviation Fuel Manufacturing Initiatives

Sorghum bicolor
photo: Kew on Flickr

Getting a sustainable aviation fuel initiative off the ground is like building a trail through the mountains: first it is necessary to scout the possible routes, then to select a route and flag it, and only after that is it possible to begin construction. The process of manufacturing sustainable aviation fuel requires that all the components line up, from feedstock through approved conversion process to the ultimate customer, the airline that will burn the fuel in its planes.

Because the capital investment required to build a sustainable aviation fuel plant can run into the hundreds of millions of dollars, it is essential to line up all of these pieces ahead of time. Sustainable aviation fuel entrepreneurs must arrange for a reliable supply of feedstocks. They—and those financing the project—must be confident of a market for their product at a viable price, by signing off-take agreements with their future customers.

As sustainable aviation fuel begins to emerge from its infancy, a number of production-scale facilities are in operation or have been announced around the world. This section provides a brief survey of a few of those initiatives, beginning with the ones located on the west coast of the United States.

Altair, California

Altair, based in southern California, will use the HEFA process to convert inedible oils and waste animal fat to jet fuel and renewable diesel, with a capacity of 30 million gallons per year. It plans to start production in 2015 in a repurposed asphalt refinery in Paramount, CA. Anchoring its market for jet fuel is an off-take agreement with United Airlines to buy 15 million gallons of jet fuel over a three-year period.[50]

Red Rock Biofuels, Oregon

Red Rock Biofuels is planning a facility in Lakeview, OR that will use the Fischer-Tropsch process to convert 140,000 dry tons of forest residues into 12 million gallons of renewable fuels each year. The woody feedstock will come from forestry operations on a nearby 97,000-acre tract, and 6 million gallons annually are already spoken for, under off-take agreements with Southwest Airlines[51] and FedEx.[52]

The project got a significant boost last year from a $70 million Defense Production Act[53] grant, as part of the US Navy's commitment to fuel its planes and fleet with non-petroleum sources.[54] The remainder of the project's capital cost will be funded with $40 to $45 million in private equity and $125 million in loans.[55] The plant is due to start up in 2016.

Fulcrum BioEnergy, Nevada

This plant, to be built near Reno, NV will use the Fischer-Tropsch process to convert 200,000 tons per year of municipal solid waste (that is, garbage) into 10 million gallons of jet fuel.[56] Fulcrum BioEnergy contracted the $200 million plant's design and construction to the Spanish conglomerate Abengoa, which has production-scale biofuel experience, having opened a 25-million-gallon-per-year cellulosic ethanol plant last year in Kansas.[57]

Fulcrum raised about half the plant's capital costs under the Defense Production Act, which authorizes the US military to support endeavors that will supply the armed forces. Backing for this project from the US Navy translated into a $105 million loan guarantee for the project from the US Department of Agriculture.[58]

In mid-2015, United Airlines announced it was purchasing a $30 million stake in Fulcrum BioEnergy, the single largest investment by a U.S. airline in sustainable fuels. United and Fulcrum agreed to consider jointly developing up to five projects near the airline's hubs that would potentially produce up to 180 million gallons of fuel a year.[59]

In addition, Cathay Pacific Airways, which has agreed to buy 375 million gallons of biofuel from Fulcrum over the next 10 years from this and future plants, bought an equity stake in the venture.[60] Production is expected to begin in 2017.

Gevo, Missouri and Texas

In June 2015, Gevo announced the opening of a demonstration project to produce biojet from wood waste using the alcohol-to-jet conversion process.[61] It will first turn the cellulosic sugars in wood waste into iso-butanol, a four-carbon alcohol, in a plant in St. Joseph, MO, using a proprietary fermentation process. It will then feed that iso-butanol into a plant in Silsbee, TX, where it will be converted to synthetic paraffinic kerosene using the alcohol-to-jet process.

This process is undergoing ASTM certification as of this writing, which is expected to be granted in the second half of 2015. Simultaneously with Gevo's announcement, Alaska Airlines announced plans for a demonstration flight in 2016 using 1,000 gallons of this fuel, which would make it the first to use biojet from this process in commercial flight.[62]

This process is being demonstrated in the Midwest and South at a smaller scale than the other initiatives listed in this section. It is also worth noting that the technology is being used by the Northwest Advanced Renewables Alliance, led by Washington State University, with an eye to using residues from the Pacific Northwest's forest industry in future projects—a pathway suggested four years earlier in the SAFN report.

