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Ready for Takeoff?

Aviation Biofuels Past, Present, and Future

David Hitchcock



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Cover: Los Angeles, CA–Aug 3, 2018, A Boeing 787 Dreamliner flies into the sunset
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FOREWORD

Energy has always represented both a vulnerability and an opportunity. It was a lesson I learned as US Ambassador to Saudi Arabia in the 1990s, and it became even clearer to me as I prepared to assume the job of Secretary of the Navy under President Obama.

The scientific verdict on the disastrous climate impacts of fossil fuels continues to be reinforced, but as secretary, I tried to highlight the key role energy plays in our national security. At the height of US involvement in Afghanistan, we were losing a marine, killed or wounded, for every fifty fuel convoys in Afghanistan. In the first few years of my tenure, multibillion-dollar increases in fuel costs forced us to cut back on training and maintenance. At the same time—and still today—Europe’s dependence on Russian gas gave Russia strategic leverage.

In October 2009, I set five goals for the US Department of the Navy, the most important of which was to have at least half of the energy the navy and Marine Corps uses—ashore and afloat, in the air, on the sea, under the sea and on land—come from alternative, renewable sources. I’m proud to say that ashore, we completed our work four years ahead of schedule. We were able to acquire 1.2 gigawatts of renewable energy at a net present value savings of \$400 million for our land-based facilities. Meanwhile, we secured two of the largest sustainable fuel contracts in US federal history, saving a penny per gallon on a 90-10 biofuel blend in 2015, and 25 cents per gallon on a 70-30 biofuel blend in 2017.

Sustainable fuels provided choices sailors and marines did not have before, improved our energy security, and had a great side benefit for the global climate, with 50 to 90 percent lower greenhouse gas (GHG) emissions. While not the driver to the navy’s pursuit of sustainable fuels, it was no less interesting to know that we were reducing emissions in an area of the economy, the transportation sector, which now generates the largest share of GHG emissions in the US.

These emissions, combined with emissions from the other sectors, are having a clear and irreversible impact on our climate. According to the US government’s Fourth National Climate Assessment, released in November 2018, the lower forty-eight states have warmed 1.8 degrees Fahrenheit since 1900, with an increase of 1.2 degrees in just the last few decades. By the end of the century, the United States will be 3 to 12 degrees hotter depending on the extent to which greenhouse gases are released into the atmosphere, according to the assessment. The science on our vulnerability to climate change is clear and incontrovertible. Just as clear are the opportunities offered by a clean energy economy. We ignore the vulnerabilities and opportunities at our peril. The time for deep reflection and contrived debate is over. We must act, and we must act now.

While so many in the sustainable fuel supply chain, from feedstock providers and fuel producers to researchers, are doing everything in their power to accelerate the maturation of a cost-competitive, environmentally

superior sustainable fuel market, more must be done, and more people must get involved. Policy makers and government and business leaders must take their cues from those dealing with these challenges in places like Queensland, Australia; Oslo, Norway; San Francisco; Singapore; and Seattle. The energy market needs clear and consistent signals, coupled with the appropriate combination of carrots and sticks.

At the same time, we cannot allow the perfect to be the enemy of the good. What we need are “both-and,” not “either-or” solutions. We must adopt solutions that derive value from existing resources and waste streams today, while simultaneously pursuing purpose-built agricultural pathways for tomorrow.

For example, leaders of large progressive corporations who see the triple bottom line value of energy alternatives must push themselves to look beyond simply buying carbon offsets. They must harness their purchasing power and influence and actively seek sustainable fuels. There is no better place to start than their executive business jet travel. With business jet fuel typically being three to four times more expensive than standard commercial aviation fuel, it's worth a hard look at buying your way into the solution, rather than just buying your way out of a problem. Make no mistake, carbon offsets are good, but shifting to more sustainable, lower carbon options is even better. Likewise, large corporations can send a strong signal to commercial airlines by shifting their travel dollars to favor airlines that are also using sustainable aviation fuels and are invested in their outcome.

Science, economics, and our security all dictate that we change the way we operate and use energy, just as we did with the navy. Now is the time for us, all of us together, to seize the moment, to lead our nation and the world to a new energy future: a future that simultaneously strives to electrify the ground transportation sector while decarbonizing the liquid fuels that will be needed for years to come.

This report—*Ready for Takeoff? Aviation Biofuels Past, Present, and Future*—provides a much-needed contemporary look at the state of sustainable aviation fuels and provides some examples of success that others can learn from and emulate to play their role in this vitally important area.

A handwritten signature in black ink that reads "Ray Mabus". The signature is written in a cursive, flowing style.

Ray Mabus

*75th Secretary of the United States Department of the Navy
Founder and CEO, The Mabus Group*

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EXECUTIVE SUMMARY

In the decade since the first biofuel-powered flight of a commercial airliner in 2008, significant progress has been made to advance the aviation biofuels industry. Efforts have included the development, testing, and certification of multiple production pathways to produce aviation-grade fuels from a variety of biomass-derived feedstocks. While critics have raised concerns regarding potential impacts of first-generation biofuels on food production and land use, second-generation aviation biofuels have made significant strides in ensuring life-cycle sustainability, preventing unwanted societal, environmental, or legal implications to their use. This new generation of direct replacement, drop-in sustainable aviation fuels (SAF) have been employed on over 130,000 passenger flights and numerous multinational military operations, helping mitigate greenhouse gas emissions and providing new economic growth opportunities across the world.

Much of this success has come in an environment of beneficial, but often poorly targeted governmental mandates, regulations, and support. Most existing biofuel policies have been focused on renewable diesel and the ground transportation market, and have failed to provide adequate incentives for aviation biofuel development. This focus creates an unnecessary economic tension for biofuel producers between production of renewable diesel and SAF, which is problematic considering the aviation industry's dependence on liquid energy and the lack of renewable, sustainable energy alternatives to liquid aviation fuel. Commercially successful players in the aviation biofuels space have been few, usually defined by producers adapting proven technologies to prevalent feedstocks, with strong partnerships across the value chain. There have also been costly failures and struggles both to launch these new ventures and to penetrate existing markets and infrastructures, all of which brings the SAF industry to a crossroads.

The next decade will present many opportunities and risks to this new and growing industry. The greatest

opportunity comes from the nexus between the robust growth forecast for the commercial aviation industry and evolving efforts to mitigate climate change. To achieve growth in an environmentally responsible manner, the commercial aviation industry has acknowledged the need for increased production and use of lower carbon-intensive fuels. There are additional opportunities derived from new regulatory frameworks with the potential to catalyze investment in biorefinery capacity and provide increased market penetration of biofuels. This includes the pending implementation of two major international initiatives aimed at mitigating emissions from commercial aviation and maritime shipping. Additionally, new innovations in feedstock production and integrated biorefinery models have the promise of providing increased economic incentives to produce advanced biofuels, including SAF. Meanwhile, as some governments expand existing policies to include aviation biofuel, Norway is on the verge of implementing a first-of-its-kind mandate for their use. This report documents these opportunities and makes several recommendations for maximizing the future benefits for SAF technologies:

- consideration of targeted mandates for the use of SAF;
- ensuring that policy incentives target SAF;
- derisking investments in SAF production; and
- continued support of SAF research and development.

The commercial aviation industry will be dependent on liquid fuels for the foreseeable future. If the environmental impacts of this growth are to be mitigated, SAF are required. The implementation of these recommendations could provide additional incentives to biofuel refiners to produce SAF over renewable diesel and create significant impetus for growth in the SAF industry.

INTRODUCTION

Since 2007, global biofuel production has more than doubled, with more than 84 million tons¹ of oil equivalent produced in 2017.² While this is a significant source of clean, renewable energy for transportation, it represents only 2.2 percent of liquid transportation fuels consumed worldwide.³ A large portion of this growth can be attributed to the doubling of corn ethanol production in the United States between 2007 and 2010, from 6.52 billion gallons to 13.3 billion gallons.⁴ Over the last decade, biodiesel production tripled in the United States⁵ and more than doubled in the European Union (EU).⁶ More recently, we have seen the development and introduction of second-generation biofuels, such as renewable diesel and SAF. (See the box with definitions for bio-derived liquid distillate fuels.) These fuels are direct replacement, drop-in hydrocarbon blends that function exactly like their petroleum-derived counterparts.⁷ For the foreseeable future, commercial aviation will be dependent on liquid fuel energy; therefore, SAF development is critical to reducing carbon emissions in the aviation sector.

BIOFUEL VALUE PROPOSITION

Biofuels offer several significant advantages over their fossil-derived alternatives. First, they offer a means to diversify global energy resources. This diversification not only provides alternatives to oil and natural gas; ideally, it is also a lower cost alternative. The best

example of this is Brazilian ethanol. Using flex-fuel vehicles and blender pumps at local gasoline stations, Brazilian automobiles can mix gasoline or ethanol seamlessly in any combination up to and including 100 percent ethanol (E100). This advantage allows Brazilian motorists to purchase a biofuel blend delivering the optimum value based on the spot price of each fuel. In addition to lowering average cost, this optionality also reduces overall price volatility for the consumer. Biofuels also tend to stimulate additive economic activity, most often generating local impact in the agricultural sector. Since biofuel feedstocks are generally more challenging to transport than crude oil, biorefineries are likely to be more dispersed than petroleum refineries, leveraging proximity to the feedstock resource. Finally, most biofuels are a lower carbon alternative when compared to petroleum-derived fuels, generating less greenhouse gas (GHG) emissions on a life-cycle basis.⁸ Additionally, biofuels generally burn cleaner, generating less particulate matter (PM) and carbon monoxide (CO) emissions than fuels derived from crude oil.⁹

The potential to reduce harmful GHG emissions and other pollutants is an oft-cited driver for increased biofuel use in the energy mix. This attribute is even more compelling considering the sobering findings released in October 2018 by the United Nations Intergovernmental Panel on Climate Change (IPCC). This report stated that limiting global warming to the 1.5° C threshold would require

1 Metric ton, approximately 2,200 US pounds.

2 *BP Statistical Review of World Energy 2018*, BP PLC, page 45, <https://www.bp.com/content/dam/bp/en/corporate/pdf/energy-economics/statistical-review/bp-stats-review-2018-full-report.pdf>.

3 Calculated from *BP Statistical Review of World Energy 2018*. From page 19 the author derives total oil-derived fuel consumption (light and middle distillates and fuel oil equal 75,195,000 barrels per day/7.33 = 10,258,526 tons per day x 365 days = 3,744,362,210 tons per year. With this, the report calculates the percentage of biofuel in the global mix by 84,121,000 tons oil-equivalent biofuel/3,744,362,210 tons oil-derived fuel production + 84,121,000).

4 "Global Ethanol Production," US Department of Energy, Alternative Fuels Data Center, accessed on November 11, 2018, <https://afdc.energy.gov/data/10331>.

5 "Biofuels Fact Sheet," University of Michigan, Center for Sustainable Systems, accessed November 11, 2018, <http://css.umich.edu/factsheets/biofuels-factsheet>.

6 "EU Production," European Biodiesel Board, accessed November 11, 2018, http://www.ebb-eu.org/images/1998-2016_prod_stats_big.jpg.

7 "Renewable Hydrocarbon Biofuels," US Department of Energy, Alternative Fuels Data Center, accessed on December 1, 2018, https://afdc.energy.gov/fuels/emerging_hydrocarbon.html

8 While it may be argued that some biofuels demonstrate life-cycle GHG emissions above or on par with petroleum-derived fuels, per the US Environmental Protection Agency website, a majority of the tested biofuel pathways produce fewer GHG emissions than petroleum-derived alternatives. See <https://www.epa.gov/fuels-registration-reporting-and-compliance-help/lifecycle-greenhouse-gas-results>.

9 *The Nexus on Biofuels, Climate Change, and Human Health*, a workshop summary, Roundtable on Environmental Health Sciences, Research, and Medicine; Board on Population Health and Public Health Practice; Institute of Medicine, (Washington, DC: National Academies Press, 2014), Chapter 4, <https://www.ncbi.nlm.nih.gov/books/NBK196452/>.

DEFINITIONS There are several different “flavors” of bio-derived liquid distillate fuels. These differences are key to understanding the dynamics of both the feedstock and final product markets.

BIODIESEL is produced from vegetable oils or animal fat by reacting these lipids with an alcohol in a process known as transesterification. This process produces glycerin and methyl esters. These methyl esters are the biodiesel, also commonly known as fatty acid methyl ester, or FAME. Biodiesel can be blended with petrodiesel and used in concentrations up to 20 percent without engine modification. It has about 8 percent less energy than petrodiesel and will gel at low temperatures.

JET FUEL is a fuel used to power aviation turbine engines and is refined from petroleum to meet strict specifications, including lower freezing point to allow for high-altitude operations. It is a mixture of hydrocarbon molecules; Jet A contains molecules with five to fifteen carbon chains. It has an energy content of approximately 124,500 BTUs/US gallon.

PETRODIESEL is diesel fuel derived from petroleum feedstocks. It is produced via a refiner distillation process and is a mixture of hydrocarbon molecules containing eight to twenty-one carbon atoms each. It has an energy content of 128,700 BTUs/US gal.

RENEWABLE DIESEL is biomass-derived fuel that is chemically similar to petrodiesel and meets industry certification standards for diesel fuel (i.e., ASTM D975). Renewable diesel can be produced from a variety of feedstocks and various processes including by hydrotreating of lipids (vegetable oils, animal fats, etc.), or by pyrolysis or gasification of cellulosic biomass (wood residue, MSW, etc.). It is made up of C13-C18 molecules and typically exhibits a higher cetane number, lower sulfur, and has similar energy content as petrodiesel.

rapid and far-reaching transitions in transportation energy systems.¹⁰ However, biofuel development and deployment, while significant, have failed to reach international climate change mitigation goals. The International Energy Agency tracks clean energy technologies and grades progress toward achieving the agency’s Sustainable Development Scenario goals, which are aligned with the climate mitigation strategy of the 2016 Paris Accord.¹¹ Both biofuels for ground transportation and the aviation industry are judged “not on track” by the International Energy Agency.¹² Due to the relatively shallow penetration in the overall transportation energy mix (approximately 2 percent), biofuels represent a compelling opportunity that can be exploited to help achieve the aggressive GHG emission-reduction goals prescribed in the recent International Panel on Climate Change report. Exploitation of this opportunity will likely require focused governmental and regulatory support.

