

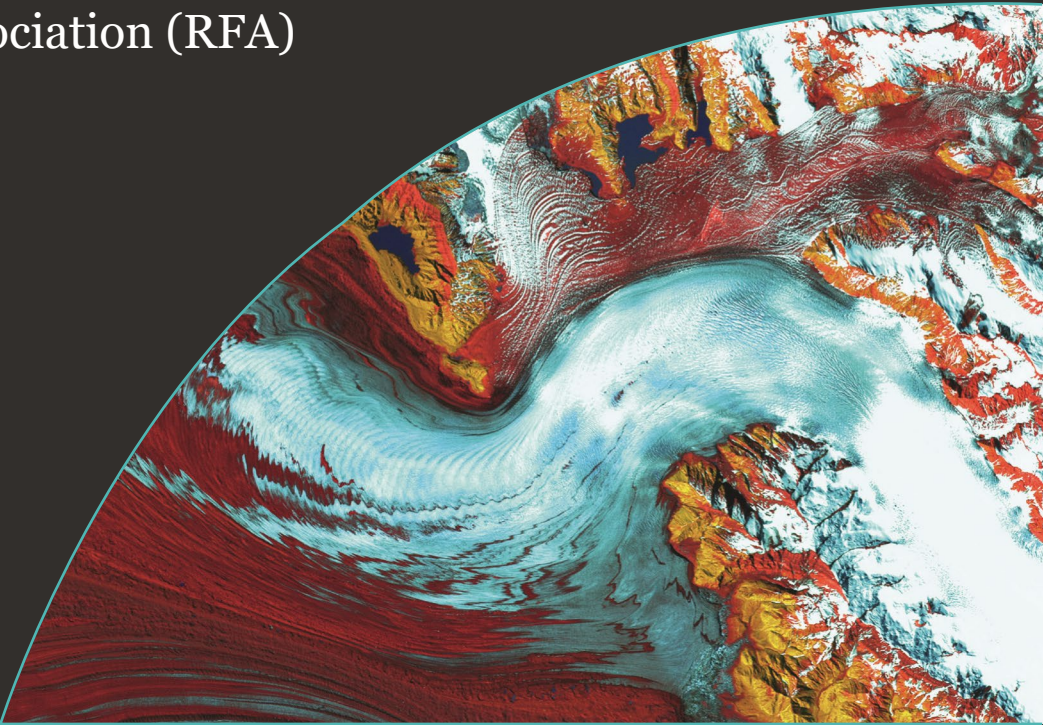
Outlook for Ethanol-to-Jet (ETJ)- Based SAF Demand, ETJ Process Technology, and the Effects on Corn Demand and Prices

Prepared for:
Renewable Fuels Association (RFA)
Topic 3 Report

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Section E: Executive Summary

The Current Sustainable Aviation Fuel (SAF) Production Process: Today, the only continuously operating commercial-scale SAF production process technology is the one that hydrogenates and isomerizes various seed oils (such as soybean oil) and waste animal fats and cooking oils. The process technology is commonly called the hydrogenated esters and fatty acids (HEFA) route.

Today's SAF Production Costs: The levelized cost of SAF produced using the HEFA technology is significantly more expensive than the similar cost of production for jet fuel derived from petroleum. Based on recent data from the International Energy Agency (IEA) and the International Air Transport Association (IATA), the average price paid for SAF by worldwide airlines in 2023 was close to US\$5.88 per gallon (/gal). Based on EcoEngineers' calculations, this US\$5.88/gal value is close to a breakeven sales price for marginal (small scale) HEFA-type SAF refiners based on D4 Renewable Identification Number (RIN) prices, Low-Carbon Fuel Standard (LCFS) credit prices and Inflation Reduction Act (IRA) credit prices, circa January 2024. As a point of reference, the average 2023 wholesale price for petroleum-based jet fuel on the U.S. Gulf Coast (USGC) was \$2.70/gal.

Production Costs for Ethanol-to-Jet (ETJ)-Type SAF: There is, currently, a high level of uncertainty regarding what the levelized production costs¹ will be for a large-scale commercial ETJ production facility. Although multiple firms have licensed ETJ process technology to project developers, only a few developers have announced plans to build ETJ facilities. One small commercial facility is currently in start-up mode (LanzaJet) and multiple airlines have announced testing agreements and flights. No commercial-scale ETJ facilities are yet operating to make on-spec SAF on a 24/7 basis. Therefore, no one has a firm estimate of the full, levelized ETJ processing costs at any scale of operation. However, based on what is known today about the ETJ process technology and its likely range of potential total installed capital costs and operating costs and the yields (which appear to be significantly lower than the HEFA route yields), the full levelized production costs for ETJ-type SAF will likely be higher than for HEFA-type SAF.

Current SAF Demand Levels: In the year 2023, worldwide SAF demand levels were less than 0.2% of total worldwide jet fuel demand. About 75% of this demand was in the European Union (EU) and about 25% was in the United States (U.S.). SAF demand levels are low because (a) in 2023 there are still only a few HEFA-type plants that were configured and registered to make SAF, (b) based on available incentives, it was more profitable for most SAF producers to make renewable diesel (RD) versus SAF, (c) by the end of 2023, when D4 RIN prices dropped to within the \$0.60 to \$0.50/gal range, the levelized production costs for HEFA-type SAF, for many producers, were more than petroleum-based jet fuel after accounting for available RINs and LCFS credits, and (d) there are no significant mandates to

¹ A common definition of levelized production cost (LPC) is that it is a form of discounted cash flow analysis that estimates the annual cost of an investment per unit of product produced. The LPC defines the price that would have to be charged per unit of production to achieve a net present value (NPV) of zero for an investment. To build the appropriate project cash flow analysis model, all project and production costs must be accounted for such as total installed capital costs, full variable, and fixed operating costs, working capital, and sustaining capital, etc.

use SAF, and thus, no incentives for airlines to pay a higher price than petroleum-based jet fuel. (Table E.1)

Table E.1: Total Worldwide Jet Fuel and SAF Demand History (000 bbl/d)

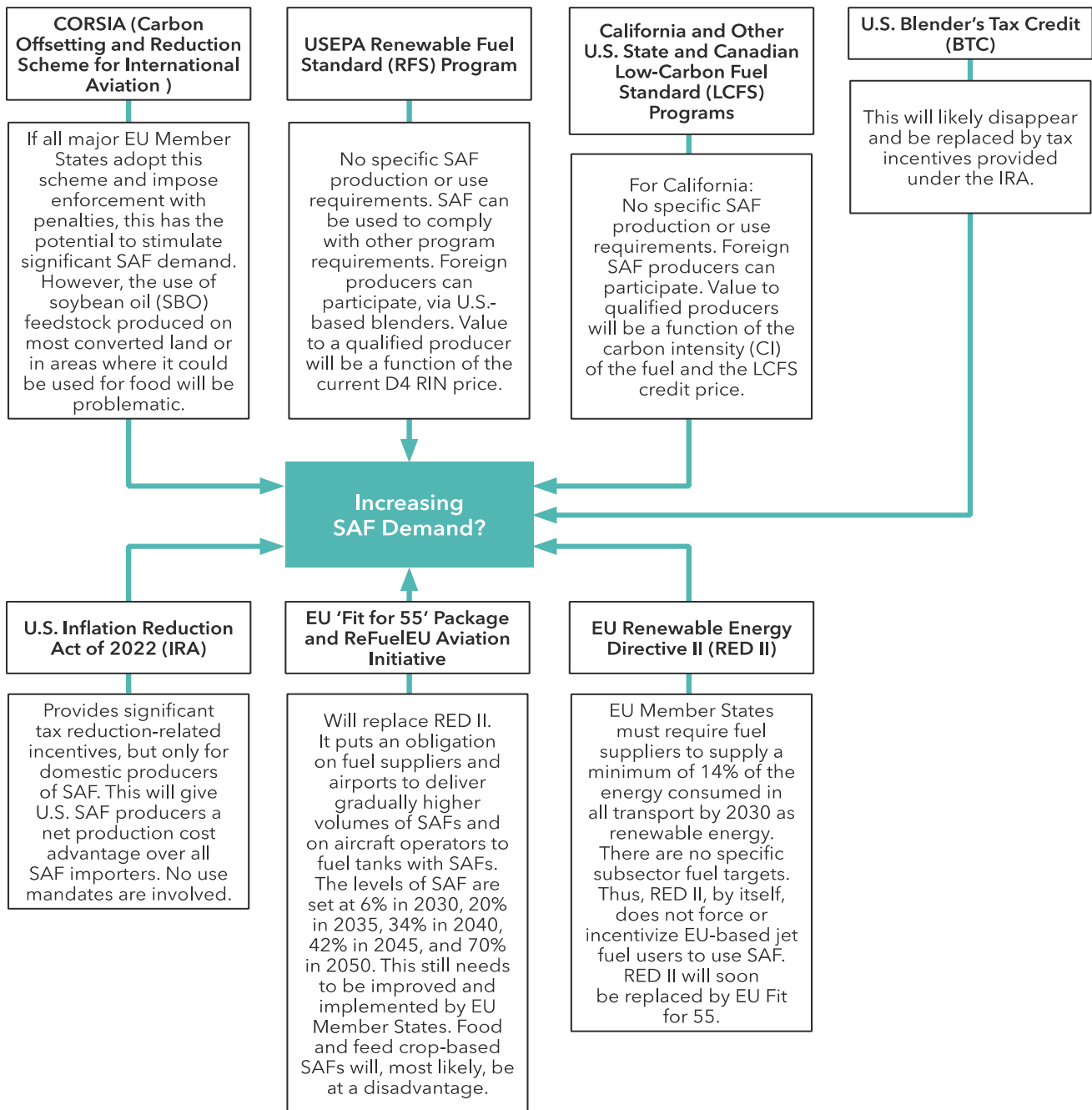
Year	2020	2021	2022	2023
Worldwide Jet Fuel Demand (From EIA)	4022	4310	5211	6128
Worldwide SAF Demand (From IEA)	0.95	1.82	8.05	10.36
SAF as a Percentage of Worldwide Jet Fuel Demand	0.02%	0.04%	0.15%	0.17%

SAF Demand Drivers, Regulations, and Mandates: Today, most of the regulations, mandates, and incentives that influence SAF demand originate in the U.S., the EU/UK, and non-governmental airline organizations. The main regulations and incentives that are likely to influence SAF demand are:

- U.S. Environmental Protection Agency’s (USEPA) Renewable Fuel Standard (RFS)
- Multiple LCFS programs
- EU Renewable Energy Directive (RED II)
- EU Fit for 55 (RED III)
- Carbon Offsetting and Reduction Scheme for International Aviation (CORSA)
- U.S. Blender’s Tax Credit (BTC)
- IRA

EcoEngineers will explain these regulations and mandates in more depth in this report. A concise summary of these drivers is provided below (Figure E.1).

Figure E.1: A Summary of SAF-Related Policy Drivers



– EcoEngineers

Forecasts for Worldwide SAF Demand: EcoEngineers explains two benchmark SAF demand forecasts from the IEA and we also describe our own recommended SAF demand forecast. (Table E.2 and Figures E.2 and E.3)

EcoEngineers' demand forecast is based partially upon the analysis of the two IEA cases. We believe that the primary driver for SAF demand growth will be the cost of jet fuel to the airlines. The ultimate SAF cost to the airlines will be the levelized cost of production plus logistics (including a small amount of profit for the SAF producers), net of all credits available. Over the 10-year forecast period, SAF demand will grow at a compound annual growth rate (CAGR) of 40%. This is very close to the remarkable CAGR for worldwide RD demand growth over the 2010-2021 period.

We believe that new SAF production process technology development that translates to lower costs per gallon of jet fuel produced will proceed at a slower rate than the IEA expects in its "Accelerated Case". This is applied to the ETJ route, the gasification routes, the E-fuel routes (including methanol-to-jet fuel), the pyrolysis routes, and the algae-based routes. We believe that the ATJ route will become the first alternate SAF production route to become competitive with HEFA-based SAF.

Most likely, the HEFA route will remain the main source of SAF volumes over the 10-year forecast period. HEFA route feedstock costs will rise slower than many market analysts expect. However, ETJ-based SAF production will most likely evolve to become cost-competitive with HEFA-based SAF over the 10-year forecast period. By 2033, SAF will, most likely, account for approximately 4% of all jet fuel used. In 2033, the majority of this SAF will still, most likely, be produced via the HEFA route and approximately 25% will be produced via the ETJ route. We see a gradual increase in the use of low-carbon intensity (CI) hydrogen in HEFA-based SAF production facilities. Low-cost carbon capture and storage (CCS) technology may just be appearing as a cost-effective add-on to SAF production trains near the end of the forecast period.

The world's economies and political systems will not be able to support the costs for SAF production routes that have production costs that are 3x-7x that of petroleum-based jet fuel. Policymakers in the U.S. and EU may learn that innovation (in terms of the development and commercialization of new, game-changing fuel, battery, or vehicle technologies) cannot be legislated. Some high-profile SAF production projects based on pyrolysis, E-fuels, ATJ, gasification plus Fischer-Tropsch (FT), algae, and pyrolysis-based technologies will shutter before the engineering/construction phase. However, there is always some potential for a process technology breakthrough in all of these routes.

We expect that the current 75/25 ratio of SAF use in the EU/UK versus the U.S. will gradually shift to close to a 60/40 ratio over the 10-year forecast period. In this report, EcoEngineers explains the negative and positive risks to its SAF demand forecast.

Table E.2: Jet Fuel Demand History and IEA's and EcoEngineers' Jet Fuel Demand Forecasts (000 bbl/d)

Year	2020	2023	2025	2028	2033
Worldwide Jet Fuel Demand (Including EIA Forecast)	4,022	6,128	6,623	7,117	7,890
CAGR (Compound Annual Growth Rate) Over the Forecast Period					2.6%

IEA Main Case Scenario					
Worldwide SAF Demand	0.95	10.4	47.1	90.3	167.9
CAGR Over Forecast Period					32%
SAF as a Percentage of Worldwide Jet Fuel Demand	0.02%	0.17%	0.71%	1.27%	2.13%
Worldwide Ethanol Demand if ETJ Provides 13% of SAF Supply in 2027 and 20% in 2033	0.2	2.2	10.2	19.6	56.0

IEA Accelerated Case Scenario					
Worldwide SAF Demand	0.95	10.4	92.1	256.5	625.8
CAGR Over Forecast Period					51%
SAF as a Percentage of Worldwide Jet Fuel Demand	0.02%	0.17%	1.39%	3.60%	7.93%
Worldwide Ethanol Demand if ETJ Provides 13% of SAF Supply in 2027 and 20% in 2033	0.2	2.2	20.0	55.6	208.6

EcoEngineers' Scenario					
Worldwide SAF Demand	0.95	10.4	65.0	145.4	302.1
CAGR Over Forecast Period					40%
SAF as a Percentage of Worldwide Jet Fuel Demand	0.02%	0.17%	0.98%	2.04%	3.83%
Worldwide Ethanol Demand if ETJ Provides 10% of SAF Supply in 2027 and 25% in 2033	0.2	2.2	14.1	31.5	125.9

(The IEA forecasts are from the IEA's Renewable 2023 Report. Jet fuel demand history is from the EIA. The EIA forecast is from the EIA's World Energy Outlook, 2023.)

Figure E.2: Worldwide SAF Demand Forecasts

(000 bbl/d)

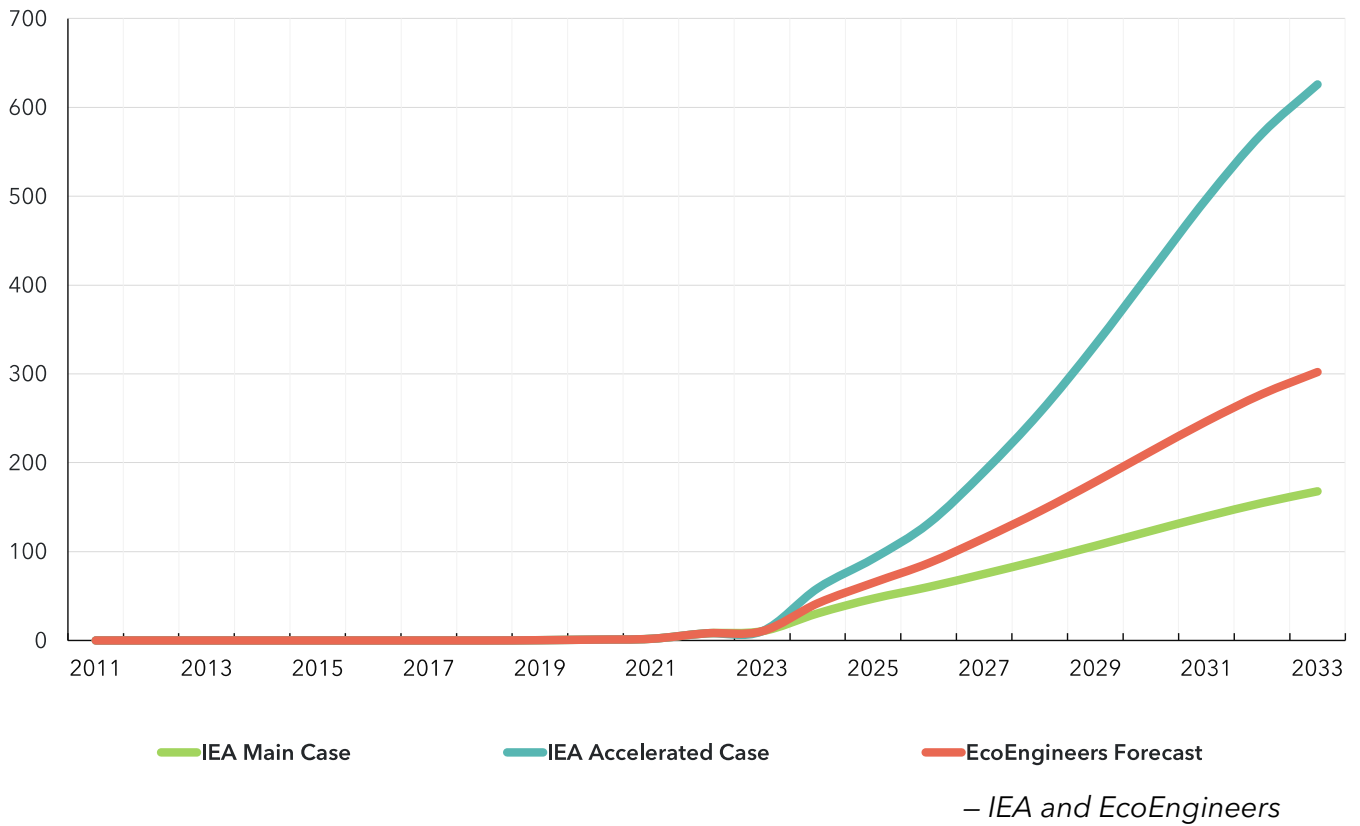
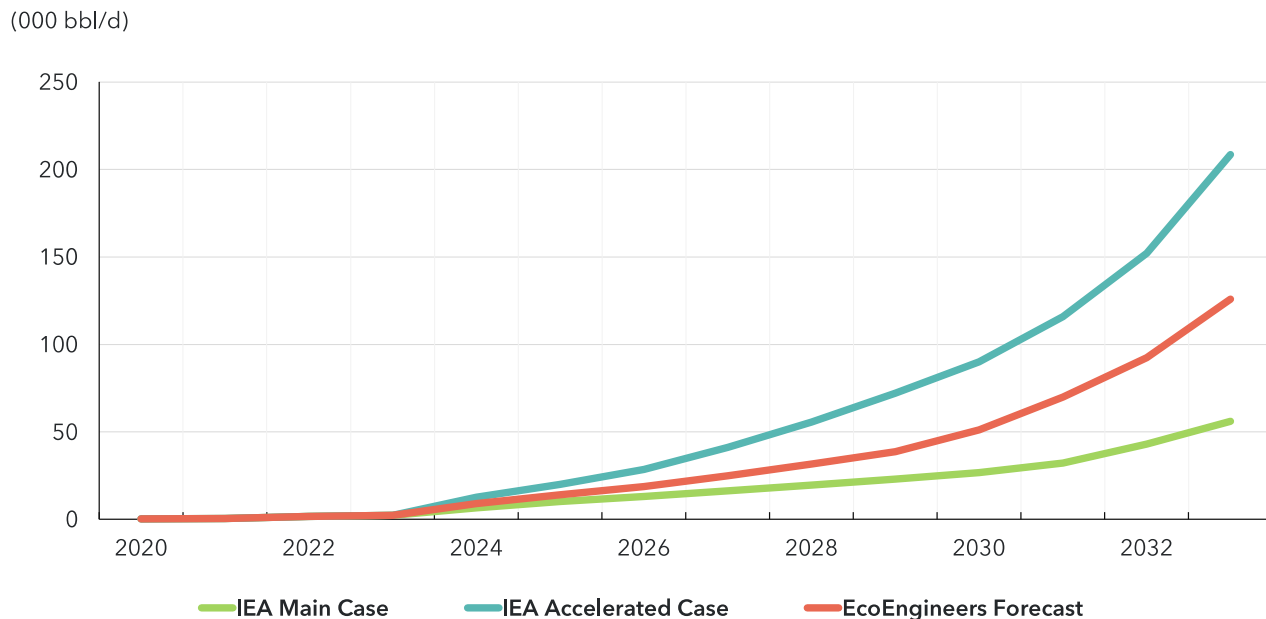


Figure E.3: Worldwide Ethanol Demand Corresponding to ETJ SAF Worldwide Demand Scenarios



– IEA and EcoEngineers

What Can Participants in the ETJ Route Do to Make the Route More Competitive?

- Build the ETJ facilities as large as possible to reduce fixed costs per barrel (/bbl).
- Consider placing large and efficient ETJ facilities in a spoke-in-wheel arrangement near the center of multiple ethanol production sites.

The Most Likely Geographic Location of ETJ Producers: EcoEngineers believes that the U.S. is the most likely location for ETJ producers due to its advantages in terms of low-priced corn-based ethanol production.

The Potential Effects of ETJ Technology on Corn Supply and Demand, and Corn Prices: Over the 10-year forecast period, EcoEngineers believes that ETJ-based SAF demand will not - by itself - result in significant changes in corn prices.

The Potential Effects of the ETJ Technology on North American Land Use: Over the 10-year forecast period, EcoEngineers believes that ETJ-based SAF demand will not—by itself—result in problematic changes in land use for corn production.

Land-Use Change Effects

Predicting the impact of additional ethanol production (for SAF) upon US land use poses significant challenges due to the complex interplay of various factors. Nonetheless, on the basis of fundamental assumptions and insights from recent history and existing research, it is possible to estimate a range of possibilities for the next decade.

The effects of the RFS on land use can be used as a guide to help predict the impact of SAF demand on ethanol production and associated land use. Also, an estimate of future US corn yield per acre can be used to predict the impact of SAF demand on ethanol production and associated land use.

EcoEngineers created two scenarios to bracket the range of potential effects of increased demand of ethanol for SAF on required corn acreage. The two scenarios are based on the EcoEngineers 2033 forecast for ETJ SAF demand (in Section 5 of this report) and two different approaches to estimating corn acreage requirements:

1. The “0.41 million acres per billion gal of additional ethanol ratio.” (This ratio was developed from an EPA-Commissioned study that evaluated the effects of the RFS introduction in 2007 upon US corn acreage increases.)
2. The estimated U.S. corn yield per acre in 2033, based on year 2022 yield levels and the average yearly increase in yield over the 2000 to 2022 period.

This approach resulted in an estimated range of between 0.52 to 0.07 million additional corn acres required in 2033. This would equate to an increase, in 2033, of between 0.6% and 0.08% above the 2023 U.S. corn acreage levels.

The Competitive Position of North American Ethanol Producers: Today and in the near term, Brazil is the only country that has the potential to realistically compete with U.S. ethanol production over the next decade and possibly export ethanol to the U.S. if U.S. ethanol demand surges and if Brazilian government policy allows it.

However, cultivating new Brazilian land for ethanol export may result in higher CI scores for Brazilian ethanol. To compensate, Brazil could employ CCS to lower the CI score of its ethanol. However, overall, the U.S. appears to be better positioned to fill a growing demand for low-CI ethanol by using available farmland in combination with CCS and available carbon dioxide (CO₂) storage sites.

Competition from Battery-and Hydrogen-Powered Flight: HEFA-type SAF and, eventually, ETJ-type SAF are seen by most market and process technology experts as the most promising ways to directly reduce greenhouse gas (GHG) emissions in the aviation sector over the next five to 10 years. This is unlikely to change unless there are significant process technology breakthroughs or breakthroughs related to the use of battery-powered or hydrogen-powered flights.

The Potential for Battery-Powered Flight: For battery-powered flight, the critical issue is energy density. Kerosene has a specific energy density of 11,944 watt-hours per kilogram (Wh/kg). The energy density of today’s lithium-ion (Li-ion) batteries is around 200 Wh/kg (with a current practical limit of 300-400 Wh/kg) at the battery pack level. For short-haul flights over 1,000 kilometers (km) (621.4 miles), a battery pack energy density of at least 800 Wh/kg would be needed. The electric vehicle (EV) industry is investing in considerable research to create lighter batteries with higher energy densities, utilizing new materials and new chemistry. Emerging technologies include lithium-sulfur and sodium-ion batteries. These options may eventually lower costs by using more abundant (cheaper) raw materials and/or by improving energy density, but neither approach appears to be a viable alternative today

or in the near term. EcoEngineers' opinion is that, given the current state of battery technology and battery system R&D, it is unlikely that any long-distance, commercially viable air travel using batteries will occur within the following decade.

The Potential for Hydrogen-Powered Flight: For hydrogen-powered flight, the issue is the requirement for high fuel storage volume, which takes away from space that could be used to carry cargo and people. Liquid hydrogen stores approximately 2.9 times more energy than kerosene by weight. However, concerning volume, the energy density of kerosene is estimated at around 35 megajoules per liter (MJ/L), a value approximately four times larger than that of liquid hydrogen, which ranges from 8.5 to 10 MJ/L. This consideration will require a redesign of conventional airframes. Whether employed in a turbine engine or a fuel cell, hydrogen takes up considerably more space per unit of energy than kerosene and cannot be stored in the wings. However, in the longer term, hydrogen-powered flight shows the best potential for practical application in the aviation sector for mid-range and, perhaps, longer-range flights. As this technology continues to develop and gain traction, it is likely to gain a small market share in regional air travel markets, perhaps by the end of the forecast period.

Section 2: Introduction

EcoEngineers has been commissioned by the Renewable Fuels Association (RFA) to provide an analysis of the potential impacts of the sizable expansion in the production and processing of ethanol into SAF, including effects on the supply, demand, price of corn, and the implications of land use.

EcoEngineers' scope for this project is as follows:

1. Provide a 10-year outlook scenario for North American and worldwide SAF supply and demand and prices. Include an explanation of the regulations, mandates, incentives, and tariffs that will likely drive SAF-related ethanol demand and trade patterns.
2. Explain the different major process technology routes to SAF and rank their potential use over the forecast period.
3. Provide an outlook for large-scale commercial use of the ETJ processing route over a 10-year timeline.
4. Provide an outlook on the most likely geographic location of ETJ producers.
5. Explain and analyze the potential effects of ETJ technology on corn supply and demand and corn prices in North America over a 10-year timeline. This analysis will incorporate an evaluation of the competing demand for North American corn use.
6. Consider the potential for the use of alternate feedstocks for ethanol production.
7. Explain and analyze the potential effects of the ETJ technology on North American land use and related issues.
8. Deliver an outlook on the competitive position of North American ethanol producers versus ethanol producers in South America, Europe, and Asia, in terms of providing feedstocks to the major likely ETJ facilities.

9. Comment on the probability of battery-powered and hydrogen-powered flights as competition to ETJ commercial technology routes.

Section 3: SAF Supply, Demand, and Price History

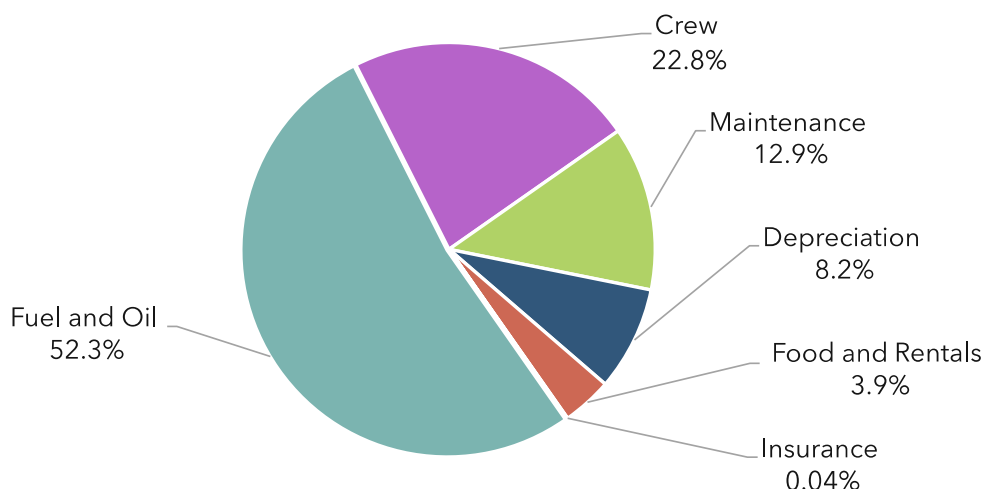
Chapter 3.1: Today's Flight Operating Costs

Jet fuel production cost and its effect on flight costs is a key issue related to SAF use.

Petroleum-based jet fuel and lubricating oil costs are the number one operating costs of modern jet flights (Figure 3.1). In the "Fuel and Oil" category shown in Figure 3.1, jet fuel costs account for more than 95% of the total amount.

This is an important cost breakdown to keep in mind when considering that, based on today's status of production process technologies, current SAF costs are estimated to be between 2x-7x² higher than petroleum-based jet fuel, depending on the SAF production method and feedstock used.

Figure 3.1: Breakdown of Typical Flight Costs (2023)



– U.S. Federal Aviation Administration (FAA) 2023

[Basis for operating cost breakdown: 2023 U.S. Federal Aviation Administration (FAA) analysis of costs for a typical U.S. widebody jet flight with over 300 passengers. This analysis does not include landing fees, gate fees, and other airport and government taxes.]

² This is based on the year 2023 status of various process technologies.

Of course, as oil prices and, thus, jet fuel prices rise and fall, as they are likely to do over the two-year forecast period, the proportion of jet fuel costs as a function of total costs will change.

However, based on this 2023 cost analysis, if SAF jet fuel costs are 2x higher than petroleum jet fuel costs, airline ticket prices would need to rise by approximately 50% for the airlines to maintain their thin operating margins. Likewise, if SAF jet fuel costs are 4x higher than petroleum jet fuel costs, airline ticket prices would need to rise by approximately 150%. If SAF jet fuel costs are 7x higher than petroleum jet fuel costs, airline ticket prices would need to rise by approximately 300%. The potential effect on the demand for airline tickets would certainly fall as SAF costs to the airlines (net of production credits) increase.

Chapter 3.2: Definition of SAF

SAF can be made from the same non-petroleum feedstocks that are used to make renewable diesel (RD). For the hydrogenated vegetable oil (HVO) (or HEFA) route to making SAF, producers can use the same process technology that is used to make cold weather-compatible RD.

Today, nearly all SAF is produced from seed oils, fats, and greases via the HEFA production route. To make HEFA-type SAF, the hydrogenation, isomerization, and fractionation processes that are used to make arctic RD are operated at slightly different conditions to make lighter, freeze-resistant kerosene that meets American Society for Testing and Materials (ASTM) specifications for jet fuel.

SAF is considered a “drop-in” fuel, meaning that once blended with conventional jet fuel, the fuel blend is fully compatible and fungible with existing infrastructure and jet engines.