Diamond Green Diesel, Louisiana

The largest advanced biofuels plant operating in North America, this facility in Norco, LA converts oils and animal fats into renewable biofuel using the Green Diesel process in a system designed by Honeywell. The plant, operated as a joint venture between Valero Energy and Darling International, has a capacity of 142 million gallons per year.[63] At the moment, it is producing renewable diesel only, which is on track to be approved for blending into jet fuel at concentrations of up to 10 percent. However, with an optional additional distillation, the refinery could separate a fraction to be blended into jet fuel at higher concentrations.[64]

Solena Fuels, London, United Kingdom

Solena Fuels' Green Sky London project will use the Fischer-Tropsch process to convert 500,000 tons a year of the British capital's waste stream into 50,000 tons (16 million gallons)[65] of jet fuel and another 50,000 tons of other biofuels such as diesel and naphtha.[66] Production is scheduled to begin in 2017[67] on the former site of an oil refinery outside London. British Airways has agreed to buy the facility's entire production run for its first 11 years, which will displace about 2 percent of the fuel the airline uses at its Heathrow hub.

Sustainable Bioenergy Research Consortium, United Arab Emirates

In January 2014, Boeing and research partners in the United Arab Emirates announced that halophytes (desert plants fed by seawater) could produce biojet fuel more efficiently than other feedstocks. The Sustainable Bioenergy Research Consortium (SBRC), affiliated with the Masdar Institute of Science and Technology in Abu Dhabi, is conducting a project to support biofuel crops in dry countries. Etihad Airways, Honeywell UOP, and Boeing are providing the funding for the SRBC work.[68]

Holland Bioport, Rotterdam-Amsterdam, The Netherlands

The challenges of introducing SAF into the jet fuel supply chain go beyond just feedstock source and manufacture to include establishing a comprehensive and stable supply chain, as described above in section VI. The Bioport Holland initiative—a joint venture of KLM Airlines, the Schiphol airport, Neste Oil, the Port of Rotterdam, biofuel development firm SkyNRG, and two Dutch government ministries—was launched in 2013 to pursue that goal.[69] The project will link the biorefining supply capacity of Neste's Rotterdam facility with the port's transportation infrastructure (including pipelines that lead to three of Europe's largest airports[70]) and the demand for fuel at Schiphol to create a viable industrial ecosystem of SAF production, distribution, and consumption.

VIII. Policy and Market Development

The Sustainable Aviation Fuels Northwest (SAFN) report and other efforts that have evaluated the potential for sustainable aviation fuels have all recognized a tremendous opportunity—but one that will only be realized through coordinated efforts between industry and government. Historically, government has participated actively in the development of the energy sector; the growth of cleaner alternatives to aviation fuels at commercial scale will be no exception.

SAFN led to the passage of legislation in Washington State (Substitute House Bill 2422, Chapter 63, Laws of 2012, which became RCW 43.333.800 effective June 7, 2012), creating a Sustainable Aviation Biofuels Work Group to recommend steps necessary to grow the aviation biofuels industry. The Work Group proposed a number of actions to enable sustainable aviation fuel in Washington State.[71] Some of the most important recommendations contained in this and other regional stakeholder efforts are described below.

Policies to Build Strong Markets

The most significant recommendation is to create a strong market pull for sustainable and low carbon biofuels through a policy such as a low carbon fuels standard or clean fuels standard, as California, British Columbia, and now Oregon have adopted to drive market development. Stakeholders have also advocated for a consistent federal Renewable Fuel Standard (RFS). The federal RFS requires that a certain amount of biofuel be blended into the motor fuel supply, while other low-carbon fuel standards require a reduction in the average carbon footprint of motor fuels, taking into account the greenhouse gas emissions resulting from the production of the fuel as well as its combustion.

Because aviation fuel use crosses state and national borders, and because SAF must meet more stringent technical specifications, the federal RPS and the state and provincial LCFSs have not included provisions requiring aviation fuel to reduce its climate footprint. By instituting long-term requirements that fuel distributors purchase biofuels, these policies build demand for biofuels and create the stable market that fuel producers and investors need before they will commit to the large capital expenditures such as building a biorefinery.

Historically, government has participated actively in the development of the energy sector; the growth of cleaner alternatives to aviation fuels at commercial scale will be no exception.