BIOFUELS ARE ESSENTIAL TO THE AVIATION SECTOR

The world is increasingly interconnected, becoming more so every day with the advent and growth of the internet and the proliferation of fast, relatively inexpensive air travel. The aviation sector has seen significant growth, nearly doubling from 2.2 billion passengers in 2007 to 4 billion in 2017.¹³ Looking forward, this trend is expected to continue with 5 percent per-year growth forecast in the coming years.¹⁴

Modern aircraft engines require energy-dense, distillate-type fuels to operate. Space, weight, and performance demands preclude the use of many forms of alternative transportation energy, such as electricity or natural gas, putting aviation in a unique position to benefit from the

10 “Global Warming of 1.5°C, Summary for Policymakers” Intergovernmental Panel on Climate Change, October 6, 2018, http://report.ipcc.ch/sr15/pdf/sr15_spm_final.pdf.

11 “Sustainable Development Scenario, A Cleaner and More Inclusive Energy Future,” International Energy Agency, accessed November 9, 2018, <https://www.iea.org/weo/weomodel/sds/>.

12 “Tracking Clean Energy Progress, Informing Energy Sector Transformations,” International Energy Agency, accessed November 9, 2018, <https://www.iea.org/tcep/>.

13 “Air Transport, Passengers Carried,” World Bank website, accessed November 9, 2018, <https://data.worldbank.org/indicator/IS.AIR.PSGR>.

14 “CAO Confident of Strong Future Growth on Higher Jet Fuel Consumption,” Platts Jet Fuel, *S&P Global Platts*, August 1, 2016, <https://www.platts.com/es/JetFuelNews/26508244>.



The BIOjet Abu Dhabi: Flight Path to Sustainability initiative aims to engage a broad range of stakeholders to develop a comprehensive framework for a UAE biofuel supply chain, including research and development and expanded investment in feedstock production and refining capability in the UAE and globally. Source: Sustainable Bioenergy Research Consortium

use of drop-in biofuels. While solar-powered manned flight has been demonstrated,¹⁵ the use of solar or electrical power for commercial flight is still decades away.¹⁶

Conversely, other forms of transportation, such as automobiles, buses, and trucks, are well-suited to take advantage of alternate sources of clean, renewable energy. For example, automobile electrification is growing, buses and other forms of public transportation have embraced electrification or cleaner burning natural gas. While biodiesel and renewable diesel are used in heavy trucking, both electrification and natural gas are

also demonstrating their viability in this challenging sector. The maritime space is harder to decarbonize than ground transportation, but major shipping lines are exploring liquified natural gas (LNG) as an option, which would bring GHG emissions down by 20 percent.¹⁷

The average lifespan of a commercial airliner is approximately twenty-five years,¹⁸ and sales are robust with more than 1,700 new aircraft delivered in 2017, with a ten-year order backlog.¹⁹ Therefore, for the foreseeable future, aviation's distinct energy density, performance, and weight requirements will continue to demand potent liquid energy.

15 Evan Gaj, "The Electric Aircraft Is Taking Off," TechCrunch, July 8, 2018, <https://techcrunch.com/2018/07/08/the-electric-aircraft-is-taking-off/>.

16 Matt Piotrowski, "Strong Jet Fuel Demand to Have Long-term Impacts on Global Oil Market," The Fuze, October 23, 2018, <http://energyfuse.org/strong-jet-fuel-demand-long-term-impacts-global-oil-market/>.

17 Paul Speraw, "SEA/LNG Makes the Case for Further Investment in LNG Marine Fuel," NGV America, July 3, 2018, <https://www.ngvamerica.org/2018/07/03/sea-lng-makes-the-case-for-further-investment-in-lng-marine-fuel/>.

18 Jason Dean, "Steven F. Udvar-Házy Is Making the World a Smaller Place," *CSQ Magazine*, June 6, 2018, <https://csq.com/2018/04/steven-f-udvar-hazy-making-the-world-a-smaller-place/#.W9sPV5NKjIU>.

19 "Record Global Aircraft Deliveries in 2017: Boeing Ahead of Airbus Again, but behind on Order Backlog," CAPA - Centre for Aviation, January 24, 2018, <https://centreforaviation.com/analysis/reports/record-global-aircraft-deliveries-in-2017-boeing-ahead-of-airbus-again-but-behind-on-order-backlog-393914>.

Ready for Takeoff? Aviation Biofuels Past, Present, and Future

The forecasted growth in commercial aviation also means increased carbon emissions. In 2016, the International Air Transport Association (IATA) estimated that civil aviation emitted 814 million tons of carbon dioxide CO₂, roughly 2 percent of all man-made carbon emissions.²⁰ IATA recently forecast that in 2018 airline carbon emission will surpass 897 million tons due to higher than expected fuel consumption.²¹ This increase comes despite sustained industry efforts to improve aircraft fuel economy and to leverage fuel-saving operational practices. Modern commercial aircraft are becoming lighter and more aerodynamically fuel efficient, and significant improvements are being made in engine technology to reduce overall fuel consumption.²² These efforts to improve efficiency should allow fuel consumption to grow at a slower pace

than the general industry, estimated at 3 percent.²³ However, without low-carbon fuel alternatives, carbon emissions from air travel are likely to rise at a similar rate. While significant advances have been made in the development and deployment of aviation biofuels, market penetration has been shallow.

Of note, SAF are typically more expensive to produce than biofuels destined for on-road or maritime use. This difference is due to the complexity of the jet fuel specification, the expense of the initial certification process, and the ongoing testing and certification costs required to ensure that only fuel certified for flight is introduced into an airport fuel-distribution system. This paper argues that priority in biofuel refining should be given to SAF over maritime biofuels, despite the cost differential, to maximize decarbonization.

WHAT'S IN A NAME?

Liquid fuels produced from renewable or bio-based feedstock have been around for centuries. One example is nineteenth-century lamp oil, traditionally produced from animal grease, vegetable fat, or whale oil. The rising price of whale oil in 1850s America helped catalyze the then-nascent petroleum industry by creating demand for a cheaper illuminant.¹ The growth of the on-road biofuel industry, climate change concerns, and rising oil commodity prices, along with other factors, spurred increased experimentation with bio-based aviation turbine fuel derivatives starting in the early 2000s. These activities have labored under many names including biojet fuel, alternative jet fuels, sustainable alternative jet fuel, and sustainable aviation fuel. In this report, the term sustainable aviation fuel (SAF) will be used to denote sustainably produced, distillate aviation turbine fuels. This is the term accepted and utilized by the International Civil Aviation Organization (ICAO), a UN specialized agency established in 1944 to manage the administration, development, and governance of international civil aviation.²

1 Daniel Yergin, *The Prize: The Epic Quest for Oil, Money, & Power*, (New York: Free Press, 2009), 6-7.

2 "About ICAO," International Civil Aviation Organization, accessed November 9, 2018, <https://www.icao.int/about-icao/Pages/default.aspx>.

WHERE DO WE GO FROM HERE?

In this environment, aviation biofuels are at a crossroads. This report examines the recent history of aviation biofuels, looks forward and attempts to discern what may be on the horizon for the aviation biofuels industry, and makes recommendations designed to increase opportunities for growth. It will first summarize the progress made over the last ten years in aviation biofuel technology, certification, and sustainability. This summary will include a comparison of the implementation and efficacy of various governmental policies and regulations designed to stimulate biofuel utilization, with emphasis on how these policies have impacted the aviation biofuels sector. With the imminent commencement of two major intergovernmental climate change and pollution-mitigation initiatives, the next decade will be a turning point for aviation biofuels. As such, this report will include an analysis of the potential impact of these initiatives and highlight some of the ongoing innovation in the space. Finally, it will conclude with targeted recommendations that have the potential to accelerate development and deployment of aviation biofuels. The report and recommendations are based on the author's analysis of US and European Union (EU) policies, interviews with industry executives, government officials, and environmental experts, and energy and aviation data trends.

20 *Carbon Offsetting for International Aviation*, International Air Transport Association, (Montreal: August 15, 2018), 1.

21 "Global CO₂ Emissions from Airlines Expected to Rise 4.4% This Year as Fuel Consumption Continues to Grow," GreenAirOnline.com, June 4, 2018, <http://www.greenaironline.com/news.php?viewStory=2490>.

22 University of Texas at Austin, "Designing the Fuel-efficient Aircraft of the Future," Science X news service, March 7, 2017, <https://phys.org/news/2017-03-fuel-efficient-aircraft-future.html>.

23 "CAO Confident of Strong Future Growth," *S&P Global Platts*.

LOOKING BACK

SUSTAINABLE AVIATION FUELS—TEN YEARS OF PROGRESS

In 2008, Virgin Atlantic made history, flying a Boeing 747-400 from London to Amsterdam with one of the aircraft's four engines utilizing a 20 percent blend of biojet fuel and petroleum jet fuel.²⁴ Over the intervening ten years, the aviation biofuels industry has advanced significantly. In 2011, KLM Royal Dutch Airlines (KLM) flew the first commercial passenger flight using biofuels from Amsterdam to Paris.²⁵ Since then, more than 130,000 additional commercial passenger flights have been performed.²⁶ Today, SAF are incorporated into the fuel supplies at major airports including Los Angeles International Airport in the United States,²⁷ and Oslo and Bergen airports in Norway.²⁸

SAF provides significant advantages to the commercial aviation industry. First, this type of fuel offers verifiable and quantifiable environmental benefits in the form of reduced carbon and other harmful emissions, like sulfur and particulates. Second, the development and deployment of alternative liquid fuel resources have the potential to diversify the market and localize aviation fuel sources. Diversification would serve to insulate the aviation sector from fluctuations in global petroleum prices and permit local aviation fuel production, which would help ensure local fuel security and resistance to potential supply disruptions from natural disaster or conflict. Finally, there are important socioeconomic advantages to biofuel production, which can stimulate growth in agricultural production and jobs, often in economically depressed rural locations. Since biofuel production is typically situated close to the feedstock, biorefineries would also provide economic stimulus and opportunities to individuals in these regions.

SHORTCOMINGS OF FIRST-GENERATION BIOFUELS

To date, first-generation biofuels, typically ethanol or biodiesel, have driven growth in the biofuel industry. This success has not come without considerable controversy and criticism. This criticism has been mainly focused along three veins: food-versus-fuel concerns, impacts to land use and biodiversity, and the fungibility and compatibility with existing engines and infrastructure. Over the last decade or so there has been considerable debate, especially in Washington, DC, over the impact of biofuel production, and particularly corn-based ethanol, on food markets and prices. However, since early spikes in corn prices in 2007 and in the 2010-2012 period, prices have declined as ethanol production and corn yields have increased. Robust harvests and reduced energy costs resulting from the lower price of crude oil drove the change.²⁹ While recent EU policy has been aimed at eliminating “food-based” biofuel, there is evidence that market and agricultural-industry adjustments have eliminated negative impacts of grain-based biofuels.³⁰ The best example is increased grain crop yields, which are outpacing demand.³¹ However, land-use change and the impacts of biofuel production on biodiversity in certain geographies have been much more concerning to both government officials and environmental advocates. Most notable have been the impacts of increased palm oil demand on Indonesian rain forests.³² Biofuel mandates in both the United States and the EU spurred a significant demand for vegetable oil as a feedstock for biodiesel production; the unintended consequence of these mandates has been deforestation in Borneo (and other places) to

24 Graham Dunn, “Partners Carry out First Biofuel Flight Using Virgin 747,” FlightGlobal, February 24, 2008. <https://www.flightglobal.com/news/articles/partners-carry-out-first-biofuel-flight-using-virgin-747-221790/>.

25 “History—KLM Corporate.” KLM Royal Dutch Airlines, November 28, 2017. <https://www.klm.com/corporate/en/about-klm/history/>.

26 “Fact Sheet Sustainable Aviation Fuels,” International Air Transport Association, June 2018, https://www.iata.org/pressroom/facts_figures/fact_sheets/Documents/fact-sheet-alternative-fuels.pdf.

27 “United Airlines Launches First-ever Jet Biofuels Initiative at LAX with Flight to San Francisco,” Los Angeles World Airports (governing body for LAX), March 11, 2016, <https://www.lawa.org/en/News%20Releases/2016/News%20Release%20122>

28 John McKenna, “Norway’s Airports Pump Planes with Biofuels,” World Economic Forum, November 17, 2017, <https://www.weforum.org/agenda/2017/11/norway-airports-biofuels-avinor/>.

29 “US Food versus Fuel: A Debate Losing its Rage,” *Financial Times*, September 5, 2016, accessed December 1, 2018, <https://www.ft.com/content/bc3b9272-7136-11e6-a0c9-1365ce54b926>.

30 Emmanuel Desplechin, “Five Things You Need to Know about the ‘Food vs Fuel’ Debate,” *Politico*, March 16, 2017, accessed December 1, 2018, <https://www.politico.eu/sponsored-content/five-things-you-need-to-know-about-the-food-vs-fuel-debate/>.

31 Ibid.

32 Abrahm Lustgarten, “Palm Oil Was Supposed to Help Save the Planet. Instead It Unleashed a Catastrophe,” *New York Times Magazine*, November 20, 2018, accessed December 1, 2018, <https://www.nytimes.com/2018/11/20/magazine/palm-oil-borneo-climate-catastrophe.html>.

address this market.³³ The resulting land-use changes wipe out any environmental benefits gained from the production and use of the resulting lower carbon fuels. On a life-cycle basis, fuels produced from palm oil often have a higher carbon footprint than petroleum-derived fuels.³⁴ First-generation fuels have also faced infrastructure challenges. Due to differing chemical properties in both ethanol and biodiesel, most engines cannot tolerate high blend ratios of these fuels without costly modifications.³⁵ These same issues can also negatively impact fuel transportation, storage, and delivery infrastructure.