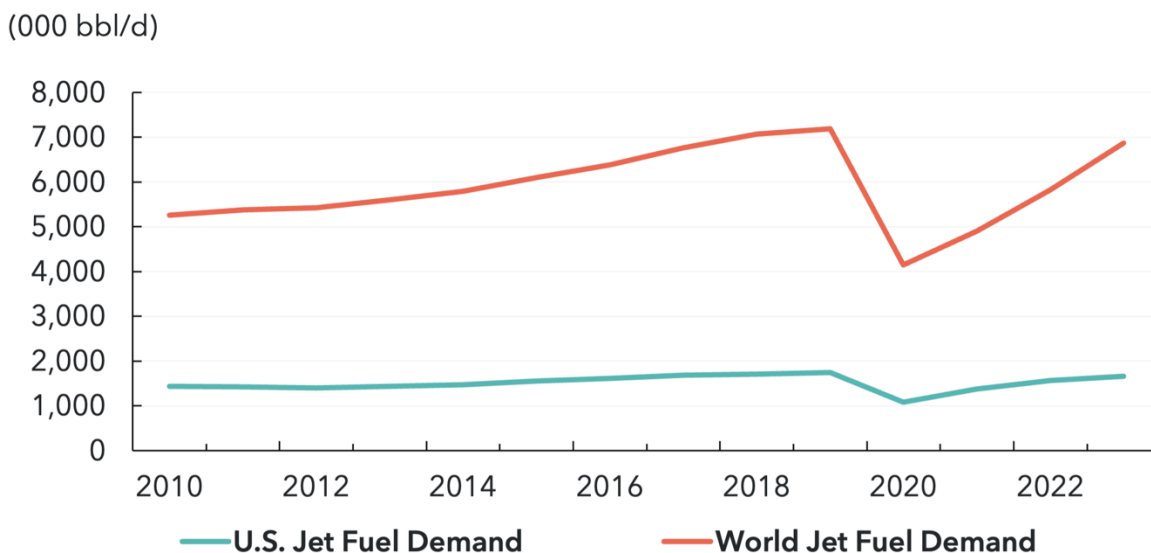
Based on current allowances, SAF can be blended at different levels (with petroleum-based jet fuel) with limits of 10%-50%, depending on the feedstock and how the fuel is produced. These blend levels may increase in the future as more experience with SAF use is gained.

Chapter 3.3: Traditional Jet Fuel and SAF Demand History

Over the 2010-2019 period (before the COVID-19 pandemic), the CAGR of worldwide jet fuel demand was 3.5%. The CAGR for U.S. jet fuel demand was 2.2%.

Since air travel declined dramatically due to the pandemic in 2020, the demand growth (per year) for jet fuel has been high as historical jet travel demand levels have since gradually returned to pre-pandemic levels (Figure 3.2).

Figure 3.2: Worldwide and U.S. Jet Fuel Demand (Yearly Average Data Through 2023)



—IEA and EIA

If recent annual average growth rates continue and if jet fuel prices (and airline ticket prices) do not increase significantly, U.S. and worldwide jet fuel demand could reach 2019 levels by 2025 or 2026. Once worldwide jet fuel demand returns to 2019 levels, whether worldwide demand growth again reaches the pre-COVID levels will mainly be a function of the following:

- The rate of air travel demand growth in India and China.
- The average price of jet fuel.
- Worldwide gross domestic product (GDP) growth.

Over the long run, jet fuel supply is essentially equal to demand as yearly average storage inventories for jet fuel change significantly from year to year.

To date, the demand levels for SAF worldwide have remained relatively low. In 2023, less than 0.2 %vol of worldwide jet fuel demand was SAF-type fuel. About 75% of the year 2023 demand originated in the EU and about 25% was in the U.S.

SAF demand levels are low because: (a) in 2023 there are still only a few HEFA-type plants that were configured and registered to make SAF, (b) based on available incentives, it was more profitable for most SAF producers to make RD versus SAF, (c) by the end of 2023, when

D4 RIN prices had dropped to within the \$0.60 to \$0.50/gal range, the levelized production costs for HEFA-type SAF, for many producers, after accounting for all RIN and LCFS credits, were more than petroleum-based jet fuel, and (d) there are no significant mandates to use SAF and, thus, there are no incentives for airlines to pay a higher price than petroleum-based jet fuel for SAF.

Table 3.1: Total Worldwide Jet Fuel and SAF Demand History (000 bbl/d)

Year	2020	2021	2022	2023
Worldwide Jet Fuel Demand (From EIA)	4022	4310	5211	6128
Worldwide SAF Demand (From IEA)	0.95	1.82	8.05	10.36
SAF as a Percentage of Worldwide Jet Fuel Demand	0.02%	0.04%	0.15%	0.17%

Nearly all of the SAF used to date (in the U.S. and the EU) has been produced via the hydrogenation of seed oils (such as soybean oil and rapeseed oil), animal fats, distiller's corn oil (DCO), and used cooking oil (UCO). SAF and RD are manufactured via the hydrogenation of seed oils, fats, and grease, and belong to the HEFA product category.

The HEFA route is not the only way to produce SAF. Five alternative routes for SAF production have passed the proof-of-concept stage and all are currently in varying stages of process and commercial development: These alternative routes include:

1. ATJ

- Either ethanol, isobutanol, or n-butanol could be used as a feedstock.
- LanzaJet and Gevo are examples of firms developing this type of processing route. LanzaJet recently started up its first small commercial facility in Georgia. EcoEngineers considers LanzaJet to be in the commercial pilot stage.

2. Gasification + FT + Hydrotreating

- Sorted municipal solid waste (MSW) or biomass material would be typical feedstocks.
- Fulcrum BioEnergy and DG Fuels are examples of firms developing this type of processing route. Both firms are at the commercial pilot stage.

3. Pyrolysis + Hydrotreating

- Waste cellulosic material would be a typical feedstock.
- Pyrocell and Alleo Energy are examples of firms developing this type of processing route.

4. E-Fuels

- Captured CO₂ and hydrogen (H₂) produced via electrolysis (powered by wind or solar) would be the typical feedstocks.

- Infinium and HIF Global are examples of firms developing this type of processing route.

5. Algae-Based, Either Via a Hydrothermal Route or Via Direct Production of Fats

- a. Viridos is an example of a company developing this type of processing route.

Why is SAF Demand So Low in 2023? Based on what EcoEngineers hears from clients and learns from its project work, there are currently three main drivers for the low SAF use levels: (1) low levels of certified production capacity, (2) it had been more profitable for most U.S.-based HEFA-type plants to make RD and sell it in California, and (3) no mandates exist for airlines to use SAF. Currently, available credits and other incentives (e.g., the IRA, the Production Tax Credit, or PTC, LCFS credits, and/or RINs) are not fully bridging the price gap between SAF and petroleum-based jet fuel. The main issue has been the drop in D4 RIN values.

We expect SAF's availability issue to improve slightly in the near term as more U.S.-based HEFA-type RD/SAF facilities start up and complete their SAF production process registrations with government agencies. However, if D4 RIN prices remain at current levels, justifying new investments may prove to be difficult, especially for non-HEFA-type facilities.

In the U.S., there is some potential that the U.S. IRA incentives, once they are fully defined, will increase the odds of large-scale SAF commercialization if the incentives help to close the gap between petroleum-based jet fuel production costs and SAF production costs. The IRA 45Z incentive, starting in 2024, provides a potential US\$0.75/gal benefit for SAF over RD.

In the EU, some new regulations and mandates may increase the demand for SAF use. These will be explained in Section 4 of this report.

SAF Demand is a Cyclic Issue. SAF producers need to charge high \$/gal to cover their levelized production costs (net of credits and other potential incentives), including a reasonable return on investment. This leads to requests for long-term offtake agreements to cover the SAF project through the investment payback period. Unless airlines or other RD/SAF offtakers are willing to sign these long-term offtake agreements, the project developers and their investors will have a harder time justifying the large investments. Even if they do decide to build, they will probably lean towards building smaller-scale facilities that will have less risk exposure but will deliver higher per-bbl levelized costs of RD/SAF products.

EcoEngineers recognizes there are multiple SAF production facilities in the process of completing their registrations for SAF production and they will, most likely, come online soon. That will, presumably, help to relieve some of the SAF availability issues. However, these new facilities will also put upward pressure on the feedstock prices used to make HEFA-type SAF.

We do not expect the production cost issue to improve in the near term (2024-2025 period). Today, HEFA-type SAF products are close to being on the same levelized cost level (after credits) as petroleum-based jet fuel. However, we see HEFA-type feedstock costs increasing with rising demand.

Regarding the ATJ route, reliable estimates of long-term levelized costs of production for this SAF product are not yet known. No commercial-scale facilities are yet operating with ATJ technologies that have been developed by UOP/Honeywell, Axens (Jetanol), Lanzajet, etc.

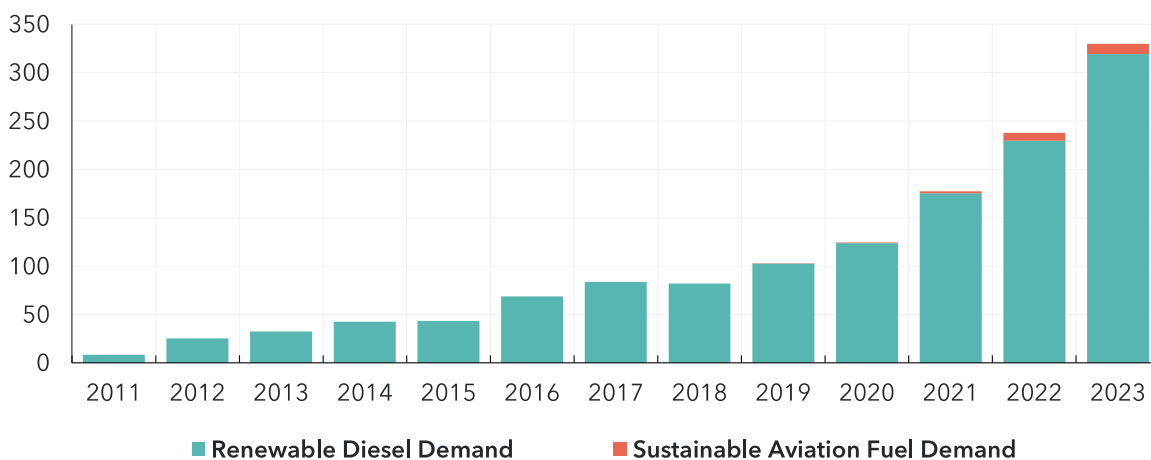
Confirmed SAF Production (Q4 2023): Per the International Air Transport Association (IATA), at least eight facilities are known to be producing some quantities of SAF in Q4 2023. Actual production volume rates are held as confidential information.

Commercial Production Validated by the IATA (Actual Volumes Proprietary)

1. Calumet/Montana Renewables (Montana, USA) - HVO
2. World Energy (Paramount, CA, USA) - HVO
3. Marathon (Martinez, CA, USA) - HVO
4. Eni (Livorno, Italy) - HVO
5. P66 (Lincolnshire, UK) - HVO
6. Repsol (Cartagena, Spain) - HVO
7. Neste (Singapore) - HVO
8. Neste (Porvoo, Finland) - HVO

Demand for RD Has Been Growing Faster Than for SAF: Currently, in the U.S., RD production via the HEFA pathway is usually more profitable than SAF production due to better credits

(000 bbl/d)



available for RD and the higher production costs for SAF. (Figure 3.3)

If SAF production costs gradually decrease, if production incentives improve, and if use mandates (with significant penalty enforcement) increase, SAF demand levels should increase. In 2023, approximately 80% of worldwide SAF production was consumed in the EU/UK and 20% in the U.S.

Figure 3.3: Renewable Diesel and SAF Worldwide Historical Demand

Section 4: SAF Demand Drivers: Regulations and Mandates

Before we explain and summarize the forecasts for SAF demand, we will summarize the multiple regulations and mandates that are the foundation for the demand forecasts. The majority of regulations, mandates, and incentives that will influence SAF demand originate in the U.S., the EU/UK, and within international non-governmental airline organizations. The main regulations and incentives that are likely to influence SAF demand are summarized below:

- **Renewable Fuel Standard (RFS)**
 - Administered by the U.S. Environmental Protection Agency (USEPA)
- **Multiple Low-Carbon Fuel Standard (LCFS) Programs**
 - Such as in California, Washington, Oregon, etc.
- **EU Renewable Energy Directive (RED II and RED III)**
- **EU “Fit for 55”**
- **Carbon Offsetting and Reduction Scheme for International Aviation (CORSA)**
- **U.S. Blender’s Tax Credit (BTC)**
- **U.S. Inflation Reduction Act (IRA)**

Chapter 4.1: A Summary of SAF-Related Policy Drivers

Figure 4.1 summarizes the current policies that are affecting and will affect SAF production and use.

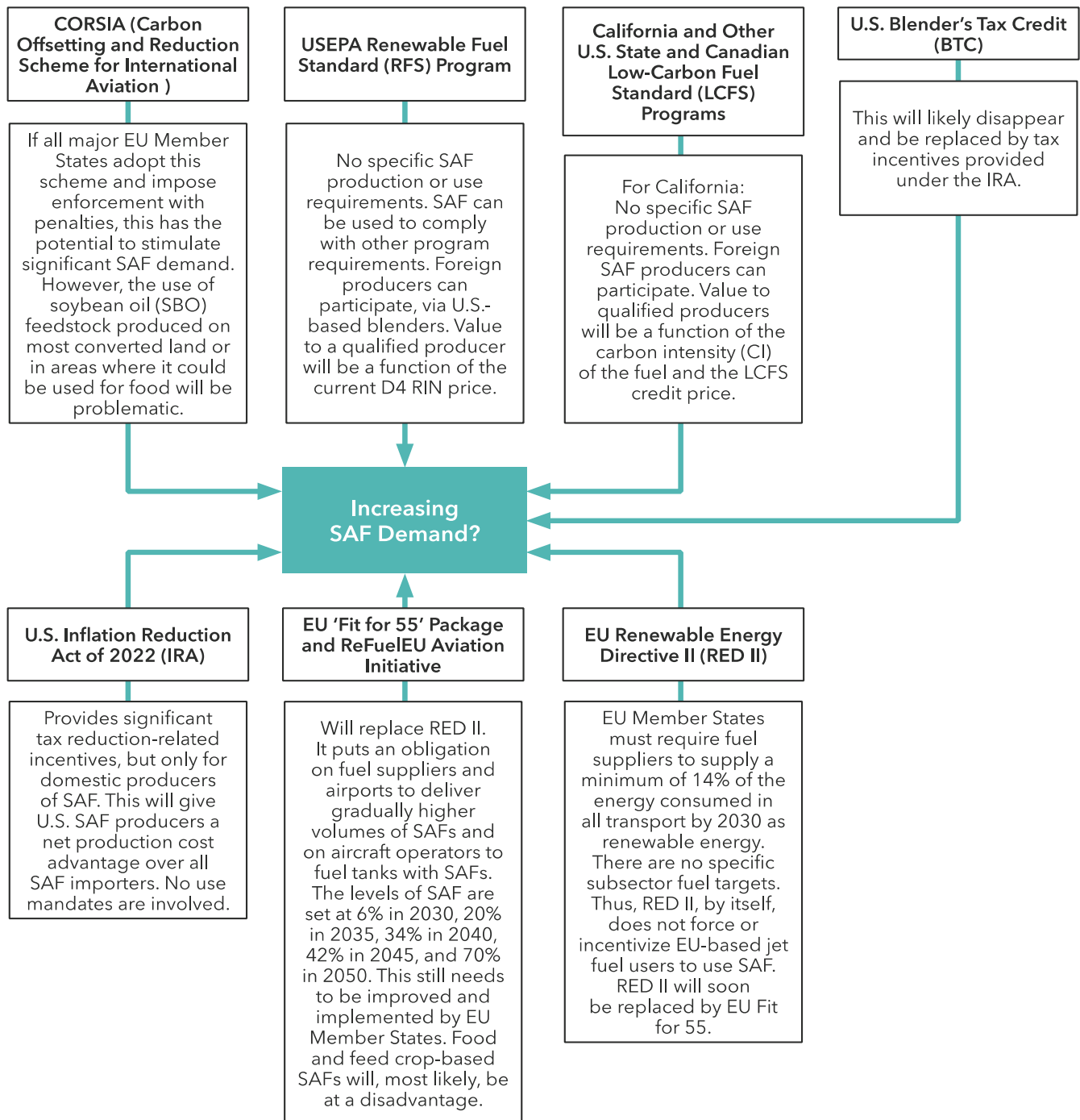


Figure 4.1: A Summary of SAF-Related Policy Drivers

– EcoEngineers

Chapter 4.2: The USEPA RFS Program and SAF

The RFS program was created under the U.S. Energy Policy Act of 2005 (EPAAct), which amended the Clean Air Act (CAA). The Energy Independence and Security Act of 2007 (EISA) further amended the CAA by expanding the RFS program. The USEPA implements the program in consultation with the U.S. Department of Agriculture (USDA) and the U.S. Department of Energy (DOE).

The RFS program is a national policy that requires a certain volume of renewable fuels to replace or reduce the quantity of petroleum-based transportation fuel or heating oil. The four renewable fuel categories under the RFS are biomass-based diesel (D4), cellulosic biofuel (D3), advanced biofuel (D5), and total renewable fuel (D6).

RIN Trading and Price Setting: When renewable fuel is produced, the respective Renewable Identification Number (RIN) is generated and the producer usually transfers the title to the renewable fuel and RINs at the same time the fuel is sold. These RINs are assigned to the renewable fuel. Usually, the price of the RIN is included in the sales price of the fuel. RINs can only be traded in the open market once they have been separated from the renewable fuel to which they were originally assigned. While there are specific circumstances under which a renewable fuel producer can separate RINs, the most common way is when it is blended into neat gasoline or diesel fuel. RINs from gaseous fuels like renewable natural gas (RNG) are handled differently and are currently immediately separated upon generation.

Separated RINs are traded in the open market, usually between non-obligated party blenders and obligated parties (i.e., oil refiners and importers of refined fuel products). There are also brokers and speculative traders in this market. The most commonly traded RINs are D-codes 4, 5, and 6, derived from the blending of biodiesel, sugarcane ethanol, and corn-based ethanol into diesel fuel or gasoline, respectively. The D3 RIN market is less liquid due to the significantly lower volumes of D3 RIN production. The price and payment terms for the sale and purchase of separated RINs are negotiated between parties and effectuated through the USEPA Moderated Transaction System (EMTS). Many companies report daily prices for each type of D-code RIN that is traded.

RIN prices often represent the marginal cost of producing and consuming the required volumes of each renewable fuel. Sometimes RIN prices can represent the cost to replace a shortage of one type of RIN with RINs for a higher nested category (as discussed previously). High RIN prices indicate a market perception that annual RVOs will be challenging to meet, while low RIN prices can signal the opposite market perception.

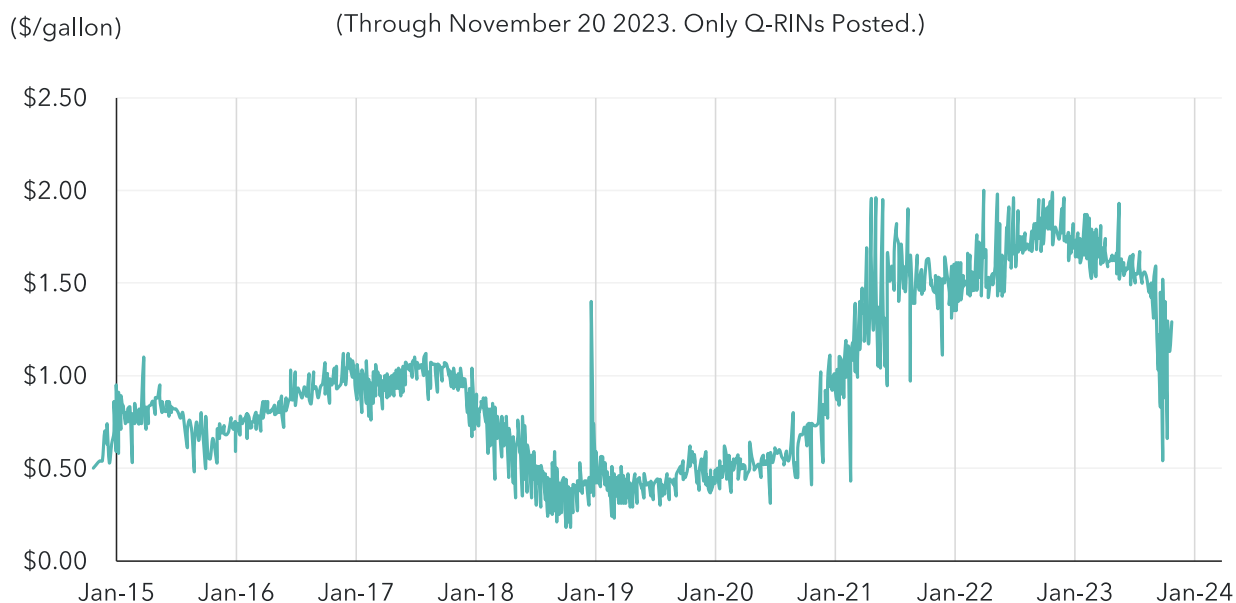
D4 RINs and SAF: D4 RINs apply to SAF use. SAF is referred to as an “opt-in” fuel under the RFS program, allowing SAF to generate compliance units (i.e., RINs) without aviation fuel-generating compliance obligations (often called renewable volume obligations, RVOs). This is a key point: there are no obligations to use specific volumes of SAF under the RFS.

RVOs: At the heart of the RFS are the RVOs, which dictate the amount of renewable fuel that obligated parties like gasoline and diesel refiners and importers must blend into the

transportation fuel supply in a given year. The USEPA sets annual RVO targets based on a percentage of the total volume of transportation fuel in the U.S. RVOs are further divided into four categories with each representing a different type of renewable fuel. Each of the categories has its own specific RVO, which together make up the total renewable fuel obligation. For 2023, the USEPA established the following RVOs for the following fuel categories:

- Conventional biofuel: 15 billion gallons
- Advanced biofuel: 5.82 billion gallons
- Cellulosic biofuel: 0.63 billion gallons
- Biomass-based diesel: 2.82 billion gallons

D4 RIN Price History: D4 RIN values have fluctuated between US\$0.50/gal and US\$2.00/gal



over the last two years. (Figure 4.2)

Figure 4.2: D4 RIN Price History

– U.S. Environmental Protection Agency (USEPA)

D4 RIN prices plummeted in 2023 due to an increase in RD production and a decline in the bean oil-heating oil (BO-HO) spread, an indicator describing the relationship between feedstock soybean oil and blendstock heating oil pricing used by the biodiesel and renewable diesel industries to gauge costs and margins. The increase in RD production led to an oversupply of D4 RINs in the market.

The increase in the D4 RIN supply due to the growth of RD production, paired with the nesting scheme of the RFS, has placed significant downward pressure on the price of D4 RINs and, consequentially, D6 RINs as well. The USEPA’s recent low RVOs for D4 RINs are also

leading to decreased RIN pricing. EcoEngineers believes this issue is likely to be sustained through 2025.

The decline in the BO-HO spread created more favorable blending economics for biomass-based diesel producers. A lower BO-HO spread will encourage fatty acid methyl ester (FAME) biodiesel and HEFA-type RD producers to maximize FAME biodiesel and RD production. In 2023, this was caused by a decrease in soybean oil prices and an increase in petroleum-based heating oil prices. The BO-HO- spread effect added to the downward pressure seen on RIN prices in 2023.

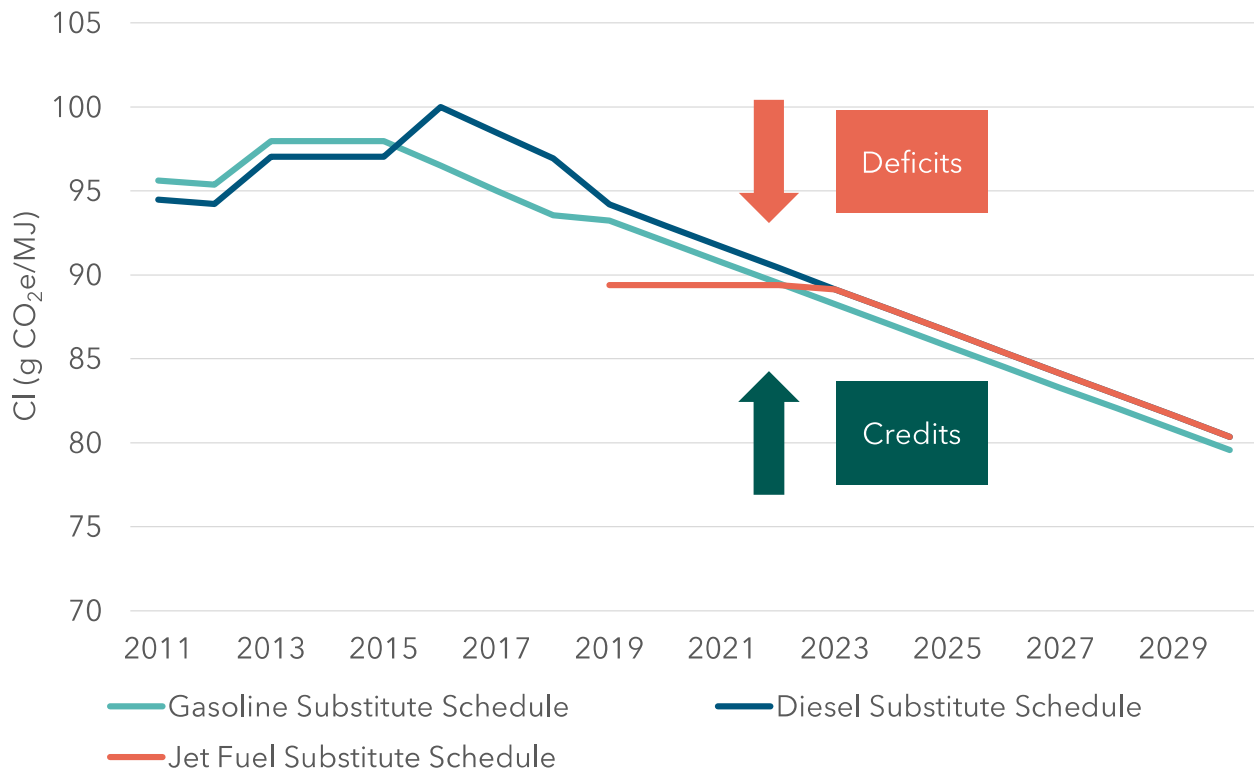
Chapter 4.3: LCFS Programs and SAF

California's Low Carbon Fuel Standard (CA-LCFS) was originally adopted in 2007, amended in 2011, and re-adopted in 2018 as a legislative tool to incentivize and regulate the carbon intensity (CI) reduction of transportation fuels within the state. The CA-LCFS was groundbreaking in that it was the first government program to value and credit fuels by their carbon emissions. The CA-LCFS has served as a template for many emerging state and federal LCFS-type programs.

LCFS Rules: The CI for transportation fuel is determined by measuring the CO₂ emissions during the fuel's lifecycle. One LCFS credit is equal to one metric ton of CO₂. The LCFS awards credits based on a produced fuel's CI score, therefore incentivizing lower CI fuels. For example, if landfill gas-derived RNG consumed in California has a CI score of 45 grams of CO₂ equivalent per megajoule (gCO₂e/MJ) and RNG produced from a municipal wastewater treatment plant has a CI score of 0 gCO₂e/MJ, then the RNG sourced from a wastewater treatment plant will generate approximately 45 more credits per megajoule of fuel compared to landfill RNG. RNG produced from manure-based digesters has—to date—received one of the lowest CI scores of any facility and fuel type, with digester scores as low as -400 gCO₂e/MJ. Electricity from dairy anaerobic digesters has even lower CI scores.

The number of LCFS credits a fuel receives depends on its CI score relative to the CI goal (in a given year) for the California fuel pool or compliance curve, which is seen in Figure 4.3. Compliance curves have been established for gasoline, diesel, and jet fuel. When a fuel has a CI score lower than the established compliance curve, it generates credits. Fuels with CI scores above the compliance curve generate deficits, and those deficits need to be satisfied by LCFS credits. It is advantageous to produce fuel with a lower CI score because the fuel can generate more credits under the LCFS program.

Figure 4.3: CA-LCFS Annual Compliance Schedule (2011-2030)



– CARB

The current CA-LCFS program provides credits for fuels that surpass a CI target that increases every year until 2030. The credit valuation formulas target a 20% GHG savings (from a 2010 baseline) by 2030, which could increase to 30% after 2030 or sooner.

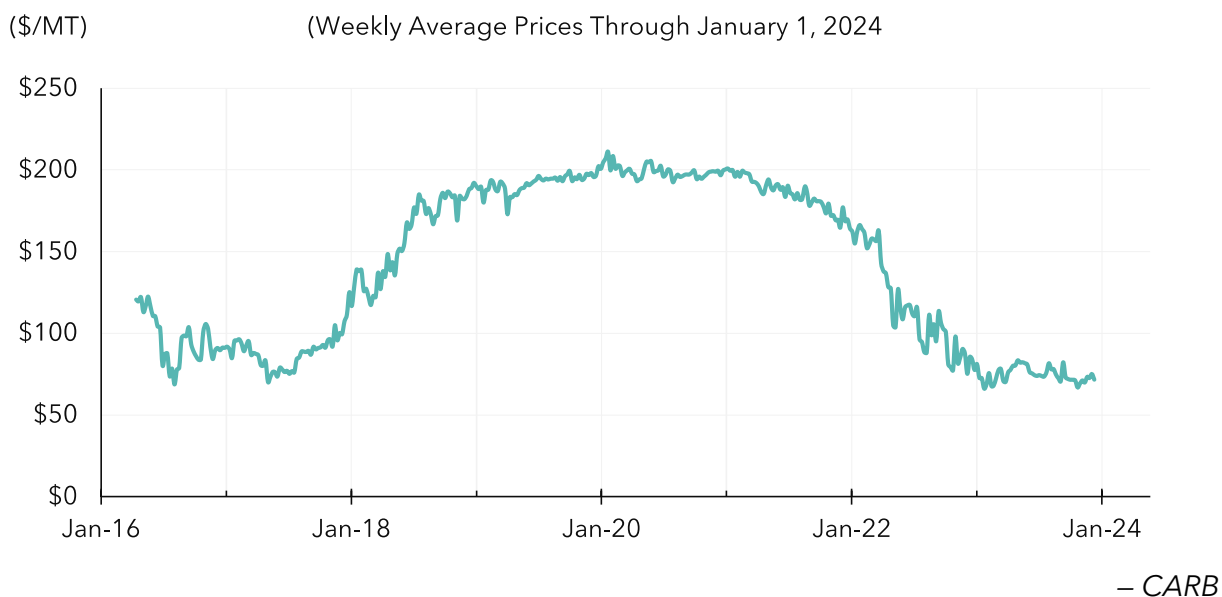
In the CA-LCFS, SAF, if produced via a California Air Resources Board (CARB)-approved SAF production pathway, can qualify for CA-LCFS credits. See Appendix F for a listing of currently certified SAF production pathways from CARB. Foreign producers of SAF can participate in the CA-LCFS program.

The value of the credits can be calculated by the CARB “LCFS Value Calculator” and the resulting value is a function of the CI score of the fuel and the current market value of the basic underlying LCFS credit.

2024 could be a key year for the CA-LCFS. An update to the program is expected to be finalized soon and it could, eventually, lift the CARB LCFS credit prices that collapsed in 2022 (Figure 4.4).

The CA-LCFS credit price collapse was due primarily to an oversupply of LCFS credits available in the market. Two key factors that contributed to the oversupply were (1) the sharp increase in the production of RD, (2) the increase in RNG volumes, and (3) ultra-low CI renewable electricity pathways.

Figure 4.4: CA-LCFS Credit Price History



CARB’s LCFS Update: The California Air Resources Board (CARB) proposed a rulemaking update to its LCFS in September 2023 to increase program efficacy.

- The most significant proposed change is to increase the level of CI reduction targets through 2030 and add an extension of declining CI targets through 2045. CARB proposed a 30% reduction by 2030 and a 90% reduction by 2045 (The current target in California is a 20% reduction in fuel CI by 2030).
- Among other changes, CARB added a mechanism that will pull forward the standards by one year if the LCFS program is in credit surplus for the previous year and the bank of credits exceeds the quarterly surplus by a factor of three.
- CARB will also require producers of crop-based biofuels to secure independent certification that the crops are not contributing to deforestation.
- Other proposed changes include: (a) creating a provision to support medium- and heavy-duty zero-emission vehicle (ZEV) refueling infrastructure, (b) establishing a phase-out date for the crediting of petroleum projects, and (c) a focus on direct delivery of biomethane.