One of the compliance mechanisms in both LCFS and RFS regulations is the creation of tradable renewable energy credits, which accrue to producers of biofuel and can be sold separately from the fuel itself. This allows fuel blenders and distributors to meet the requirements even while purchasing less biofuel than their nominal obligation, provided their shortfall is balanced out by increased biofuel production elsewhere in the market. In the federal system these credits are known as Renewable Identification Numbers (RINs).

This system of credits offers a way to bring SAF under the auspices of a low-carbon or renewable fuel standard. Even if there isn't a specific blending requirement for SAF in the jet fuel supply, biojet producers could sell their credits to other parties who must meet the blending requirement. For instance, the Oregon Clean Fuels Standard provides that biojet fuel consumed in Oregon can generate compliance credits, even though aviation fuel is not required to reduce its carbon intensity under the state standard.[72]

Financing Mechanisms

Because constructing biorefineries is capital intensive, financing is one of the hurdles that often stands in the way of a biofuel enterprise growing from the demonstration stage into commercial production. Public policy can help overcome this challenge by supporting biofuel firms in raising capital through three mechanisms: loan guarantees for qualifying projects such as the $105 million guarantee extended to the Fulcrum project; grants such as the $70 million provided under the Defense Production Act to partially underwrite the Red Rocks project; and low-interest direct loans. Public sector entities, such as ports, can provide low-cost financing for SAF projects or critical infrastructure. All of these mechanisms decrease the risk of the projects, making them more attractive to the investors who fund the remainder of the capital costs.

Infrastructure Investment

As explained above, all currently approved forms of SAF must be blended with fossil-derived jet fuel before delivery to the aircraft, which introduces an additional complexity into the process compared to producing and delivering purely petro-jet fuel. The infrastructure to deliver petro-jet to major regional airports was installed long ago, centering on pipelines that can transport the fuel cheaply and in large quantities from refinery to airport. For SAF to be consumed at significant scale, additional fueling infrastructure is needed at airports to accept bulk delivery of biofuel through barge or pipeline; hold it in inventory on site; blend it at the correct proportion with fossil jet; and then test the blend to make sure it meets ASTM specifications. Since the shift to sustainable fuel sources is a project in the public interest, it is appropriate for the public to participate in the cost of that new infrastructure, through the port or other local government entity that oversees the airport.

Research and Development

Few of the technologies for making SAF have been scaled for commercial production, and some are so new that many of the technical bugs are still being worked out with regard to conversion and feedstock supplies. The experience with other energy technologies—such as photovoltaics, fuel cells, and energy-efficient windows—is that public funding for R&D is crucial in moving technologies off the whiteboard and into production.

SAF has begun to benefit from that kind of support. The Northwest Advanced Renewables Alliance (NARA) led by Washington State University (WSU) has received nearly $40 million in federal funding[73] toward the development of biofuel from forest residues, as has the Advanced Hardwood Biofuel Northwest (AHB) led by the University of Washington,[74] both of which bring together universities and industry to solve the technical challenges of SAF production.

The Federal Aviation Administration Center of Excellence for Alternative Jet Fuels and the Environment (ASCENT) is also a notable investment in continued R&D in this sector. WSU and MIT co-lead ASCENT, which is a 10-year, $40 million effort to explore and support sustainable jet fuels and other key environmental challenges for the aviation sector.

Public support of R&D in this field is beginning to pay dividends, with the planned 2016 flight by Alaska Airlines on fuel made from wood waste converted into iso-butanol and then into biojet (see above, page 26) a direct result of the NARA work.[75] Continued public investment in this area remains a high priority for the growth of SAF.

Building Demand

Public entities can play a key role by contracting to purchase a portion of the output of the SAF refineries at pre-established prices. The U.S. military has identified reducing petroleum dependence and increasing SAF as strategically critical. Practically, though, its interest in supporting SAF development has been hampered by Congressional requirements; these provisions prevent it from contracting for alternative fuels at prices that are higher than the cost of fossil jet and limit the duration of any off-take agreements. Congress should support, rather than obstruct, the military's interest in developing low-carbon alternatives to fossil-based fuels.

While there are many encouraging developments in technology and feedstocks, SAF needs strong policy support at the federal and state level to achieve commercial-scale production. Public action will be instrumental to achieving that goal by ensuring steady demand in the nascent biojet market; by investing in the physical infrastructure that delivers SAF to market; by supporting research and development; and by facilitating the financing for capital expenditures to ramp up biofuel production.