DEFINING SUSTAINABILITY

Sustainable aviation fuel can be defined as a certified, drop-in, distillate fuel that satisfies jet fuel form, fit, and function requirements, while meeting verifiable sustainability standards. Adopting and complying with established sustainability standards will ensure these fuels are produced in an ethical and sustainable manner, and that their use will deliver equal performance with a lower life-cycle GHG footprint.

There are a variety of internationally recognized sustainability certification regimes, most of which are tied closely to a specific issue or industry. The International Social and Environmental Accreditation and Labelling Alliance is the global membership association which provides community standards for certification systems, ensuring that these regimes utilize best practices and credible sustainability standards.³⁶ The two Alliance-recognized regimes most widely utilized by aviation biofuel producers to accredit their sustainability are the Roundtable on Sustainable Biomaterials (RSB) and the International Sustainability & Carbon Certification (ISCC).

In general, any certification regime will focus on at least three critical aspects of sustainability: ecological, social, and legal. The ecological impacts to soil and water conservation, air quality, life-cycle GHG emissions,

waste management, and indirect land-use change, including the protection of biodiversity and avoidance of deforestation, are quantified and assessed. Social impacts, including human rights, fair labor practices and work conditions, local food security, and rural development are considered. Finally, the certification regime will ensure that the biofuels are produced in a manner that complies with applicable local, regional, and international laws and treaties, including climate change, emissions, or GHG reduction mandates. Different certification regimes and their environmental impact are described in more detail below.

There is a fourth, unwritten but extremely important, factor that defines a “sustainable” biofuel technology: financial sustainability. This aspect is driven by input (feedstock) availability, predictability, value, conversion costs, certification costs, end-user demand, and often governmental financial or regulatory support. Some technologies have been better able than others to achieve this final measure of sustainability and achieve a level of commercial success. Financial sustainability is a critical component of SAF’s history and future.

PROVEN PERFORMANCE AND COMPATIBILITY THROUGH RIGOROUS FUEL CERTIFICATION

Jet fuel is a kerosene-grade fuel formulated to meet stringent commercial or military performance standards, including energy content, combustion quality, stability, lubricity, fluidity, volatility, noncorrosivity, and cleanliness.³⁷ Jet fuel is a mixture of hydrocarbon molecules; Jet A contains molecules with five to fifteen carbon chains and has an energy content of approximately 124,500 British Thermal Units/US gallon. The most widely recognized commercial performance standards³⁸ are ASTM International’s D1655 Standard Specification for Aviation Turbine Fuels³⁹ in the United States and Defence Standard 91-91 in the United Kingdom.⁴⁰ To be utilized in flight, SAF must be thoroughly tested and must meet the same rigorous standards as petroleum-derived fuels.

33 Abrahm Lustgarten, “Palm Oil Was Supposed to Help Save the Planet. Instead It Unleashed a Catastrophe,” *New York Times Magazine*, November 20, 2018, accessed December 1, 2018, <https://www.nytimes.com/2018/11/20/magazine/palm-oil-borneo-climate-catastrophe.html>.

34 Ibid.

35 To learn more about biodiesel impacts, see “Using Biodiesel Fuel in Your Engine,” Pennsylvania State University, June 9, 2016 Can E15 Gasoline Really Damage Your Engine?” by Mike Allen in *Popular Mechanics*, December 21, 2010, <https://www.popularmechanics.com/cars/hybrid-electric/a6244/e15-gasoline-damage-engine/>.

36 “About ISEAL,” ISEAL Alliance, accessed November 9, 2018, <https://www.isealalliance.org/about-iseal>.

37 *Aviation Fuels Technical Review*, Chevron Products Co., 2007, 3-13.

38 Please note that these ASTM standards measure fuel performance only and do not address environmental benefits or sustainability.

39 “ASTM D1655-18a, Standard Specification for Aviation Turbine Fuels,” ASTM International, accessed November 9, 2018, <https://www.astm.org/Standards/D1655.htm>.

40 “Civil Jet Fuel, Grades and Specifications,” Royal Dutch Shell PLC, accessed November 9, 2018, <https://www.shell.com/business-customers/aviation/aviation-fuel/civil-jet-fuel-grades.html>.

To date, the majority of SAF gallons have been developed and produced in the United States. US certification efforts have been facilitated by the Commercial Aviation Alternative Fuels Initiative, a consortium of aircraft and jet-engine manufacturers, biojet fuel producers, airline end users, academic and research entities, and other interested parties.⁴¹ The certification process is governed by ASTM’s D4054 Standard Practice for Evaluation of New Aviation Turbine Fuels and Fuel Additives.⁴² This is a multiphase process consisting of lab analysis, testing, and verification, independent third-party ground and airborne component and engine testing, technical and functional assessments by aircraft and engine manufacturers, ASTM evaluation and approval, and a final review by the Federal Aviation Administration.⁴³ This process generally takes several years to complete and can represent a significant financial and technical barrier to nascent technologies.⁴⁴ Once certified, the new SAF “pathway” is listed as an annex to ASTM’s D7566 Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons, and shall be regarded as D1655-compliant turbine fuel.⁴⁵

These certified fuels are direct replacement, “drop-in” fuels. This means that they are fully compatible with

the existing transportation, storage, and distribution networks and all engines specified to use traditional petroleum turbine fuels. These drop-in SAFs have the same energy density and will perform as well as, or in some cases better than, petroleum fuels of the same specification and grade. While there is the potential to develop a 100 percent bio-based SAF,⁴⁶ all currently certified pathways require blending with petroleum fuel at various concentrations from 10 percent to 50 percent SAF for the fuel blend to meet all performance specifications such as lubricity, freeze point, and aromatics content. As of publication of this report, there have been five pathways certified under ASTM D4054. Details of these pathways, including typical feedstock resources, are summarized in Table 1 below.⁴⁷

In addition to the five pathways above, several other technologies have initiated the certification process utilizing various thermochemical or biochemical processes. Further, there are numerous other entities exploring innovative technologies or business models leveraging one of the five currently approved pathways. One of these innovative approaches, led by the Masdar Institute of Science and Technology, will be highlighted in greater detail later in the report.

Table 1: Approved Alternative Aviation Fuel Pathways

Alternative Aviation Fuel Pathway	Approved	Blending Limit	Feedstock
Fischer-Tropsch Synthetic Paraffinic Kerosene (FT-SPK)	2009	Up to 50 percent	Renewable biomass (such as agricultural wastes, forestry residues, and purpose grown energy crops) or municipal solid waste
Hydroprocessed Esters and Fatty Acids (HEFA-SPK)	2011	Up to 50 percent	Waste fats, oils, and grease, and/or oil-bearing biomass (such as algae, Camelina, Carinata, and Salicornia)
Hydroprocessed Fermented Sugars to Synthetic Iso-paraffins (HFS-SIP)	2014	Up to 10 percent	Conversion of sugars to Hydrocarbon
FT-SPK with aromatics (FT-SPK/A)	2015	Up to 50 percent	Renewable biomass (such as agricultural wastes, forestry residues, and purpose grown energy crops) or municipal solid waste
Alcohol-to-Jet Synthetic Paraffinic Kerosene (ATJ-SPK)	2016	Up to 30 percent	Agricultural wastes products (such as corn stover, grasses, forestry residue, and straw)

41 “About CAAFI,” Commercial Aviation Alternative Fuels Initiative (CAAFI), accessed November 9, 2018, <http://www.caafi.org/about/caafi.html>.

42 “ASTM D4054-17, Standard Practice for Evaluation of New Aviation Turbine Fuels and Fuel Additives,” ASTM International, accessed November 9, 2018, <https://www.astm.org/Standards/D4054.htm>.

43 Steve Czonka, “Sustainable Aviation Jet Fuel (SAJF): Progress, Challenges, and Path Forward,” CAAFI presentation to Washington Sustainable Aviation Biofuel Working Group, September 17, 2018.

44 *Alternative Aviation Fuels: Overview of Challenges, Opportunities, and Next Steps*, US Department of Energy, Office of Energy Efficiency and Renewable Energy, March 2017, 15.

45 “ASTM D7566-18, Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons,” ASTM International, accessed November 9, 2018, <https://www.astm.org/Standards/D7566.htm>.

46 Andrea Watters, “Navy Tests 100-percent Advanced Biofuel,” Naval Aviation News, September 16, 2016, https://www.navy.mil/submit/display.asp?story_id=96702.

47 Table adapted from Air Transport Action Group’s *Beginner’s Guide to Sustainable Aviation Fuel: Edition 3*, (Geneva: 2017), 19.

THE ROLE AND EFFECTS OF GOVERNMENT POLICIES

Given the benefits described above, numerous governmental policies have been enacted, with varying effect, in an attempt to promote the development, production, and use of biofuels. Generally, these policies have been fuel-type and technology agnostic, designed to promote biofuel use to achieve socioeconomic or GHG reduction goals. As we will see, this lack of specificity has proven problematic for SAF development.

Governmental programs can be regional, national, or global in reach. The most prominent are the US Renewable Fuel Standard, the EU's Renewable Energy Directive, the California Low Carbon Fuel Standard, and the soon-to-be-implemented International Civil Aviation Authority's Carbon Offsetting and Reduction Scheme for International Aviation.

THE US APPROACH: RENEWABLE FUEL STANDARD 2

The cornerstone of US policy on biofuels is the Renewable Fuel Standard (RFS). The standard was passed into law in 2005 as part of the Energy Policy Act⁴⁸ and then modified and expanded in 2007 as part of the Energy Independence and Security Act.⁴⁹ The revamped RFS, best known as RFS2, is still in force. RFS2 is administered by the Environmental Protection Agency (EPA) and like any other federal regulation, much of the detail of execution is found in the regulatory rulemaking and the decisions made by the EPA regarding implementation and enforcement.

RFS2 mandates the use of biofuels by imposing biofuel-blending obligations on petroleum fuel refiners or importers proportional to their share of the US ground-transportation fuel market (gasoline and diesel). The mandate takes the form of annual volumetric quotas

of specified biofuel categories. Petroleum refiners may comply with their annual volumetric mandates either by blending the specified biofuel into transportation fuels sold in the United States, or by obtaining credits, known as renewable identification numbers (RINs), from others who comply.⁵⁰

RFS2 identifies four categories of biofuels: renewable fuel, advanced biofuel, bio-based diesel, and cellulosic biofuel. Each type must meet a defined life-cycle GHG reduction standard, versus a 2005 petroleum-fuel threshold, to be utilized for compliance. (See Table 2 below.) Under RFS2, only gasoline and diesel sales are used to determine a refiner's compliance obligation; petroleum-derived jet fuel does not count toward the refiner's obligation. However, SAF producers are permitted by the regulation to generate RINs, which can be sold and used by obligated parties for compliance. While RFS2 is a biofuels mandate, it does not specifically mandate the use of SAF.

RINs represent added value that can be captured by biofuel producers, including those that produce and sell SAF in the United States. RINs are traded in open markets and their prices can fluctuate based on supply and demand. As of October 18, 2018, RINs range in price from \$0.1115 per gallon for renewable fuel (corn starch ethanol), to \$0.30525 per gallon for advanced biofuel, \$0.33475 for biomass-based diesel, and \$1.9835 per gallon for the harder-to-come-by cellulosic biofuel.⁵¹ Refiners are obligated to show compliance in each of these categories, commensurate with their respective share of the gasoline and diesel market. SAF can fit into one or more of these classifications (bio-based diesel, advanced biofuel, or cellulosic biofuel) depending on the production process and feedstock,⁵² and can generate RINs to be traded in the respective market.