A final, comprehensive rules package was released for public comment on December 19, 2023, triggering a 45-day comment period beginning on January 5, 2024, followed by a planned public hearing and vote by the full CARB Board on March 21, 2024. The new CARB targets could come into effect by late 2024 or CARB could wait until January 1, 2025. CARB said it would not retroactively apply the ruling to any part of the 2024 compliance year.

EcoEngineers’ LCFS credit price forecast models show LCFS credit prices similar to those we see today for the next several years with potential for upswings in the back half of the decade.

Chapter 4.4: Other LCFS Programs

Oregon: Oregon has its own LCFS-type Clean Fuels Program (OR-CFP), which started in 2016 and is similar, in many aspects, to the CA-LCFS program.

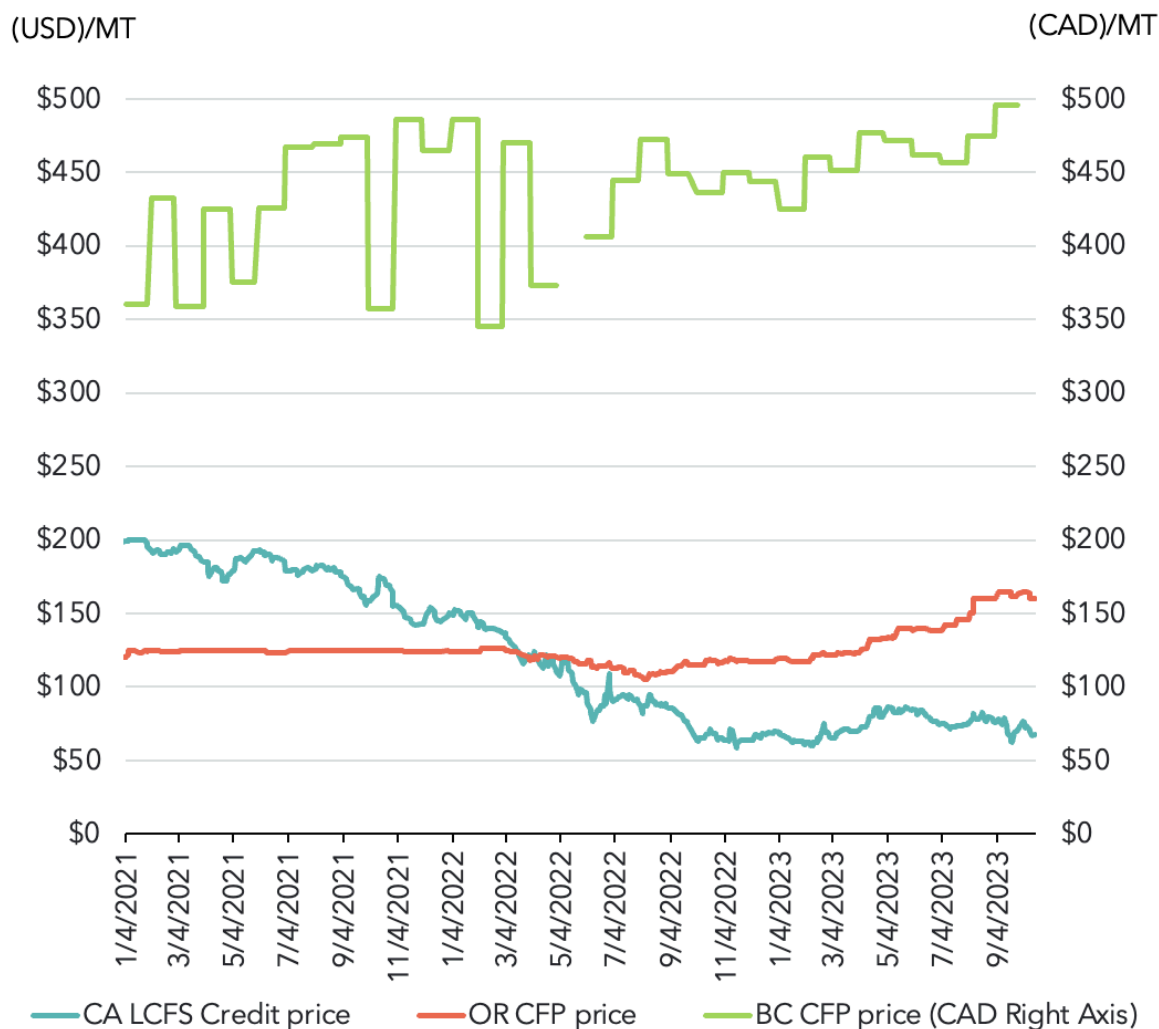
The Oregon Environmental Quality Commission (EQC) proposed legislation to establish the OR-CFP to incentivize the use of low-carbon fuels and minimize emissions from the transportation sector. In 2015, the legislation was passed, and the OR-CFP was fully implemented in 2016. The OR-CFP closely mirrors the CA-LCFS program and aims to reduce the CI of transportation fuels by 10% by 2025. In early 2020, the governor of Oregon issued an executive order to reduce the CI of transportation fuels by 20% by 2030 and at least 25% by 2035.

Producers of renewable fuels can submit facility-specific pathway applications to the Oregon Department of Environmental Quality (DEQ) or producers with certified CA-LCFS pathways can register the certified pathway under the OR-CFP. The CI score is determined through OR-GREET modeling, which is similar to CA-GREET with the transportation distance now calculated to Oregon instead of California. Fuel pathways that have been approved under the CA-GREET model can be approved in Oregon by updating the transportation distance to Oregon.

By consuming renewable fuel in Oregon, it is possible to earn both RINs and OR-CFP credits. However, the fuel can only get credit from one state and cannot stack OR-CFP and CA-LCFS credits. The OR-CFP offers an additional market for the fuel considering the competitive nature of the CA-LCFS. Renewable fuel producers can send a certain portion of fuel to the CA-LCFS and the remainder to the OR-CFP. The OR-CFP is less attractive than the CA-LCFS as there is less overall demand. Oregon is a significantly smaller market than California, has a substantially smaller population, and uses approximately 10% of the total fuel used by California.

Figure 4.5 summarizes the OR-CFP credit prices to date.

Figure 4.5: California, Oregon, and British Columbia Credit Price Comparison



– EcoEngineers and BC BM

Washington: Washington first attempted to pass a statewide LCFS in 2019 and again in 2020. In July 2021, the Washington legislature adopted the Clean Fuel Standard (WA-CFS) to reduce the CI of transportation fuels within the state by 20% from 2017 levels by 2034. The program officially began in January 2023. The emissions-reduction schedule is as follows:

- No more than 0.5% reduction each year in 2023 and 2024.
- No more than an additional 1% each year beginning in 2025 through 2027.
- No more than an additional 1.5% each year beginning in 2028 through 2031.
- No change in 2032 and 2033.

Producers of renewable fuels can submit facility-specific pathway applications to the Washington DEQ or producers with certified CA-LCFS or OR-CFP pathways can register the certified pathway under the WA-CFS. The CI score is determined through WA-GREET modeling, which is similar to CA-GREET with the transportation distance now calculated to Washington instead of California. Fuel pathways that have been approved under the CA-GREET model can be approved in Washington by updating the transportation distance to Washington. The WA-CFS program is very new and limited data exists concerning credit prices.

British Columbia: British Columbia (BC) is setting more aggressive targets for its LCFS in a bid to grow its market for alternatives to conventional gasoline and diesel fuel and reduce GHG emissions from the transportation sector.

The provincial government finalized a 10-year extension of its LCFS and related renewable fuel regulations with a new mandate for a 20% reduction in the CI of transportation fuels by 2030. The rule also sets an average of 5% renewable content in gasoline and 4% in diesel fuels.

The extension of British Columbia's LCFS is an indication that policymakers and fuel industry participants intend to stay the course on emission-reduction targets even during a dramatic downturn in energy markets. British Columbia's new LCFS rules align closely with Oregon's and California's LCFS programs but do not link with the U.S. programs.

British Columbia's relatively high credit prices are likely to continue as they update their schedule for further requirements past 2030. This program will likely continue as a separate program as Canada rolls out a similar low-carbon fuel program nationwide (see Canadian Clean Fuel Regulations below), much like the CA-LCFS is layered over the federal RFS program.

Figure 4.5 summarizes the BC credit pricing history.

British Columbia and SAF: In December 2023, British Columbia said that it would be the first jurisdiction in North America to require fuel suppliers to incorporate low-carbon jet fuel into fossil jet fuel. The new requirement is that fuel suppliers must incorporate low-carbon jet fuel into fossil jet fuel used in the province. The regulations require renewable fuel to comprise at least 1% of jet fuel starting in 2028, increasing to 2% in 2029, and 3% in 2030 and subsequent compliance periods. The regulations also include a CI-reduction requirement for jet fuel that phases in at 2% in 2026, 4% in 2027, 6% in 2028, 8% in 2029, and 10% in 2030 and subsequent compliance periods.

Canada Clean Fuel Regulation (CFR): On April 10, 2010, the Canadian federal government first established the Renewable Fuels Regulations (RFR), which established the following minimum volumetric requirements:

- 5% low-CI fuel content in gasoline.
- 2% low-CI fuel content in diesel fuel and light fuel oil.

The Clean Fuel Regulations (CFR), published in July 2022, completely replaced the RFR. The CFR maintains the minimum volumetric requirements from the RFR in addition to requiring

producers and importers of gasoline and diesel to reduce the CI of the fuel they produce from 2016 levels by 3.5 g CO₂e/MJ in 2023, decreasing by 1.5 g CO₂e/MJ each calendar year to 14 g CO₂e/MJ in 2030. The CI reduction schedule is shown in Table 4.1.

Table 4.1: CI Reduction Schedule of Canada’s CFR

Compliance Period	CI Limit for Diesel Class Fuel (g CO ₂ e/MJ)	CI Limit for Gasoline Class Fuel (g CO ₂ e/MJ)
2023	89.5	91.5
2024	88.0	90
2025	86.5	88.5
2026	85.0	87.0
2027	83.5	85.5
2028	82.0	84.0
2029	80.5	82.5
2030 and after	79.0	81.0

- *Government of Canada*

Registration and compliance credit generation were available to begin in June 2022. The CI reduction requirements began on July 1, 2023. Currently, the CFR is aimed at reducing the CI of liquid fuels only; however, producers can fulfill up to 20% of their obligation with RNG and they can also use RNG to reduce the CI score of their petroleum facility.

Potential Emerging LCFS Programs

Other U.S. states have announced plans to explore the use of an LCFS.

- There is strong interest in the U.S. Midwest, particularly in Illinois, Minnesota, and Wisconsin. A task force advising Wisconsin Governor Tony Evers (D) recently recommended that the state consider developing an LCFS proposal as soon as the summer of 2024 as part of a broader plan to address climate change. Wisconsin, along with Minnesota and Illinois, has embraced the work done by the Midwestern Clean Fuels Policy Initiative. Colorado has started an impact study, the first step in potential LCFS legislation. It completed an LCFS feasibility study last year.
- New Mexico has recently (February 2024) passed legislation that will set up an LCFS program in the state.
- Nevada officials, in December 2020, said they are considering an LCFS program to help reach the state's climate policy goals.
- The U.S. states in the Regional Greenhouse Gas Initiative (RGGI), a group that works to lower states’ emissions from power generation, and others announced their intentions to explore a regional emissions-reduction plan for transportation fuels. The states that have announced interest (Pennsylvania, Virginia, Maryland, Delaware, New Jersey, Massachusetts, Vermont, Rhode Island, as well as Washington D.C.) intend to produce

a directive on how to proceed. New York, Maine, and New Hampshire, all members of the RGGI, may decide at a later time. The program would be a cap-and-trade program or other format with an LCFS-type program being a possible design.

- New York State is considering an LCFS program to meet its steep decarbonization goals. A 17-member advisory group is developing transportation policy recommendations for the New York Climate Action Council, which is tasked with coming up with a plan for implementing major climate legislation the state enacted last year. The law requires New York to cut GHG emissions by 40% by 2030 and 85% by 2050, both from 1990 levels. Environmentalists and biofuel producers hope to persuade New York State lawmakers to adopt the LCFS next year. They launched the Clean Fuels NY Coalition this year to campaign for an LCFS that would help meet its new climate goals. But that effort was put on hold to allow the state to deal with COVID-19. The LCFS program has received more broad support than the Transportation and Climate Initiative's (TCI) development of a cap-and-trade program for emissions from the use of gasoline and diesel that could cover much of the U.S. Northeast.
- In addition, a bill recently introduced in the U.S. House of Representatives would establish a national LCFS specifically for aviation fuels.

Chapter 4.5: Inflation Reduction Act (IRA) and SAF

The U.S. IRA, administered by the U.S. Internal Revenue Service (IRS), provides multiple substantial incentives for SAF production. They only apply to domestic producers of SAF. These incentives will put foreign SAF importers at a disadvantage to multiple current and planned U.S. domestic SAF producers.

40B SAF Credit: This is the first part of the IRA's two-phase approach to SAF. The Section 40B tax credit expires at the end of 2024, at which point the Section 45Z Clean Fuel Production Credit will take over. Under 40B, producers of SAF that reduce GHG emissions by 50% are eligible for a tax credit of US\$1.25/gal, with an additional \$0.01/gal credit added for each percent point exceeding the 50% reduction, to a maximum credit allowance of \$1.75/gal.

40B Eligibility: Producers and blenders of SAF-kerosene fuel mixtures for aviation are eligible for the credit. The qualified SAF mixture must be made in the U.S. and fueling of the aircraft must occur in the U.S.

40B Stackability: The 40B credit cannot stack (be applied together) with the Carbon Oxide Sequestration (Section 45Q) credit or the Extension of Tax Credits for Biodiesel and Renewable Diesel (Section 40A).

45Z Clean Fuel Production Credit: This is a tax credit for domestic producers of clean transportation fuels with an emissions factor at or below 50 kg of CO₂ equivalent per million British thermal units (kg CO₂e/MMBtu). The IRS considers a "clean fuel" to be a fuel with an emissions level at or below 50 kg CO₂e/MMBtu.

Eligible transportation fuels must be produced from applicable biomass material and cannot be derived from coprocessing from a non-biomass feedstock. Among the qualifications for

the 45Z credit eligibility; the fuel must be produced in the U.S. but can be sold domestically or exported internationally.

The value of the 45Z credit varies by fuel type and use. For clean transportation fuel, the credit value ranges from \$0.20 to \$1.00 (max value is captured for meeting prevailing wage and apprenticeship requirements). For SAF, the credit value ranges from \$0.35 to \$1.75 (max value when prevailing wage requirements). The 45Z credit value also adjusts with inflation.

Timeframe: The 45Z tax credit is available for fuel producers to produce clean fuels produced after December 31, 2024, and used or sold before December 31, 2027. For SAF, it effectively replaces the 40B tax credit, which expires on January 1, 2025.

Stackability: The 45Z tax credit cannot stack with the Clean Hydrogen Production Credit (Section 45V), the Clean Energy Property Credit (Section 48), or the Carbon Oxide Sequestration (Section 45Q) tax credits.

For the IRA Sections 40B and 45Z credits, SAF is defined as meeting the following requirements:

- Either ASTM International Standard D7566 or the Fischer-Tropsch (FT) provisions of ASTM International Standard D1655, Annex A1.
- Is not derived from coprocessing an applicable material (or materials derived from an applicable material) with a feedstock that is not biomass.
- Is not derived from palm fatty acid distillates or petroleum.
- Has a lifecycle GHG emission-reduction percentage of at least 50%.

REET Model and IRA Tax Credit Guidance: Up until mid-December 2023, there was some uncertainty and concern regarding which version of the Life-Cycle Analysis (LCA) model (Greenhouse gases, Regulated Emissions, and Energy use in Technologies, or REET, or the International Civil Aviation Organization's, ICAO, Carbon Offsetting and Reduction Scheme for International Aviation, CORSIA) will be or could be applied to calculating CI for SAF-type fuels (under Section 40B(e) of the IRA) and what assumptions would be used when estimating the CI of SAFs, especially SAFs that would be produced from grain-based ethanol. Many market participants held that the ICAO model (the default model for evaluating SAF) is not state-of-the-art and misses key aspects of decarbonization, including climate-smart and regenerative feedstock practices, biorefining production efficiencies, and GHG-reduction strategies that are practiced by U.S. farmers and biofuel producers.

This was substantially, but not completely resolved, in mid-December 2023. The IRS said:

"... numerous fuels will qualify for the credit, including valid biomass-based diesel, advanced biofuels, cellulosic biofuel, or cellulosic diesel that have been approved by the USEPA under the Renewable Fuel Standard (RFS).

Fuels that achieve a 50% or greater reduction in lifecycle greenhouse gas emissions under the most recent Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) standard will continue to qualify under today's guidance.

In addition, USEPA, USDOT, USDA, and USDOE are announcing their commitment to release an updated version of DOE's GREET model by March 1, 2024.

Pending further guidance from the Treasury Department, the updated GREET model will provide another methodology for SAF producers to determine the lifecycle GHG emission rates of their production for the purposes of qualifying for the SAF credit for SAF sold or used during calendar years 2023 and 2024.

The updated model will incorporate new data and science, including new modeling of key feedstocks and processes used in aviation fuel. The updated model will also integrate other categories of indirect emissions like crop production and livestock activity, in addition to the best available science and modeling of indirect land use change emissions. The updated model will also integrate key greenhouse gas emission reduction strategies such as carbon capture and storage, renewable natural gas, renewable electricity, and climate-smart agriculture practices."

Chapter 4.6: CORSIA

Established in 2019, the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) is an aircraft GHG-emissions offsetting scheme adopted by the International Civil Aviation Organization (ICAO). It is a global aircraft CO₂ emissions monitoring, reporting, and verification plan designed specifically for SAFs.

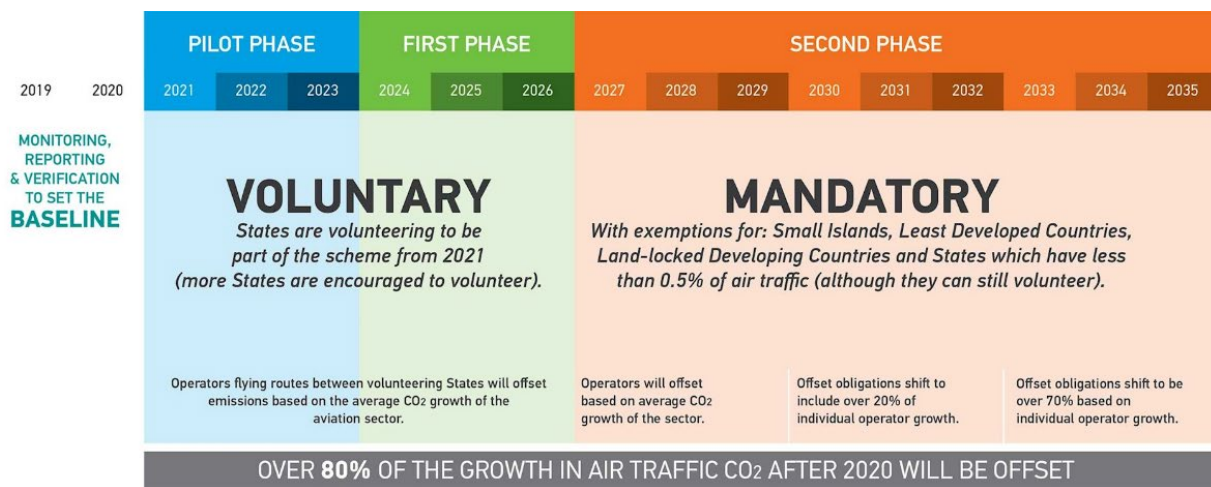
The CORSIA scheme applies to international flights only. Domestic aircraft emissions fall under the purview of another United Nations agency, the United Nations Framework Convention on Climate Change, or UNFCCC, and are covered by the Paris Agreement. The plan is voluntary through 2026 and "mandatory" after 2026. Enforcement is by EU Member States. However, enforcement mechanisms (and penalties) are not specified. (Figure 4.7)

The "Four Pillars" for achieving compliance are:

1. **Design Technology** (i.e., aerodynamics, propulsion, weight reduction, etc.).
2. **Operation and Infrastructure** (i.e., air traffic management).
3. **Alternative Fuels** (i.e., clean energy fuels, or CEF, electric, hybrid, etc.).
4. **Market-Based Measures** (i.e., offsets that follow CORSIA emissions unit eligibility criteria).

If offsets remain low-priced, there may be little or no incentive for airlines to pay for relatively expensive SAF.

Figure 4.6: Overview of Voluntary and Mandatory Schemes Under CORSIA



- CORSIA

As part of the UN, the IACO has no legal authority for enforcement in any country. Therefore, it will rely on EU Member States to adopt CORSIA into their laws governing aviation emissions and to enforce compliance. To date, no EU Member State has adopted CORSIA rules into its aviation emissions law.

However, the EU's Emissions Trading System (EU ETS) does have a model for aviation emissions enforcement. Under the EU ETS, the penalty for non-compliance is €100/MT (US\$105/MT) of CO₂ emitted, plus additional local fees and penalties. Each EU Member State is allowed to legislate the enforcement as they choose, so penalties, if they arise, may vary from country to country.

EcoEngineers' opinion is that CORSIA will face the same issues with enforcement that are faced by the marine industry under the International Maritime Organization (IMO) 2020 standard.

For additional information on CORSIA, see Appendix B.

Chapter 4.7: EU Renewable Energy Directive (RED II)

RED II targets all forms of transport, including on-road and off-road such as rail, inland maritime, and aviation in EU countries. EU Member States must require fuel suppliers to supply a minimum of 14% of the energy consumed in all transport by 2030 as renewable energy. There are no specific sub-sector fuel targets. Thus, RED II, by itself, does not force or incentivize EU-based jet fuel users to use SAF.

The RED II regulation defines a series of sustainability and GHG-emission criteria that bioliquids used in transport must comply with to be counted towards the overall 14% target and to be eligible for financial support by public authorities.

RED II introduced many changes compared to the older RED I regulation. The key (new) sustainability criteria are:

- Land-related criteria (no-go areas: high biodiversity, high-carbon stock, and peatland).
- GHG emission-reduction threshold (e.g., 65% reduction as compared with fossil fuels for installations in operation since 2021).

Chapter 4.8: EU Fit for 55

Fit for 55 introduces changes to RED II. It will become RED III. Fit for 55 is a holistic legislative package put forward by the European Commission (EC) in July 2021 to “make the EU’s climate, energy, land use, transport, and taxation policies fit for reducing net greenhouse gas emissions by at least 55% by 2030, compared to 1990 levels.”

The 14% target for renewable energy in transportation by 2030 is replaced by a new target.

EU Member States may choose between a 14.5% reduction of GHG intensity in transport fuels from the use of renewables or a 29% share of renewables in the final energy consumption in transportation.

There are sub-targets for advanced biofuels (non-food-based feedstocks) and renewable fuels of non-biological origin such as hydrogen-based synthetic fuels. Aviation fuels count under the targets.

The Fit for 55 package includes multiple new proposals or revisions of existing legislation, some of which target the aviation sector and aviation fuels:

- The EU ETS, coupled with CORSIA implementation, is expanded to include the aviation sector. ETS is a cap-and-trade system that aims to reduce CO₂ emissions from aviation by setting emissions limits and allowing airlines and general aviation operators to buy and sell emissions allowances.
- The associated ReFuelEU Initiative is a proposed initiative to increase the use of SAF to reduce CO₂ emissions from aviation. This initiative is designed to increase the uptake of SAFs. It puts an obligation on fuel suppliers and airports to deliver gradually higher volumes of SAFs and on aircraft operators to fuel their tanks with SAFs.
- Revision of the Energy Taxation Directive (still under negotiations by EU Member States and unlikely to be agreed on soon) would introduce separate taxation on SAFs that would be in the first 10 years and increase 1/10th of the final minimum rates for sustainable fuels each year after the transition period. Food and feed crop-based biofuels, unsustainable biofuels, and high indirect land-use change (ILUC)-risk biofuels would be taxed as fossil fuels.

The ReFuelEU Initiative proposal requires EU fuel suppliers to ensure that all fuel made available to aircraft operators at EU airports contains a minimum share of SAF from 2025 onward.

- The levels of SAF are set at 6% in 2030, 20% in 2035, 34% in 2040, 42% in 2045, and 70% in 2050.
- A part of the fuel mix (1.2% in 2030, 2% in 2032, 5% in 2035, and progressively reaching 35% in 2050) must comprise synthetic fuels like e-kerosene.

- Aircraft operators are obliged to ensure that the yearly quantity of aviation fuels uplifted at a given EU airport is at least 90% of the yearly fuel required for all flights from the airport.

During a transitional period, fuel suppliers can reach the SAF blending mandate as a weighted average of the quantities they have supplied across the EU.

The ReFuelEU Initiative proposal is still waiting to be published in the Official Journal and implemented by EU Member States. The allowable SAF will, most likely, include synthetic fuels, certain biofuels produced from agricultural or forestry residues, algae, bio-waste, used cooking oil, certain animal fats, and recycled jet fuels produced from waste gases and waste plastic.

Chapter 4.9: U.S. SAF Grand Challenge

The SAF Grand Challenge (the Challenge) is a detailed strategy plan (or “Road Map”) for scaling up new technologies or low-CI and nonfood-based feedstock production supply chains to produce SAF on a commercial scale (to meet 100% of U.S. aviation fuel needs by 2050).

It was developed by the U.S. Department of Transportation (USDOT), U.S. Department of Agriculture (USDA), U.S. Department of Energy (USDOE), and other federal government agencies. The development of this strategic plan is essentially a recognition that U.S. GHG policy is far ahead of the required enabling process technologies.

Unfortunately, the Challenge offers few incentives or ideas that are likely to ensure near-term commercialization.

The level of investment-ready (final investment decision, or FID-ready) required process development innovation will, most likely, need much more than the 2-4 years of work outlined in the plan. There are no breakthrough technologies at present that are shovel-ready to produce meaningful commercial volumes of SAF beyond the existing HEFA process.

Chapter 4.10: A Note on EU and UK Tariffs

These tariffs could have an impact on worldwide SAF supply and demand.

In the EU:

- The EU currently imposes an anti-dumping duty (tariff) on U.S. and Canadian RD and fatty acid methyl ester (FAME) biodiesel. This is because the EU is trying to protect its HVO producers.
- It is a good assumption that they would impose similar duties on RD imports from other countries that would attempt to import into the EU. Imposed in 2008, the EU anti-dumping duty of RD and FAME biodiesel was extended in 2021 to be active through 2027, with an anti-dumping duty rate of up to €198 per metric ton (/MT) (US\$208/MT) of RD/FAME biodiesel product imported from the U.S. and Canada.
- Will they do the same for imported SAF?

In the UK:

- The UK's RD use goals in place today are like when it was an EU Member State. The UK recently lifted import tariffs on U.S.-produced HVO, previously imposed when the UK was a member of the EU, recognizing that HVO could be used in several different decarbonization pathways, including home heating. Any resulting increase in imports would not hurt domestic businesses because there is no HVO production industry in the UK. Diamond Green Diesel (DGD), a joint venture between Valero Energy Corp. and Darling Ingredients Inc., which is in a good position to export to Europe, has already started importing some RD into the UK, competing with Finland's Neste for the UK market.

Chapter 4.11: Airlines and SAF Use Commitments

The airline industry's voluntary desire to reduce GHG footprints, to meet shareholders' and customers' desires and requirements will drive demand, to some extent. This, in conjunction with CORSIA and other use mandates, has led to verbal and published commitments by numerous airlines to use substantial, growing quantities of SAF for their flights. However, none of these commitments, as far as EcoEngineers knows, are legally binding or connected to penalties for non-use of SAF.

To be effective, the demand drivers need to compensate for or negate the higher production cost of SAF vs. its petroleum-based jet fuel counterpart. To date, there is no penalty-based mandate for SAF use in the U.S. Running an airline is, over time, a low-margin business. Airlines will need to pass their increased fuel costs onto their customers unless they are subsidized to use SAF.

Most of the world's major airlines have publicly stated that they are "committed" to or "targeting" using specific volumes of SAF in the future. Some public statements by airlines and current or future SAF producers say that the airline is committed to using X amount from the producer over a Y-year timeframe.

EcoEngineers' consultants have only seen a few of the confidential "agreements" upon which producer-specific commitments are based and cannot say if they are representative of most or all SAF use "agreements." One of the agreements reviewed was a non-binding Memorandum of Understanding (MOU). Another agreement stated that the airline would purchase up to a specific total volume over a specific time for a set price per gallon. The purchase price was below the levelized manufacturing cost of the particular SAF.

A summary of over 25 of the world's major airlines' commitments (that have recently appeared in news publications) is summarized below. This list includes the world's 15 top airlines in terms of passengers carried. Most of these statements do not indicate the location of purchase. None of the statements mention commitment agreement details.

- **United Airlines:** In May 2023, United Airlines said it "is planning to use 10 million gallons of sustainable aviation fuel in 2023." This is equivalent to 650 bbl/d, about 1/10th of the yearly production of a mid-range HEFA-type RD/SAF facility. United also said that it has "committed to purchasing 1.5 billion gallons of this new SAF over the next 20 years." This is equivalent to 49,000 bbl/d if these purchases were spread out

over 20 years. In May 2023, United said that it had allocated US\$100 million to invest in SAF production firms to help ensure adequate availability. In July 2023, United announced that its "United Airlines Ventures Sustainable Flight Fund - a way for companies and consumers to come together and increase the supply of SAF through the support of start-ups - has increased its investment power to nearly US\$200 million and added eight new corporate partners, five months after its initial launch."

- **American Airlines:** American recently said it "has commitments covering more than 620 million gallons of SAF from 2025-2030." This is equivalent to 6,700 bbl/d if these purchases were spread out over 20 years.
- **Virgin Atlantic:** Virgin recently stated, "We agreed to purchase 70 million gallons per annum of SAF, produced by Gevo." This is equivalent to 900 bbl/d if these purchases were spread out over five years.
- **Alaska Airlines:** The company said it is "set to offtake 185 million gallons of SAF from Gevo over five years beginning in 2026." This is equivalent to 2,400 bbl/d if these purchases were spread out over five years. Gevo employs an ATJ process, and its plant is not in the commercial phase yet.
- **Southwest Airlines:** Southwest recently stated that, by 2030, "we plan to replace 10% of our total jet fuel consumption with SAF". Based on Southwest Airlines' year 2021 purchases of jet fuel, which was approximately 1.7 billion gallons, this plan would equate to 11,000 bbl/d of SAF in 2030.
- **Delta Airlines:** Delta says that it "committed to replacing 10% of current jet fuel use with SAFs by 2030 and has agreements with three SAF producers: Neste, Gevo, and Northwest Advanced Bio-Fuels." Delta uses 3.9 billion gallons of jet fuel annually based on its most recent data. The 10% commitment by 2030 would amount to 25,000 bbl/d of jet fuel by 2030.
- **Qatar Airways:** Qatar Airways and Gevo signed an offtake agreement where the airline will purchase 25 million gallons of SAF over five years with deliveries expected to commence in 2028 at various airports in California. This use rate is equivalent to 320 bbl/d.
- **LATAM Airlines:** Committed to 5% SAF use in 2030, favoring production in South America.
- **GOL Airlines:** Recently stated that it is "committed to achieving zero net emissions by 2050." The airline says it is advocating for a regulatory framework that incentivizes SAF production in Brazil.
- **Air France-KLM:** Air France-KLM stated that it aims "to incorporate at least 10% of SAF on all our flights by 2030."
- **Lufthansa:** Plans "to have at least 5% of our total fuel requirement coming from SAF by 2030."