IX. Conclusion

Since publication of the SAFN report in 2011, substantial progress has occurred in the approval of conversion processes to produce biojet fuel, and a handful of projects have broken ground to actually begin operations. Progress has been held up largely by the difficulty of crossing the so-called "valley of death" between the technical demonstration of a fuel manufacturing process's feasibility and the initiation of commercial-scale operations. This leap requires a different kind of expertise in project management, and a successful round of financing at a much larger scale.

Emboldening investors and entrepreneurs to attempt such a crossing will require consistent policy incentives that are aligned with society's interest in low-carbon aviation fuels, as well as sources of capital, including grants and loan guarantees, that reduce the risks for investors willing to back these enterprises.

With the manufacturing initiatives listed above, however, it appears that the first wagon trains are venturing across that valley of death. In the coming years, the success of SAF efforts will depend on the regulatory environment supporting the production of biofuels as one of many solutions to our climate challenge, and the willingness of project developers to invest in these budding technologies.

Notes

1 “Facts & Figures,” *Air Transport Action Group (ATAG)*, accessed August 7, 2015, http://www.atag.org/facts-and-figures.html.

2 Air Transport Action Group, “Aviation Benefits Beyond Borders,” April 2014, http://aviationbenefits.org/media/26786/ATAG__AviationBenefits2014_FULL_LowRes.pdf. Share of carbon pollution: p. 22. Projected growth 4.7% per year over 20 years, p. 13.

3 The 28th Session of the United Nations Framework Convention on Climate Change (UNFCCC) Subsidiary Body for Scientific and Technological Advice, held June 3, 2013. International Civil Aviation Organization, “Emissions from Fuel Used for International Aviation and Maritime Transport,” UNFCCC Subsidiary Body for Scientific and Technological Advice (Bonn, Germany: UNITED NATIONS FRAMEWORK CONVENTION ON CLIMATE CHANGE, June 3, 2013), http://unfccc.int/resource/docs/2013/smsn/un/127.pdf.

4 Office of Transportation and Air Quality, “EPA Takes First Steps to Address GHG Emissions from Aircraft Engines” (United States Environmental Protection Agency, June 2015), http://www.epa.gov/otaq/documents/aviation/420f15023.pdf.

5 “SUSTAINABLE AVIATION FUELS NORTHWEST: Powering the Next Generation of Flight” (SAFNW, 2011), http://www.climatesolutions.org/sites/default/files/uploads/safn_2011report.pdf.

6 Air Transport Action Group, “Aviation Benefits Beyond Borders,” 7. 72.2 billion gallons / year, divided by 42 gallon / barrel, divided by 365 days / yr. These figures are attributed to an IATA economic analysis using 2013 figures.

7 According to International Energy Statistics, accessed September 10, 2015, total global petroleum consumption in 2013 was 91.2 million barrels per day. http://www.eia.gov/cfapps/ipdbproject/iedindex3.cfm?tid=5&pid=5&aid=2&cid=ww,&syid=2010&eyid=2013&unit=TBPD This same data series gives the world consumption of jet fuel as 5.4 mbd, with the excess over IATA’s figure of 4.7 likely due to non-commercial uses (e.g., military). http://www.eia.gov/cfapps/ipdbproject/iedindex3.cfm?tid=5&pid=63&aid=2&cid=ww,&syid=2010&eyid=2013&unit=TBPD

8 Air Transport Action Group, “Aviation Benefits Beyond Borders,” 7. Emissions in 2013 were 705 million tonnes. It cites 688.7 million tonnes as the main figure. However, this must be for 2012, not 2014, since report appeared in April 2014.

9 “International Energy Statistics” (Independent Statistics & Analysis: U.S. Energy Information Administration), accessed August 7, 2015, http://www.eia.gov/cfapps/ipdbproject/IEDIndex3.cfm?tid=90&pid=44&aid=8. Data on other countries CO_2 emissions from International Energy Outlook, EIA. Italy was 386 million tons, Spain was 312, totaling 698.

10 ICAO Secretariat, “ICAO 2013 Environmental Report” (International Civil Aviation Organization, 2013), 18, http://cfapp.icao.int/Environmental-Report-2013/files/assets/basic-html/index.html#3.