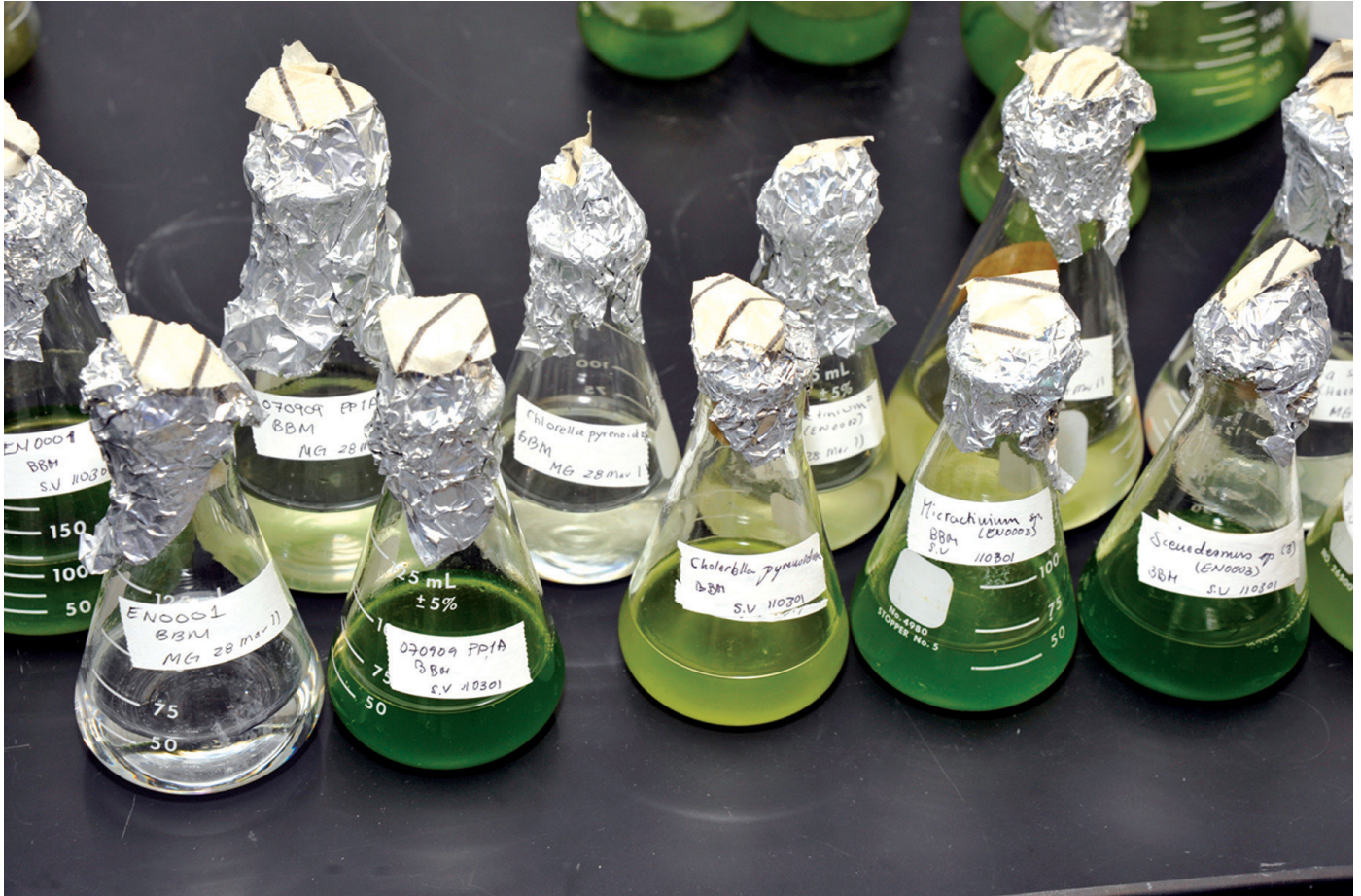
48 Energy Policy Act of 2005, Pub. L. 109-58, 119 Stat. 594 (2005).

49 Energy Independence and Security Act of 2007, Pub. L. 110-140, 121 Stat. 1492 (2007).

50 "Overview of the Renewable Fuel Standard," US Environmental Protection Agency, accessed November 2, 2018, <https://www.epa.gov/renewable-fuel-standard-program/overview-renewable-fuel-standard>.

51 "Ethanol & Biodiesel Information Service," Oil Price Information Service, 15, No. 43, October 22, 2018, 1.

52 "Approved Pathways for Renewable Fuel," US Environmental Protection Agency, accessed November 2, 2018, <https://www.epa.gov/renewable-fuel-standard-program/approved-pathways-renewable-fuel>.



Glass beakers and aluminum foil mark the beginning for different breeds of algae, as part of the Life Sciences Research Center's research into harvesting algae for biofuels. Source: Bill Evans/US Air Force

While the RFS has provided a powerful incentive for the production and use of biofuels in the United States, there have also been considerable challenges and controversy. Initially, the program was beset by RIN fraud. Entities would fraudulently claim biofuel production in a computerized tracking system, generate a RIN, and then sell the RIN to an obligated party without producing and blending the associated biofuel. This practice was exposed and resulted in several high-profile prosecutions.⁵³ There also is an annual battle between biofuel producers and obligated parties over EPA adjustment of volumetric mandates. The 2007 Energy Independence and Security Act incorporated annual biofuel targets within RFS2, but also authorized the EPA to adjust those targets (generally downward) to match expected biofuel production capacities. Obligated parties advocate for lower targets that would

RFS2 Biofuel Category	Life-Cycle GHG Reduction Threshold	Typical Feedstock/Product
Renewable Fuel	20 percent	Corn Starch Ethanol
Advanced Biofuel	50 percent	Sugarcane Ethanol
Biomass-Based Diesel	50 percent	Vegetable Oil, Waste Oils, Fats, Grease
Cellulosic Biofuel	60 percent	Conversion of Cellulosic Biomass to Fuel

⁵³ Mario Parker, Jennifer A. Glouhy, and Brian Gruley, "The Fake Factory That Pumped Out Real Money," *Bloomberg*, July 13, 2016, <https://www.bloomberg.com/features/2016-fake-biofuel-factory/>; "Fraudulent RIN Cases Underscore Continuing Concerns for Renewable Fuel Credit Program," *Husch Blackwell*, October 17, 2016, <https://www.emergingenergyinsights.com/2016/10/fraudulent-rin-cases-underscore-continuing-concerns-renewable-fuel-credit-program/>.

lower compliance costs, while biofuel producers fight for higher quotas that would increase RIN values and market share. An additional challenge is the perceived uncertainty about RFS2 after 2022, the final year with stated volumetric targets in the governing law. This uncertainty affects investor confidence in the mandate and the associated financial value of RIN sales. Finally, the EPA has granted compliance waivers from time to time, allowing obligated parties to delay or avoid compliance costs altogether, which further depresses RIN values.⁵⁴ While well-intentioned, RFS2's complexity has proven problematic and produced uncertainty that make financing of biorefinery projects challenging.⁵⁵

THE EUROPEAN APPROACH: RED II

The EU has established policies and ambitious goals designed to reduce carbon emissions and to achieve or exceed the GHG reduction goals established by the 2016 Paris Accord.⁵⁶ In June 2018, the European Commission, European Parliament, and European Council reached an agreement on a revised Renewable Energy Directive (RED II) that set new, more ambitious targets for renewable energy consumption; by 2030, renewables are to account for 32 percent of all energy consumed, with renewables providing 14 percent of the transportation fuels.⁵⁷ RED II also incorporates a provision that would limit and then phase out first-generation biofuels that have been shown to impact food markets or have significant indirect land-use change impacts.⁵⁸ In order to qualify, advanced biofuels will have to meet strict GHG reduction standards that start at 50 percent and grow to 65 percent by 2021. While some caution that these goals are too ambitious and may result in unintended consequences⁵⁹ (such as the aforementioned land-use change), others argue that such ambitious and long-range goal setting will provide the surety required to

spur investment in renewable energy projects, generally, and biofuel production, specifically.⁶⁰

Of note, just like the US RFS2, RED II does not mandate use of SAF for compliance by the aviation sector. Instead, to incentivize the development and use of SAF, RED II provided a compliance multiplier for SAF, allowing 1 liter of SAF to receive 1.2 liters of credit. While this is certainly beneficial, it may not suffice in overcoming the cost premium of SAF relative to the renewable diesel alternative currently available to biofuel refiners. IATA, the air transportation industry group, advocated a two-times multiplier and was “disappointed in the outcome of RED II.”⁶¹ The IATA spokesman went on to observe that “the important issue was to create a differential from maritime sustainable fuels, which are much easier to produce and therefore if there is no differential we won’t expect to see much incentive to produce SAF.”⁶² This highlights the fundamental challenge to growth in SAF deployment, much like in the United States. Without a mandate or strong economic incentive, biorefinery operators often choose to produce lower-cost renewable diesel, which can be used in road or maritime transportation applications, over the more complex and expensive-to-produce SAF.

POLICY CASE STUDY: CALIFORNIA LOW CARBON FUEL STANDARD

California has become the center of SAF development and deployment in the United States. The primary driver has been a strong commitment by the state government to reducing GHG emission as part of a larger climate change mitigation effort. In 2011, California put in place an ambitious program to reduce the GHG footprint of transportation, the Low Carbon Fuel Standard (LCFS). This program successfully spurred the development

54 Meghan Sapp, “RIN Prices Fall to Lowest Level Since January 2014,” *Biofuels Digest*, October 8, 2018, <http://www.biofuelsdigest.com/bdigest/2018/10/08/rin-prices-fall-to-lowest-level-since-january-2014/>.

55 Antoine Schellinger, “2019 Proposed RFS Volumes: The Deep-Dive Analysis,” *Biofuels Digest*, August 23, 2018, <https://www.biofuelsdigest.com/bdigest/2018/08/23/2019-proposed-rfs-volumes-the-deep-dive-analysis/>.

56 “Tackling Climate Change in the EU,” European Council, October 23, 2017, <https://www.consilium.europa.eu/en/policies/climate-change/>.

57 Erin Voegelé, “EU Reaches Deal on REDII, Sets New Goals for Renewables,” *Biomass Magazine*, June 14, 2018, <http://biomassmagazine.com/articles/15371/eu-reaches-deal-on-redii-sets-new-goals-for-renewables>.

58 Ibid.

59 Sarantis Michalopoulos, “EU Set Bar ‘Too High’ on Advanced Biofuels,” *Euractiv.com*, March 19, 2018, <https://www.euractiv.com/section/agriculture-food/news/eu-set-bar-too-high-on-advanced-biofuels/>.

60 Voegelé, “EU Reaches Deal on REDII.”

61 “Sustainable Aviation Fuels Incentive under New EU Renewable Energy Directive Not Enough, Says IATA,” *GreenAirOnline.com*, June 19, 2018, <http://www.greenaironline.com/news.php?viewStory=2493>.

62 Ibid.



A line-up of international airliners at Los Angeles International Airport (LAX), including British Airways, China Airlines, Emirates, Air France, Japan Airlines, Lufthansa, and Asiana. Source: Alan Wilson/Flickr

and deployment of electric vehicles and alternative fuels such as hydrogen and biofuels. The LCFS is administered by the California Air Resources Board (CARB) and requires petroleum-fuel manufacturers to reduce the life-cycle carbon intensity (CI)⁶³ of their fuel 10 percent by 2020 and 20 percent by 2030.⁶⁴ Petroleum refiners can accomplish this by developing their own lower carbon products, or by buying credits from others who develop and deploy lower CI transportation technologies and fuels. Like RFS2, the petroleum refiner's obligation is set proportionally to their market share of road transportation fuels, namely gasoline and diesel.

Of special note, CARB voted on September 27, 2018, to allow producers of SAF to "opt in" to the program and generate LCFS credits. Like RFS2 and RED II, aviation fuel would not add to the refiner's obligation, but provide

additive credits to the compliance markets. The LCFS does require biofuel producers to certify their pathway and obtain a CI "score" that would determine the credit value of their product. The CI score is compared to a petroleum fuel baseline; the differential establishes the magnitude of the credit for a specific biofuel product, rewarding carbon reduction over volumes sold. These LCFS credits provide an additional financial incentive to biofuel producers to deliver and sell fuel in California. CARB currently uses the Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET[®]) model 2.0⁶⁵ developed by Argonne National Lab⁶⁶ to calculate CI scores. However, during the HEFA-SPK⁶⁷ SAF pathway certification process, the GREET model calculated, and CARB adopted, a smaller CI differential between SAF and petroleum-based jet (petrojet) fuel than the one established between renewable diesel and petrodiesel.⁶⁸ Given the greater CI differential,

63 Definition of carbon intensity (CI) per California Air Resources Board: "CI is expressed as the amount of lifecycle greenhouse gas emissions per unit of fuel energy in grams of carbon dioxide equivalent per megajoule (gCO₂e/MJ). CIs include the direct effects of producing and using this fuel, as well as indirect effects that may be associated with how the fuel impacts other products and markets," <https://www.arb.ca.gov/fuels/lcfs/fuelpathways/fuelpathways.htm>.

64 "CARB Extends Low Carbon Fuel Standard by 10 Years, Doubles the Intensity Reduction Target to 20 Percent," Green Car Congress, September 28, 2018, <http://www.greencarcongress.com/2018/09/20180928-lcfs.html>.

65 "CA-GREET Model," California Air Resources Board, accessed November 10, 2018, <https://www.arb.ca.gov/fuels/lcfs/ca-greet/ca-greet.htm>.

66 "GREET Model," Argonne National Lab, accessed November 10, 2018, <https://greet.es.anl.gov/>.

67 See Table 1 above.

68 Graham Noyes, "Proposed LCFS Regulations Pertaining to Alternative Jet Fuel," Comments to California Air Resources Board, April 23, 2017, made on behalf of alternative jet-fuel producers by Noyes Law Firm, Nevada City, CA.

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biorefineries have an economic incentive to produce renewable diesel over SAF.

Road transportation fuels (gasoline and diesel) are sold to retailers via a wholesale fuel terminal, not directly from a refinery. The point in the terminal where individual fuel trucks are loaded for shipment to retail locations is known as the “rack.” As part of its Cap-and-Trade Program, California imposes “rack fees,” such as the Cap at the Rack (CAR) fee,⁶⁹ on petrodiesel that are not imposed on petrojet at this juncture. Jet fuel, biodiesel, and renewable diesel are not distributed in this manner, and are not subject to these fees. Since renewable diesel is exempt from the CAR fee, this represents another economic incentive for renewable diesel production over SAF production. Depending on the process, biorefineries can modulate up or down the amount of SAF range molecules they produce. The unintended consequence of the CI differential delta and the rack fees is to disincentivize SAF production to maximize renewable diesel output.

Several biorefineries in operation or under construction will have the option to “opt in” and earn LCFS credits when producing SAF. In 2016, AltAir launched the world’s first SAF biorefinery in Paramount, CA, and began supplying HEFA-SPK SAF for use at Los Angeles International Airport. This marked the first use of SAF in routine commercial operations.⁷⁰ On October 24, 2018, AltAir, now part of World Energy,⁷¹ announced an additional \$350 million investment to expand capacity at this facility. At the end of the two-year

over 300 million gallons per year of SAF, renewable diesel, renewable gasoline, and propane.⁷² In addition to the World Energy facility, Fulcrum BioEnergy Inc. has broken ground⁷³ on a new Fischer-Tropsch (FT-SPK) municipal solid waste-to-biofuel facility near Reno, Nevada. The low-carbon syncrude⁷⁴ produced at this facility can be refined into renewable diesel or SAF, and Fulcrum has already submitted a renewable diesel LCFS pathway application to CARB with an impressive CI value of 37.5 (for reference, petroleum diesel has a CI of approximately 100).⁷⁵ Fulcrum has established offtake agreements with multiple airline partners including United Airlines, Cathay Pacific, and Japan Air Lines. In Oregon, Red Rocks Biofuels LLC has also broken ground on an FT-SPK facility that will convert woody biomass waste to biofuel, including SAF, for customers Southwest Airlines, FedEx Corp., and the US Department of Defense.⁷⁶ However, based on this facility’s location along Oregon’s southern border, it is logical to assume the bulk of the biofuels produced there will be renewable diesel sold in California to take advantage of the LCFS credit market.