- **ANA and JAL:** In January 2023, both committed to using SAF to meet 10% of their fuel needs by 2030. Last year, JAL agreed to buy SAF from Gevo in 2027, while ANA had previously secured a SAF supply deal with Neste.
- **Emirates Airlines:** In October 2023, Emirates and Neste expanded their partnership by solidifying their collaboration for the supply of over 3 million gallons of blended Neste MY Sustainable Aviation Fuel (at a 30% blend level) to Emirate air flights in 2024 and 2025. The SAF, which will be blended with conventional jet fuel, will be supplied throughout 2024 and 2025 for Emirates flights departing from Amsterdam Schiphol and Singapore Changi airports. This use level is equivalent to approximately 33 bbl/d of SAF.
- **Clean Skies for Tomorrow Coalition:** The biggest commitment seen so far happened at the World Economic Forum’s Clean Skies for Tomorrow Coalition event in September 2021 when 60 companies committed to work together to power global aviation with 10% SAF by 2030. The commitment, which included airlines, airports, fuel suppliers, aviation innovators, and non-aviation companies that rely on air travel, demonstrated a significant shift in fueling plans for a large number of airlines.
- **Alaska Airlines, American Airlines, British Airways, Finnair, Japan Airlines, and Qatar Airways:** Announced in July 2023, these airlines plan to purchase up to 200 million gallons of ethanol-based SAF per year over five years from renewable fuels producer Gevo. “Commencing in 2027, the deal will see these airlines use SAF for several major Californian international airports.”
- **China Southern, Air China, Hainan Airlines, and China Eastern:** All these China-based airlines have completed flights with SAF fuel blends, but no commitments to SAF use levels have been published in Western publications.
- **Cathay Pacific:** Hong Kong’s Cathay Pacific says that 10% of its aviation fuel will be sustainable by 2030.
- **IAG Group (British Airways, Iberia, Vueling, Aer Lingus, LEVEL, IAG Loyalty, and IAG Cargo):** It has a target to meet 10% of its fuel needs from SAF by 2030.
- **Turkish Airlines:** Plans to use SAF on multiple flights but has made no hard use-level commitment.
- **Ryanair:** Plans “to use 12.5% SAF use by 2030”.
- **IndiGo:** Expects to use a maximum blend of 10% SAF by 2030.
- **Air Canada:** Is committed to reaching net-zero emissions by 2050 and is currently using SAF on multiple flights per year. It mentions no SAF use-level targets.

In summary, most of the world’s major airlines and all the world’s major airline industry organizations say that they are committed to reaching net zero by 2050. SAF is mentioned as one potential method to be used for reaching this net-zero goal for commercial airline flights.

When EcoEngineers adds up all the SAF use volume (by 2030) commitments from the airlines that have been mentioned in this analysis, **the year 2030 SAF use volume commitments add**

up to approximately 3.5 vol% of the year 2023 worldwide total jet fuel use levels (assuming that yearly worldwide jet fuel volumes will increase between 2023 and 2030, in alignment with the jet flight miles forecasts developed in the next section of this report). The SAF use percentage for the world's top 20 airlines represents less than 3.5% of total likely jet fuel use in 2030.

IATA and ATAG Statements

The worldwide airline industry, through the International Air Transport Association (IATA) and the Air Transport Action Group (ATAG), has "committed to net zero by 2050." IATA, ATAG, and the ICAO have said that net zero "will be achieved through five levers (listed below)." SAF is mentioned as a lever, but target quantities are not mentioned. A strategy related to dealing with the likely higher relative costs of SAF is not mentioned.

- Efficiency gains (design and operational improvements to reduce fuel burn).
- SAFs
- Carbon offsetting (investment in out-of-sector emission reductions or removal).
- New propulsion systems such as electric batteries and hybrid aircraft.
- The use of hydrogen.

Chapter 4.12: Summary

While many potential SAF markets are nascent or in development, the increasing number of market options along with increasing commitments to utilize SAF as a lower carbon fuel is a strong driver for SAF project and process technology development. The biggest obstacle to SAF commercialization continues to be the production cost of SAF.

Section 5: Outlook for SAF Supply/Demand

In this section, EcoEngineers will provide a set of 10-year market outlook scenarios for worldwide and North American SAF supply and demand.

SAF demand will be driven by the use-related regulations, incentives, and mandates that have been described in the previous section. The cost of production of SAF will also be a key factor affecting demand.

Chapter 5.1: The International Energy Agency's (IEA) SAF Demand Forecasts

The IEA's two renewable fuel demand scenarios (generated in 2023 and summarized in their publication *Renewables 2023*) are generally recognized as two of the best available SAF industry benchmarks for forecasts. Regardless, the IEA scenarios, the "Main Case" and the "Accelerated Case" are not linked to any quantitative assumptions regarding the reduction in process technology production costs or process yield improvements. Furthermore, the IEA does not provide a probability-of-occurrence estimate for either of its SAF demand cases. It does, however, imply that its Main Case has a higher probability of occurrence.

The IEA links its RD and SAF demand forecasts (and so will EcoEngineers) because in many HEFA-type facilities, both RD and SAF can be produced, and many facilities will be able to shift between maximizing the production of these two products as demand trends and profitability dictate.

Both of the IEA's demand cases extend to 2028. EcoEngineers has completed a best-efforts extension of both IEA cases to 2033 to simulate what the IEA may have provided for a 10-year forecast if it had assumed the same demand growth rate trends extended forward by five years. Table 5.1 and Figures 5.1 and 5.2 summarize the two IEA-extended forecasts.

In the IEA's Main Case, total worldwide demand for SAF hits 168,000 bbl/d in 2033, up from 10,000 bbl/d in 2023. This represents demand growth at a CAGR of 32%. In this case, SAF demand accounts for more than 2% of worldwide aviation fuel demand by 2033.

For this case, the IEA assumes that:

1. The U.S., Europe, and Japan will be responsible for most of the SAF demand growth, where demand will be driven by "strong policy support," including mandates.
2. The RFS RINs, LCFS credits, and IRA credits "will help to narrow the price gap with fossil jet fuel in the U.S." The IEA believes that approximately 38% of global SAF demand will originate in the U.S. by 2028, up from less than 25% in 2023.
3. EU's ReFuelEU Aviation Initiative legislation, which sets blending obligations of 2% for 2025 and 6% for 2030, is forecast to increase the SAF fuel share to 4% of Europe's jet fuel demand by 2028.
4. In the Asia-Pacific region, Japan is the main source of demand growth with its goal of 10% SAF use by 2030.
5. Feedstock diversification will occur for the HEFA route to SAF. This means that cover crops like *Camelina sativa* will see increased use. The IEA also sees the commercial entry of the gasification route, which will use cellulosic materials and sorted MSW as feedstocks.
6. Planned ATJ projects deliver nearly 13% of total SAF demand by 2028 and the gasification of woody residues and MSW deliver another 13% of total SAF demand by 2028. (The IEA thus places the ATJ and gasification routes to SAF on similar production growth trajectories.)
7. E-fuels-type SAF production remains a very small fraction of the total SAF supply. The IEA assumes that the route does not progress to become cost-competitive during the 2023-2028 period.

In the IEA's Accelerated Case, total worldwide demand for SAF hits 626,000 bbl/d in 2033, up from 10,000 bbl/d in 2023. This represents demand growth at an extraordinary CAGR of 51%. **SAF demand accounts for nearly 8% of worldwide aviation fuel demand by 2033.**

The IEA differentiates the Accelerated Case from the Main Case by assuming that:

1. Active policy discussions in Singapore, Malaysia, Indonesia, India, the United Arab Emirates, Brazil, and the UK help trigger an additional 30% increase in SAF fuel demand by 2028.
2. Under a more stringent RFS, higher state-level LCFs, and extended IRA credits, SAF fuel production would nearly triple versus the Main Case, advancing the country two-thirds of the way to achieving its SAF Grand Challenge goal.
3. By the end of the case period, E-fuel-based SAF production growth is slightly higher than in the Main Case. Production costs start to become competitive in areas where high-purity CO₂ and lost-cost, low-CI power are available.
4. More feedstock diversification occurs.
5. Process technology development and optimization accelerate significantly.

EcoEngineers' Analysis of the IEA Cases

EcoEngineers believes that both IEA cases are plausible. The IEA brackets a range of realistically probable events. We believe that the Main Case is probably underestimating the most likely SAF demand future (over the next 5-10 years) and that the Accelerated Case is probably too optimistic regarding the potential for process technology development to quickly reduce production costs and the evolution of political will and consensus (to create and enforce mandates and create and implement more rigorous SAF use incentives).

We believe that the most likely SAF demand trajectory will fall somewhere in between the two cases because:

1. Significant reductions in production costs will be required to make the Accelerated Case a reality. However, the history of fuels and chemical process development over the last 75 years tells us that 2x-6x reductions in production costs generally occur over five years to 20 years versus over periods of two to five years. (Yes, we do occasionally see a dramatic process technology breakthrough that can quickly be translated to the commercial scale, but these events are rare.) This means that increased incentives and mandates will need to help fill the void, which is possible and probable, in our opinion.
2. Airlines will push back on large-scale mandates without cost relief. Small increases in fuel costs can have a dramatic effect on their operating margins. On average, running an airline is a thin-margin business. Most airlines are not likely to pay even US\$0.10/gal more for jet fuel unless they are forced to, and if they are forced to do so, they will quickly pass the added costs onto plane passengers. The impact of 2x-7x higher jet fuel costs will be dramatic in terms of ticket price increases, even at bending levels of 5 %vol to 30 %vol of total fuel used, as described earlier in this report.

We also believe that:

3. The gasification route to SAF (from MSW and cellulosic feedstocks) will develop slower than the IEA expects. We do not believe that this production route will have a SAF supply market share similar to the ATJ route of 13 %vol within five years. We instead believe that the ATJ route will, by the end of the 10-year forecast period, fill

much of the market share that the IEA predicted for SAF via the gasification route. Our opinion is that issues with consistently sourcing qualified MSW, obtaining sorted MSW at the expected price over the long term, higher-than-expected costs for delivered cellulosic material to economically sized production facilities, and technical issues related to long-term, consistent operability of the gasifier plus synthesis gas (syngas) clean up and FT production trains will translate to slower progress toward large-scale commercialization than the IEA expects.

4. E-fuel process technology progress (levelized production cost reduction) will be slower than predicted. We believe that the rate of electrolysis system cost improvement has slowed down or stalled.
5. The feedstock costs for the HEFA route will not rise as fast as many market analysts, including the IEA, expect. This means that, at least in the U.S., the HEFA route will probably continue to be a major source of SAF over the next 10 years, unless the regulatory agencies in the U.S. and the EU continue to accelerate their support of the alternate routes for SAF over the HEFA route.

EcoEngineers 10-Year SAF Demand Forecast

EcoEngineers' demand forecast is based, partially, on the analysis of the IEA's Cases, which are discussed above.

We believe that the primary driver for SAF demand growth will be the cost of jet fuel to the airlines. The ultimate SAF cost to the airlines will be the levelized cost of production plus logistics (including a small profit for the SAF producers), net of all credits available.

Over the 10-year forecast period, SAF demand will grow at a CAGR of 40%. This is very close to the remarkable CAGR for worldwide RD demand growth over the 2010-2021 period.

We believe that new SAF production process technology development that translates to lower costs per gallon of jet fuel produced will proceed at a slower rate than the IEA expects in its Accelerated Case. This is applied to the ATJ route, the gasification routes, the E-fuel routes (including methanol-to-jet), the pyrolysis routes (i.e., FT), and the algae-based routes. We believe that the ATJ route will, most likely, become the first alternate SAF production route to become competitive with HEFA-based SAF.

In our view, the HEFA route will remain the main source of SAF over the 10-year forecast period. HEFA route feedstock costs will rise slower than is expected by many market analysts. This is because we do not expect that the HEFA route feedstock prices will rise as fast as many market analysts expect (recent market price trends for most HEFA feedstocks support this expectation.). However, we believe that ETJ-based SAF production will, most likely, gradually evolve to become cost-competitive (accounting for applicable credits) with the HEFA route to SAF over the 10-year forecast period. By 2033, ETJ-based SAF could account for close to 25% of all SAF used.

We see a gradual increase in the use of low-CI hydrogen in HEFA facilities. Low-cost CCS technology will just be appearing as a cost-effective add-on to SAF production trains near the end of the forecast period.

The world's economies and political systems will not be able to support the high production costs for SAF production routes that have production costs that are 3x-7x that of petroleum-based jet fuel. Policymakers in the U.S. and EU may learn - again - that innovation (in terms of the development and commercialization of new, game-changing fuel, battery, or vehicle technologies) cannot be legislated.

Some high-profile SAF production projects based on pyrolysis, E-fuels, ATJ, gasification plus FT, algae, and pyrolysis-based technologies will shutter before the engineering/construction phase. However, there is always some potential for a process technology breakthrough in all of these routes.

We expect that the current 75/25 ratio of SAF use in the EU/UK versus the U.S. will gradually shift to close to a 60/40 ratio over the 10-year forecast period.

The EcoEngineers' forecast is summarized in Table 5.1 and Figure 5.3.

Table 5.1: Jet Fuel Demand History and IEA's and EcoEngineers' Jet Fuel Demand Forecasts (000 bbl/d)

Year	2020	2023	2025	2028	2033
Worldwide Jet Fuel Demand (Including EIA Forecast)	4,022	6,128	6,623	7,117	7,890
CAGR (Compound Annual Growth Rate) Over the Forecast Period					2.6%

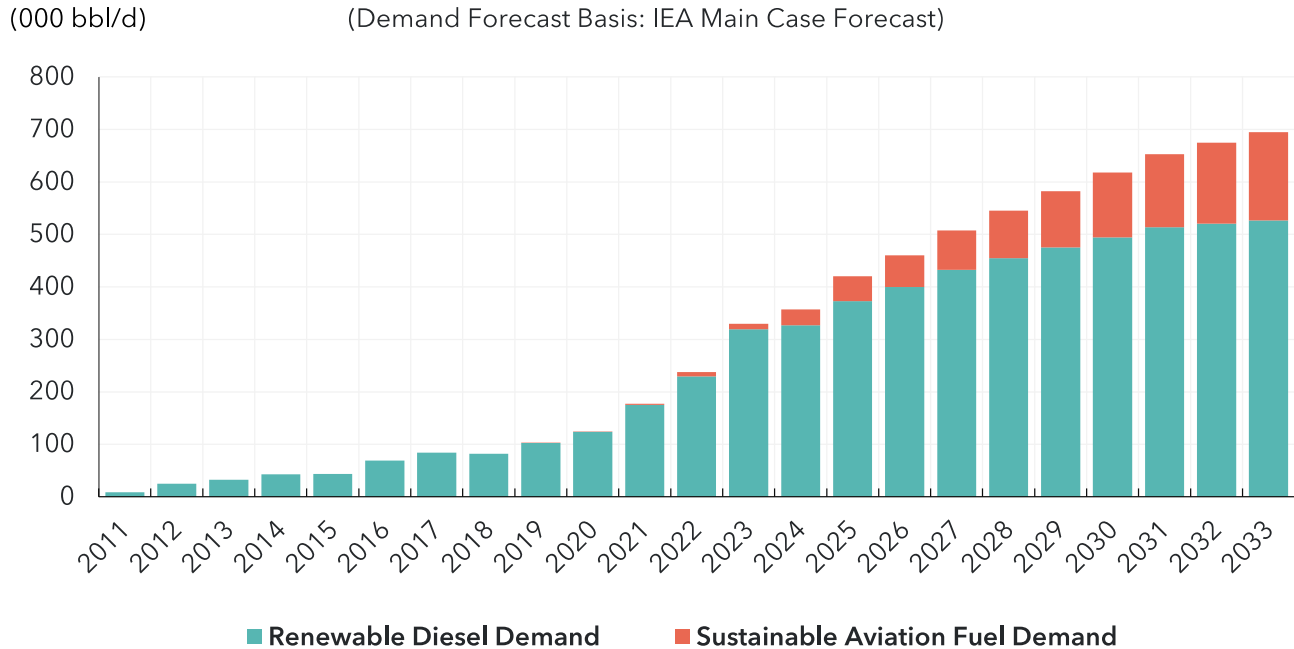
IEA Main Case Scenario					
Worldwide SAF Demand	0.95	10.4	47.1	90.3	167.9
CAGR Over Forecast Period					32%
SAF as a Percentage of Worldwide Jet Fuel Demand	0.02%	0.17%	0.71%	1.27%	2.13%
Worldwide Ethanol Demand if ETJ Provides 13% of SAF Supply in 2027 and 20% in 2033	0.2	2.2	10.2	19.6	56.0

IEA Accelerated Case Scenario					
Worldwide SAF Demand	0.95	10.4	92.1	256.5	625.8
CAGR Over Forecast Period					51%
SAF as a Percentage of Worldwide Jet Fuel Demand	0.02%	0.17%	1.39%	3.60%	7.93%
Worldwide Ethanol Demand if ETJ Provides 13% of SAF Supply in 2027 and 20% in 2033	0.2	2.2	20.0	55.6	208.6

EcoEngineers' Scenario					
Worldwide SAF Demand	0.95	10.4	65.0	145.4	302.1
CAGR Over Forecast Period					40%
SAF as a Percentage of Worldwide Jet Fuel Demand	0.02%	0.17%	0.98%	2.04%	3.83%
Worldwide Ethanol Demand if ETJ Provides 10% of SAF Supply in 2027 and 25% in 2033	0.2	2.2	14.1	31.5	125.9

(The IEA forecasts are from the IEA's Renewable 2023 Report. Jet fuel demand history is from the EIA. The EIA forecast is from the EIA's World Energy Outlook, 2023.)

Figure 5.1: Renewable Diesel and SAF Worldwide Demand and Capacity Outlook



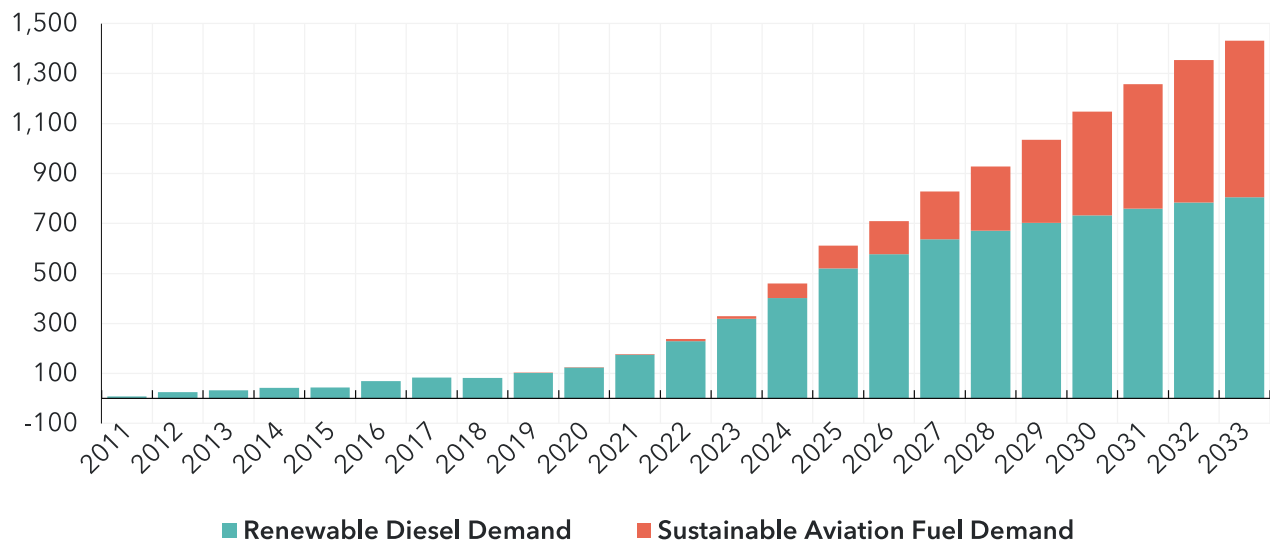
– IEA and EcoEngineers

(The 167,900 bbl/d SAF demand forecast for 2033 is approximately 2% of the EIA’s most recent forecast for total worldwide jet fuel demand in 2033.)

Figure 5.2: Renewable Diesel and SAF Worldwide Demand and Capacity Outlook

(Demand Forecast Basis: IEA Accelerated Case Forecast)

(000 bbl/d)

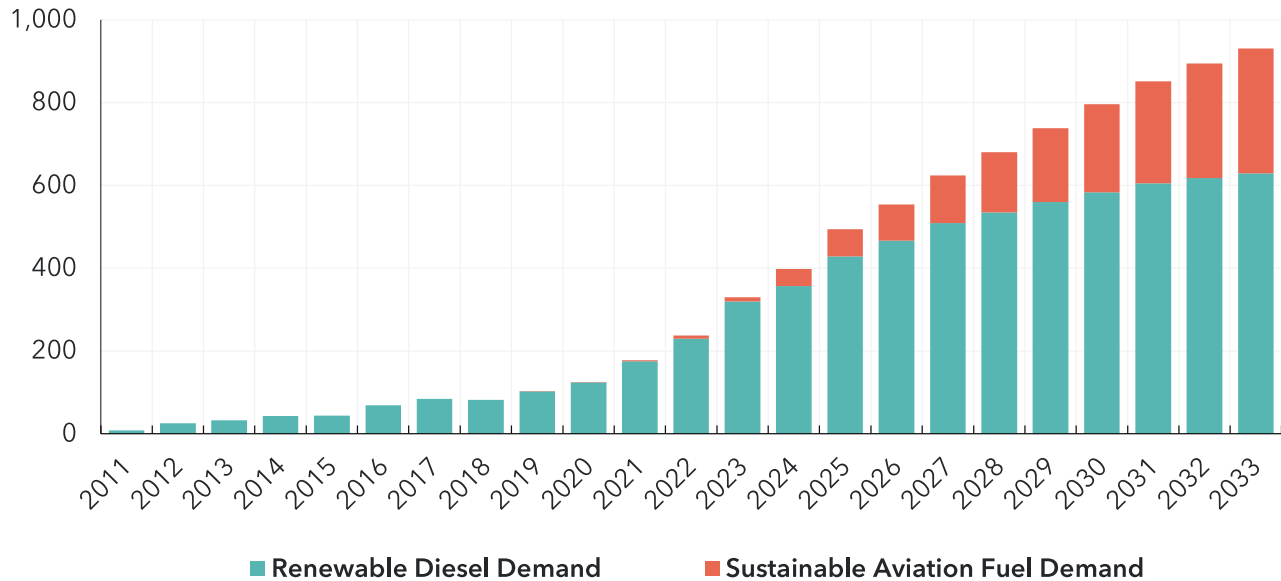


– IEA and EcoEngineers

(The 625,800 bbl/d SAF demand forecast for 2033 is approximately 8% of the 2033 forecast for total worldwide jet fuel/kerosene demand.)

Figure 5.3: EcoEngineers’ Renewable Diesel and SAF Worldwide Demand Scenario

(000 bbl/d)



– IEA and EcoEngineers

(The 302,100 bbl/d SAF demand forecast for 2033 is approximately 3.8% of the EIA’s most recent forecast for total worldwide jet fuel demand in 2033.)

All three SAF worldwide demand forecasts are shown in Figure 5.4. The ATJ-based SAF demand forecasts for the IEA cases and EcoEngineers’ forecast are summarized in Figure 5.5. We assumed a 60% yield by weight (from ethanol) across the ATJ-based SAF process.

Figure 5.4: SAF Worldwide Demand Forecasts

(000 bbl/d)

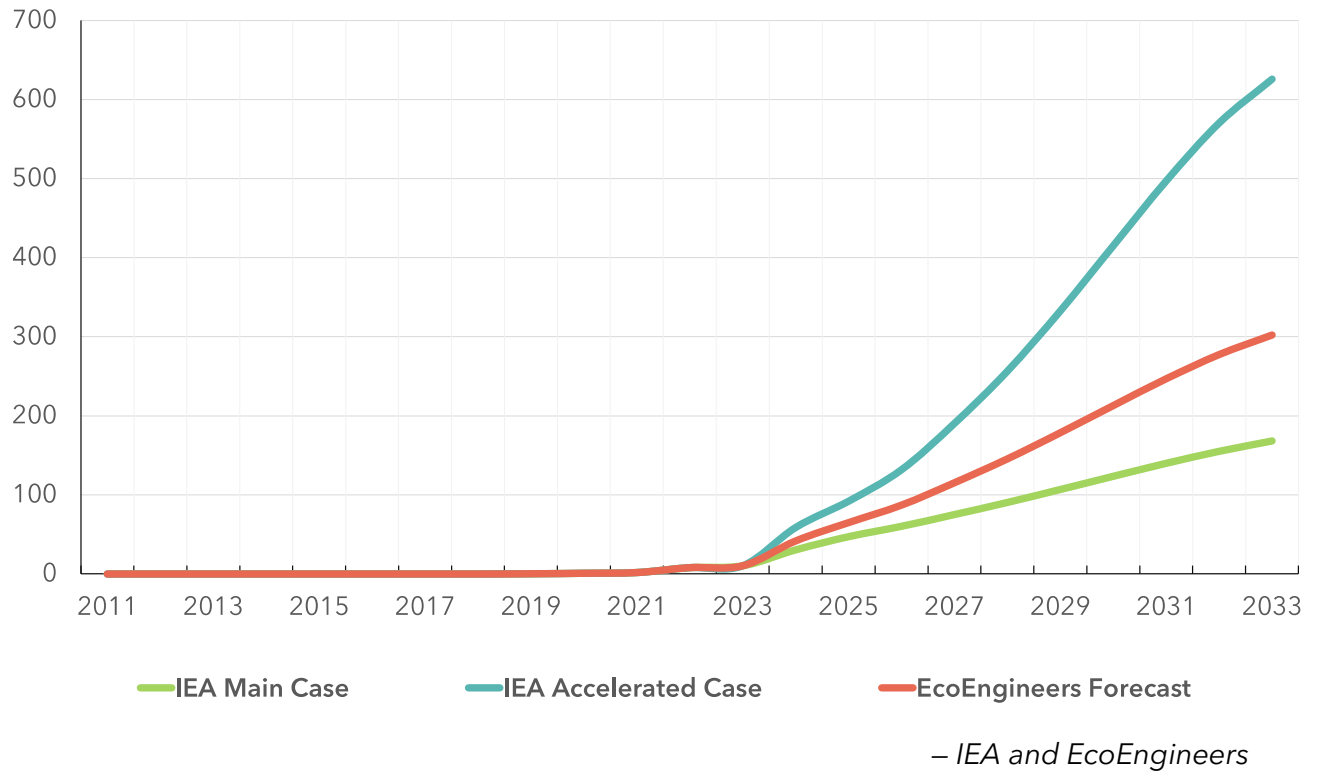
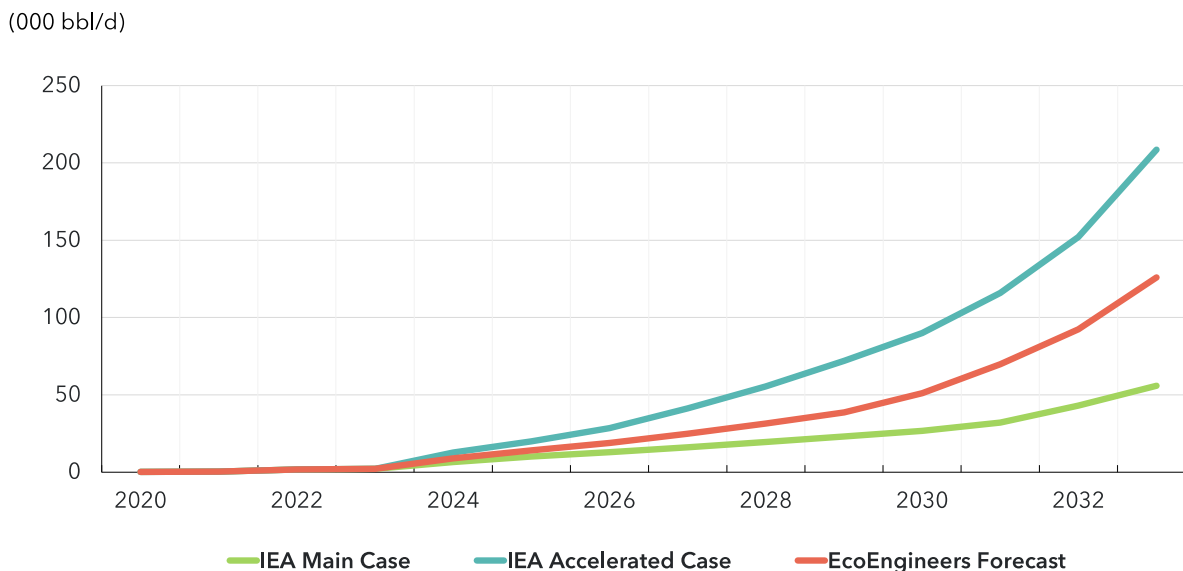


Figure 5.5: Worldwide Ethanol Demand Corresponding to ATJ SAF Worldwide Demand Scenarios



– IEA and EcoEngineers

Negative Risks to EcoEngineers’ Forecast:

- ATJ process technology improvements come slower than expected (historically, process technology improvements appear at an uneven rate).
- The rate of SAF-use mandate imposition is slower than expected attenuated due to the lack of political will (mandates will most likely increase airline fuel costs and, eventually, ticket prices) and generate push-back from airlines.
- Average feedstock costs for the HEFA route do not rise as fast as expected.
- Lower-CI feedstocks for the HEFA route to SAF, such as specially engineered cover crops like *Camelina sativa*, make the route more competitive. Likewise, relatively low-cost, low-CI hydrogen use in the HEFA process could make the route more cost-competitive.
- Renewable energy policy developers in the U.S. and/or the EU emphasize the use of E-fuels over ATJ- and HEFA-generated fuels.
- The SAF LCA model input questions (related to U.S. IRA incentives) are largely resolved in directions that do not favor the U.S.-based ATJ route.
- CCS technology in combination with the lower product CI levels proves to be an ineffective combination in terms of CCS levelized application costs and use incentives.
- The middle class responds negatively to the higher airline tickets required by SAF mandates due to the lack of support via production incentives.

- A technology breakthrough occurs in an alternate SAF-production route: The HEFA route, the combined gasification, FT, and hydrotreating route, or an E-fuels route.
- Offsets, such as those currently allowed by CORSIA will become a common method for effectively compensating for GHG emissions from airline flights.
- Brazilian politicians support low-CI ethanol imports.

Positive Risks to EcoEngineers' Forecast:

- ATJ process technology improvements come sooner than expected.
- SAF use mandates arrive sooner than expected and at higher levels than expected. (A carefully designed worldwide carbon tax system could result in the same effect, but EcoEngineers believes that this event has a low probability of occurrence.)
- CCS technology in combination with lower product CI final SAF product levels proves to be an effective combination in terms of CCS-levelized application costs and use incentives. The improved credit values make SAF a more attractive fuel.
- The SAF LCA model input questions (related to U.S. IRA incentives) are largely resolved in directions that favor the U.S.-based ATJ route.

Section 6: The Routes to SAF, Production Costs, and Market Prices

In this section, EcoEngineers will explain the different major process technology routes for SAF production and rank their current and potential future use. The focus here will be to provide an outlook for the large-scale commercial use of the ethanol-to-jet (ETJ) processing route over a 10-year timeline, as well as provide an outlook on the most likely geographic location of ATJ producers.

Chapter 6.1: Approved SAF Pathways

There are multiple process technology pathways approved by ASTM to produce SAF. Blending limitations exist for each pathway.

ASTM D7566 Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons describes fuel quality standards for non-petroleum-based jet fuel and outlines approved SAF-based fuels and the allowable percentage in a blend with petroleum-based jet fuel. ASTM D1655 Standard Specification for Aviation Turbine Fuels allows the co-processing of biomass feedstocks at a petroleum refinery in blends up to 5%. Both ASTM standards are continuously updated to allow for advancements in process technology.

The pathways in Table 6.1 represent those currently approved for SAF production by the ASTM through Q4 2023.