11 Steve Wilhelm, “As Global Pressure to Reduce CO2 Mounts, Boeing Looks to Biofuels,” *Puget Sound Business Journal*, June 10, 2015, http://www.bizjournals.com/seattle/news/2015/06/10/as-global-pressure-to-reduce-co2-mounts-boeing.html.

12 “Aircraft Co2 Emissions Standard Metric System,” ICAO Fact Sheet (International Civil Aviation Organization), accessed September 1, 2015, http://www.icao.int/Newsroom/Documents/CO2%20Metric%20System%20-%20Information%20Sheet_FINAL.PDF.

13 Air Transport Action Group, “Aviation Benefits Beyond Borders,” 22.

14 “IATA - New IATA Passenger Forecast Reveals Fast-Growing Markets of the Future,” October 16, 2014, http://www.iata.org/pressroom/pr/Pages/2014-10-16-01.aspx.

15 WWF 2011, The Energy Report: 100% renewable energy by 2050. http://wwf.panda.org/what_we_do/footprint/climate_carbon_energy/energy_solutions22/renewable_energy/sustainable_energy_report/ p. 153

16 “Facts & Figures.”

17 “Navy and Air Force Test Flights,” *Sustainable Oils*, 2009, http://www.susoils.com/flights.php.

18 Feedstocks for fuel listed here: “Lufthansa Launches First Scheduled Flights Using Biofuel,” *Lufthansa Group*, July 15, 2011, http://www.lufthansagroup.com/en/press/news-releases/singleview/archive/2011/july/15/article/1980.html; Joe Skipper, “Lufthansa Ends Biofuel Trial with U.S. Flight,” *Reuters*, January 9, 2012, http://www.reuters.com/article/2012/01/09/uk-lufthansa-biofuels-idUSLNE80802I20120109.

19 The duration and number of flights described here: Joe Skipper, “Lufthansa Ends Biofuel Trial with U.S. Flight,” *Reuters*, January 9, 2012, http://www.reuters.com/article/2012/01/09/uk-lufthansa-biofuels-idUSLNE80802I20120109.

20 “Alaska Air Prepares for a Series of Used Cooking Oil Biofuel Flights Using Boeing and Bombardier Aircraft,” *GreenAir Communications*, November 8, 2011, http://www.greenaironline.com/news.php?viewStory=1370. See also: Cassandra Profita, “Used Cooking Oil Fuels Seattle to Portland Flights,” *Ecotrope*, November 7, 2015, http://www.opb.org/news/blog/ecotrope/used-cooking-oil-fuels-seattle-to-portland-flights/.

21 “Sustainable Aviation Fuel Users Group – SAFUG,” accessed August 7, 2015, http://www.safug.org/.

22 “Our Pledge,” *Sustainable Aviation Fuel Users Group*, accessed August 7, 2015, http://www.safug.org/safug-pledge/.

23 A Pawlowski, “How Old Is the Plane You’re Flying On?,” *CNN*, February 1, 2010, http://www.cnn.com/2010/TRAVEL/02/01/planes.age.dreamliner/.

24 “Biodiesel Fuel Specifications and Comparison to Diesel Fuel” (Denver, CO: Crimson Renewable Energy, n.d.).

25 Ethanol boiling point is 172˚F = 77˚C; its flash point is 55˚F = 13˚C; and energy density = 84,100 BTU/gal at a density of 6.61 lb/gal, which is the equivalent of 29.5 MJ/kg, well below the spec for jet fuel: “Alternative Fuels Data Center,” *U.S. Department of Energy*, accessed August 7, 2015, http://www.afdc.energy.gov/fuels/fuel_properties.php.

26 Aromatic compounds include one or more six-carbon benzene rings.

27 Richard Alterman, founding executive director of CAAFI, in Paul Hoversten, “The Commercial Aviation Alternative Fuels Initiative,” *Air & Space Magazine*, January 2011, http://www.airspacemag.com/as-interview/aamps-interview-richard-altman-71821836/?no-ist=&page=2. “We need a certain percentage of those [aromatic] molecules in order for the airplane engine seals to swell in order to prevent leakage.”

28 “Our Pledge.”

29 George T. Totten, *Fuels and Lubricants Handbook* (ASTM International, 2003), 98, https://books.google.com/books?id=J_AkNu-Y1wQC&pg=PA98&lpg=PA98

30 “What Is the RSB?,” *RSB Roundtable on Sustainable Biomaterials*, accessed August 7, 2015, http://rsb.org/about/what-is-rsb/.