In application, the LCFS has clear advantages as public policy over the RFS. First, its focus on carbon reduction, not gallons sold, rewards outcomes over effort.⁷⁷ Second, while both are complex, the LCFS carbon market approach is simpler and less prone to fraud and abuse than RIN trading. Third, California, the world’s fifth-largest economy, has shown steadfast governmental and regulatory commitment to the LCFS, in contrast to the US government’s inconsistent approach to the RFS2.

expansion project, the facility will be able to process

However, the higher costs to produce and certify SAF

69 For more information about these fees, see “Projecting the Costs of California’s Cap & Trade and Low Carbon Fuel Standard Programs,” by Jim Mladenik and Kendra Seymour, Stillwater Associates, October 25, 2018, <https://stillwaterassociates.com/projecting-the-costs-of-californias-cap-trade-and-low-carbon-fuel-standard-programs/>.

70 Chelsea Harvey, “United Airlines Is Flying on Biofuels. Here’s Why That’s a Really Big Deal,” *Washington Post*, March 11, 2016, https://www.washingtonpost.com/news/energy-environment/wp/2016/03/11/united-airlines-is-flying-on-biofuels-heres-why-thats-a-really-big-deal/?utm_term=.f99cc1f7f8ce.

71 Jim Lane, “The Paramount Deal: World Energy Takes off with Audacious \$72M Acquisition of AltAir and the Paramount Oil Refinery,” *Biofuels Digest*, March 19, 2018, <http://www.biofuelsdigest.com/bdigest/2018/03/19/the-paramount-deal-world-energy-takes-off-with-audacious-72m-acquisition-of-altair-and-the-paramount-oil-refinery/>.

72 Sarah Pollo, “World Energy to Complete Conversion of California Petroleum Refinery to Renewable Fuels,” *GlobeNewswire*, October 24, 2018, <http://www.globenewswire.com/news-release/2018/10/24/1626529/0/en/World-Energy-to-Complete-Conversion-of-California-Petroleum-Refinery-to-Renewable-Fuels.html>.

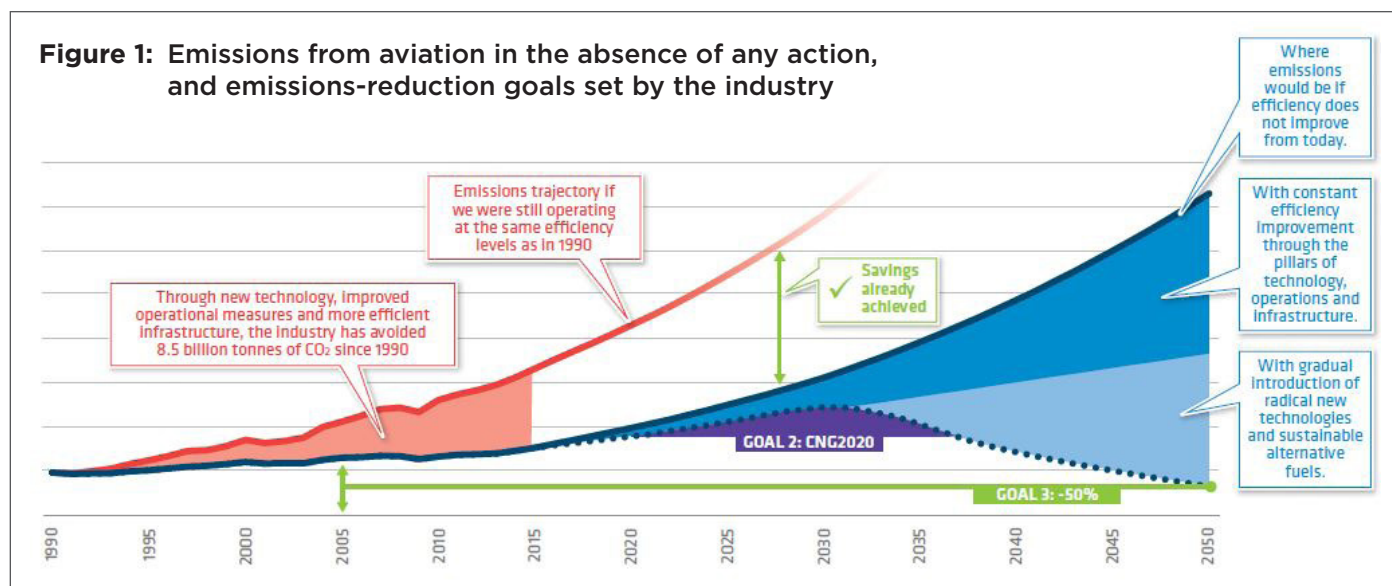
73 “Fulcrum BioEnergy Breaks Ground On Sierra BioFuels Plant,” *PR Newswire*, May 16, 2018, <https://www.prnewswire.com/news-releases/fulcrum-bioenergy-breaks-ground-on-sierra-biofuels-plant-300649908.html>.

74 “Fulcrum BioEnergy Facilities,” Fulcrum BioEnergy, accessed November 2, 2018, <http://fulcrum-bioenergy.com/facilities/>.

75 “Fulcrum BioEnergy Files LCFS Application for Municipal Solid Waste to FT Diesel Pathway with Low CI of 37.47 g/MJ,” *Green Car Congress*, January 3, 2016, <http://www.greencarcongress.com/2016/01/20160103-fulcrum.html>.

76 Kurt Liedtke, “Fueled for the Future: Red Rock Biofuels Facility Breaks Ground in Lakeview,” *Herald and News*, July 19, 2018, https://www.heraldandnews.com/news/local_news/fueled-for-the-future/article_b824da9c-49ad-5094-acac-21e71828b49d.html.

77 Jim Lane, “LCFS vs RFS: As Two Contend for the Renewables Heavyweight Championship, Who Is the Greatest?” *Biofuels Digest*, May 10, 2017, <https://www.biofuelsdigest.com/bdigest/2017/05/10/lcfs-vs-rfs-as-two-contend-for-the-renewables-heavyweight-championship-who-is-the-greatest/>.



Source: Air Transport Action Group

can make it less financially attractive to a biorefinery, compared to on-road renewable diesel. Without an SAF mandate, and with economic incentives favoring renewable diesel production, the LCFS is not optimized to drive increased SAF production and use.

INTERNATIONAL CIVIL AVIATION ORGANIZATION: CHARTING A PATH TO CARBON-NEUTRAL GROWTH

The International Civil Aviation Organization (ICAO) is tasked with creating and maintaining international standards to help ensure “a safe, efficient, secure, economically sustainable, and environmentally responsible civil aviation sector.”⁷⁸ Since 2004, ICAO has embraced a goal of reducing the impact of aviation-generated GHG on the global climate.⁷⁹ This goal has been reaffirmed in ICAO Assembly resolutions adopted in 2016 and 2018.

ICAO’s stated objective is to achieve carbon-neutral growth in civil aviation from 2020 onward. It is utilizing a “basket of measures”⁸⁰ strategy to achieve

this goal. These measures include improvements in aircraft technology, such as increased aerodynamic efficiency, the use of lightweight materials, and greater engine efficiency; and the implementation of innovative operational strategies designed to reduce fuel consumption and emissions, such as Global Positioning System-enabled direct routing, single engine taxiing, and reduced use of the auxiliary power unit while parked. While these efforts will help, they will not be adequate to achieve carbon-neutral growth, given the projected increase of 5 percent per year in global commercial passengers, and 3 percent per year in fuel consumption.⁸¹ Therefore, deployment and use of low-carbon SAF is the third item in the “basket of measures” and is viewed as an integral and essential part of ICAO’s strategy. This is a pointed and direct endorsement of SAF as a vital component of a global, industrywide GHG-reduction scheme. See Figure 1 above.

Unfortunately, the pace of SAF development and deployment has not been robust enough to meet ICAO goals, so in 2016, a global market-based measure

78 “About ICAO,” International Civil Aviation Organization.

79 “Environmental Protection,” International Civil Aviation Organization, accessed November 2, 2018, <https://www.icao.int/environmental-protection/Pages/default.aspx>.

80 “Resolution A39-3,” Resolutions Adopted by the Assembly, 39th Session, International Civil Aviation Authority, Montreal, September 27-October 6, 2016, https://www.icao.int/Meetings/a39/Documents/Resolutions/a39_res_prov_en.pdf.

81 “CAO Confident of Strong Future Growth,” *S&P Global Platts*.

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was adopted that provides a method to offset carbon emission above targets.⁸² This program will require entities that fail to meet their GHG emissions-reduction targets to purchase the difference in carbon credits. This additional compliance cost should encourage more rapid technological improvements and greater operational efficiencies, and it may spur increased utilization of SAF to meet the ICAO's goals.

ICAO believes that a single, global, market-based measurement scheme that will allow entities an option to purchase offsets as needed to meet overall GHG reduction goals is preferable to a patchwork of regional or national schemes with individual and possible divergent compliance requirements.⁸³ ICAO's program is known as Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA)⁸⁴ and will be implemented in phases. During the two-year period from January 2019 through December 2020, all operators will have to report emissions from all international flights. This information will be used to establish the 2020 baseline. From 2021 to 2026, participation will be voluntary, and by November 2018, seventy-six states had indicated their intent to participate.⁸⁵ Beginning in 2027, all international flights (with exceptions for

developing or isolated countries) between ICAO signatory states will be subject to CORSIA.⁸⁶

ICAO has yet to publish specific sustainability standards for SAF for compliance credit under CORSIA, however it may be assumed that these standards will closely align to generally accepted sustainability certification practices like those discussed earlier. Since ICAO's environmental policies are focused on attaining carbon-neutral growth, it should be expected that ICAO's yet-to-be-published standards will place emphasis on CO₂ reduction. Each certified biofuel-production pathway and feedstock combination should have a verifiable CO₂ avoidance score, likely depicted in a percentage of CO₂ reduction versus a petroleum fuel baseline. SAF have the potential to deliver up to an 80 percent reduction in CO₂ emissions across their life cycle.⁸⁷ When coupled with certification under a sustainability-certification regime like the Roundtable on Sustainable Biomaterials or the International Sustainability & Carbon Certification, the SAF would be both sustainable and effective in reducing CO₂ emissions in support of the ICAO CORSIA or other GHG emission-reduction schemes.

82 "Resolution A39-3."

83 *Carbon Offsetting for International Aviation*, 3.

84 "Resolution A39-3."

85 "CORSIA States for Chapter 3 State Pairs," International Civil Aviation Organization, accessed on November 11, 2018, <https://www.icao.int/environmental-protection/CORSIA/Pages/state-pairs.aspx>.

86 *Carbon Offsetting for International Aviation*, 2, 6.

87 *Beginner's Guide*, 7.

ACHIEVING SUCCESS IN SAF DEPLOYMENT

The supportive, if untargeted, regulatory environment, along with the successes in certification of the various pathways, has led to a steady stream of demonstrations of the technology and limited commercial successes. Over twenty airlines have conducted demonstration flights,⁸⁸ SAF have been regularly introduced into the aircraft fueling logistics at several major airports, including Los Angeles International Airport (LAX), and these fuels have been used in both demonstrations and operations by the US military. There have been dozens of research and development or offtake agreements for future production announced between airlines and SAF producers, as airlines try to gain access to the SAF market in anticipation of both public interest and regulatory initiatives aimed at reducing GHG emissions. The importance of partnerships across the value chain cannot be overstated, and one of the most significant successes demonstrates how partnerships, both public and private, are a key enabler of success.

ALTERNATIVE SUPPORT MECHANISMS

While incentives and mandates can be effective, they are not the only tools available or employed by governments to spur growth in the second-generation, drop-in biofuel industry. Research grants are also helpful and have been employed by national and local governments in the United States, Brazil, Europe, and the Middle East to facilitate research in biofuel feedstocks and production technologies. In the United States, the Department of Energy's Bioenergy Technologies Office⁸⁹ and the Department of Transportation's Volpe Center⁹⁰ have each provided numerous grants to developers of SAF technologies, including funding initial pathway-certification efforts in coordination with the Commercial Aviation Alternative Fuels Initiative.

In addition to providing funding, these efforts have also helped create partnerships among researchers, feedstock providers, fuel producers, government regulators, industry experts, and end users.

Another example of government involvement that created partnerships and opportunity for biofuels was the US Department of the Navy's Great Green Fleet initiative. In response to the challenges of rising energy costs and global climate change, as well as a desire to reduce the liquid-fuel demands of deployed forces, then-US Secretary of the Navy Ray Mabus announced an array of initiatives designed to reduce the navy's and Marine Corps' reliance on fossil energy. One of the key elements of this comprehensive program was the Great Green Fleet.⁹¹ The concept, announced in 2009, was to demonstrate fleet operations, including ships and aircraft, on a biofuel blend in 2012, followed by a fleet deployment using a biofuel blend by 2016. To accomplish this effort, the navy partnered with the US Department of Energy and the US Department of Agriculture, with the latter two entities providing support for and expertise in biofuel technologies and feedstock supply chains, respectively.

The US Department of Defense is the single largest consumer of petroleum in the US.⁹² Therefore, the navy provided an enormous market opportunity to biofuel producers. The challenge was to produce fuel that met military performance requirements and was cost competitive with petroleum alternatives. Working with its governmental partners and industry, the navy was able to conduct a series of stepping-stone demonstrations,⁹³ culminating in 2012 with a fleet demonstration during the annual Rim of the Pacific exercise near the Hawaiian Islands. During this demonstration, 900,000 gallons of a 50/50 blend of

88 *Beginner's Guide*, 7.