Table 6.1: Approved SAF Production Pathways by ASTM (Through Q4 2023)

Pathway	Approved Name	Blending Limitation	Approved Feedstocks	Approved Chemical Process
Fischer-Tropsch (FT) Synthetic Paraffinic Kerosene (SPK)	FT-SPK, ASTM D7566 Annex A1, 2009	50%	Municipal solid waste, agricultural and forest wastes, energy crops	Woody biomass is converted to syngas using gasification, and then an FT synthesis reaction converts the syngas to jet fuel. Feedstocks include various sources of renewable biomass, primarily woody biomass such as municipal solid waste, agricultural wastes, forest wastes, wood, and energy crops. ASTM approved in June 2009 with a 50% blend limit.
Hydroprocessed Esters and Fatty Acids (HEFA)	HEFA-SPK, ASTM D7566 Annex A2, 2011	50%	Oil-based feedstocks (e.g., jatropha, algae, camelina, and yellow grease)	Triglyceride feedstocks such as plant oil, animal oil, yellow or brown greases, or waste fat, oil, and greases are hydroprocessed to break apart the long chain of fatty acids, followed by hydroisomerization and hydrocracking. This pathway produces a drop-in fuel and was ASTM-approved in July 2011 with a 50% blend limit.
Hydroprocessed Fermented Sugars to Synthetic Isoparaffins	HFS-SIP, ASTM D7566 Annex A3, 2014	10%	Sugars	Microbial conversion of sugars to hydrocarbons. Feedstocks include cellulosic biomass feedstocks (e.g., herbaceous biomass and corn stover). Pretreated waste fat, oil, and greases are also eligible feedstocks. ASTM approved in June 2014 with a 10% blend limit.

Pathway	Approved Name	Blending Limitation	Approved Feedstocks	Approved Chemical Process
FT-SPK with Aromatics	FT-SPK/A, ASTM D7566 Annex A4, 2015	50%	Same as A1	Biomass is converted to syngas, which is then converted to synthetic paraffinic kerosene and aromatics by FT synthesis. This process is similar to FT-SPK ASTM D7566 Annex A1, but with the addition of aromatic components. ASTM approved in November 2015 with a 50% blend limit.
Alcohol-to-Jet (ATJ) Synthetic Paraffinic Kerosene	ATJ-SPK, ASTM D7566 Annex A5, 2016	30%	Cellulosic biomass	Conversion of cellulosic or starchy alcohol (isobutanol and ethanol) into a drop-in fuel through a series of chemical reactions—dehydration, hydrogenation, oligomerization, and hydrotreatment. The alcohols are derived from cellulosic feedstock or starchy feedstock via fermentation or gasification reactions. Ethanol and isobutanol produced from lignocellulosic biomass (e.g., corn stover) are considered favorable feedstocks, but other potential feedstocks (not yet ASTM approved) include methanol, iso-propanol, and long-chain fatty alcohols. ASTM approved in April 2016 for isobutanol and in June 2018 for ethanol with a 30% blend limit.

Pathway	Approved Name	Blending Limitation	Approved Feedstocks	Approved Chemical Process
Catalytic Hydrothermolysis Synthesized Kerosene	CH-SK or CHJ, ASTM D7566 Annex A6, 2020	50%	Fatty acids or fatty acid esters or lipids from fat oil greases	Also called hydrothermal liquefaction, clean free fatty acid oil from processing waste oils or energy oils is combined with preheated feed water and then passed to a catalytic hydrothermolysis reactor. Feedstocks for the CH-SPK process can be a variety of triglyceride-based feedstocks such as soybean oil, jatropha oil, camelina oil, carinata oil, and tung oil. ASTM approved in February 2020 with a 50% blend limit.
Hydrocarbon-Hydroprocessed Esters and Fatty Acids	HC-HEFA-SPK, ASTM D7566 Annex A7, 2020	10%	Algal oil	Conversion of the triglyceride oil, derived from <i>Botryococcus braunii</i> , into jet fuel and other fractionations. <i>Botryococcus braunii</i> is a high-growth alga that produces triglyceride oil. ASTM approved in May 2020 with a 10% blend limit.
Fats, Oils, and Greases (FOG) Co-Processing	FOG Co-Processing ASTM D1655 Annex A1	5%	Fats, oils, and greases	ASTM approved 5% fats, oils, and greases coprocessing with petroleum intermediates as a potential SAF pathway. Used cooking oil and waste animal fats are two other popular sources for coprocessing.
FT Co-Processing	FT Co-Processing ASTM D1655 Annex A1	5%	FT biocrude	In association with the University of Dayton Research Institute, ASTM approved 5% FT syncrude coprocessing with petroleum crude oil to produce SAF.

– USDOE, Alternative Fuels Data Center, EcoEngineers

Chapter 6.2: SAF Production Plans

By the end of Q2 2023, over 70 projects have been announced or are operating worldwide, adding up to over 20 billion gallons per year of total capacity or approximately 1.2 million gallons per year (MMgy). (Table 6.2)

Most of the projects are still in the initial planning stages and are probably far from a final investment decision (FID) stage. For many projects, SAF is part of a wider product slate. Co-products are often RD and renewable naphtha.

Based on history, only some of these projects will reach the engineering, procurement, and construction (EPC) stage. Today, very few facilities (probably less than 10) are producing commercial-scale volumes of SAF.

Nearly all the currently producing facilities are using the HEFA route. The announced, but not operating projects, are based on HEFA, ATJ, gasification plus FT, pyrolysis, algae-based, and E-fuels process technology routes.

Chapter 6.3: RD/SAF Production Pathways

Today, eight different pathways can be used to produce renewable liquid fuels such as RD and SAF (Figure 6.1).

All these pathways have demonstrated “proof of concept,” which means that the required reactions work on the bench-top or at the pilot scale, and on-spec products can be produced. Of course, demonstrating proof of concept does not guarantee that cost-effective production and commercialization are possible.

Today, only the HEFA route is commercial in terms of consistent, large scale 24/7 production. The gasification-FT, pyrolysis plus hydrotreating, and ATJ routes are at the commercial pilot stage.

Table 6.2: Announced and Current SAF Projects Worldwide (as of Q4 2023)

(ATJ facilities highlighted in red)

	Firm	Facility Location		Firm	Facility Location
1	Acelen	Brazil	38	Nacero	Texas (MTJ)
2	Aemetis	Riverbank, CA	39	Neste Rotterdam	Netherlands
3	Alder Fuels	CA	40	NEXT	Oregon
4	Alfanar Energy	UK	41	Nordic Electrofuel	Poragrunn, Norway
5	Alleo	Alabama	42	NorthWest Adv. Biofuels	Washington
6	Atmosfair	Germany	43	Oceania Biofuels	Gladstone, Australia
7	Azure	USA	44	Omega Green	Paraguay
8	BP Castellon	Spain	45	OMV Schwechat	Austria
9	BP Lingen	Germany	46	Oriental Energy	Guangdong, China
10	Braya	Come by Chance, NF	47	Phillips 66 Rodeo	CA
11	China Aviation Fuel Group	China	48	Pertamina Cilacap	Indonesia
12	CVR, Wynnewood	Wynnewood, OK	49	Petronas	Malaysia
13	DG Fuels	St. James Parish, LA	50	Preem Gothenburg	Sweden
14	Diamond Green Diesel	Texas	51	Project Speedbird	UK
15	Eneos Holdings/Ampol	Japan	52	Raven SR/EFT	CA
16	ENI Taranto	Italy	53	RPR	Rio Grande, Brazil
17	Firefly	UK	54	Saffitre Renewables	USA
18	Fulcrum Indiana	Whiting, Indiana	55	SAFuelsX	North Dakota
19	Fulcrum NorthPoint	UK	56	SGP Bioenergy	Panama

	Firm	Facility Location		Firm	Facility Location
20	Fulcrum Sierra Nevada	Reno, Nevada	57	Shandong Haike Chemical	China
21	Gevo	Lake Preston, SD	58	Shell Eastern Petroleum	Philippines
22	Gron Fuels	Louisiana	59	Shell Rotterdam	Netherlands
23	HCS Group	Speyer, Germany	60	Sinopec	China
24	HFSinclair, Cheyenne	Cheyenne, WY	61	SkyNRG	Pacific NW, USA
25	HIF Global	USA	62	Slate	Wyoming
26	HOBO 2	USA	63	Strategic Biofuels	Caldwell Parish, LA
27	Idunn H2	Iceland	64	Summit Next Gen	USGC
28	Imperial Oil, Strathcona, AB	Alberta Canada	65	T2C energy	USA
29	Indaba , Missouri	Missouri	66	Total Grandpuits	France
30	Indaba, California	CA	67	Total Le Mede	France
31	Indian oil	India	68	Total Oudalle	France
32	Infinium Heartland	Midwest, USA	69	Tupras, Izmir	Izmir, Turkey
33	Jet Zero Australia	Australia	70	Twelve/EFT	USA
34	LanzaJet Dragon	UK	71	Velocys Altalto	Immingham, UK
35	LanzaJet Freedom Pines	Georgia	72	Velocys Bayou Fuels	Natchez, MI
36	Marquis Energy	Hennepin, IL	73	Velocys E-Fuels	UK
37	Mitsubishi/Boeing/ Total	Japan	74	World Energy	Houston, TX

Chapter 6.4: Commercialization Status of SAF Production Pathways

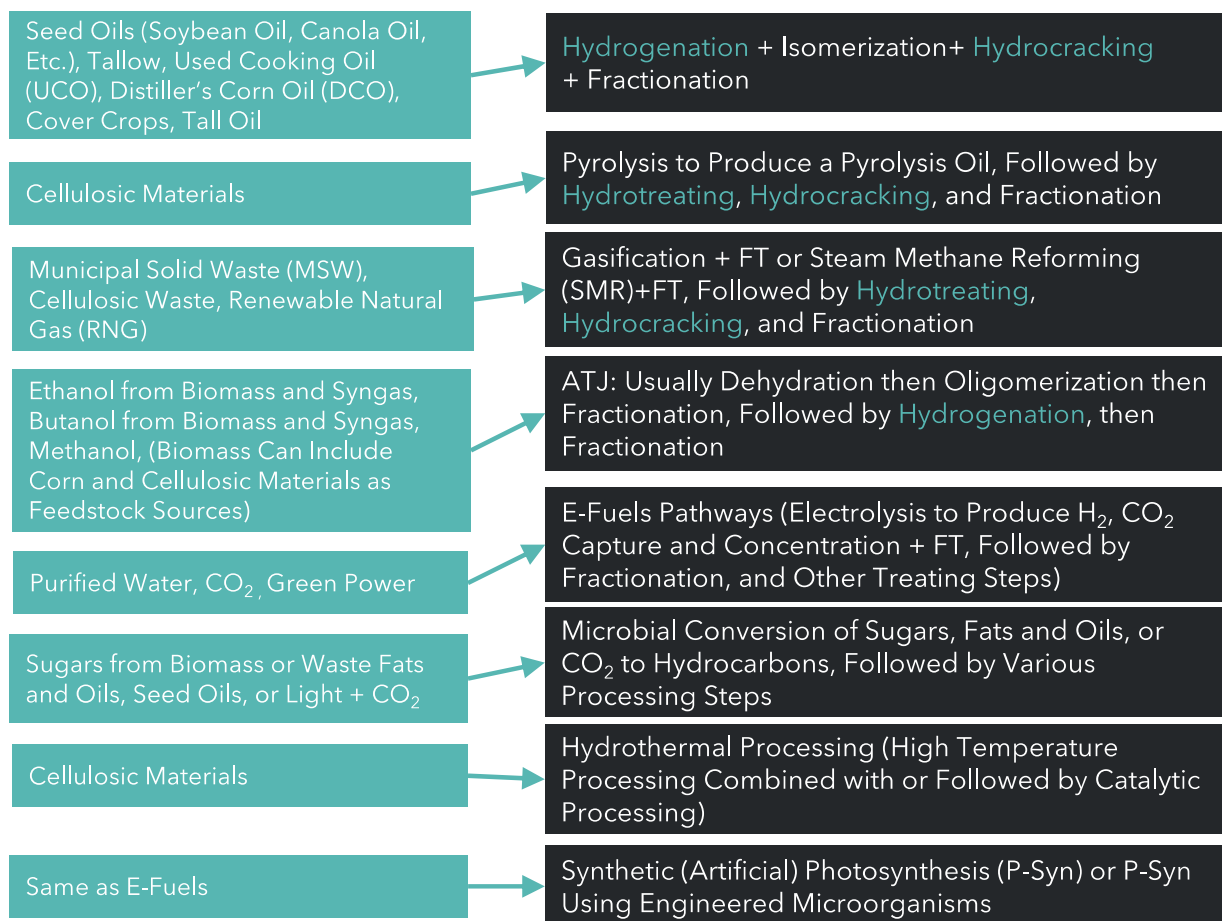
Today, the HEFA process produces the vast majority of SAF used in commercial flights. The ATJ, gasification/FT, and pyrolysis processes have been used in a few demonstration flights. However, the history of transportation fuel process development instructs us that not all new processes at the demonstration stage or commercial pilot stage reach effective (profitable) commercialization. The fuels need to be sold at a price that airlines and their customers are willing to pay.

E-fuels and algae-based processes are, most likely, many years away from commercialization. The ATJ pathway, the MSW-to-SAF pathway (via gasification and FT and hydrotreating), and

the cellulosic-to-SAF pathway (via pyrolysis and hydrotreating) are still in the commercial pilot phase and may also be years away from full-scale commercialization (Figure 6.2).

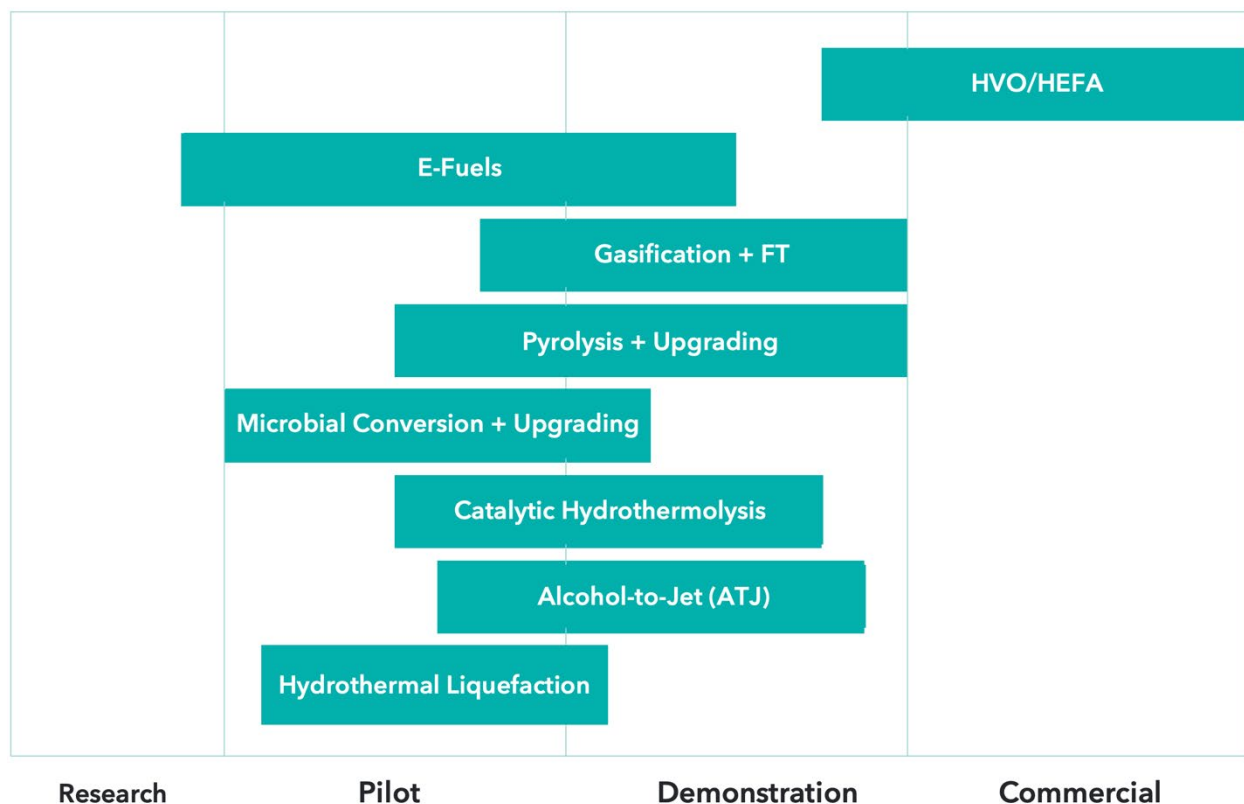
Government-produced technology development “road maps” and voluntary targets will not solve the cost of the supply problem. History has demonstrated that process development innovation cannot be legislated. It is not guaranteed that all the SAF pathways under development will eventually reach commercial status.

Figure 6.1: Overview of Renewable Diesel and SAF Production Pathways



– EcoEngineers

Figure 6.2: Commercialization Status of SAF Pathways (as of Q4 2023)



– International Renewable Energy Agency (IRENA) and EcoEngineers

Chapter 6.5: SAF Production Costs

The additional cost of SAF production compared to petroleum-based jet fuel production is summarized as follows:

- The smaller production scale of current SAF production facilities (relative to most petroleum-based jet fuel production refineries). This increases the fixed costs per barrel of product for smaller refineries.
- Higher feedstock costs for SAF (relative to crude oil).
- The relative complexity of many SAF production process schemes (compared to the processes used to make petroleum-based jet fuel).
- The ability of a crude oil refinery to spread fixed costs over multiple products.

The Operating Scale and Fixed-Cost Issues

Many different products are produced in today's petroleum (crude oil) refineries. The major products are gasoline and diesel/gasoil (distillate fuel oils). Jet fuel is a relatively minor product, at less than 9% of total products produced (in 2022) in the U.S. Jet fuel could almost be categorized as a byproduct (Table 6.3).

The wide petroleum refining product slate allows refiners to spread their levelized operating costs (fixed costs, variable costs, sustaining capital, and shareholder ROI) over many products.

Table 6.3: U.S. Petroleum Refineries Net Production of Products (2022)

	000 bbl/d	% of Total
Finished Motor Gasoline	9,569	49.3%
Distillate Fuel Oil	5,011	25.8%
Jet Fuel	1,615	8.3%
Petcoke	807	4.2%
Refinery Gas	661	3.4%
Gas Liquids	352	1.8%
Asphalt	341	1.8%
Olefins	259	1.3%
Petchem Feedstocks and Naphthas	255	1.3%
Resids	251	1.3%
Lubricants and Waxes	163	0.8%
Misc. Products	89	0.5%
Kerosene	12	0.1%
Aviation Gasoline	11	0.1%
Sum	19,396	100.0%

– U.S. Energy Information Administration (EIA)

In addition, the core process technologies used to produce modern jet fuel were developed over 50 years ago and have benefited from continuous improvement. Most process technologies that are used to make RD and/or SAF are relatively new and are less developed (optimized).

Most importantly, the scale of nearly all the world’s petroleum refineries is much larger than the current scale of all the world’s operating HEFA-type and most other planned RD/SAF production facilities. This results in tremendous economies of scale in terms of fixed costs, initial total installed capital costs, maintenance costs, and sustaining capital costs, per barrel of refined crude oil product produced.

Table 6.4 shows the differences in scale between all currently operating U.S. petroleum refineries and all currently operating U.S. RD/SAF refineries. When considering the effect of fixed operating costs per barrel of product, this difference is significant.

Table 6.4: 2023 Comparison of the Size of U.S. Petroleum Refineries and U.S. HEFA Refineries Producing Renewable Diesel and SAF

Bbl/d Production Range	Number of Operating U.S. Petroleum Refineries	Number of Operating U.S. HEFA Refineries
600,000 to 650,000	1	
550,000 to 600,000	3	
500,000 to 550,000	1	
450,000 to 500,000	1	
400,000 to 450,000	1	
350,000 to 400,000	4	
300,000 to 350,000	3	
250,000 to 300,000	10	
200,000 to 250,000	8	
150,000 to 200,000	13	
100,000 to 150,000	19	
50,000 to 100,000	28	
1,500 to 50,000	34	6
50 to 1,500		14

– EcoEngineers

The difference in the size of the operation shown in Table 6.4 is extraordinary. The largest U.S. RD/SAF refineries (all HEFA types today) are at the extreme lower end of the size range of all current U.S. petroleum refineries. This general size relationship is the same in the EU and Asia. As a point of reference, the largest HEFA RD production facility in the U.S. today, the Diamond Green Diesel (DGD) diesel facility in Norco, LA, has an operating capacity of close to 700 MMgy. This equates to approximately 45,600 bbl/d of RD product.

Within the next 10 years, based on future facility plans that are in the early planning stages today, we do not expect that any potential new HEFA, ATJ, gasification/FT, or pyrolysis/hydrotreating-based RD/SAF production facilities will be much larger than the largest currently operating HEFA-type RD/SAF facilities.

This means that the levelized operating costs per barrel of the final product are and will, most likely, continue to be significantly lower in petroleum refineries than in the RD/SAF facilities, unless we see an extraordinary process technology breakthrough for one or more of the RD and SAF production processes.

History tells us that refining facilities' fixed costs (labor, insurance, general maintenance, some utilities, some taxes) are reasonably proportional to total installed capital costs (or replacement costs) for a refining facility. We also know, based on evaluations of actual total installed costs for liquid fuel refineries, the capital cost to build a facility scale, as a function of the size of the facility, based on an exponential factor of between 0.6 and 0.7. This phenomenon is loosely referred to as the "economy of scale" effect.

Comparing Levelized Costs of Production for SAF vs. Petroleum-Based Jet Fuel

In general, most independent analysts like the National Renewable Energy Laboratory (NREL), International Renewable Energy Agency (IRENA), U.S. Department of Energy (USDOE), IEA, and EcoEngineers agree that the correct total levelized costs of RD/SAF production ranges from **between 2x-7x higher** than petroleum-based ultra-low sulfur diesel and jet fuel. (This is based on benchmark oil prices at around US\$80/bbl). This comparison is based on our estimates of the current technology readiness levels of the various process technologies.

Large-scale HEFA-type RD and SAF facilities with the latest process technologies will perform at the lower end of the range and E-fuels and some algae-based processes will be at the higher end. ATJ, gasification/FT, pyrolysis/hydrotreating, and some algae-based processes will probably be in the mid-range. For the newer process technologies, the estimates are all range-based because no full-time commercial-scale facilities are operational.

Until a new fuel production process technology is up and running 24/7 at a commercial scale (providing product regularly to contracted offtakers) and demonstrates that it can generate a profit, no one knows what the true levelized costs of production for the process technology will be.

For the HEFA Pathway: Significant levels of hydrogen per barrel of product are required due to the necessity to remove significant quantities of oxygen from the feedstock material. As noted previously, fixed costs per barrel of product and total installed capital costs per barrel of product will be higher than in most petroleum refineries. Relatively expensive metallurgy is required in parts of the system due to the presence of produced water and some corrosive byproducts. The preferred feedstocks are relatively expensive and may soon be supply-limited.

For the ATJ Pathway: After alcohol (ethanol or isobutanol) production and purification, three additional catalytic reaction steps, with some yield loss through each section are required: dehydration to ethylene, oligomerization (polymerization), and finally, hydrotreating. As in the HEFA process, the final reaction is followed by a fractionation section. Catalyst costs will be a significant part of operating expenditure (opex). Obtaining solid guarantees for all catalysts used, covering minimum catalyst life, and regenerability (covering minimum activity retention and regeneration time) will be critical. As noted previously, fixed costs per barrel of product and total installed capital costs per barrel of product will, most likely, be higher than in nearly all petroleum refineries. Most ATJ plants currently in the planning/design stages are much smaller than most petroleum refineries.

In Q1 2024, there is a very high level of uncertainty regarding the ultimate levelized costs of production for SAF produced via the ETJ process. There is, as yet no credible public domain

information regarding the expected total installed capital costs and full operating costs of a commercial ETJ facility. We find conflicting estimates and forecasts of SAF via ETJ cost of production information in the public domain. At this time, EcoEngineers expects that for the first few commercial ETJ facilities, their full leveled costs of production will be noticeably higher than the current costs for the HEFA pathway to SAF for three main reasons:

1. The ETJ process is more complex than the HEFA to SAF process. The ETJ process employs three core reaction steps, whereas the HEFA process employs two.
2. The yields (weight of final salable product/weight of feedstock charged to reactors) for the ETJ process are expected to be significantly lower than the yields from the HEFA process. However, based on today's feedstock prices for the HEFA and ETJ processes, the lower price of ethanol versus most HEFA feedstocks helps to compensate for the lower yields of the ETJ process.
3. The ETJ route has not yet reached a successful 24/7 commercial scale, and the history of new commercial fuels process development instructs us that the ultimate full leveled costs of SAF production for the first commercial ETJ process facilities will, most likely, be noticeably higher than most of the current estimates by various academic and consulting groups. As a point of reference, the HEFA process for RD and SAF is based on permutations of oil refining technology that has been under development and undergoing process improvement since the 1950s. The first commercial HEFA plants were brought online in 2007 (Neste) and Diamond Green (2013). There has been continual process improvement and process cost reduction since those initial start-ups.

For the MSW (or Biomass)-to-SAF via Gasification/FT/Hydrotreating Pathway: The gasification reactor, the syngas clean-up section, and the FT reactor system are all relatively complex. Syngas clean-up costs (to protect the FT catalysts) are often underestimated by project entrepreneurs. As noted previously, fixed costs per barrel of product and total installed capital costs per barrel of product will be higher than in most petroleum refineries. An effective and consistent MSW feed composition, sorting, and sizing system is critical to keeping potential foulants out of the gasifier feedstock. This adds significant expense to the overall system. The FT product requires hydrotreating and other processing to produce on-spec RD and SAF.

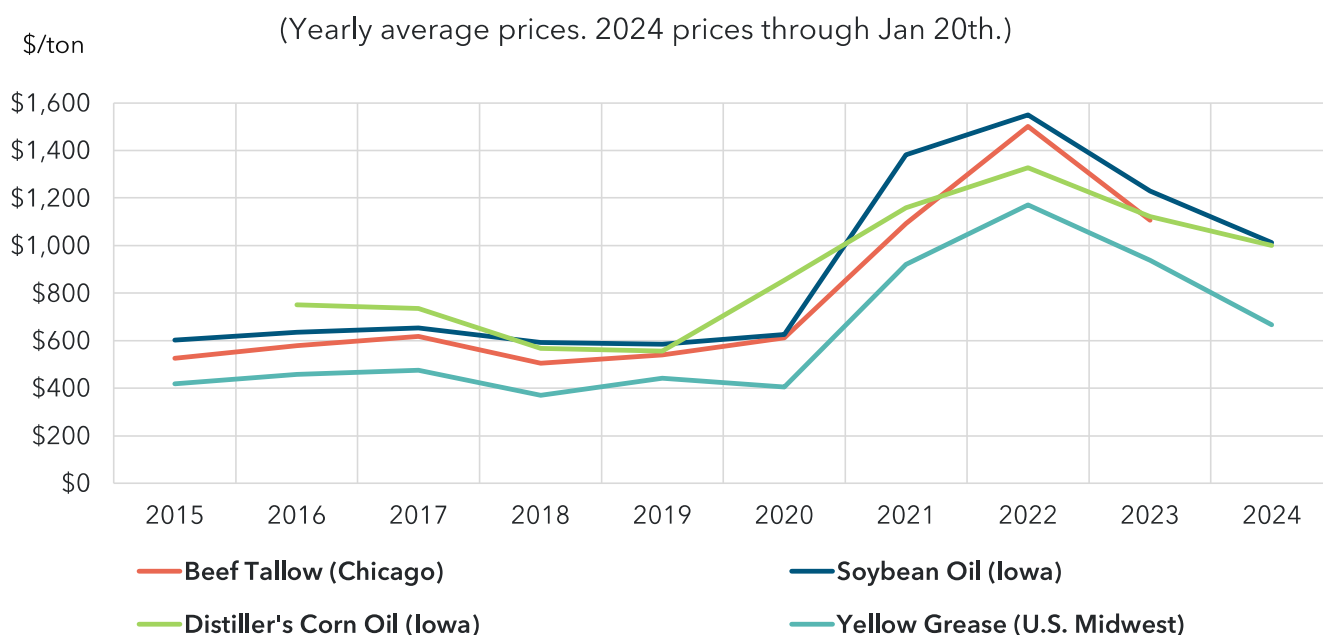
For the Cellulosics-(or Plastics)-to-SAF via Pyrolysis/Hydrotreating Pathway: As noted previously, fixed costs per barrel of product and total installed capital costs per barrel of product will be higher than in most petroleum refineries. The prevention of fouling presents design issues that usually add significant capital and operating costs to the processing system. Feedstock must (usually) be dried. For many plastics-fed systems, careful sorting of plastics is a relatively high opex/barrel step. For cellulosic feedstock, proximity to the source of feedstock is necessary and this often limits the scale of the system. Drying feedstock to be transported over long distances adds significant opex and capex/barrel to the overall project.

For the E-fuels Pathway: The process technology is still in the pilot stage or early demonstration stage. Electrolysis systems to produce low-CI hydrogen from water have very high capex and opex/barrel of product. CCS systems are expensive on a per-barrel basis and

usually require a concentrated CO₂ stream to be viable. Today's synthesis systems (that turn CO₂ and H₂ into SAF and RD) require relatively high capex and opex per barrel of product.

The HEFA Route Feedstock Cost Issue: A major driver for HEFA-based RD and SAF product prices is feedstock prices. HEFA feedstock prices rose dramatically in 2021 in response to a rapid expansion in worldwide RD facility start-ups and to weather issues that affected harvest volumes in multiple countries. Many RD/SAF plants can use multiple feedstocks. Therefore, supply and price pressure on one feedstock can easily transfer to another. This effect will likely be magnified in the future as RD/SAF production capacity increases worldwide. (Figure 6.3)

Figure 6.3: Renewable Diesel and SAF HEFA Route Feedstock Price History



– U.S. Department of Agriculture (USDA), Iowa State University, and EcoEngineers

The HEFA route feedstock prices continued to rise in 2022. Russia's invasion of Ukraine in February 2022 resulted in shortages of soybean oil (SBO) for multiple months.

Feedstock prices have dropped slightly in 2023 as SBO shipments from Ukraine have partially resumed and as alternate sources of feedstock supply have compensated. The prices continued to drop in 2024.

In the future, we expect continued upward pressure on RD/SAF feedstock prices for the HEFA route, especially as many more HEFA-based RD/SAF plants come online and as government policymakers gradually realize that the alternate routes to large-scale RD/SAF production (especially the E-fuels, pyrolysis/hydrogenation, and gasification-FT routes) are, most likely, many years away from large-scale, cost-effective commercialization.

Even the ATJ route to RD/SAF may face some significant commercialization headwinds for both the corn and sugarcane routes due to potential problems related to food versus fuel issues. We do not expect RD/SAF HEFA route feedstock prices to return to their 2015–2020 trends. Our current expectation for the next three to four years is US\$100/MT–\$200/MT below the 2023 price range, on average.

The HEFA Route Hydrogen Cost Issue: Hydrogen costs are another key price driver for the HEFA route to RD/SAF. It takes significantly more hydrogen per barrel of product to make RD and SAF than it does to make conventional diesel and jet fuel. This is because of the need to remove all the oxygen that is in the various feedstocks. Natural gas is the typical feedstock for producing hydrogen in most RD/SAF plants that are in operation or in the design phase today. Hydrogen prices are proportional to natural gas prices. If natural gas prices experience a prolonged run-up like that seen during the first six months of the war in Ukraine, RD/SAF suppliers will need to charge more for their products to break even. (Figure 6.4)

An extra cold winter season (in the U.S. or Europe), an increase in worldwide liquefied natural gas (LNG) demand, and the inability to inject normal volumes of natural gas into storage during the spring, summer, and fall months, are all market events that would lead to higher natural gas and - ultimately - hydrogen prices.