31 “Member List,” *RSB Roundtable on Sustainable Biomaterials*, accessed August 7, 2015, http://rsb.org/about/organization/member-list/.

32 “RSB Assembly of Delegates (AOD),” *RSB Roundtable on Sustainable Biomaterials*, accessed August 7, 2015, http://rsb.org/about/organization/rsb-assembly-of-delegates/.

33 “Sustainability Certification for Biofuels,” NRDC Fact Sheet (National Resource Defense Council, July 2014), 3, http://www.nrdc.org/energy/files/biofuels-sustainability-certification-FS.pdf.

34 "Betting on Best Quality: A Comparison of the Quality of Assurance of Sustainability Standards for Biomass Soy and Palmoil" (National Committee of The Netherlands), accessed August 7, 2015, http://cmsdata.iucn.org/downloads/betting_on_best_quality.pdf.

35 "The top three schemes are: the Roundtable on Sustainable Palm Oil (RSPO), the Roundtable on Sustainable Biomaterials (RSB) and the Roundtable on Responsible Soy (RTRS)." In: "ANALYSIS: How Sustainable Are Biofuels Used in the EU?," WWF, 2015, http://wwf.panda.org/what_we_do/how_we_work/businesses/transforming_markets/solutions/certification/agriculture/biofuels/searching_for_sustainability/.

36 Helena Kennedy, "Roundtable on Sustainable Biomaterials Concludes Annual General Assembly Program," *BioFuels Journa*l, June 5, 2015, http://www.biofuelsjournal.com/articles/roundtable_on_sustainable_biomaterials_concludes_annual_general_assembly_program-150490.html.

37 "New RSB Standard for Low iLUC Biofuels" (Geneva: The Roundtable on Sustainable Biomaterials, April 29, 2015), http://www.rsb.org/pdfs/Press%20Releases/29%20April%202015%20-%20RSB%20Releases%20iLUC%20Indicators.pdf. See also: "RSB Low iLUC Risk Biomass Criteria and Compliance Indicators" (Roundtable on Sustainable Development, June 1, 2015), http://www.rsb.org/pdfs/standards/RSB-STD-04-001-ver0.3RSBLowiLUCCriteriaIndicators.pdf.

38 A Elgowainy and et. al., "Life-Cycle Analysis of Alternative Aviation Fuels in GREET" (Argonne National Laboratory: Energy Systems Division, June 2012), https://greet.es.anl.gov/publication-aviation-lca.

39 D.A. Faaij and M. van Dijk, "White Paper on Sustainable Jet Fuels" (Amsterdam: Sky NRG, June 2012), http://skynrg.com/wp-content/uploads/2013/11/White-paper-on-sustainable-jet-fuel-June-2012-Faaij-van-Dijk-copy.pdf.

40 "Technical Overview," *LanzaTech*, accessed August 20, 2015, http://www.lanzatech.com/innovation/technical-overview/.

41 Sophie Fougeres, "First Solely-Biofuel Jet Flight Raises Clean Travel Hopes," *ASDNews*, November 8, 2012, http://www.asdnews.com/news-46032/First_solely-biofuel_jet_flight_raises_clean_travel_hopes.htm%20and%20http://www.agr.gc.ca/eng/news/feature-articles/carinata-an-oilseed-ready-for-lift-off/?id=1389626028671.

42 Amy Yee, "Airlines Fly the Skies on a Sugar High," *The New York Times*, October 7, 2014, http://www.nytimes.com/2014/10/08/business/energy-environment/airlines-fly-the-skies-on-a-sugar-high.html.

43 "IATA 2014 Report on Alternative Fuels" (Geneva: International Air Transport Association, December 2012), 10, http://www.iata.org/publications/documents/2014-report-alternative-fuels.pdf.

44 Misha Valk, Personal communication, August 27, 2015. This figure can also be confirmed from the figures given below by Fletcher (showing Neste Oil's production capacity at 2 million tons per year) and Bloomberg New Energy Finance (indicating that Neste holds 61 percent of the world's current green diesel production capacity), using a conversion factor of 6.8 pounds per gallon of jet fuel.