89 "Bioenergy Technologies Office," US Department of Energy Office of Energy Efficiency & Renewable Energy, accessed November 7, 2018, <https://www.energy.gov/eere/bioenergy>.

90 "Volpe National Transportation Systems Center," Volpe National Transportation Systems Center, US Department of Transportation, accessed November 7, 2018, <https://www.volpe.dot.gov/>.

91 "The Great Green Fleet Explained," US Department of the Navy, June 27, 2016, https://www.navy.mil/submit/display.asp?story_id=95398.

92 Daniel Orchard-Hays and Laura A. King, "Realize the Great Green Fleet," *Proceedings*, U.S. Naval Institute, August 2017, <https://www.usni.org/magazines/proceedings/2017-08/realize-great-green-fleet>.

93 Liz Wright, "Navy Tests Biofuel-Powered 'Green Hornet,'a" US Department of the Navy, April 22, 2010, https://www.navy.mil/submit/display.asp?story_id=52768.



PEARL HARBOR (JULY 18, 2012) The Military Sealift Command fleet replenishment oiler USNS Henry J. Kaiser (T-AO 187), left, delivers a 50-50 blend of advanced biofuels and traditional petroleum-based fuel to the guided-missile cruiser USS Princeton (CG 59) during the Great Green Fleet demonstration portion of Rim of the Pacific (RIMPAC) 2012 exercise. In the background are the aircraft carrier USS Nimitz (CVN 68) and the guided-missile destroyer USS Chung-Hoon (DDG 93). Twenty-two nations, more than forty ships and submarines, more than 200 aircraft and 25,000 personnel are participating in the biennial RIMPAC exercise from June 29 to Aug. 3, in and around the Hawaiian Islands. The world's largest international maritime exercise, RIMPAC provides a unique training opportunity that helps participants foster and sustain the cooperative relationships that are critical to ensuring the safety of sea lanes and security on the world's oceans. RIMPAC 2012 is the 23rd exercise in the series that began in 1971. Source: Mass Communication Specialist Seaman Apprentice Ryan J. Mayes/US Navy

renewable distillate fuel and petrodiesel were utilized by naval ships and aircraft, including 200,000 gallons of SAF.⁹⁴ However, due to the relatively small volume purchased and the associated high costs of production, the biofuel use in this demonstration was purchased at an average cost of \$26 per gallon.⁹⁵

Despite the high initial cost, the effort continued, and in 2016, the Great Green Fleet initiative culminated

with the purchase of over 7.7 million gallons of neat, unblended biofuel. This fuel was produced in a commercial-scale facility and sold to the navy at an average price of \$2.05 per gallon. The biorefinery also would have captured RFS2 RIN revenue, and possibly a biodiesel-production tax credit.⁹⁶ It is unclear if the biorefinery received any benefit from LCFS on this transaction. This highlights the importance of governmental-incentive support to this industry. In

94 Jim Lane, "The Navy's Green Strike Group Sails on Biofuels Blend: Will It Sail Again?" *Biofuels Digest*, July 19, 2012, <http://www.biofuelsdigest.com/bdigest/2012/07/19/the-navys-green-strike-group-sails-on-biofuels-blend-will-it-sail-again/>.

95 Jim Lane, "Launch of the Great Green Fleet," *Biofuels Digest*, January 20, 2016, <http://www.biofuelsdigest.com/bdigest/2016/01/20/launch-of-the-great-green-fleet/>.

96 Ron Kotrba, "Retroactive Biodiesel Tax Credit Signed into Law for 2017 Only," *Biodiesel Magazine*, February 9, 2018, accessed on December 2, 2018, <http://biodieselmagazine.com/articles/2516276/retroactive-biodiesel-tax-credit-signed-into-law-for-2017-only>.

addition to meeting performance requirements, this cost-competitive price point is critical since current US Department of Defense policy states: “Alternative fuels for operational purposes [may be] purchased when cost competitive with traditional fuels and when qualified as compatible with existing equipment and infrastructure.”⁹⁷

This fuel was blended at 10 percent concentration to produce over 77 million gallons of blended fuel, supporting the deployment of a carrier strike group from San Diego, CA.⁹⁸ The fuel was supplied by World Energy’s Paramount, CA refinery, the same facility that currently provides SAF for airline use at LAX. This effort also clearly demonstrated the drop-in nature of second-generation biofuels, including renewable diesel and SAF. As expected, the drop-in biofuel blends performed exactly like the petroleum products they displaced, with no noticeable effect on ship or aircraft operations. The key enabler for the success of this project was the strong government and industry collaboration, which provided research and development funding, technological expertise, off-take agreements, and the political will to see the project to completion.

BIOREFINERY CAPACITY LAG

Despite these successes in biofuel certification, cost reduction, and policy support, biorefinery capacity remains relatively small. During 2017, only 84 million tons oil equivalent,⁹⁹ 143 billion liters¹⁰⁰ of biofuels, were produced worldwide. While this may sound like a substantial amount, it is still less than the 92 million tons of oil produced on average worldwide *each day* of that same year.¹⁰¹ First-generation ethanol accounted for 65 percent of this total, fatty acid methyl ester biodiesel represented 29 percent, and second-generation renewable diesel accounted for 6 percent. Of the three,

renewable diesel exhibited the fastest rate of growth, expanding from 5.9 to 6.5 billion liters, roughly 10 percent over the year.¹⁰²

Unfortunately, this is a negligible amount when the entirety of the liquid fuels market is considered. Even if all renewable diesel produced worldwide were upgraded to SAF and dedicated to the aviation market, current installed capacity of 6.5 billion liters per year production would only represent 1.8 percent of the 356-billion-liter annual worldwide aviation fuel market.¹⁰³ However, the recently announced expansion of World Energy’s Paramount, California, facility (for an additional 130 million gallons per year), coupled with the commencement of construction in 2018 at both Red Rocks Biofuel’s facility in Lakeview, Oregon, (15 million gallons per year), and Fulcrum Bioenergy’s Sierra Biofuels Plant in Nevada (10+ million gallons per year) represent over 155 million gallons or nearly 600 million liters per year of additional capacity—a 10 percent increase in the global supply.

CHALLENGES TO SUCCESS IN A MATURE MARKET

While the past decade has been one of success and advancement for the biofuels industry, there have also been headwinds and failures. The volatility of global oil markets has taken a toll. The distillate fuel market is benchmarked by the price of ultra-low sulfur diesel (ULSD) in the US market. For the week ending on October 18, 2018, the average for ULSD was approximately \$2.32 per gallon on both the Chicago and New York commodity markets.¹⁰⁴ As the global price for crude oil goes up or down, this benchmark will rise and fall in a similar fashion. During 2008, the year of the first biofuel flight, Brent crude peaked above \$134 per barrel. It fell to below \$40 per barrel before the end of that year. While the price hovered above \$100 per

97 “DoD Management Policy for Energy Commodities and Related Services,” US Department of Defense Instruction Number 4140.25, Change 2, August 31, 2018, 2.

98 Jim Lane, “Navy to Launch Great Green Fleet with 77 Million Gallon Buy of Cost-Competitive, Non-Food Advanced Biofuels Blends,” *Biofuels Digest*, January 7, 2016, <http://www.biofuelsdigest.com/bdigest/2016/01/07/navy-to-launch-great-green-fleet-with-77-million-gallon-buy-of-cost-competitive-non-food-advanced-biofuels/>.

99 *BP Statistical Review 2018*, BP, 45.

100 *Renewables 2018 Global Status Report*, Renewable Energy Policy Network for the 21st Century (REN21), (Paris: 2018), 72-73.

101 *BP Statistical Review 2018*, BP, 14.

102 *Ibid.*

103 Ninety-four (94) billion gallons estimated in 2018 equals approximately 356 billion liters; see “Global CO₂ Emissions from Airlines Expected to Rise,” GreenAirOnline.com.

104 “Ethanol & Biodiesel Information Service,” Oil Price Information Service, 1.

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barrel from 2011 to 2014, it was back below \$40 by 2016. This volatility and uncertainty can be very challenging, especially for new biofuel production technologies seeking investment.

The market price of ULSD, plus any additional value derived from the associated RINs, LCFS carbon credits, and other governmental supports, like the Blenders Tax Credit,¹⁰⁵ represent the revenue potential of a gallon of biodiesel or renewable diesel in the US market. Most of these same incentives would be available to SAF producers, however the higher cost to produce and certify SAF may make it an unattractive alternative to the less cost-intensive on-road diesel market.

In addition to these economic challenges, there have been high-profile failures in the space that have affected the public perception of the industry. The prime example of this in the United States was KiOR,

a highly touted, well-financed biofuel production company with the goal of using a modified thermo-catalytic process known as “catalytic cracking.”¹⁰⁶ The process is commonly used in petroleum refineries to convert woody biomass to a “renewable crude” that can then be upgraded into drop-in biofuels. The company secured significant venture funding and a large incentive package from the state of Mississippi to convert a former paper mill near the city of Columbus into a biorefinery designed to convert locally-sourced wood chips to biofuel. Unfortunately, the company was attempting to leap from the lab to commercial production before results and processes were proven at demonstration scale.¹⁰⁷ The results were predictable as the Columbus facility struggled with chronically poor yields, while still experiencing operational challenges typical of new plant commissioning. In 2014, KiOR shut down the Columbus facility; before the end of that year, the company had filed for bankruptcy protection.¹⁰⁸

105 Kotrba, “Retroactive Biodiesel Tax Credit Signed into Law for 2017.”

106 Katie Fehrenbacher, “How A Tech Billionaire’s Biofuel Dream Went Bad,” *Fortune*, December 4, 2015, <http://fortune.com/kior-vinod-khosla-clean-tech/>.

107 Jim Lane, “KiOR: The Inside True Story of a Company Gone Wrong,” *Biofuels Digest*, May 17, 2016, <https://www.biofuelsdigest.com/bdigest/2016/05/17/kior-the-inside-true-story-of-a-company-gone-wrong/9/>.

108 Fehrenbacher, “How A Tech Billionaire’s Biofuel Dream Went Bad.”

LOOKING AHEAD

HOW WILL CORSIA AFFECT SAF DEVELOPMENT?

It is very challenging to quantify the potential impacts of CORSIA implementation on the SAF industry. The market-based aspect of CORSIA will allow “carbon neutral” growth in the commercial aviation industry through either avoidance by using low-carbon SAF or offsetting through the purchase of carbon credits from global carbon-credit exchanges. Despite the aviation industry’s vocal support for SAF development, this optionality was built in by design. It allows the industry to stay ahead of climate change mitigation measures and public perception, while providing them the ability to choose the most cost-effective means of compliance. Therefore, while some parties may choose to purchase SAF as a compliance measure, many will also choose offsets, with this decision rationally driven by the relative economics.

In addition to this optionality, it is also very difficult to estimate the overall cost of compliance. CORSIA is designed to ensure carbon-neutral growth above the to-be-established 2020 baseline, not carbon-neutral operations. CORSIA also only applies to international flights; it is not applicable to domestic commercial operations. Moreover, during the pilot phase (2021-2023) and first phase (2024-2026), only flights between participating states will be subject to the regulation.

As of November 5, 2018, seventy-six states, representing over 75 percent of international aviation activity, have committed to voluntarily participate in CORSIA from the outset.¹⁰⁹ What this means, however, is that only carbon emissions from international flights that represent market growth between participating states will be subject to CORSIA. IATA has stated that “CORSIA will mitigate around 2.5 billion tons of CO₂ between 2021 and 2035, which is an annual average of 164 million tons of CO₂.”¹¹⁰ With carbon offsets recently trading at

€20, or approximately \$23, per ton,¹¹¹ this represents an average annual cost of \$3.77 billion. However, since only growth will be offset, the cost will likely be nonlinear.

The financial impact to individual airlines or countries is harder to determine. Industry representatives from international airlines and airline-industry groups admit that their organizations have used internal, proprietary estimations of market demand and growth to estimate their own specific CORSIA compliance costs, but they are understandingly unwilling to share these estimates publicly. While it would be speculative to attempt to estimate the impact of CORSIA on individual airlines or member states, it is possible to calculate the relative impact of the regulation on the price (in today’s dollars) of a gallon of fuel consumed in a regulated flight operation, which is defined as market growth between participating states.

Burning a ton of aviation fuel produces 3.24 tons of CO₂.¹¹² At \$23 per ton, the current cost to offset these emissions would be \$74.66. With 2,204 pounds per ton, and using 6.5 pounds per gallon of jet fuel,¹¹³ there are 339 gallons of jet fuel per ton. Dividing the \$74.66 compliance cost across these gallons results in \$0.22 per gallon in compliance cost. The carbon intensity of SAF varies by feedstock and conversion pathway, but for the purposes of this example assume that the subject fuel achieves a 67 percent reduction in CO₂ emissions. Applying this factor to the compliance cost nets a per gallon premium of \$0.148. In this example, in order to be the more economical compliance option compared to purchasing carbon-offset credits, SAF would need to be no more than \$0.14 per gallon more expensive than the petrojet alternative. Even given the potential for the \$3.77 billion in annual compliance cost noted above, it is unlikely that a 14-cent CORSIA premium alone will be adequate to cover the additional costs of producing SAF versus the simpler renewable diesel.

109 “CORSIA States for Chapter 3 State Pairs,” ICAO website, accessed November 9, 2018, <https://www.icao.int/environmental-protection/CORSIA/Pages/state-pairs.aspx>.

110 “Fact Sheet on CORSIA,” International Air Transportation Association, October 29, 2018, 1-2.

111 Rachel Morrison and Jeremy Hodges, “Carbon Reaches 10-Year High, Pushing Up European Power Prices,” *Bloomberg*, August 23, 2018, <https://www.bloomberg.com/news/articles/2018-08-23/carbon-reaching-20-euros-a-ton-in-europe-raises-price-for-power>.