Figure 6.4: U.S. Henry Hub Natural Gas Prices (Monthly Averages Through December 2023)



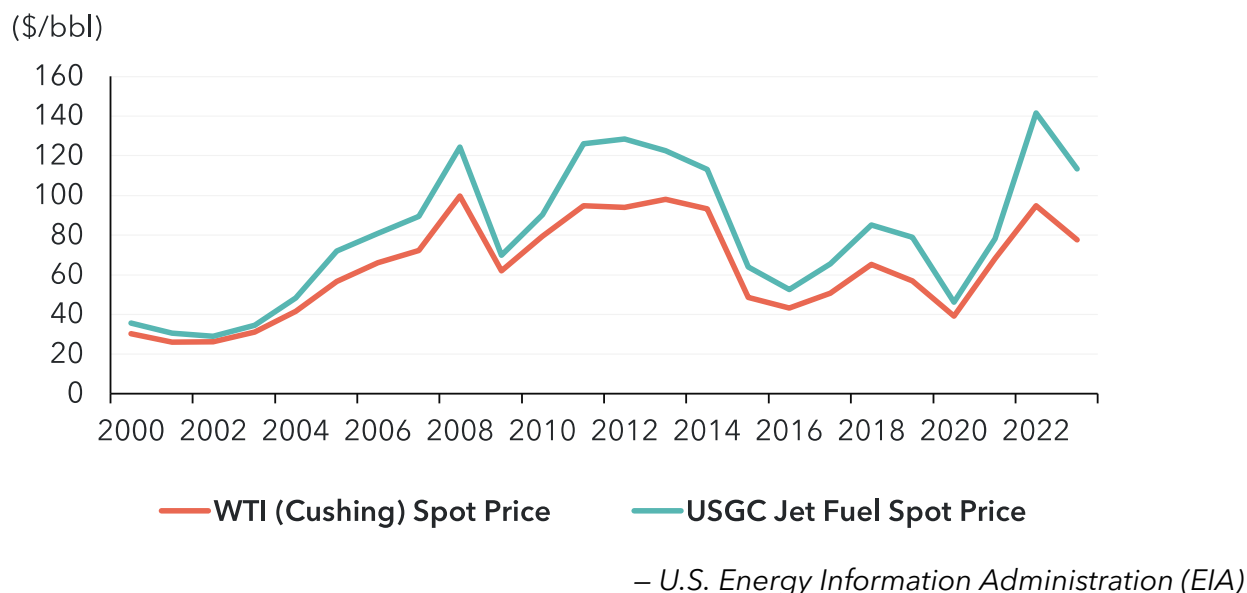
– U.S. Energy Information Administration (EIA)

Chapter 6.6: Petroleum-Based Jet Fuel Market Prices (A Point of Reference)

The major driver of the petroleum-based jet fuel price is the cost of crude oil (Figure 6.5). Petroleum refinery margins are typically set by the marginal suppliers to the market who generally will sell their products at close to the breakeven price. Marginal suppliers are usually the smaller, less efficient refineries.

Periods of oversupply will also cause refining margins to shrink, such as during the pandemic when shutdowns curtailed flights.

Figure 6.5: Crude Oil and Jet Fuel Price Comparison (Yearly Average Prices)



Chapter 6.7: SAF Market Prices

Today, due to the low market volumes and a lack of transaction transparency, there are no traditional spot market-based prices posted for SAF like what we see for major crude oils and petroleum-based jet fuel.

Platts (S&P Global), Argus Media, and General Index all offer estimates of regional SAF market prices. The methods used for their estimations range from “calculated” to “based on market survey” approaches. The “calculated” approaches use “production cost-based models” based on estimates of actual feedstock and processing fixed costs for the HEFA production method. The market survey approach is not transparent. There is no indication that the estimated prices are close to the average actual transaction prices.

As noted earlier, most estimates for the breakeven production costs of SAF **range from 2x-7x that of petroleum-based jet fuel production costs**, depending on the process technology and the feedstock used to produce the SAF. These estimates are calculations of levelized costs of production based on expert knowledge of the total installed costs and processing costs for the traditional aspects of a particular SAF production process plus public domain information from new process technology suppliers, project developers, and information from pathway registrations and patents.

Based on projects we have reviewed, EcoEngineers believes that some HEFA-type SAF production processes, at large facilities, are close to the 2x factor.

Chapter 6.8: Potential Locations of ATJ SAF Producers

As shown in Table 6.2, proposed and current SAF production facilities may be located all over the world. Only seven out of the 74 confirmed operating or proposed commercial facilities are ATJ facilities and one of these (Nacero) is a proposed methanol-to-jet (MTJ) facility.

Note: The feedstock for the planned LanzaJet Dragon ATJ facility would be waste gases, potentially sourced from Tata Steel’s adjacent steelworks facility in Port Talbot, UK. These would be transformed via LanzaTech’s gas fermentation platform to make ethanol as a feedstock for the Dragon ATJ facility.

Table 6.5 shows a breakdown of RD and SAF project “players” based on process technology type. This also indicates that proposed ATJ projects are a relatively small fraction of all the proposed SAF production facilities.

Not surprisingly, the announced ETJ (ethanol-to-jet) producers are all located in the U.S. and are relatively close or accessible to fuel ethanol production regions. EcoEngineers expects that most future ETJ production, starting from grain-based ethanol, will be located in the U.S., or perhaps, eventually, Canada, close to the locations of most of the world’s grain-based ethanol production. EcoEngineers is aware of two additional, unannounced U.S. Midwest-based ETJ projects that are currently still in the confidential project development and planning stages.

Despite its high levels of sugarcane-based ethanol production, we have seen no firm announcements of ETJ projects in Brazil.

Table 6.5: Overview of SAF, Renewable Diesel Production Pathways, and Project Development Firms



Company Key: Black Font: In commercial operation // Green Font: In commercial pilot phase // Red Font: Process/project development phase // Cross-outs are no longer in RD/SAF business, in the category.

Section 7: Potential Effects on Corn Supply, Demand, and Prices

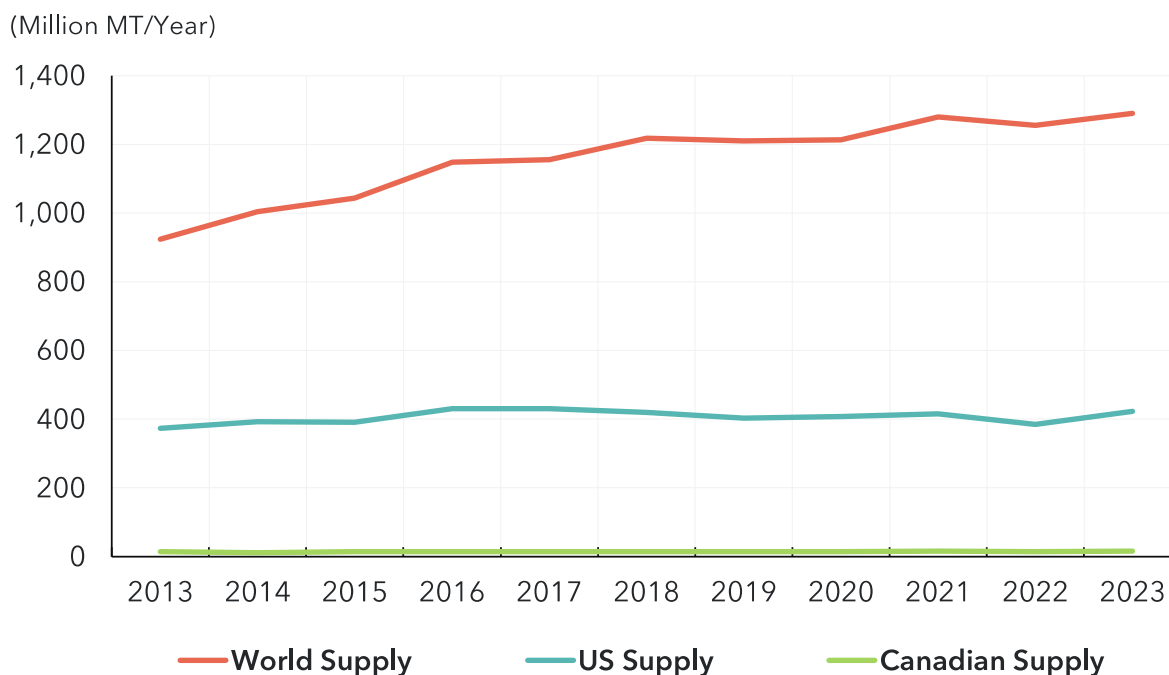
In this section, EcoEngineers provides an evaluation of the potential effects of SAF demand and other demand drivers on corn supply, demand, and prices in North America over 10 years. We will also consider the potential for imports and the effects of that activity. We will also evaluate the potential for the use of alternate feedstocks for ethanol production.

We will start with a review of North American and worldwide corn supply, demand, and price history.

Chapter 7.1: North American and Worldwide Corn Supply/Demand History

Total North American corn supply and domestic production have grown at a relatively slow rate over the last 10 years (Figure 7.1 and Table 7.1). Yearly corn supply is defined as starting stocks for the year plus domestic production plus imports.

Figure 7.1: Worldwide and North American Corn Supply



– USDA ERS Feed Grains Database

The CAGR for the U.S. corn supply was approximately 1.2%, which is significantly less than the U.S. GDP growth rate over the same period and less than the worldwide corn supply which saw a 10-year CAGR of approximately 3.4%. U.S. domestic corn production had a CAGR of 1.0%. The Canadian contribution to North American corn supply has been marginal.

U.S. total domestic corn demand, over time, can be assumed to be essentially equal to supply as internal corn stocks are not building year-to-year. The breakdown of U.S. corn demand is shown in Figure 7.2, Figure 7.3, and Table 7.2.

Fuel alcohol production is currently the largest single use of corn supply in the U.S. after assuming that somewhere between 2%-4% of the "Feed and Residual" use category is waste and unaccounted-for material across all use categories.

Note the wide range in the 10-year CAGR for U.S. corn use in the high-use level categories (Table 7.2). The use of corn for animal feed has been increasing at a rate of close to 1.2% per year while alcohol for fuel use has been growing at a rate of 0.4% per year. Total corn use has been growing at a CAGR of 1.2% over the last 10 years compared to a U.S. GDP growth rate of 4.7% over the same period.

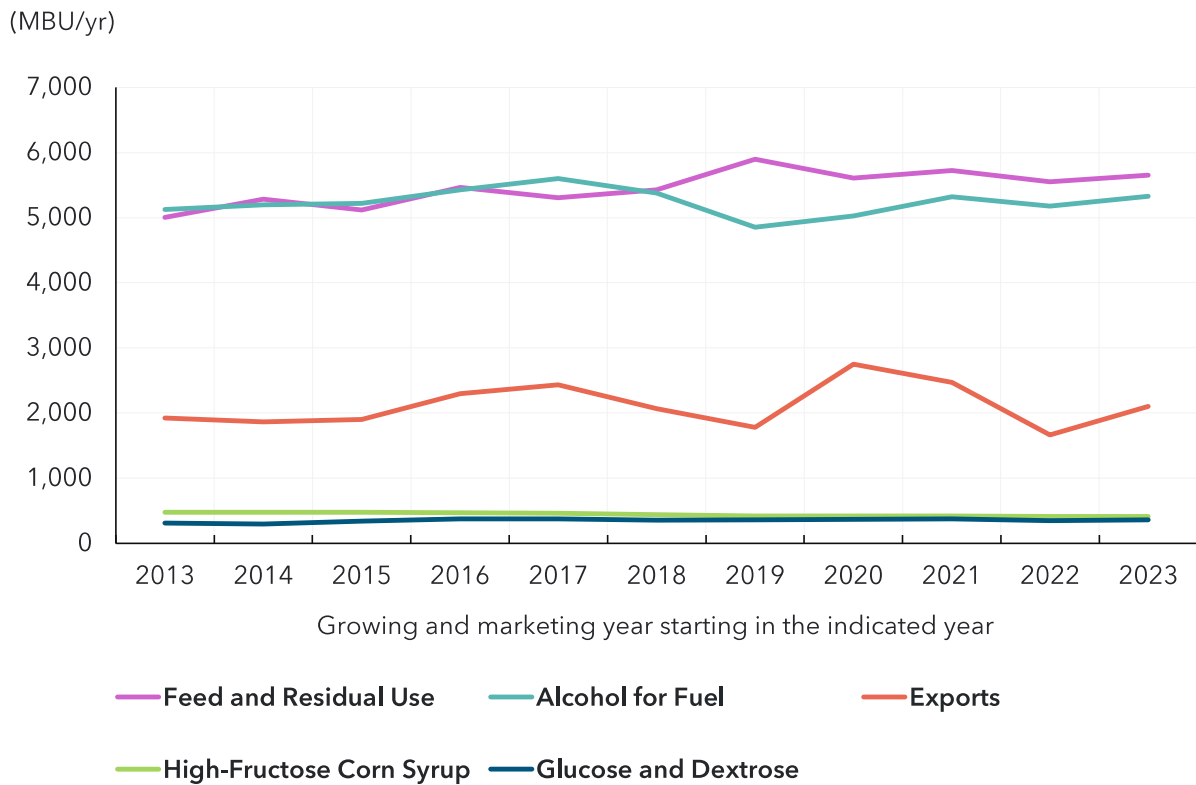
Table 7.1: Corn Supply and Production Data (Million MT/Year)

Million MT	World Supply	U.S. Supply	Canadian Supply	Total North American Supply	North American Domestic Production	American Production as % of Worldwide Supply	World GDP (Trillion US\$)	U.S. GDP (Trillion US\$)
2013	924	373	14.2	387	351	38%	77.7	16.8
2014	1,005	393	11.6	405	361	36%	79.8	17.6
2015	1,044	391	13.7	405	346	33%	75.3	18.2
2016	1,148	430	13.9	444	385	34%	76.5	18.7
2017	1,156	430	14.1	444	371	32%	81.5	19.5
2018	1,217	419	13.9	433	364	30%	86.5	20.5
2019	1,210	403	13.4	417	346	29%	87.8	21.4
2020	1,214	408	13.6	421	358	30%	85.3	21.1
2021	1,280	415	14.6	429	383	30%	97.5	23.3
2022	1,256	384	14.5	399	348	28%	101.3	25.4
2023	1,292	422	15.1	437	387	30%	104.4	26.7
CAGR	3.4%	1.2%	0.6%	1.2%	1.0%		3.0%	4.7%

– USDA ERS Feed Grains Database and World Bank (Estimated 2023 GDP)

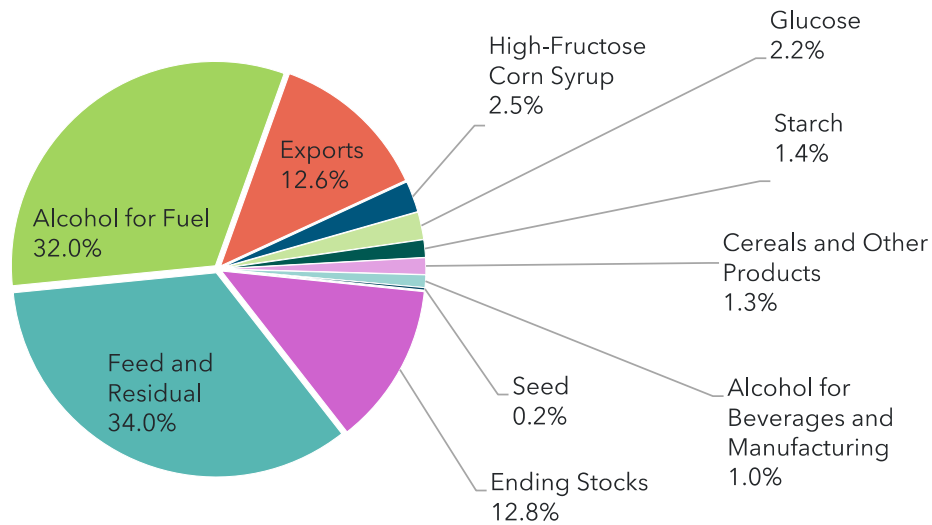
In 2023, the U.S. was still the top corn producer in the world with China and Brazil being the second and third largest producers, respectively (Table 7.3).

Figure 7.2: U.S. Corn Use Breakdown (Five Largest Markets)



– USDA ERS Feed Grains Database

Figure 7.3: Breakdown of U.S. Corn Use (2023)



– USDA ERS Feed Grains Database

Table 7.2: U.S. Corn Use by Market Year (Million-Bushel Basis)

Use By Year	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	CAGR
Feed and Residual	5,004	5,287	5,118	5,468	5,304	5,427	5,899	5,607	5,726	5,549	5,650	1.2%
Alcohol for Fuel	5,124	5,200	5,224	5,432	5,605	5,378	4,857	5,028	5,320	5,176	5,325	0.4%
Exports	1,921	1,867	1,899	2,296	2,437	2,068	1,778	2,747	2,472	1,661	2,100	0.9%
High-Fructose Corn Syrup	478	478	472	467	459	441	418	421	415	409	410	-1.5%
Glucose	307	298	337	371	372	355	356	365	371	344	360	1.6%
Starch	251	246	238	235	236	231	232	252	246	219	230	-0.9%
Cereals and Other Products	200	201	203	204	207	209	220	214	214	217	219	0.9%
Alcohol for Beverages and Manufacturing	142	142	143	146	149	150	173	157	161	162	165	1.5%
Seed	30	29	31	29	30	29	30	31	29	31	31	0.4%
Ending Stocks	1,232	1,731	1,737	2,293	2,140	2,221	1,919	1,235	1,377	1,361	2,131	5.6%
Total	14,688	15,480	15,401	16,942	16,938	16,509	15,882	16,056	16,332	15,129	16,621	1.2%

–USDA ERS Database

Table 7.3: U.S. Corn Use by Market Year (Million-Metric-Ton Basis)

Use By Year	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	CAGR
Feed and Residual	127	134	130	139	135	138	150	142	145	141	144	1.2%
Alcohol for Fuel	130	132	133	138	142	137	123	128	135	131	135	0.4%
Exports	49	47	48	58	62	53	45	70	63	42	53	0.9%
High-Fructose Corn Syrup	12	12	12	12	12	11	11	11	11	10	10	-1.5%
Glucose	8	8	9	9	9	9	9	9	9	9	9	1.6%
Starch	6	6	6	6	6	6	6	6	6	6	6	-0.9%
Cereals and Other Products	5	5	5	5	5	5	6	5	5	6	6	0.9%
Alcohol for Beverages and Manufacturing	4	4	4	4	4	4	4	4	4	4	4	1.5%
Seed	1	1	1	1	1	1	1	1	1	1	1	0.4%
Ending Stocks	31	44	44	58	54	56	49	31	35	35	54	5.6%
Total	373	393	391	430	430	419	403	408	415	384	422	1.2%

–USDA ERS Database

Table 7.4: Distribution of Global Corn Production

2022-2023 Growing Year	
United States	30.2%
China	24.0%
Brazil	11.9%
EU	4.5%
India	3.1%
Argentina	2.9%
Mexico	2.4%
Ukraine	2.3%
South Africa	1.5%
Russia	1.4%
Canada	1.3%
Indonesia	1.1%
Nigeria	1.1%
Ethiopia	0.9%
Other	11.4%

– USDA Foreign Agricultural Service (FAS)

Chapter 7.2: North American and Worldwide Corn Price History

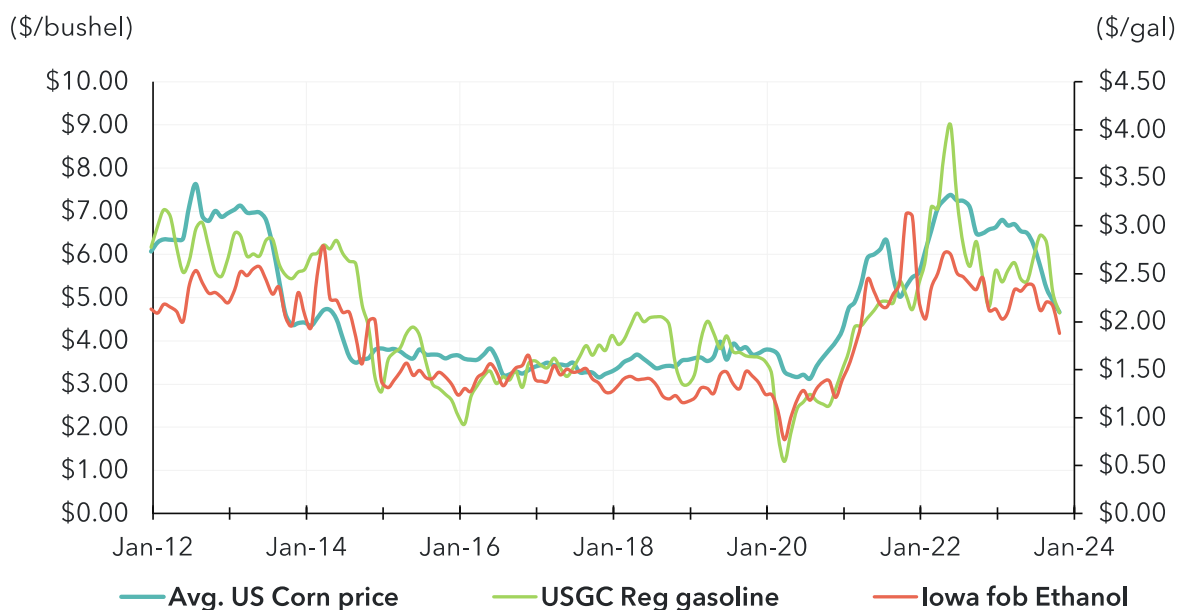
Over the last 12 years, U.S. corn prices have experienced a reasonable correlation to U.S. ethanol gasoline prices (Figure 7.4). The rough correlation between corn and ethanol prices is not surprising given that corn is the main feedstock for fuel ethanol production in the U.S.

Since fuel ethanol is blended with most of the gasoline consumed in the U.S.³ it is no surprise that the price of ethanol tends to move - approximately - with the price of gasoline, and with the price of crude oil to the extent that gasoline and crude oil prices move together (Figure 7.5). The same market forces that affect gasoline demand affect the demand for fuel ethanol in the U.S. The main use of fuel alcohol in the U.S. is as an additive for gasoline.

³ Current average levels of ethanol in U.S. gasoline are now at approximately 11 vol%.

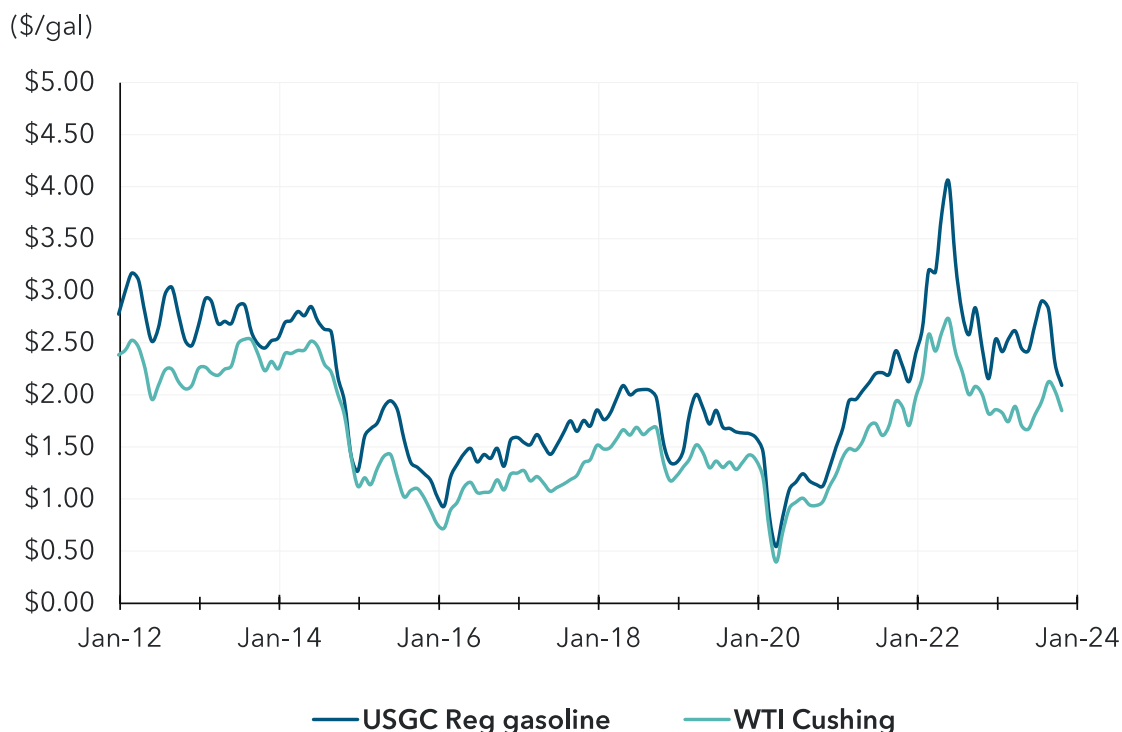
Based on EcoEngineers' forecast for ETJ use in the U.S. (an incremental 5% increase in ethanol demand due to ETJ use in 2033), we do not expect that this price correlation will change over the forecast period.

Figure 7.4: U.S. Average Monthly Producer Prices for Corn, USGC Spot Prices for Regular Conventional Gasoline, and Iowa Ethanol Plant Gate Price for Ethanol



– USDA National Agricultural Statistics Service, EIA Spot Price Database, Iowa State University Ethanol Profitability Database

Figure 7.5: USGC Spot Prices for Regular Conventional Gasoline and WTI Cushing Spot Price for Crude Oil



– EIA Spot Price Database

Explaining the Major Fluctuations in Oil, Gasoline, and Ethanol Prices: Oil, gasoline, and ethanol prices plunged in Q1 2020 due to the onset of the COVID-19 pandemic and the subsequent dramatic drop in gasoline and oil demand. Starting in late Q2 2020, oil, gasoline, and ethanol prices started a gradual return to price levels seen during the relatively stable price period of 2015-2019 as supply and demand trends gradually equilibrated.

The Russian invasion of Ukraine in February 2022 sent oil, gasoline, ethanol, and corn prices upward. Staring near the end of Q2 2022, oil, gasoline, ethanol, and corn prices began a gradual and semi-turbulent return to lower levels as the world’s markets adapted to the development of alternate supply channels and supply level adjustments to changing demand trends.

Chapter 7.3: Forecasting North American Corn Demand and Supply

Multiple key drivers must be considered when developing the total U.S. corn and ethanol demand forecasts. These include the demand for gasoline, target levels of ethanol in gasoline, all the additional U.S. domestic uses for ethanol and corn, export demand, and, finally, the demand for ethanol use to produce SAF and RD via the ETJ production process.

However, because we want to understand the effect ETJ-type SAF may have on North American ethanol demand (and ultimately North American corn demand) we will focus on

just the ETJ demand effects. Our high-level analysis tells us that, based on EcoEngineers' SAF demand and worldwide ethanol demand forecast, ethanol for the ETJ route will, most likely, not compete significantly with U.S. ethanol demand for gasoline blending, considering the current trajectories of U.S. gasoline demand and popular forecasts for electric vehicle (EV), plug-in hybrid vehicle (PHEV), and hydrogen vehicle (HV) adoption.

Starting with the IEA's SAF Demand Cases and EcoEngineers' Demand Forecast: In Section 5 of this report, we explained two IEA scenario-based forecasts and developed our own scenario-based forecast for worldwide SAF demand and ethanol (for ETJ use) demand (Table 5.1). For each of the IEA and EcoEngineers scenarios, we have also developed scenario-based forecasts for U.S. ethanol demand for SAF production via U.S.-based ETJ production facilities.

Now, for each U.S. alcohol-to-SAF demand scenario we will assume that the amount of U.S.-based SAF production (of all types) will increase from the estimated level of 25% or worldwide SAF production in 2023 to 40% of worldwide SAF production in 2033. Based on these assumptions we developed forecasts for U.S.-based ethanol demand for use in U.S.-based ETJ facilities. (Table 7.4).

For example, for the year 2033, in the EcoEngineers scenario, we arrive at a scenario-based forecast for additional U.S. ethanol demand for SAF production of approximately 51,000 bbl/d. This level of ethanol demand is calculated in the following manner.

- Assumed worldwide level of SAF demand: 302,120 bbl/d.
- Assumed level of worldwide SAF demand served by ETJ process: 25%.
- Assumed wt% yield through ETJ process: 60%.
- Resulting level of ethanol feedstock required worldwide: 125,883 bbl/d.
- Assumed fraction of worldwide SAF demand in the U.S. in 2033: 40%.
- Resulting level of North American ethanol demand: 50,353 bbl/d.

As the results in Table 7.5 indicate, if the assumptions that were the basis for the three ethanol demand scenarios are accurate, in the year 2033, the effects on the overall North American ethanol supply will, most likely, be noticeable. For the IEA Main Case forecast, the IEA Accelerated Case forecast, and EcoEngineers' forecast the levels of additional ethanol demand are, respectively, 2.1%, 7.9%, and 3.8% of the year 2023 North American ethanol demand level of 1,030 thousand bbl/d.

Table 7.5: Previous SAF Demand Forecasts and Worldwide Ethanol Demand (for ETJ Route) Forecasts Translated to North American Ethanol Demand Levels (000 bbl/d)

Year	2020	2023	2027	2031	2033
Worldwide Jet Fuel Demand (Including EIA Forecast)	4,022	6,128	6,951	7,576	7,890
CAGR Over Forecast Period					2.6%

IEA Main Case Scenario					
Worldwide SAF Demand	0.95	10.4	75.0	139.6	167.9
CAGR Over Forecast Period					32.1%
SAF as a Percentage of Worldwide Jet Fuel Demand	0.02%	0.17%	1.08%	1.84%	2.13%
Worldwide Ethanol Demand if ETJ Provides 13% of SAF Supply in 2027 and 20% in 2033	0.2	2.2	16.2	32.1	56.0
Forecast for North American Additional Ethanol Demand for SAF	0.1	0.6	5.0	11.9	22.4

IEA Accelerated Case Scenario					
Worldwide SAF Demand	0.95	10.4	190.3	497.0	625.8
CAGR Over Forecast Period					50.7%
SAF as a Percentage of Worldwide Jet Fuel Demand	0.02%	0.17%	2.74%	6.56%	7.93%
Worldwide Ethanol Demand if ETJ Provides 13% of SAF Supply in 2027 and 20% in 2033	0.2	2.2	41.2	116.0	208.6
Forecast for North American Additional Ethanol Demand for SAF	0.1	0.6	12.8	42.9	83.5

EcoEngineers' Scenario					
Worldwide SAF Demand	0.95	10.4	115.3	246.7	302.1
CAGR Over Forecast Period					40.1%
SAF as a Percentage of Worldwide Jet Fuel Demand	0.02%	0.17%	1.66%	3.26%	3.83%
Worldwide Ethanol Demand if ETJ Provides 10% of SAF Supply in 2027 and 25% in 2033	0.2	2.2	25.0	69.9	125.9
Forecast for North American Additional Ethanol Demand for SAF	0.1	0.6	7.7	25.9	50.4

Chapter 7.4: Forecasting the Effect of SAF Demand on North American Corn and Ethanol Prices

Given that the forecasts for additional North American ethanol demand to service the ETJ SAF route are such a small fraction of current ethanol demand, since we expect the transition to the ETJ route to happen gradually, and because we also expect that ethanol use as a U.S. gasoline blendstock will, most likely, slowly diminish due to decreasing U.S. gasoline demand (unless E15 is a mandated blending level) we do not expect to see an immediate, significant effect on ethanol and corn prices throughout the forecast period.

Over the next ten years (ignoring weather and geopolitical effects), the main price drivers for U.S. ethanol and corn are likely to remain the price of oil and gasoline, as well as the stocks of corn relative to demand.

Chapter 7.5: The Potential for Alternate Feedstocks That Could Feed the ATJ Route

EcoEngineers sees four potential alternatives to ethanol as feedstocks for the ATJ process. Our opinion is that none of these are likely to appear as serious competition to the ETJ route over the 10-year forecast period.

Methanol: The methanol-to-jet (MTJ) process technology has been available for years and two firms are now offering this process technology for license. EcoEngineers' opinion is that this process technology will, most likely, not be competitive with ATJ routes during the forecast period. Eventually, electrolyzer costs (for hydrogen production), CCS costs, and methanol synthesis costs will fall.

Other U.S. Grain Crops: We see none of these competing, at a large scale, on a levelized total production cost per barrel of ethanol produced basis.

Waste Industrial Gases (CO and CO₂): LanzaTech has a process technology (available for license) that will convert industrial waste gases into ethanol that can then be used to feed the ATJ process. This technology is proven but has not yet been used at full 24/7 commercial large scale. LanzaTech is co-planning a project in the UK that is slated to use this technology. The feedstock for the planned facility would be waste gases, including potentially from Tata Steel's adjacent steelworks facility in Port Talbot, UK. These waste gases would be transformed via LanzaTech's gas fermentation platform to make ethanol as a feedstock for the ATJ facility. EcoEngineers' opinion is that this process technology will see only niche applications (where significant quantities of low-price industrial waste gas are available) and that the ultimate levelized production cost for the process scheme will, in most locations, be higher than corn-ethanol-based ATJ products.