45 "Flight Test by Boeing's ecoDemonstrator 787 Marks First-Ever Use of Green Diesel as an Aviation Biofuel," *GreenAir Online*, December 4, 2014, http://www.greenaironline.com/news.php?viewStory=2015.

46 Paul Ausick, "Boeing 757 Flies Cross-Country on Green Diesel Fuel Blend," *247wallst.com*, June 19, 2015, http://247wallst.com/aerospace-defense/2015/06/19/boeing-757-flies-cross-country-on-green-diesel-fuel-blend/.

47 Katie Fletcher, "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 Production capacity of 1,980,000 tons per year converted to barrels at 7.93 bbl/ton, using conversion factor from US EIA. http://www.eia.gov/cfapps/ipdbproject/docs/unitswithpetro.cfm .

48 Bloomberg New Energy Finance, "Hydrotreatment update: Neste restructures its business," n.d., http://about.bnef.com/landing-pages/hydrotreatment-update-neste-restructures-business/

49 That is, compounds containing one or more benzene rings, irrespective of their perceived aroma.

50 United Hub team, "United Teams up with AltAir on Aviation Biofuels," *United Hub*, June 6, 2013, /en-us/news/company-operations/pages/united-and-altair-partner-on-biofuels.aspx.

51 "Southwest Airlines Agrees to Purchase Three Million Gallons per Year of Renewable Jet Fuel Sourced from Forest Residues," *GreenAir Online*, September 30, 2014, http://www.greenaironline.com/news.php?viewStory=1988; "Red Rock's First Commercial Scale Renewable Jet Fuel Refinery Edges Closer as It Secures Venture Capital Funding," *GreenAir Online*, April 16, 2015, http://www.greenaironline.com/news.php?viewStory=2069.

52 Mark Jaffe, "Red Rock Biofuels to Power FedEx Jets under New Contract," *The Denver Post*, July 21, 2015, sec. Business, http://www.denverpost.com/business/ci_28513304/red-rock-biofuels-power-fedex-jets-under-new.

53 "Advanced Drop-In Biofuels Production Project (ADBPP)," *Defense Production Act Title III*, accessed September 1, 2015, http://www.dpatitle3.com/dpa_db/project.php?id=190.

54 "Investment from Flagship Ventures Brings Red Rock Biofuels Closer to Construction of Its First Commercial Biofuel Refinery," *Flagship Ventures*, March 17, 2015, http://www.flagshipventures.com/about/news/investment-flagship-ventures-brings-red-rock-biofuels-closer-construction-its-first-comme.

55 Wendy Culverwell, "Boston Firm Backs Lakeview's $200M Biomass Plan," *Portland Business Journal*, March 17, 2015, http://www.bizjournals.com/portland/morning_call/2015/03/boston-firm-backs-lakeviews-200m-biomass-plan.html.

56 10 M gal / 200,000 tons = 50 gal / ton. One gallon weighs approximately 7 pounds, so 350 pounds of fuel can be made from 2000 pounds of garbage.

57 "Grand Opening of Abengoa's Biorefinery: Nation's Third Commercial-Scale Facility," *Energy.gov*, October 17, 2014, http://energy.gov/eere/bioenergy/articles/grand-opening-abengoa-s-biorefinery-nation-s-third-commercial-scale-facility.

58 Jim Lane, "US Navy, DOE, USDA Award $210M for 3 Biorefineries and Mil-Spec Fuels," Biofuels Digest, (September 19, 2014), http://www.biofuelsdigest.com/bdigest/2014/09/19/breaking-news-us-navy-doe-usda-award-210m-for-3-biorefineries-and-mil-spec-fuels/.

59 "United Airlines Purchases Stake in Fulcrum BioEnergy with $30 Million Investment," *United*, June 30, 2015, http://newsroom.united.com/2015-06-30-United-Airlines-Purchases-Stake-in-Fulcrum-BioEnergy-with-30-Million-Investment.

60 "Cathay Pacific Enters Equity Deal and 10-Year Offtake Agreement with MSW-to-Biojet Developer Fulcrum," *GreenAir Online*, August 12, 2014, http://www.greenaironline.com/news.php?viewStory=1963, accessed Aug. 7, 2015.

61 Inc. Gevo, "Gevo's Jet Fuel to Be Used in First Ever Test Flight Flown on Fuel Derived From Wood Waste," *Yahoo Finance*, June 4, 2015, http://finance.yahoo.com/news/gevos-jet-fuel-used-first-123848981.html.