112 Per the US Energy Information Administration, one gallon of jet fuel produces 21.1 pounds of CO₂. At 6.5 pounds per gallon this equates to 3.24 pounds of CO₂ per pound of fuel. See https://www.eia.gov/environment/emissions/co2_vol_mass.php.

113 Paul Laherty, “Calculating Aircraft CO₂ Emissions,” January 26, 2015, <https://paulaherty.com/2015/01/10/calculating-aircraft-co2-emissions/>.



The Masdar Institute Seawater Energy and Agricultural System (SEAS) is a pilot research facility that will evaluate a process to grow seafood and biomass for food, fuel, and byproduct production using seawater. Credit: Sustainable Bioenergy Research Consortium

FEEDSTOCK INNOVATION

The majority of current and soon-to-be-operational SAF production utilizes one of the well-established, technologically mature pathways, HEFA-SPK or FT-SPK. In either case, tight feedstock supply, caused by short supply or competition, can increase the cost of production. The supply of waste oil and grease is finite, and the market demand for this feedstock is high. As of November 2018, the spot price for “yellow grease,” as this material is known, on the West Coast of the United States ranged between \$0.205 and \$0.245 per pound.¹¹⁴ Fisher-Tropsch processes using municipal solid waste (MSW) compete with landfills and waste-to-power companies,¹¹⁵ while an FT process that uses wood

waste as a feedstock will have to compete with wood-to-power and wood pellet mills for their feedstocks.¹¹⁶ More work is needed to develop innovative feedstock supply chains that can supply biorefineries with low-cost inputs, without unintended negative impacts on food production or land use.

Numerous public and private entities are working to create novel feedstock models. The best option for increasing the global supply of HEFA feedstock is to expand farming of purpose-grown oilseed crops. For example, the Canadian company Agrisoma Biosciences Inc. is developing Carinata, a nonfood oilseed plant that can be grown on fallow land or as an off-season cover crop.¹¹⁷ Others are working to expand production, reduce

114 “National Weekly Ag Energy Round-Up,” US Department of Agriculture, Agricultural Marketing Service, accessed November 10, 2018, <https://www.ams.usda.gov/mnreports/lswagenergy.pdf>.

115 “Energy from Waste,” Covanta, accessed November 10, 2018, <https://www.covanta.com/Sustainability/Energy-from-Waste>.

116 “About Enviva,” Enviva, accessed November 10, 2018, <http://www.envivabiomass.com/about/>.

117 “About Agrisoma,” Agrisoma Biosciences Inc., accessed November 10, 2018, <https://agrisoma.com/biofuel/about>.

conversion cost, and increase output of purpose-grown lignocellulosic biomass resources.¹¹⁸ Some of these crops could be thermochemically converted to sugars and then processed into biofuels and biochemicals. As noted earlier, SAF could be produced in this manner via the approved ATJ-SPK pathway. This biomass could also be converted using existing FT-SPK technologies. Access to lower cost, purpose-grown biomass feedstocks would benefit biofuel production by increasing feedstock supply and avoiding competition inherent in the wood market.

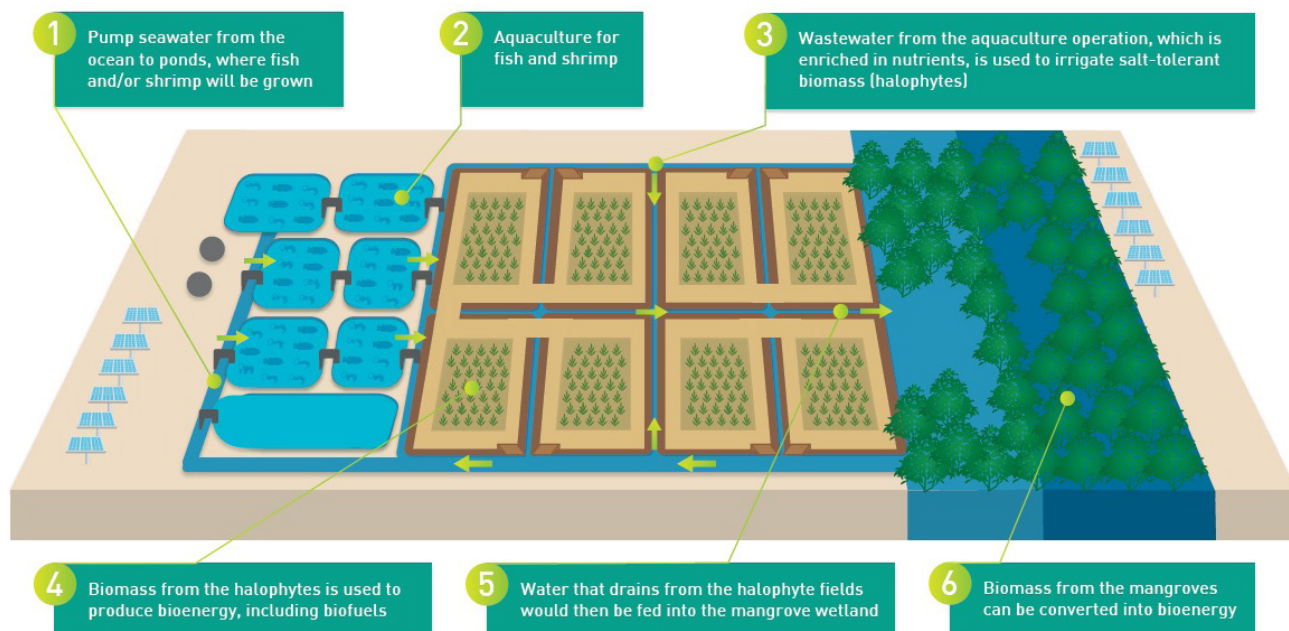
INNOVATION CASE STUDY: SUSTAINABLE BIOENERGY RESEARCH CONSORTIUM

One way to increase the use of renewable energy resources, including SAF and renewable diesel, is through innovative models that integrate feedstock

production with other products, creating an economic ecosystem that delivers multiple value streams. An example of this type of innovation can be found in the United Arab Emirates (UAE), where a dedicated team of scientists and engineers is working on an integrated approach to deliver food protein and energy from saltwater and nonarable desert land.

The Sustainable Bioenergy Research Consortium is a partnership founded in 2011 between the Masdar Institute, which is now part of Khalifa University of Science and Technology, Etihad Airways, Honeywell UOP, the Abu Dhabi National Oil Company (ADNOC), Safran SA, Boeing Co., General Electric Co. and Bauer Resources GmbH.¹¹⁹ The Consortium operates a 2-hectare research facility near Abu Dhabi that seamlessly integrates aquaculture with energy feedstock production. This system is known as the Seawater Energy and Agriculture System (SEAS).¹²⁰ Its

Figure 2: The Seawater and Agriculture System (SEAS)



Source: Sustainable Bioenergy Research Consortium

¹¹⁸ Allyson Mann, "Gene Improves Plant Growth and Conversion to Biofuels," Science X news service, February 13, 2018, https://phys.org/news/2018-02-gene-growth-conversion-biofuels.html#jCp_; "ISEE Helps Secure \$6M in New Grants," Institute for Sustainability, Energy, and Environment, University of Illinois at Urbana-Champaign, September 14, 2018, <https://sustainability.illinois.edu/isee-helps-secure-6m-in-new-research-grants-for-university/>.

¹¹⁹ "Sustainable Bioenergy Research Consortium (SBRC)," Masdar Institute, accessed November 10, 2018, <https://www2.masdar.ac.ae/research-education/research-centers-and-institutes/sustainable-bioenergy-research-consortium>.

¹²⁰ "Masdar Institute's SEAS Harvest Marks Critical Milestone in Development of Sustainable Aviation Biofuel," Green Car Congress, October 2, 2017, <https://www.greencarcongress.com/2017/10/20171002-masdar.html>.

novel process uses the effluent stream generated by a fish or shrimp farm to irrigate fields of salt-tolerant (halophyte) plants. The nitrogen-rich effluent stream contains a large volume of suspended solids and in many cases would require pretreatment before being returned to the ocean or groundwater.¹²¹ SEAS uses this waste stream to irrigate and fertilize the halophyte plants, turning a potential cost center or environmental hazard into a reusable byproduct of production. The mangrove wetland further filters the aquaculture effluent before it is returned to the environment.

The halophyte plants produce oilseeds that can be crushed to create a vegetable oil feedstock that can be processed, using the well-established HEFA-SPK fuel pathway, into SAF. The mangrove wetland provides additional carbon capture and storage that may create an opportunity to apply for and secure carbon credits, which could be traded on the global market. This potential project revenue stream could increase the financial returns for investors. Both the halophyte plants and, eventually, the mangroves will produce lignocellulosic biomass that can also be utilized as bioenergy feedstocks. See Figure 2 below for an illustration of the SEAS process.

One of the unique aspects of SEAS is the local and global imperative for enhanced food production. UAE imports over 90 percent of its food¹²² and, with the world population expected to grow to nine billion by 2050, the demand for food protein will provide enormous incentive for development of aquaculture projects.¹²³ Integrated projects of this type have the potential to address local food security concerns while also producing low-carbon energy alternatives, thereby generating additive environmental benefits.

In addition to these environmental benefits, this integrated process also exhibits high financial sustainability. The revenue generated by the food production process alone has the potential to make this system commercially viable. The additional profitability generated from the production and sale of SAF and the marketing of carbon credits, coupled with the revenue generated by sales or conversion of the lignocellulosic biomass stream, has the potential to make this approach very attractive to investors. Alejandro Rios Galvan, director of the Sustainable Bioenergy Resource Consortium, indicated plans are pending for a hundred-times scale-up of the process to a 200-hectare demonstration facility, which would put the front-end aquaculture stage at commercial scale.¹²⁴ The oilseed produced at this scale can be refined into 10,000 gallons per year of SAF.

THE POTENTIAL IMPACT OF IMO 2020 ON THE SAF MARKET

On January 1, 2020, the International Maritime Organization (IMO) will implement its latest and most stringent fuel regulations. The new policy, which limits sulfur in oceangoing ships' fuel oil to 0.50 percent mass by mass (m/m), is a significant increase from the current global limit of 3.5 percent m/m mandated in 2012.¹²⁵ There has been speculation that biofuels could be a potential low-sulfur blendstock alternative.¹²⁶ While renewable diesel can be blended with marine fuels to reduce sulfur content, the relatively small installed or forecast biorefinery capacity and the fact that existing biorefineries may not be proximate to the major marine fuel terminals relegate renewable diesel to merely an overall diesel fuel volume extender. Market forces that drive up the spot price of ULSD will benefit renewable

121 Sarah A. Castine, A. David McKinnon, Nicholas A. Paul, Lindsay A. Trott, and Rocky de Nys, "Wastewater Treatment for Land-based Aquaculture: Improvements and Value-adding Alternatives in Model Systems from Australia," *Aquaculture Environment Interactions*, 4 (2013), 286.

122 "UAE Launches World's First Food and Fuel Research Facility," *ArabianBusiness.com*, March 12, 2016, <https://www.arabianbusiness.com/uae-launches-world-s-first-food-fuel-research-facility-623992.html>.

123 *Fish to 2030: Prospects for Fisheries and Aquaculture*, World Bank, (Washington, DC: 2013), xiii.

124 Interview by the author on September 20, 2018, and personal communications on October 21, 2018.

125 "Sulphur 2020-Cutting Sulphur Oxide Emissions," International Maritime Organization, accessed November 10, 2018, <http://www.imo.org/en/MediaCentre/HotTopics/Pages/Sulphur-2020.aspx>.

126 Jim Lane, "\$200 Oil in 2020? The Impending Energy Crisis and Biofuels' Role in Relieving the Refining Capacity Crunch," *Biofuels Digest*, July 24, 2018, <http://www.biofuelsdigest.com/bdigest/2018/07/24/200-oil-in-2020-the-impending-energy-crisis-and-biofuels-role-in-relieving-the-refining-capacity-crunch/>.

diesel producers by increasing the underlying value of their product. This would further incentivize the production of renewable diesel over SAF, in this case for creating a maritime distillate that satisfies the IMO mandate. However, unlike SAF, there has been limited compatibility testing with the currently installed maritime fuel infrastructure (distribution and propulsion systems), making shipowners hesitant to switch from petroleum-derived fuels.¹²⁷

The IMO mandate is driven by environmental concerns. Sulfur oxides (SO_x) are harmful pollutants with wide-ranging consequences. Known to cause respiratory and cardiovascular diseases, they also increase the threat of acid rain and imperil biodiversity, particularly for coastal regions not covered by the current 0.10 percent m/m IMO sulfur-emission restriction for coastal Emission Control Areas. The UN approximates that 13 percent of sulfur dioxide emissions stem from the maritime industry, a consequence of its preference for bunker fuel.¹²⁸ This low-grade residual fuel, taken from the remnants of a petroleum refining column, is high in sulfur and low in cost. Currently, offtakes of this low-quality fuel oil satisfy most of the marine shipping industry's enormous demand for 3.9 million barrels per day.¹²⁹

The sulfur level in these fuels is well above the forthcoming limit, with a global average of 2.4 percent m/m in 2015.¹³⁰ Thus by January 2020, substantial alternatives must be in place. For some sellers in the refining industry, this could mean blending the “heavy” residual bunker fuel with the lighter distillate fuel oil currently used in the designated Emission Control Areas or with ultra-low sulfur diesel to create fuels with compliant sulfur levels. Some shipowners, as fuel buyers who fear a shortage or spike in fuel prices, are installing additional infrastructure known as “scrubbers,” which collect excess sulfur and permit the continued used of

low-cost, high-sulfur traditional marine bunker fuels.¹³¹ Others, such as Maersk, are looking to LNG to power future generations of ships, but this is unlikely to ameliorate acute supply issues in 2020.¹³²

Both the shipping and petroleum-refining industries face the need to invest billions of dollars to address this massive shift in demand, but neither has taken the necessary steps, hoping for a postponement of the mandate. There remains substantial uncertainty regarding both how fuel demand will be met and, consequently, how the overall oil supply market will recalibrate. Some analysts have forecast a significant short-term impact on global petroleum markets as the system adjusts, with forecasts of \$6 per gallon gasoline and \$8 per gallon diesel in the US market.¹³³

Lacking a clear market-competitive alternative to the high-sulfur residual fuel oil and confronted by both the shipping and refining industries' unwillingness to internalize the added cost, the most likely outcome is a combination of solutions. A short-term spike in low-sulfur crude prices and high demand, and higher prices, for low-sulfur distillate fuels are also likely. Large-vessel maritime consumers will likely invest in scrubbers, with others choosing the alternative of blending the most egregious residual fuels with higher-cost, low-sulfur cutter stock, such as renewable diesel and low-sulfur distillate fuel oil. This shared burden mitigates the consequence of any one industry bearing the entire expense. Any increase in renewable diesel demand will tend to divert feedstock and biorefinery capacity away from SAF production. While in the short term, the net carbon reductions will be roughly the same whether the fuel is used for maritime or air transport, incentives should be put in place to encourage shipping to move to lower-carbon LNG, freeing up refining capacity for SAF and maximizing carbon reduction.¹³⁴

127 Chia-wen Carmen Hsieh and Claus Felby, “Biofuels for the Marine Shipping Sector,” IEA Bioenergy, December 2017, <https://www.ieabioenergy.com/publications/biofuels-for-the-marine-shipping-sector/>.