Isobutanol and n-Butanol: These routes are proven. The isobutanol-based route has reached the pilot stage. EcoEngineers' opinion is that this process technology will see only niche applications. We estimate the ultimate net levelized production costs for this process scheme will, in most locations, be higher than corn-ethanol-based ATJ products.

Sugarcane: This could, at times, prove competitive, in terms of ethanol imports from Brazil, as discussed in the previous report section. However, the potential for higher ethanol CI scores

(tied to land change issues) and Brazilian regulations and incentives that discourage export leads EcoEngineers to rank this as a low (but potential) risk issue that deserves additional analysis.

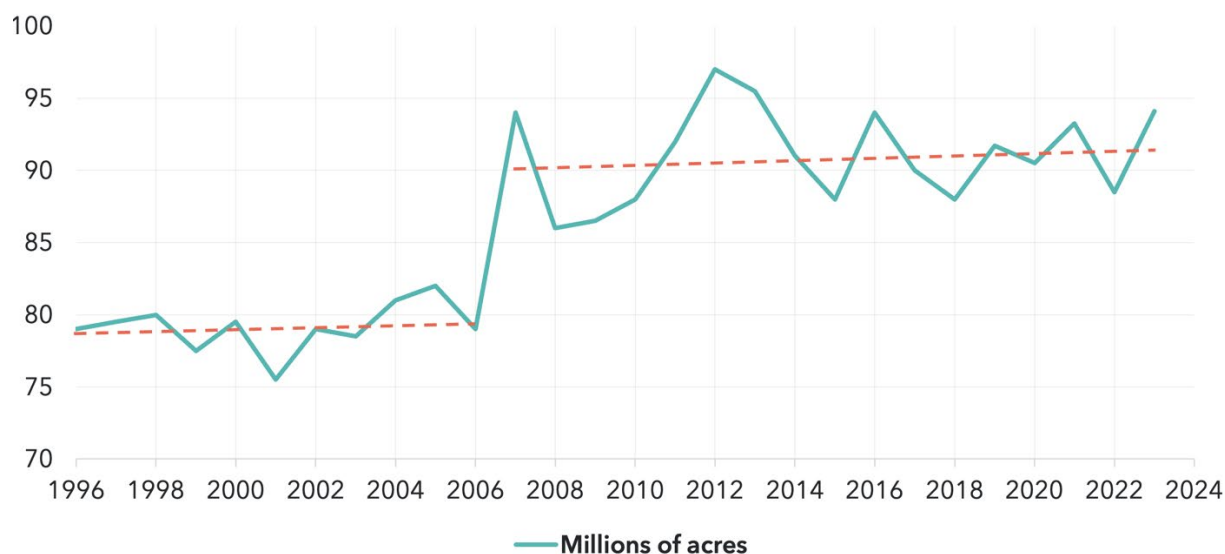
Section 8: Land-Use Effects and Ethanol Production

Chapter 8.1: Historical Land-Use Trends for U.S. Corn Production

Land-use change (LUC) refers to the process by which human activities transform the natural landscape, emphasizing the functional role of land for economic activities. In this report, LUC specifically refers to instances when non-agricultural lands such as forest or prairie are converted to agricultural purposes such as cropland. LUC can occur because of policy decisions or macroeconomic events. This section addresses how SAF mandates could result in LUC. An example that can serve as a case study is the implementation of the U.S. RFS. Was there a LUC change associated with the RFS and how can this be used to help predict the effect of future mandates and policies?

In the 10 years before the passing of the RFS in 2007, corn acres planted in the U.S. remained semi-constant, averaging at 79 million acres over 10 years before 2007. A sharp increase of approximately 15 million acres planted was observed in 2007 following the introduction of the RFS and has since averaged at approximately 91 million acres and has been slowly trending higher (Figure 8.1). The growth rates pre- and post-RFS are nearly identical and can likely be attributed to GDP growth. However, this increase in planted corn acres does not necessarily imply LUC; a further look is required to understand what is happening.

Figure 8.1: U.S. Corn Acres Planted (1996-2023)⁴



⁴ https://d35t1syewk4d42.cloudfront.net/file/2001/LUC-Ethanol-Plant-Proximity-Crop-Prices_Li-et-al_2018-12.pdf

Figure 8.1 shows the acreage increase in 2007 because of the RFS. The drop in planted acreage over the 2008-2010 period is the result of the economic slowdown related to the Great Recession. The decline in 2013-14 was due to an increase in supply when stocks replenished from a major drought in 2012.

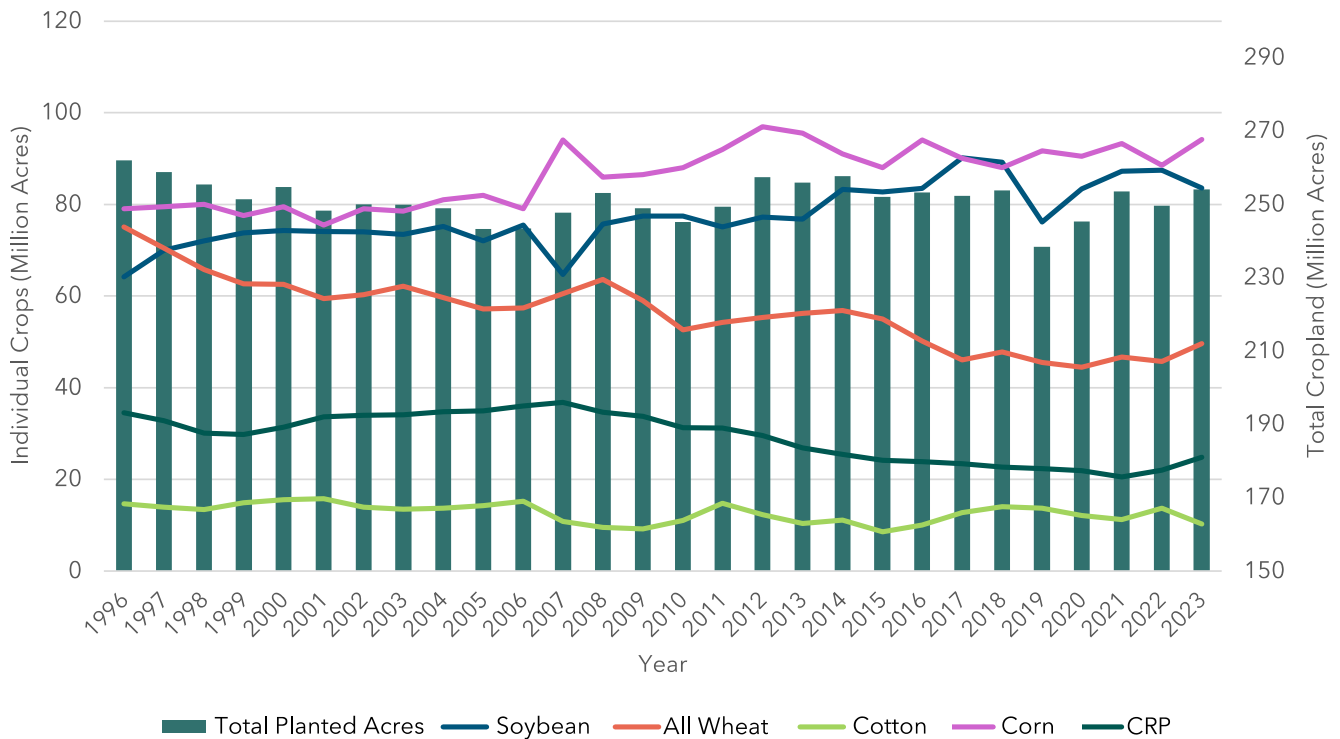
Concerning high-productivity cropland, corn competes most directly with soybeans as a rotational crop. Because of this relationship, a sharp increase in corn demand can be compensated for by decreases in soybean acreage in the short term. This relationship can be seen in Figure 8.2 where corn acreage spiked approximately 15 million acres in 2007 and soybean acreage declined approximately 10 million acres. The remaining five million acres of corn were likely accounted for through changes in the planting of other crops. However, this is difficult to quantify and likely occurred on fringe acreage where corn competes with many other crops.

The Conservation Reserve Program (CRP) also plays a role in addressing this issue. Given that cropland in the CRP is usually enrolled in 10-15-year contracts, this cropland could not be quickly deployed to meet new demand as was seen in 2007. However, CRP total enrollment began to decline after 2007 following the introduction of the RFS and appears to bottom out in 2022, 15 years after the implementation of the RFS, consistent with the CRP enrollment period.

By 2008, planted soybean acreage rebounded to pre-RFS levels, and planted corn acreage leveled, averaging approximately 10 million more acres than pre-RFS levels. Following 2008, planted corn and soybean acres continued to gradually increase. This cropland most likely came from cropland leaving the CRP or from reducing acreage for other crops such as wheat, which show a steady decline in planted acreage through this time.

Figure 8.2 shows the annual variation in planted crop acreage for soybean, wheat, cotton, corn, and CRP enrollment, and combined total crop acreage. Total crop acreage includes all wheat, corn, sorghum, barley, oats, rice, soybean, and cotton acreage.

Figure 8.2: U.S. Cropland Acres



– Modified from USDA data

In conclusion, based on the data shown in Figure 8.2, the increase in planted corn acreage in 2007 was largely accommodated by crop rotation with soybeans rather than LUC. Although corn and soybean acreage have generally been increasing, wheat has shown a steady decline during the referenced period. Additionally, CRP enrollment began to decline following the RFS. The average total cropland is slightly lower post-RFS compared to pre-RFS. Thus, there is no indication of significant levels of LUC during the 1996-2023 period.

Influences on Cropland Use

Historically, the amount of cropland associated with U.S. corn production is influenced by many variables. These include:

- **Corn Price:** When corn prices increase, farmers are incentivized to increase the amount of cropland dedicated to corn production.
- **Corn yield per acre:** This has been steadily increasing over time. The U.S. average corn yield was approximately 130 bushels per acre in 2000 and was approximately 175 bushels per acre in 2022.⁵ This is a 34.6% increase over 22 years, or approximately 1.6% per year. An observation of the trends over the last 22 years does not indicate that the rate of increase is tapering.

⁵ USDA-NASS Crop Production Reports 2023.

- **CRP:** This is a cost-share and rental payment program managed by the USDA. In exchange for a yearly rental payment, farmers enrolled in the program agree to remove environmentally sensitive cropland from agricultural production and plant species that will improve environmental health and quality.

As corn prices increase, and potential profit exceeds rental payments, cropland may be removed from the CRP to be actively planted. Additionally, there is an enrollment cap under each farm bill that puts constraints on the land coming into the program. The enrollment period and cap protect CRP acreage from excessive fluctuations, often delaying and spreading the impact of policy decisions over the years. It is important to note that land held within the CRP is designated as cropland and does not constitute LUC when brought back into rotation.

- **Proximity to Ethanol Plants:** Considering the scenarios where North American fuel ethanol demand increases to meet SAF use mandates and incentives, land proximal to ethanol plants is more likely to be influenced by price fluctuations. However, this does not necessarily imply a LUC as this land may already be designated as cropland. A county-level study shows that ethanol production has a statistically significant effect on corn acreage and aggregate cropland acreage. However, land use is inelastic due to changes in ethanol production capacity and crop prices, resulting in a small indirect effect on corn and total crop acreage. A 1% increase in the effective ethanol capacity in a county increases corn acreage in that county by about 0.03%-0.1%.⁴
- **Land Quality:** Land quality refers to the potential of a given area to produce corn or other crops. This is generally a combination of soil quality, topography, and current use. Historically, farmers prioritized the use of higher-quality land over lower-quality land. Low-quality lands tend to have more sloped and erodible soils, experience more nutrient runoff, and may harbor more species of imperiled plants and animals than croplands that remain in cultivation. Both formerly uncropped lands and marginal or abandoned agricultural lands are likely to produce lower crop yields and be more susceptible to environmental issues. The characteristics that render these croplands more prone to environmental degradation may be heightened by certain farming practices. For instance, sloping lands are inherently susceptible to erosion and present challenges for cultivation with their erodibility being potentially exacerbated by farming activities. However, land quality can improve if native root systems are restored, and no-till farming practices are implemented.

In a status-quo situation, farmers would generally not choose to cultivate on lower-quality lands because of their poor productivity and higher upfront conversion costs, both of which translate into lower profitability.⁶ However, when demand is high and/or crop prices are high it becomes easier to clear these hurdles. Thus, an interesting question is how corn cultivation has expanded on lower-quality lands in response to high corn prices and whether such a

⁴ https://d35t1syewk4d42.cloudfront.net/file/2001/LUC-Ethanol-Plant-Proximity-Crop-Prices_Li-et-al_2018-12.pdf

⁶ Role of land quality in corn acreage response to price and policy changes: evidence from the Western Corn Belt; Nazli Z Uludere Aragon 2019 Environ. Res. Communication. 1 061004

response has varied before and after the change in U.S. biofuel policy, which now routinely consumes over one-third of U.S. corn output. If the lands that move in and out of corn cultivation have lower productivity, are more environmentally vulnerable, and at the same time are more sensitive to high prices, then high prices would generate larger environmental impacts.

Sources of Additional Cropland

When corn price increases and additional cropland is required, where does that additional acreage come from? Answering that question is critical. The U.S. utilized 94 million acres for corn production in 2023. Subsequent acreage added may, on average, not be as productive as the previously added acres.

The additional cropland can come from various sources such as:

Switching Crops: Cropland for products such as soybeans and wheat can be converted to corn. However, there can be economic and social repercussions for doing so that may impact the CI of the corn. It is important for ethanol not to compete or be perceived to compete with food crops. Otherwise, farmers will generally try to maximize the profitability of their acreage and plant accordingly.

Idle Cropland: Programs such as the CRP hold significant acreage. Approximately 23 million acres in 2023 can be deployed if there is an economic incentive to do so. However, this land is already designated as cropland and would not be considered a land-use change.

Converting Land: Additional land can be converted to cropland. Depending on the classification of the land this can impact the CI of the corn grown and ethanol produced. For example, if virgin forest or prairie is converted, there will be an environmental impact that will need to be quantified as stored carbon in these environments can be released, potentially offsetting any benefits. As prices increase, new swaths of once marginal land may become economic and could be converted to cropland. However, this may not constitute a LUC. As an example, pastureland is considered marginal, but given that it is designated agricultural land, converting it to cropland is not a LUC.

Chapter 8.2: Potential Future Land-Use Issues Related to Increased Levels of Corn Production

Understanding and predicting the potential future land-use changes associated with an increase in corn demand is challenging. However, by understanding the impacts of past events, such as the implementation of the RFS, assumptions can be made regarding how land use would respond to a significant increase in SAF demand. Multiple studies, models, and simulations have been run to not only understand historical trends but also to anticipate LUC in response to an increase in demand associated with biofuel production.

One interesting analysis evaluated and compiled studies published since 2008 linking the RFS program and domestic corn-ethanol production to changes in corn acreage in the U.S. (Figure 8.3)

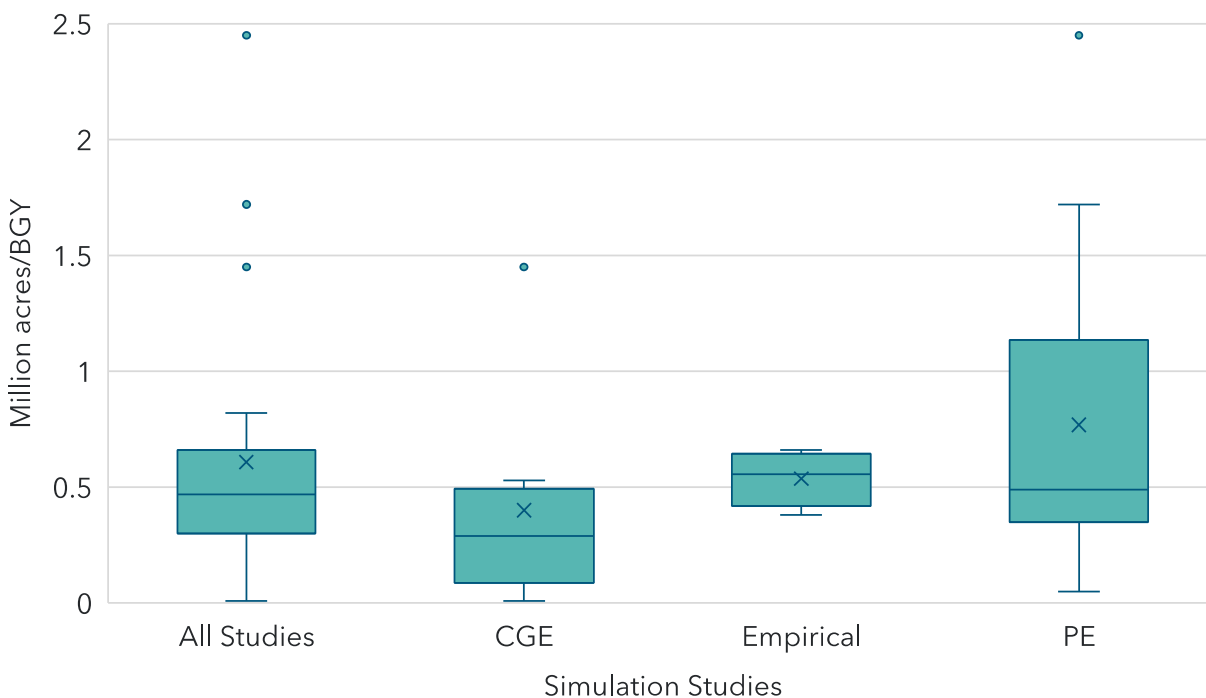


Figure 8.3: Cropland Expansion Due to Biofuel Increase⁷

Figure 8.3 shows a box and whisker plot of the results developed by the economic simulation models described in this study. The “X” represents the mean, the line within the box represents the median, the two stacked boxes represent the data range of the second and third quartiles,⁸ the “whiskers” represent the maximum extent of the data, and the dots are considered to be outlier data points. This summary figure shows the results from different studies that estimated the increase in land use due to an additional 1 billion gallons of ethanol production per year.

Note that the study summarized in Table 8.3 does not use the same definition of LUC that EcoEngineers uses. What they are identifying is “net cropland expansion.” The study authors identify multiple activities qualifying as “land use change,” such as corn acreage expanding or contracting (without accounting for effects on other crop acreage), and land going in and out of the CRP. Therefore, this study should not be used to estimate LUC.

Figure 8.3 summarizes the results from three types of economic models that simulate market behavior. The models are built from actual market data. The three types of models used are

⁷ A review of domestic land use change attributable to U.S. biofuel policy, EPA Manuscript, Renew Sustain Energy Rev. 2022 May ; 159: 1-16. doi:10.1016/j.rser.2022.112181

⁸ 25% of the data are within the range of the top line of the top box and the top whisker and 25% of the data are within the range of the bottom line of the bottom box and the bottom whisker.

called: (1) Computable General Equilibrium (CGE), (2) Empirical, and (3) Partial Equilibrium (PE), each approaching the simulation from different perspectives. Studies such as this can serve as a proxy to anticipate the effects of an increase in policy driven SAF demand on land use.

A range of 0.01 million-2.45 million acres of cropland expansion per 1-billion-gallon increase in biofuel production is shown. The wide range in values is due to differences in underlying assumptions, methodology, and quantity of simulations for each model type. Fewer empirical studies have been performed relative to PE and CGE, which explains the narrow range of values.

Given the wide range of the study, the study median of 0.41 million additional acres planted per 1 billion gallons of biofuel demand will be used as a basis for our analysis. (Other experimental approaches reporting national-scale estimates fall within this range, reporting 0.38 million-0.66 million acres per 1-billion-gallon biofuel increase.)

Using the 0.41 Million Acres/Billion Gallon of Additional Biofuel Production Ratio to Predict the Potential Effects of SAF

We have estimated the additional planted acres that would be required to reach the EcoEngineers' target for ETJ-based SAF production in the U.S. in 2033. We have used two different bases for corn acreage required per amount of SAF gallons required: (a) the 0.41 ratio (derived from the 2022 USEPA study) and (b) the projected year 2033 values of U.S. corn yields (bushels per acre) estimate of the additional acres that would be required. Table 8.1 summarizes the results.

Key assumptions used to build the analysis summarized in Table 8.1 are:

- The recent IEA projection of a 3 vol% decrease in gasoline demand in the coming decade is a reasonable expectation for planning purposes.⁹ We will assume that this gasoline demand decrease will occur by 2033.
- U.S. corn yields per planted acre will increase by 1.5%/year over the forecast period, in line with the stable yield increase trend over the 2000 to 2022 period.

The results of our analysis are summarized in Table 8.1. After analyzing the current U.S. corn acreage level, which is more than 92 million acres, and comparing it to the average required for ETJ feedstock, the analysis shows that producing the extra amount of U.S. ethanol required to meet the ethanol-to-SAF forecast in the EcoEngineers scenario for the year 2033 will not have a significant impact on required U.S. corn acreage regardless of the basis for acreage requirement used.

Between 0.52 million and 0.07 million additional corn acres would be required. This would equate to an increase in 2033 of between 0.6% and 0.08% above 2023 U.S. corn acreage levels.

⁹ [IEA Oil 2023](#)

Table 8.1: An Estimate of Additional U.S. Cropland That Would be Required in 2033 to Meet the EcoEngineers' 2033 Ethanol Demand Scenario for Additional U.S. Alcohol for ETJ – EcoEngineers

2023 US Ethanol Production	15.8	billion gal/year ethanol	A reference point
2023 US Ethanol Production	1030	thousand bbl/day ethanol	A reference point
wt% yield of SAF from ethanol	60%	weight percent	
vol% yield of SAF from ethanol	59%	weight percent	
Additional ethanol required to meet EcoEngineers' 2033 Scenario	50.4	thousand bbl/day ethanol	
	0.8	billion gal/year ethanol	
Extra ethanol available due to 3% reduction in US gasoline consumption by 2030	0.47	billion gal/year ethanol	Also assuming E15 gasoline does not replace significant E10 gasoline market share
Conversion Metrics			
Million additional acres planted per billion gallons of biofuel demand per 2022 study	0.41	million acres/billion gal ethanol	
Gallons of ethanol per bushel of corn in 2023 in US	2.80	gal/bushel	
Bushels of corn per acre, in 2023 in US	175.0	bushel/acre	
Assumed increase per year in US corn yield per acre	1.5%	percent increase per year	
US planted acres required to meet EcoEngineers' 2033 Scenario for Additional US Ethanol for ETJ			
Million additional acres required on basis of estimated year 2033 corn yields and ethanol yields	0.52	million acres	
Million additional acres required on basis of EPA's 0.41 Ratio	0.07	million acres	

CI Measurement of Jet Fuel Produced from Ethanol and How the CI May Change

The marketability (in the U.S.) of SAF produced from ethanol will depend, to a great extent, on which CI calculation model is used as the basis for assigning credit values for SAF production and how the model may be refined over time, as more data become available for generating the best inputs to the model.

Recent 40B tax credit guidance (in April 2024) from the U.S. Treasury Department provided some encouraging news to US ethanol producers in terms of assigning a modified GREET model (versus the current ICAO model) as the basis for estimating SAF from ethanol credit values.

The modified GREET model incorporates the effects of (a) certain climate-smart agricultural practices, (b) the use of renewable process energy and (c) carbon capture and sequestration.

The coming U.S. Treasury guidance on the model design that will be the basis for the 45Z tax credit will be even more critical, because the 40B tax credit ends in 2025. The more the modified GREET model is designed to accurately recognize additional low carbon practices and process technologies and the evolution of those practices and technologies, the better that SAF produced from ethanol will be positioned in the marketplace.

Chapter 8.3: Conclusions

Predicting the impact of additional ethanol production (for SAF) upon US land use poses significant challenges due to the complex interplay of various factors. Nonetheless, on the basis of fundamental assumptions and insights from recent history and existing research, it is possible to estimate a range of possibilities for the next decade.

The effects of the RFS on land use can be used as a guide to help predict the impact of SAF demand on ethanol production and associated land use. Also, an estimate of future US corn yield per acre can be used to predict the impact of SAF demand on ethanol production and associated land use.

EcoEngineers created two scenarios to bracket the range of potential effects of increased demand of ethanol for SAF on required corn acreage. The two scenarios are based on the EcoEngineers 2033 forecast for ETJ SAF demand (in Section 5 of this report) and two different approaches to estimating corn acreage requirements:

1. The “0.41 million acres per billion gal of additional ethanol ratio.” (This ratio was developed from an EPA-Commissioned study that evaluated the effects of the RFS introduction in 2007 upon US corn acreage increases.)
2. The estimated U.S. corn yield per acre in 2033, based on year 2022 yield levels and the average yearly increase in yield over the 2000 to 2022 period.

This approach resulted in an estimated range of between 0.52 to 0.07 million additional corn acres required in 2033. This would equate to an increase, in 2033, of between 0.6% and 0.08% above the 2023 U.S. corn acreage levels.

From analyzing the RFS, we have seen that a 10-15 million acre increase in corn cropland was accommodated through various means such as crop rotation and CRP enrollment. Given the current trends of cropland growth, there is no indication that the high-end case of adding 0.52 million additional acres of corn cropland over the next decade would cause significant LUC.

From a technical and historical standpoint, this suggests that meeting the EcoEngineers potential ETJ-based SAF demand scenario through additional U.S.-based ethanol production is feasible without significant LUC.

Section 9: Competitive Position of U.S. Ethanol Producers

In this section, EcoEngineers will provide an opinion and outlook on the competitive position of North American ethanol producers in terms of serving a growing demand for ethanol for U.S. SAF production. We will evaluate the current and predicted future competitive position of ethanol producers in South America, Europe, and Asia in terms of providing feedstocks to the major likely U.S. ETJ facilities.

Chapter 9.1: A Summary of Ethanol Supply and Demand in Competing Regions

Global ethanol production can be categorized effectively into three groups: The U.S., Brazil, and the rest of the world (Figure 9.1). In 2023, the U.S. again emerged as the leading producer, contributing to 55% of the world's total ethanol production, while Brazil ranked as the second-largest producer with a 27% share. Both Brazil and the U.S. stand out as the largest consumers of fuel ethanol, actively engaging in import and export activities.

The anticipated growth in production over the next decade among the remaining countries—China, India, Canada, Thailand, and Argentina—is expected to be modest. Their contributions are projected to remain a relatively small fraction of the overall global ethanol production.

China: The motivation behind the biofuel program in the People's Republic of China (PRC) differs from that of the U.S. In the PRC, the primary objective of biofuel mandates is to effectively manage the corn supply, with the secondary goal of addressing air quality and climate change concerns. The challenges to the program arise from the high price of imported corn in 2023, leading to difficulties for ethanol plants in achieving profitability. Despite the conclusion of COVID-19-related lockdowns, the demand for fuel ethanol remains sluggish, compounded by the impracticality of ethanol imports due to the PRC's high tariffs. Moreover, the weak enforcement of the PRC's E10 blending mandate diminishes any motivation to import. There is an anticipated unofficial adjustment of scaling back E10 blending to E5,¹⁰ which would further weaken ethanol demand.

EU: The surge in fuel prices triggered by the Russia-Ukraine War in 2022 has led to the reversal of many biofuel mandates. Furthermore, the ongoing conflict has elevated grain

¹⁰ USDA China: Biofuels Annual Report, 2023

feedstock prices, exerting sustained pressure on the profit margins of ethanol producers. These difficulties are expected to persist, especially with the EU showing signs of entering a recessionary environment.¹¹

India: The "Roadmap for Ethanol Blending in India 2020-25"¹² outlines ambitious targets to elevate blending to 20%. Achieving this goal necessitates advancements in production methods, the development of E20-tuned vehicles, and the exploration of alternative feedstocks with lower water requirements. Nevertheless, it seems that India is placing limitations on the use of sugarcane as a biofuel feedstock, prioritizing it for domestic consumption.¹³

Thailand: Ethanol consumption in Thailand is on the decline and the local ethanol industry is grappling with overcapacity. The dissolution of parliament has resulted in a regulatory freeze. Additionally, there has been a significant policy change by the Thai government, which has shifted away from supporting ethanol.

In 2022, the government ceased using the Oil Fund to back biofuels and has redirected its support towards the adoption of EVs, aligning with its "30@30" policy. This initiative aims to have 30% of new vehicles with zero emissions by the year 2030.¹⁴

Canada: The consumption of fuel ethanol in Canada saw an approximate 20% increase last year, accompanied by a substantial rise of around 40% in Canadian imports of fuel ethanol from the U.S.

In July 2022, Canada implemented the Clean Fuel Regulation (CFR), a law designed to reduce the CI of liquid transportation fuels. The CFR is anticipated to drive the consumption of ethanol, biobased diesel, and other renewable fuels. According to estimates from Environment and Climate Change Canada mentioned in the report, the CFR has the potential to increase the consumption of low-CI diesel by 2.2 billion liters (581.18 million gallons) and ethanol consumption by 700 million liters (264.98 million gallons) by the year 2030. Beyond the federal CFR, various provincial regulations in Canada also contribute to the support of biofuel consumption.¹⁵

Argentina: In 2023, ethanol production witnessed a 1% year-on-year decline, marking a shift from three consecutive years of growth propelled by robust gasoline demand and a high blend rate.¹⁶ Bioethanol derived from corn is projected to constitute 62% of the total production while sugarcane-based bioethanol is expected to contribute the remaining 38%.

¹¹ S&P Global Commodity Insights, <https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/agriculture/010523-european-ethanol-market-to-face-high-energy-costs-feedstock-challenges-in-2023>

¹² https://www.niti.gov.in/sites/default/files/2021-06/EthanolBlendingInIndia_compressed.pdf

¹³ <https://www.reuters.com/world/india/india-plans-discourage-ethanol-production-prioritise-sugar-sources-2023-12-06/>

¹⁴ <https://www.czapp.com/analyst-insights/thailands-ethanol-industry-in-crisis/>

¹⁵ <https://ethanolproducer.com/articles/report-canadian-ethanol-consumption-continues-to-grow>

¹⁶ <https://www.biofuelsdigest.com/bdigest/2024/01/02/argentinas-ethanol-production-declines-by-1-year-on-year-in-2023>

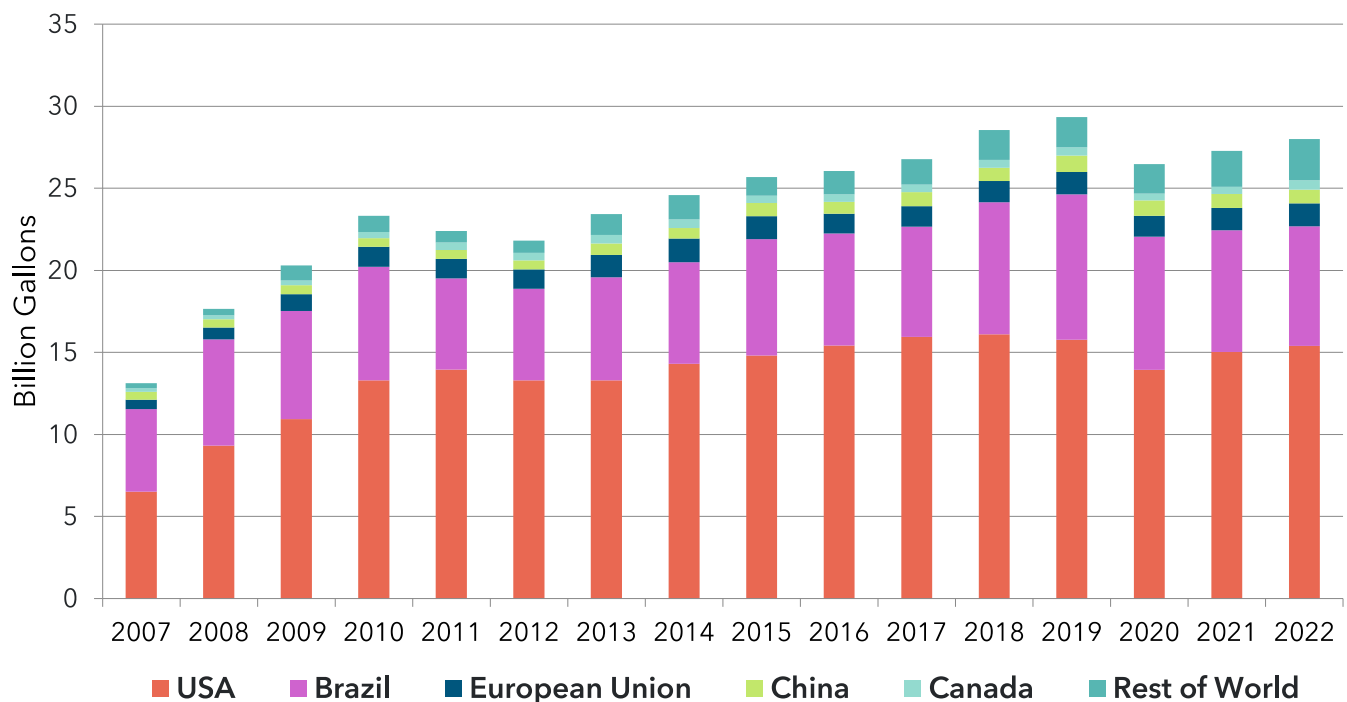
The substantial impact of a severe drought in 2022 and 2023 extended across various crops and regions in the country, particularly affecting the sugarcane industry, resulting in a diminished output of ethanol production.¹⁷

Figure 9.1: Global Ethanol Production by Country or Region

– Renewable Fuels Association (RFA) and U.S. DOE Alternative Fuels Data Center

Chapter 9.2: A Comparison of Competing Production Regions to U.S. Ethanol Production

In 2019, the U.S. average ethanol production cost was US\$1.55/gal with Brazil following



closely at \$1.67/gal. China and the EU incur higher production costs for ethanol, amounting to \$1.85/gal and \$1.78/gal, respectively (Table 9.1).