62 Cynthia King, "Alaska Airlines Plans Biofuel Test Flight in WSU Partnership," *WSU News*, June 3, 2015, https://news.wsu.edu/2015/06/03/alaska-airlines-plans-biofuel-test-flight-in-wsu-partnership/.

63 Jim Lane, "Diamond Green Diesel Starts Up, Largest Advanced Biofuels Facility Goes Online : Biofuels Digest," *Biofuels Digest*, May 15, 2014, http://www.biofuelsdigest.com/bdigest/2014/05/15/diamond-green-diesel-starts-up-largest-advanced-biofuels-facility-goes-online/.

64 “UOP/Eni Ecofining™ Process for Green Diesel Production,” *Honeywell UOP*, accessed August 7, 2015, http://www.uop.com/hydroprocessing-ecofining/.

65 The gallons/year comes from the conversion of 50,000 tons x 1000 kg/ton ÷ 0.8 kg/liter ÷ 3.875 liter/gal.: “BIOFUELS: Making Jet Fuel out of Garbage -- a First,” *Climate Wire*, April 25, 2014, http://www.eenews.net/stories/1059998443.

66“Green Sky London,” *International Civil Aviation Organization*, accessed August 7, 2015, http://www.icao.int/environmental-protection/GFAAF/Pages/Project.aspx?ProjectID=22.

67 Graham Warwick, “Waste Watch,” *Air Transport World*, April 21, 2015, http://atwonline.com/eco-aviation/waste-watch.

68 “Boeing, United Arab Emirates Partners Look to Harvest Biofuel from Desert Plants,” *Boeing*, January 22, 2014, http://boeing.mediaroom.com/2014-01-22-Boeing-United-Arab-Emirates-Partners-Look-to-Harvest-Biofuel-from-Desert-Plants.

69 ICAO website, “Dutch Initiative – ‘Bioport Holland,’” accessed September 10, 2015. http://www.icao.int/environmental-protection/GFAAF/Pages/Project.aspx?ProjectID=37

70 GreenAir Online, “SkyNRG gets Dutch government backing to set up a BioPort Holland sustainable jet biofuel supply chain,” Nov. 12, 2013, http://www.greenaironline.com/news.php?viewStory=1783 accessed Sept. 10, 2015.

71 “Aviation Biofuels Update” (Innovate Washington, December 2012), http://climatesolutions.org/sites/default/files/uploads/pdf/aviation_biofuels_work_group_2012_update_1.pdf.

72 Oregon Administrative Rules, sections 340-253-100, -250, -400 and -1010. http://arcweb.sos.state.or.us/pages/rules/oars_300/oar_340/340_253.html accessed September 18, 2015.

73 Northwest Advanced Renewables Alliance (NARA), “Recent Awards,” *USDA National Institute of Food and Agriculture*, accessed September 25, 2015, https://portal.nifa.usda.gov/lmd4/recent_awards?report_title=Recent%20Awards&from_site=NIFA&search_label=Awards%20Listing.

74 System for Advanced Biofuels Production, “Recent Awards,” *USDA National Institute of Food and Agriculture*, accessed September 25, 2015, https://portal.nifa.usda.gov/lmd4/recent_awards?report_title=Recent%20Awards&from_site=NIFA&search_label=Awards%20Listing.

75 Northwest Advanced Renewables Alliance, “Northwest Forest Residuals to Power a Commercial Flight,” accessed September 25, 2015, https://nararenewables.org/docs/one-pager/Alaska-policymaker.pdf.

Strategic Innovation

climatesolutions.org/programs
1402 Third Avenue, Suite 1305
Seattle, WA 98105

Ross Macfarlane
ross@climatesolutions.org
206.443.9570 x 218 (o)
206.913.9800 (m)

Eileen V. Quigley
eileen@climatesolutions.org
206.443.9570 x 209 (o)
206.579.9644 (m)

Climate Solutions
PRACTICAL SOLUTIONS TO GLOBAL WARMING

SEATTLE
1402 Third Avenue, Suite 1305
Seattle, WA 98101
Phone: 206.443.9570

OLYMPIA
219 Legion Way SW, Suite 201
Olympia, WA 98501
Phone: 360.352.1763

PORTLAND
610 SW Broadway, Suite 306
Portland, OR 97205
Phone: 503.206.4837

www.climatesolutions.org