128 Timothy Puko and Benoit Faucon, “U.S. Seeks More Time for Ships to Switch to Cleaner Fuels,” *Wall Street Journal*, October 18, 2018, https://www.wsj.com/articles/white-house-seeks-to-slow-rollout-of-rules-for-cleaner-ship-fuels-1539900741_

129 “Tighter Marine Fuel Sulfur Limits Will Spark Changes by Both Refiners and Vessel Operators,” *Today in Energy*, US Energy Information Administration, November 30, 2016, <https://www.eia.gov/todayinenergy/detail.php?id=28952>.

130 “Frequently Asked Questions, The 2020 Global Sulphur Limit,” International Maritime Organization (IMO), accessed November 10, 2018, <http://www.imo.org/en/MediaCentre/HotTopics/GHG/Documents/2020%20sulphur%20limit%20FAQ%202018.pdf>.

131 Emma Kettley, George Griffiths, and Tamara Sleiman, “Feature: Bunkering Sector Mulls Biofuel Use in New 2020 Sulfur Standards,” *S&P Global Platts*, September 21, 2018, <https://www.spglobal.com/platts/en/market-insights/latest-news/shipping/092118-feature-bunkering-sector-mulls-biofuel-use-in-new-2020-sulfur-standards>.

132 Mike Wackett, “Maersk Hints at Using LNG in Post-2020 Low Sulphur Shipping,” *The Loadstar*, February 22, 2018, <https://theloadstar.co.uk/maersk-hints-using-lng-post-2020-low-sulphur-shipping/>.

133 Lane, “\$200 Oil in 2020.”

134 Because of refining processes, incentivizing refiners to produce more SAF will still leave some lower-grade fuel available for maritime use. It is not a binary choice, but one of preferences for producing more of one or the other.

THE FUTURE OF SUSTAINABLE FUEL CERTIFICATION

BY THOMAS W. HICKS

Whether it's a fair burden for the sustainable fuel industry to bear or not, full transparency about and 100 percent accuracy in the characteristics, environmental attributes, and sourcing of sustainable fuel will determine user confidence. Organizations such as the Roundtable on Sustainable Biomaterials (RSB) among others have risen up to answer the challenge in providing a third-party, multistakeholder, multiattribute standard to assess sustainable fuels throughout the supply chain. However effective a standard might be, issues of accuracy, speed, and cost will be paramount to wide-scale market adoption of any standard.

One Swiss company, SICPA, which has long provided secure and technologically advanced identification, traceability, and authentication solutions for governments and companies, proposes a technical solution that may be able to enhance or provide alternative compliance pathways for existing sustainable fuel standards. The proposed solution is straightforward: combine in-product, covert nanotechnology liquid markers with blockchain, the purportedly incorruptible digital ledger of economic transactions. Originally designed for the cryptocurrency Bitcoin, blockchain has since succeeded in enabling secure transactions among

people or businesses who know nothing about one another.

As is being contemplated, the secure and covert fuel markers, when combined with mobile fuel analyzers, would permit fuels to be marked at any point in the supply chain, allowing controls to be implemented at the point of production. Blockchain solutions, in turn, would register all entities that provide data in the supply-chain ecosystem and secure the event data throughout production and distribution.

If SICPA's hypothesis for the sustainable fuel market is correct, this combined capability could enhance the adoption of existing market standards, ensuring that sustainable fuels are distributed and sold without adulteration in a fair and transparent business environment and protecting the producers and users alike from the specter of fraud.

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NORWAY CHARTS A NOVEL COURSE: MANDATING SAF USE

Norway has a history of leadership in both traditional and clean energy production. The country is pursuing increased biofuel utilization as a method of reducing carbon emission and other air pollutants. Oslo was the first major airport to introduce biofuel into its refueling infrastructure, essentially distributing SAF, at relatively small concentrations, into every refueling operation.¹³⁵ Through aggressive governmental policies, Norway has

been able to achieve 20 percent penetration of biofuels into the road transportation sector well ahead of a stated 2020 timeline.¹³⁶

On October 4, 2018, the Norwegian Ministry of Climate and Environment announced that, beginning in 2020, all aviation fuel used in Norway would be required to contain 0.5 percent advanced biofuel.¹³⁷ This action should have the effect of both creating demand for SAF as well as incentivizing SAF investment. Mandates, such as RFS2 in the United States and ethanol policies

¹³⁵ "Biofuel for All at Oslo Airport," Visit Oslo, January 25, 2016, <http://www.visitoslo.com/en/product/?TLp=1081113&Biodrivstoff-til-alle-pa-Oslo-Lufthavn>.

¹³⁶ Victoria Garza, "Biofuel Targets Reached a Few Years before Time," *Norway Today*, December 22, 2017, <http://norwaytoday.info/finance/biofuel-targets-reached-years-time/>.

¹³⁷ Erin Voegelé, "Norway to Implement Biofuel Mandate for Aviation Fuel in 2020," *Biomass Magazine*, October 9, 2018, <http://biomassmagazine.com/articles/15657/norway-to-implement-biofuel-mandate-for-aviation-fuel-in-2020>.

in Brazil, have proven very effective in catalyzing growth in the biofuel industry in the past. Norway's mandate is a significant milestone: the first to specifically target SAF utilization. SAF supply should not be a limiting factor as the Norwegian market is relatively small,¹³⁸ and energy company Neste Oyj, which is based in Finland, has already indicated that global supplies of SAF would be adequate to meet Norwegian market demands.¹³⁹ The compliance costs of this mandate are estimated at \$6.6 million per year.¹⁴⁰ Stakeholders who seek to ensure that SAF is a meaningful portion of the aviation fuels market should closely monitor the implementation and impacts of this mandate on SAF production and pricing.

IS THE CLIMATE CHANGE NARRATIVE SHIFTING IN THE UNITED STATES?

While much of the rest of the world is advancing measures to combat global climate change, the US discussion continues to lack internal consensus for action. As the world's leading economy, active measures by the United States are essential to the success of any scheme designed to mitigate the effects of GHG emission and their impacts. Since the initial 1988 climate hearing in the US Senate, action (or rather inaction), on climate change has often been attributed to a lack of perceived personal risk. However, a majority (59 percent) of Americans, and two-thirds of those who live near a coast, now think climate change affects their local community, and 39 percent say it affects them personally, according to a May 2018 Pew Research Center survey.¹⁴¹ The ideological obstacle of the past three decades—mere acknowledgement of the implications of human-caused climate change—may soon be irrelevant. For those under the age of forty, causes and consequences of climate change are as uncontested as they are alarming. The UN's recent

IPCC assessment warns that the catastrophic effects of climate change, even if limited to the 1.5 degrees Celsius increase upon preindustrial temperatures as outlined by the Paris Agreement, may be evident by 2040.

While the US government largely remains stalled by the issue's politicization, the private sector is increasingly confronted by the economically inconvenient reality of climate change. In 2019 millennials will overtake baby boomers as the largest US generation, and with this ascension comes buying power. Sustainability is not merely a net benefit, but an increasingly critical consumer priority.

In October 2018, ExxonMobil Corp. pledged \$1 million over two years to Americans for Carbon Dividends, a 501(c)(4) group under the Internal Revenue Code that advocates implementation of a carbon tax-and-dividend program.¹⁴² Historically opposed to sustainability initiatives, Exxon, and the other companies associated with Americans for Carbon Dividends, may now perceive policies such as California's Low Carbon Fuel Standard as an inevitability. While the preemptive advocacy is likely in hopes of simultaneously shaping the eventual laws and generating some millennial goodwill, ultimately this action favors a carbon tax, long considered to be the most effective but politically untenable policy to mitigate the effects of climate change. Despite the cynical origins, should young consumers continue to demand growth and investment in credible sustainability initiatives, there is an opportunity to affect considerable change across a variety of industries. This shift in perceptions on climate change has the potential to lead to the introduction of public policies that may have positive impacts on the development of SAF.

¹³⁸ Demand at 0.5 percent penetration is estimated by Aviation Fuelling Services Norway at 6,000 cubic meters per year; this equals approximately 1.6 million US gallons of SAF. See http://www.miljodirektoratet.no/PageFiles/41100/Horing2018-6537_uttalelse_fra_AFSN.pdf.

¹³⁹ "Norway Introduces 0.5 Percent Biofuel Mandate for Aviation for 2020," Green Car Congress, October 9, 2018, <http://www.greencarcongress.com/2018/10/20181009-norway.html>.

¹⁴⁰ "In Another First, Norway Mandates Blending of 0.5 Percent Advanced Biofuel into Jet Fuel from 2020," F&L Daily, October 12, 2018, <https://www.fuelsandlubes.com/first-norway-mandates-blending-0-5-advanced-biofuel-jet-fuel-2020/>.

¹⁴¹ Brian Kennedy, "Most Americans Say Climate Change Affects Their Local Community, Including Two-thirds Living Near Coast," Pew Research Center, May 16, 2018, <https://pewrsr.ch/2Gmxge4>.

¹⁴² Steven Mufson, "ExxonMobil Gives \$1 Million to Promote a Carbon Tax-and-Dividend Plan," *Washington Post*, October 9, 2018, https://www.washingtonpost.com/energy-environment/2018/10/09/exxonmobil-gives-million-promote-carbon-tax-and-dividend-plan/?utm_term=.9495fbd1cef3.

CONCLUSIONS AND RECOMMENDATIONS

The size and growth of the global aviation market will continue to devour enormous volumes of liquid aviation fuel for the foreseeable future. While most of these fuels will still be derived from petroleum refining, the SAF industry provides an important low-carbon alternative necessitated by the threats of climate change. The SAF industry has just gotten off the ground, and significant support from both public and private sectors will be required if it is to soar to the lofty heights envisioned by advocates. These will include continued investment in research and development and the implementation of targeted policies designed to improve SAF market penetration.

Among the many methods that may be employed to ensure growth in the SAF industry, here are several for consideration. While all these recommendations are helpful, some are more powerful than others. Therefore, the recommendations below are ordered from most to least effective.

- Implement targeted mandates that direct the use of SAF. The strongest incentive is a mandate, like the one recently enacted in Norway. The Norwegian policy would be even stronger if it had included annual escalations of the SAF mandate above 0.5 percent. In addition to national policies, SAF mandates could also be enacted by local governments in high-pollution areas to reduce sulfur and particulate emissions near major airports, as part of a comprehensive program to improve local air quality.
- Ensure existing policy-incentive frameworks originally designed to incentivize biofuel use in ground-transportation networks are modified in a way to prioritize aviation-biofuel use. Implement stronger financial incentives that favor sustainable aviation-fuel production and use over ground and maritime transportation biofuels. Ground and maritime transportation both have more optionality in the sustainable and renewable energy markets.
- Derisk investments into sustainable aviation-fuel production plants by implementing long-term policies that incentivize SAF production and use. Policy time-frames should be chosen that match return-on-investment time-frames, usually ten to twenty years to reduce investment risk. Seek opportunities for public-private partnerships for sustainable aviation-fuel production, offtake, and supply chains to distribute investment risk.
- Continued support for sustainable aviation-fuel research and development, including development of feedstock supply chains, new and innovative production technologies, and development of innovative business models that increase the value of all products and by-products of SAF production operations.

The decade since 2008 has laid a good foundation for SAF. The next decade has the potential to be transformative as the aviation industry and others begin to grapple with the effects of climate change. SAF, and biofuels in general, are a potential lever that can be used to mitigate GHG emissions in the transportation sector.

ABOUT THE AUTHOR



David Hitchcock has an extensive background in both aviation and clean energy technologies. He began his professional career in the US Marine Corps as an F/A-18 Hornet fighter pilot. He amassed over 3,000 mishap-free flight hours in tactical jets, including service in Europe and East Asia, two combat tours to the Middle East, and command of the Marine Corps' largest flying squadron. Since leaving the Marines, David has held leadership positions in three innovative cleantech companies, spanning the automotive, biofuel and biochemicals, and waste-to-energy industries. Currently a managing partner of Watershed Strategy LLC and affiliated with the Mabus Group, he provides consulting services to clients in the energy, petrochemical, agribusiness, and government services sectors. David and his wife reside in rural Virginia, and in his spare time he teaches flying at a local airport. David holds a BSc from the US Naval Academy and a MA from the US Naval War College.

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