Note that an additional layer of complexity is present due to fluctuating foreign exchange rates. For example, in 2019, the Brazilian Real and the Indian Rupee weakened, contributing to a decrease in Brazilian and Indian ethanol production costs when expressed in USD.

Conversely, the euro and the Chinese yuan strengthened against the U.S. dollar, leading to an increase in the production costs for the EU and China.¹⁸

¹⁷ USDA, 2023 Argentina: Biofuels Annual

¹⁸ Mizik, T. Economic Aspects and Sustainability of Ethanol Production—A Systematic Literature Review. *Energies* 2021, 14, 6137. <https://doi.org/10.3390/en14196137>

Table 9.1: Ethanol Costs of the Major Producing Regions in 2019¹⁶

Countries	US\$/gal
Brazil	1.67
EU	1.78
India	1.40
China	1.85
USA	1.55

The variability of ethanol production cost between countries can be explained by the differences in feedstocks, agricultural practices, government policies and incentives, gasoline demand, blend rates, and economies of scale. Each country listed in Table 9.1 represents a unique blend of challenges and opportunities that shape its specific ethanol market.

Although India is the lowest-cost producer, its volumes represent approximately 5% of U.S. ethanol production.

Brazilian Ethanol

Given that the U.S. and Brazil are the largest producers and exporters of ethanol, it is not surprising that trade occurs between the two countries when the right market conditions are present.

Figure 9.2¹⁹ shows the recent history of the relationship between the two countries and how past policy has incentivized imports. Ethanol imports increased drastically in 2006 in response to the signing of the RFS. Before the RFS, Brazil was the top ethanol producer in the world, and the U.S. needed that ethanol to meet obligations until U.S. fermentation capacity could be developed. Imports declined over the following five years as U.S. ethanol producers ramped up production to meet demand.

The year 2011 marked the introduction of the California LCFS and an increase in ethanol imports from Brazil. The low-CI sugarcane ethanol was needed to meet demand fueled by the new policy and regulations. U.S. imports of low-CI sugarcane ethanol from Brazil reached over 400 million gallons in 2012, spurred by a rare uplift from RINs and CI score advantages under the California LCFS. Since that time, imports from Brazil have declined as the country rolled out a domestic RenovaBio²⁰ biofuels regulation supporting local ethanol use.

Brazil was a significant export destination for U.S. ethanol but has declined significantly under the same program.

¹⁶ Mizik, T. Economic Aspects and Sustainability of Ethanol Production—A Systematic Literature Review. *Energies* 2021, 14, 6137. <https://doi.org/10.3390/en14196137>

¹⁹ https://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=PET&s=MFEIM_NUS-NBR_1&f=M

²⁰ <https://www.gov.br/mme/pt-br/assuntos/secretarias/petroleo-gas-natural-e-biocombustiveis/renovabio-1/renovabio-ingles>

These examples show that when ethanol demand increased rapidly due to policy, Brazil was able to respond quickly and supply the volumes needed in the U.S.

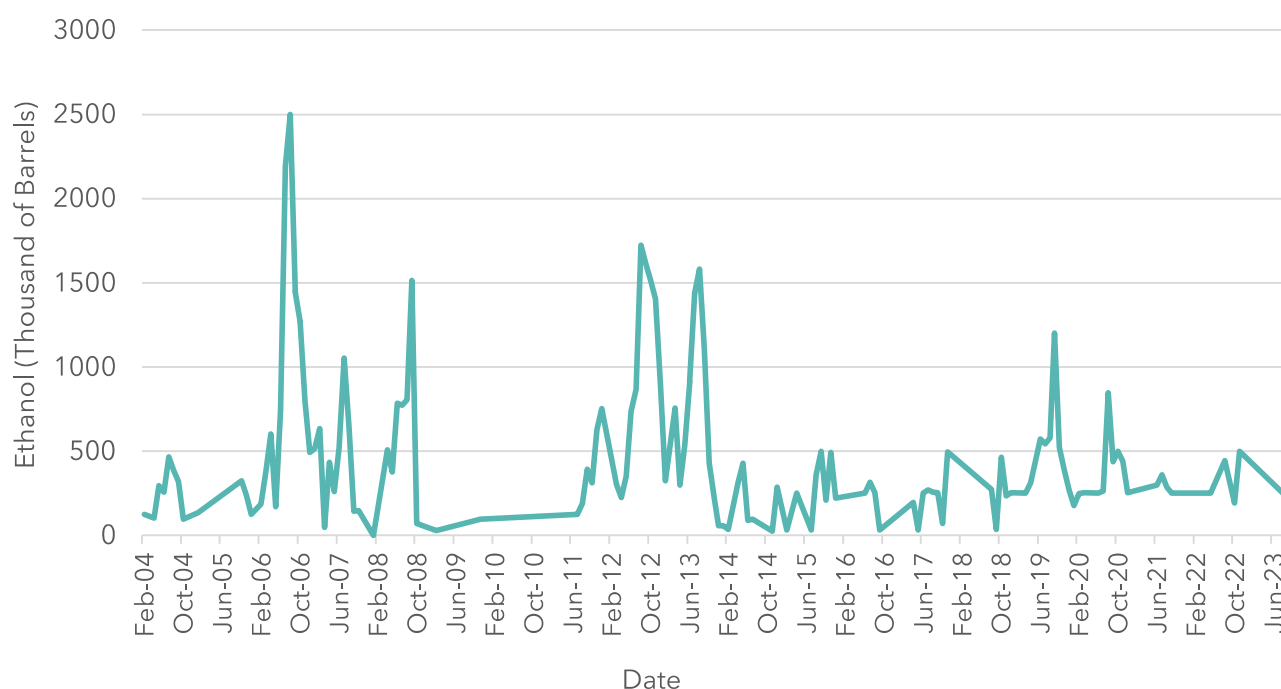
If a new U.S.-based policy emerged to substantially increase ethanol demand for SAF then Brazil may be enticed to be able to respond to government policy if it allowed it and the monetary incentives were sustained.

Figure 9.2: U.S. Ethanol Imports from Brazil (2004-2023)

–EIA

Carbon Capture and Sequestration (CCS)

This is an appropriate time to mention the role of CCS in the ethanol market. As natural



limitations with feedstock and production efficiency are reached, fewer options are available to reduce the CI of ethanol. For U.S. ethanol to remain competitive in the global market, CI scores will probably need to be managed and reduced. Currently, a combination of CCS and the use of credits from voluntary programs such as the CA-LCFS or the voluntary carbon market (VCM) are viable options in the U.S. and other producing regions.

Here, it is important to highlight the strategic advantage of CCS in the U.S. Given that storage differs considerably across regions, with the Russian Federation, North America, and Africa holding the largest capacities,²¹ few countries can compete with the U.S. in terms of onshore geologic resources that enable CCS. Simply put, most other parts of the world, such as Europe and Southeast Asia, have unique and complex geologic histories resulting in limited options for the geologic storage of CO₂. The U.S. is relatively undisturbed, allowing for the

²¹ <https://www.iea.org/commentaries/the-world-has-vast-capacity-to-store-co2-net-zero-means-we-ll-need-it>

formation of many sedimentary basins, not only for oil and gas production but also for geologic storage.²² When combining this natural advantage with the technical know-how, regulatory processes, infrastructure, and proximity to the market, the U.S. is strategically positioned to benefit from CCS and potentially create a very competitive low-CI ethanol product. However, even the U.S. is facing headwinds to integrate CCS with the ethanol industry.

Given that most U.S. ethanol production is occurring in geographic areas that have limited or poor geologic storage options, pipeline transportation of CO₂ to more suitable areas is often required.²³ Various proposed pipeline projects are facing intense scrutiny from the public and regulatory bodies, delaying, or even forcing some projects to be abandoned. Navigator CO₂ Ventures recently scrapped one of its projects, citing the “unpredictable nature of the regulatory and government processes.”²⁴

Combining CCS tax incentives with voluntary programs can be a powerful option for ethanol producers to monetize their low-carbon activities and bridge the gap, whether it be timing or financial, that is left by CCS tax incentives. If a financial justification exists, tax credits can be stacked with voluntary credits. In the U.S., the 45Q tax credit provides \$85/MT of geologically sequestered CO₂. However, that may not be enough to financially incentivize an ethanol plant to go through the costly permitting process and purchase the necessary capture equipment. If this is the case, then the project could qualify to receive credits in the VCM.

Another scenario to consider is that the application process for voluntary programs such as the CA-LCFS can take multiple years. VCM pathways can be used to bridge the financial gap left while waiting for these applications to be processed. Ultimately, these voluntary programs can be used as an additional tool to help ethanol producers implement CCS projects and earn additional revenue, increasing margins without raising prices for the end consumer.

The Future for CCS: One technology providing significant promise for lowering product CI is carbon sequestration, which often works in tandem with voluntary programs and markets. CARB estimates²⁵ that CCS lowers the CI of starch fermentation for ethanol plants by as much as 32 CI points and has additional tax incentives that assist the overall economics. This has been implemented in one U.S. ethanol plant to date: Red Trail Energy LLC.

Chapter 9.3: Conclusions

Today and in the near term, Brazil is the only country that has the potential to compete with U.S. ethanol production over the next decade and possibly export ethanol to the U.S. if ethanol demand surges.

²² https://19january2017snapshot.epa.gov/climatechange/carbon-dioxide-capture-and-sequestration-overview_.html

²³ <https://summitcarbonsolutions.com/project-footprint/>

²⁴ <https://www.spglobal.com/commodityinsights/en/market-insights/blogs/energy-transition/102523-navigator-co2-carbon-capture-heartland-greenway-pipeline-cancellation>

²⁵ Staff Summary, Red Trail application D0005 Plant achieved a full CI improvement of ~39 gmCO₂e/MJ: https://ww2.arb.ca.gov/sites/default/files/classic/fuels/lcfs/fuelpathways/comments/tier2/d0005_summary.pdf

However, cultivating new Brazilian land for ethanol export may result in higher Brazilian ethanol CI. Brazil could employ CCS to lower the CI score of its ethanol. However, overall, the U.S. appears to be better positioned to fill the demand for low-CI ethanol by using available farmland in combination with CCS and available CO₂ storage sites.

Over the Next 10 Years: Minor ethanol-producing countries appear to be struggling to enforce mandates and source feedstock, and EcoEngineers believes that these countries will not see significant growth in ethanol production capacity over the next decade. They are unlikely to compete with U.S. ethanol. A more likely scenario is that the U.S. and Brazil will continue to dominate and grow their respective world market shares.

However, it is challenging to make predictions regarding ethanol given that it is strongly influenced by unpredictable factors such as government policy changes and oil prices. Lastly, the appeal of low-CI ethanol will continue to grow and may present opportunities for other countries using low-CI feedstocks and/or CCS to enter the U.S. market and compete with U.S. ethanol in niche markets with LCFS programs.

Section 10: Competition from Battery- and Hydrogen-Powered Flight

In this section, EcoEngineers will comment on the near-term probability of battery-powered and hydrogen-powered flights as competition to ETJ commercial technology routes.

Status and Overview

SAF, especially SAF derived from the HEFA route, is currently the most viable option to directly lower carbon emissions from the aviation sector. As a drop-in fuel, this transition requires little to no technological shift to implement, leaving only process optimization and building facilities at larger scales to lower production costs as a significant barrier. Battery or hydrogen-powered flight, although proven, is years and possibly decades away from making a measurable impact on aviation sector emissions.²⁶

²⁶ IEA Global Hydrogen Review 2023

Battery-Powered Flight

The primary challenge related to the use of batteries in planes is energy density. When compared to any jet fuel, a lithium-ion battery delivers significantly fewer watt-hours per kilogram (Wh/kg).

Kerosene has a specific energy density of 11,944 Wh/kg. The energy density of today's Li-ion batteries is around 200 Wh/kg (with a current practical limit of 300-400 Wh/kg) at the pack level. For short-haul flights over 1,000 kilometers (km), a battery pack energy density of at least 800 Wh/kg would be needed.²⁷

This ultimately translates to an aircraft needing to carry significantly more weight to deliver the same amount of power. This approach is antithetical to the current aviation mindset to reduce weight at all costs to keep ticket prices low enough to attract fliers and keep margins high enough to stay in business.

One company, Elysian Aircraft, plans to transform electric aviation by introducing a prop-driven electric plane designed to accommodate 90 passengers, expected to be operational by 2033²⁸. The aircraft is equipped with a 50-mile (800-km) range and features a fossil fuel turbogenerator in its tail cone. This innovative design serves the purpose of recharging the batteries and powering the motors in the event of diversions or delays. Notably, the aircraft's wingspan is uniquely wide at 140 feet (43 meters), facilitating efficient battery placement within the wings and concurrently reducing structural load on the fuselage.

The EV industry is putting in considerable research to create lighter batteries with new materials, higher energy densities, and utilizing new chemistry. Emerging technologies include lithium-sulfur and sodium-ion batteries. These options may lower costs by sourcing more abundant materials or improving energy density, but neither is a viable alternative today.²⁹

EcoEngineers believes that the odds are extremely low for a major technology breakthrough that will enable anything but short-haul flights within the next 10 years.

Hydrogen-Powered Flight

There are multiple companies developing technology and infrastructure to make commercial hydrogen flight a reality. Some of these opportunities could be available as early as 2026 and could allow small- to mid-size sub-regional commercial flights.

The world's major aircraft builders are still divided. While Airbus is pursuing hydrogen flight by 2035, Boeing is focusing on efficiency and a transition to 100% SAF.³⁰

ZeroAvia: The company has retrofitted its prototype ZA600 hydrogen fuel cell engine to power the left-side propeller of its Dornier 228. The aircraft made history with a milestone first flight on January 19, 2023. ZeroAvia intends to power zero-emission commercial aircraft by 2025. Additionally, it has been announced that American Airlines will potentially order 100

²⁷ <https://www.iea.org/energy-system/transport/aviation>

²⁸ <https://interestingengineering.com/transportation/elysian-aircraft-electric-90-passenger>

²⁹ <https://www.iea.org/reports/global-ev-outlook-2023/trends-in-batteries>

³⁰ <https://www.flyingmag.com/boeing-and-airbus-a-stark-contrast-on-hydrogen/>

ZeroAvia aircraft and the company claims to have had pre-orders for 1,000 engines.³¹ ZeroAvia is partnering with Absolut Hydrogen to develop liquid hydrogen refueling infrastructure for aircraft operations.³²

ZeroAvia plans to test its new 600-kilowatt powertrain, set for certification in 2024, on two 19-seat Dornier 228 planes. One of these planes will incorporate a battery to complement the fuel cells, while the other will utilize a conventional engine, at least initially. These aircraft are tailored for niche markets as mainstream regional operators require turboprops with a minimum of 50 seats and a range of 400 miles.

ZeroAvia's next-generation powertrain, expected to generate between 2,000 and 5,000 kilowatts, is set for delivery by 2026. However, for longer distances, the weight of fuel cells poses challenges. ZeroAvia's CEO, Mr. Miftakhov, envisions technology improvements that could power A320-style planes by the 2030s, although experts consider burning liquid hydrogen a more practical option for such ranges.³³

H2FLY: H2FLY, together with its partner Air Liquide, is the first company to successfully run its hydrogen-electric powertrain on liquid, cryogenic hydrogen.³⁴ Commercialization plans are not clear.

Airbus: Has stated goals to bring to market the world's first hydrogen-powered commercial aircraft by 2035. To get there, its "ZEROe" project is exploring a variety of configurations and technologies, as well as preparing the ecosystem that will produce and supply the hydrogen.³⁵

Airbus is exploring both hydrogen-combustion and fuel-cell propulsion technologies, for which demonstrations have been launched. It has also set up dedicated product development centers in France, the UK, Germany, and Spain to work on tanks and cryogenic fuel systems.

Hydrogen combustion has its drawbacks, however, as it is less efficient than fuel cells and generates significant emissions of non-carbon gases like water vapor and nitrogen oxides. Airbus, acknowledging the uncertainties, plans to use hydrogen test gliders to study the environmental impact of the line-shaped clouds they generate, showcasing the cautious approach to adopting this technology as a green alternative.

Rolls-Royce: Has announced a comprehensive series of rig and engine tests to prove that hydrogen can safely and efficiently deliver power for small- to mid-size aircraft from the mid-2030s onwards. The company is working with easyJet to develop hydrogen combustion engine capabilities capable of powering a range of aircraft, including those in the narrow-body market segment.³⁶

³¹ [Hydrogen Planes Show Promise—and Their Limitations - WSJ](#)

³² <https://zeroavia.com/absolut-hydrogen-partnership/>

³³ [Hydrogen Planes Show Promise—and Their Limitations - WSJ](#)

³⁴ <https://www.h2fly.de/company/>

³⁵ <https://www.airbus.com/en/innovation/low-carbon-aviation/hydrogen/zeroe>

³⁶ <https://www.rolls-royce.com/innovation/alternative-fuels/hydrogen.aspx>

Universal Hydrogen Co: Is leveraging existing infrastructure to create a flexible, scalable, and capital-light approach to hydrogen logistics by transporting it in modular capsules over the existing freight network. At the airport, the modules are loaded directly into the aircraft using existing cargo handling equipment. No new infrastructure is needed. Starting with regional airplanes, the company is also developing conversion kits to retrofit the existing fleet with a hydrogen fuel cell powertrain.³⁷

Cranfield Aerospace Solutions/Britten-Norman: Announced the intention to merge operations to create the world's first fully integrated, zero-emission sub-regional aircraft for entry into service in 2026.³⁸

Dymond Aerospace: Signed a Memorandum of Understanding (MoU) for 200 hydrogen-powered motors from Duxion Motors. Duxion will supply 20 patented e-jet motors per year for 10 years starting in 2026.³⁹

The Hydrogen Storage Issue: Storage is the weak link when it comes to large-scale applications of hydrogen fuel for flight.⁴⁰

Liquid hydrogen stores approximately 2.9 times more energy than kerosene in terms of weight. However, concerning volume, the energy density of kerosene is estimated at around 35 MJ/L, a value approximately four times larger than liquid hydrogen, which ranges from 8.5 MJ/L to 10 MJ/L (Figure 10.1).

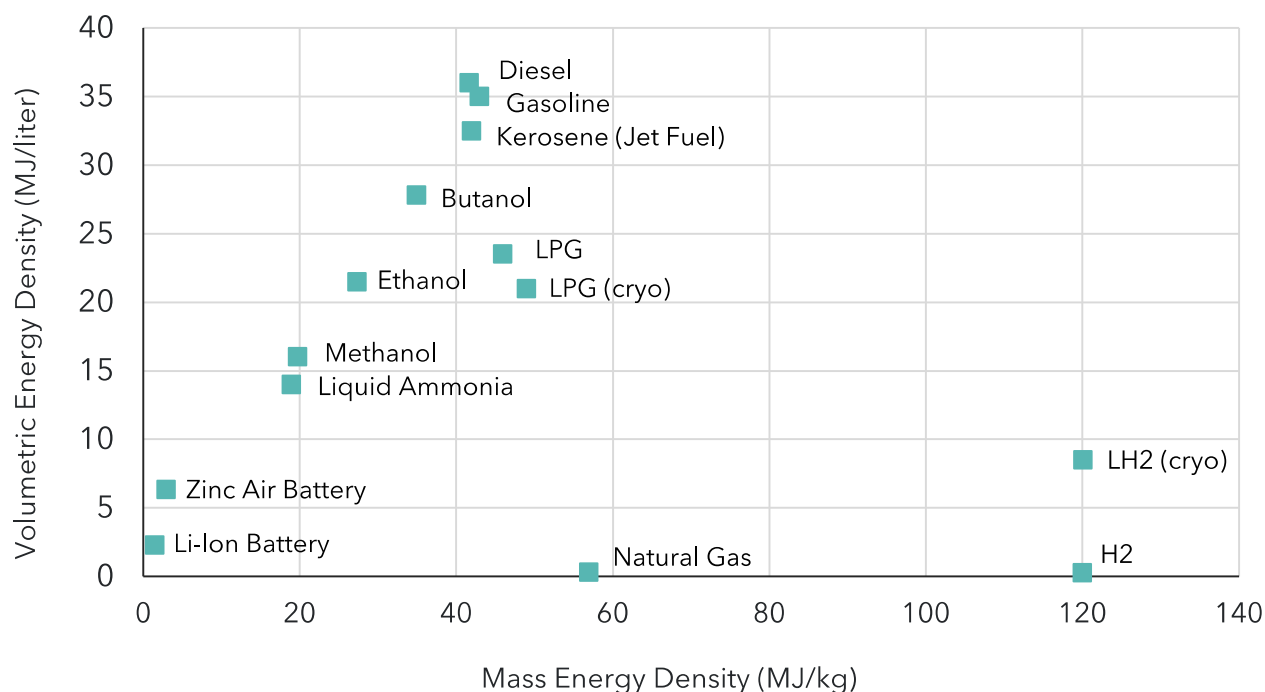
³⁷ <https://hydrogen.aero/>

³⁸ IEA, Global Hydrogen Review 2023

³⁹ <https://fuelcellsworks.com/news/hydrogen-fuel-cell-flights-duxion-signs-500-million-cad-memorandum-of-understanding-for-ejet-motor-order/>

⁴⁰ <https://hysafe.info/uploads/papers/2021/189.pdf>

Figure 10.1: Energy Density Comparison of Various Fuels



– Yin and Rao, 2012: “A Hybrid Engine Concept for Multi-fuel Blended Wing Body”

This consideration would require a redesign of conventional airframes.⁴¹ Whether employed in a turbine engine or a fuel cell, liquid hydrogen takes up considerably more space per unit of energy than kerosene, making storage in the wings impractical. Liquid hydrogen must be stored in cylindrical tanks and placement within the wings would limit size and efficiency. Additionally, companies such as Universal Hydrogen are making modular tanks that would be replaced rather than refilled. In this scenario, fewer, larger tanks would be needed.

What Needs to Happen for Battery-Powered Flight

Battery-powered flight is an option for smaller aircraft and short-range flights. However, a meaningful transition to battery-powered flight for longer-range flights would necessitate significant advancements in battery technology. Such advancements are possible given the current focus on battery-powered transportation and innovation. However, it is EcoEngineers’ opinion that any breakthroughs that would have a measurable impact on the aviation sector are unlikely within the next 10 years. While advances are gradually coming in electric plane development, the energy density of batteries remains a major obstacle for large aircraft and long-distance flights.

⁴¹ https://www.iata.org/contentassets/d13875e9ed784f75bac90f000760e998/fact_sheet7-hydrogen-fact-sheet_072020.pdf

What Needs to Happen for Hydrogen-Powered Flight

In terms of technical feasibility, hydrogen is positioned well to eventually aid the aviation sector in its transition away from fossil fuels, at least for short-haul flights. Current jet engines can be modified to use hydrogen and even combined to create electricity through hydrogen fuel cells to create a hybrid power system. In the short term, existing hydrogen delivery and storage infrastructure can be leveraged and aircraft retrofitted. This will buy the airline industry time to develop, test, and deploy purpose-built aircraft and infrastructure.

The key obstacle that the industry must overcome is how to store liquid hydrogen safely and efficiently, meaning in a way that does not reduce the number of passengers/cargo and increase the costs per passenger or unit of cargo. Additionally, the designers must ensure that the fuel storage and delivery system is rugged enough to withstand the wear and tear associated with commercial air travel.

Conclusion

SAF is seen by many as the most promising way to directly reduce GHG emissions in the aviation sector. This is unlikely to change over the next decade unless there are technological breakthroughs to increase the energy density in batteries and decrease hydrogen volume in storage systems. Space and weight conservation is important in terms of economical long-distance air flight.

In the longer term, hydrogen-powered flight shows the best potential for practical application in the aviation sector for longer-range flights. As this technology continues to develop and gain traction, it is likely to gain a small market share in regional air travel.

Given the current state of battery and hydrogen technology, it is unlikely that any long-distance, commercially viable air travel will occur within the following decade.

Section 11: Appendix A: Acronyms and Abbreviations Used in the Report

ASTM	American Society for Testing and Materials (known as ASTM International)
ATAG	Air Transport Action Group
ATJ	Alcohol-to-jet
Bbl	Barrels
Bbl/d	Barrels per day
BTC	Blender's Tax Credit
CAGR	Compound annual growth rate
CI	Carbon intensity
CO₂	Carbon dioxide
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
DCO	Distiller's corn oil (a byproduct of ethanol manufacturing)
EIA	Energy Information Administration (a unit of the U.S. Department of Energy, or DOE)
USEPA	U.S. Environmental Protection Agency
ETJ	Ethanol-to-jet
EU	European Union
FT	Fischer-Tropsch
HEFA	Hydroprocessed esters and fatty acids
HVO	Hydrogenated vegetable oil
HT	Hydrotreating
IATA	International Air Transport Association
IEA	International Energy Agency
ILUC	Induced Land-Use Change
IRA	Inflation Reduction Act
GAO	U.S. Government Accountability Office
GHG	Greenhouse gas

LUC	Land-use change
LCFS	Low Carbon Fuel Standard
MBU	Million bushels
MSW	Municipal solid waste
MM	Million
MT	Metric ton (1,000 kilograms)
MTJ	Methanol-to-jet
PTC	Producers Tax Credit
RED	Renewable Energy Directive
RD	Renewable diesel
RIN	Renewable Identification Number (These are credits used for compliance with the U.S. Renewable Fuel Standard program and are the "currency" of the program)
RFS	U.S. Renewable Fuel Standard
SAF	Sustainable aviation fuel
UCO	Used cooking oil
UK	United Kingdom
WH	Watt-hour

Section 12: Appendix B: Additional Information on CORSIA

During the initial phases of implementation, CORSIA will only apply to international flights between states that have volunteered to take part. International flights to and from states that have not volunteered will be exempt.

During the mandatory stage, which begins in 2027, CORSIA will cover all international flights, including those traveling to or from states that had not volunteered for the early phases. There will, however, be some small exceptions:

- Least developed countries, small island developing states, and landlocked developing countries (the United Nations directs which states are covered by these definitions). However, these states can volunteer if they wish.
- States that have a very small share of international traffic.

Eighty-eight EU Member States volunteered to participate in the CORSIA offsetting pilot phase from 2021, including all EU and European Free Trade Association (EFTA) States. This has increased to 107 States in 2022 and represents most ICAO Member States. States that represent the vast majority of aviation activity have volunteered and the airline industry is working hard to encourage as many States as possible to volunteer. Brazil has stated it will join CORSIA in 2027.

How will the Offsets Work? CORSIA says that “offsetting is done through the purchase and cancellation of emissions units arising from different sources of emissions reductions achieved through mechanisms, programs, or projects.”

“The buying and selling of eligible emissions units (credits) happens through the carbon market. The price of the emissions units in the carbon market is influenced by the law of supply (availability of emissions units) and demand (level of offsetting requirements).”

As of January 1, 2019, all aircraft operators with emissions greater than 10,000 MT of CO₂ will need to report their emissions to their national authority annually.

To guarantee data accuracy, an independent third-party verification body must verify annual emissions reports before submission. Governments will then work with ICAO to inform airlines of the number of offset credits they need. Member States are supposed to manage enforcement efforts.

In 2018, ICAO adopted detailed requirements for the monitoring, reporting, and verification of emissions as part of the Chicago Convention. These rules are essential to ensuring aircraft operators and states comply with the terms of CORSIA. Uniform requirements for monitoring emissions are critical to ensure all operators compete on similar terms and ensure the scheme's integrity.

Requirements: “Under CORSIA, all operators with annual emissions greater than 10,000 MT of CO₂ will have to report their emissions on an annual basis, with monitoring starting from January 1, 2019 (international flights only).”

More on Enforcement: As part of the U.N., the ICAO has no legal authority for enforcement in any country. Therefore, it will rely on Member States to adopt CORSIA into their laws governing aviation emissions and to enforce compliance.

To date, no Member State has adopted CORSIA rules into its aviation emissions law. However, the EU ETS does have a model for aviation emissions enforcement. Under the EU ETS, the penalty for non-compliance is €100 per ton (US\$105 per ton) of CO₂ emitted, plus additional local fees and penalties. Each Member State is allowed to legislate the enforcement as they choose, so penalties, if they arise, may vary from country to country.

CORSIA will likely face the same issue with enforcement that is faced by the marine industry under IMO 2020.

Eligible SAF, Feedstocks, and “Themes”: Fourteen (14) “themes” cover the eligible SAFs, feedstocks, and production criteria for the CORSIA program. They are:

- Greenhouse gases (GHGs)
- Carbon stock (feedstock)
- GHG emissions reduction permanence
- Water
- Soil
- Air
- Conservation
- Waste and chemicals
- Seismic and vibrational impacts
- Human labor rights
- Land-use rights and land use
- Water use rights
- Local and social development
- Food security

Theme 1/GHGs: “CORSIA-eligible fuel will achieve net greenhouse gas emissions reductions of at least 10% compared to the baseline life cycle emissions values for aviation fuel on a life cycle basis.”

Theme 2/Carbon Stock: “CORSIA SAF will not be made from biomass that is either obtained/extracted from land or aquatic ecosystems converted after January 1, 2008, that was primary forest, wetlands, peat lands, coral reefs, kelp forests, seagrass meadows, estuaries, tidal salt marshes or mangrove forests or contributes to degradation of the carbon stock in primary forests, wetlands, peat lands, coral reefs, kelp forests, seagrass meadows, estuaries, tidal salt marshes or mangrove forests as these systems all have high carbon stocks.”

- In the event of land-use conversion after January 1, 2008, as defined based on the Intergovernmental Panel on Climate Change (IPCC) land categories, direct land-use change (DLUC) emissions will be calculated. If DLUC GHG emissions exceed the default induced land use change (ILUC) value, the DLUC value will replace the default ILUC value.

Compliance with Themes 1 and 2 is granted based on independent attestation by sustainability certification schemes included in the ICAO document “CORSIA-Approved Sustainability Certification Schemes”, which is available on the ICAO CORSIA website.

Theme 3/GHG Emissions Reduction Permanence: “Operational practices will be implemented to monitor, mitigate, and compensate any material incidence of non-permanence resulting from CCS activities.”

Theme 4/Water: “Operational practices will be implemented to maintain or enhance water quality. Operational practices will be implemented to use water efficiently and to avoid the depletion of surface or groundwater resources beyond replenishment capacities.”

Theme 5/Soil: “Agricultural and forestry best management practices for feedstock production or residue collection will be implemented to maintain or enhance soil health, such as physical, chemical, and biological conditions.”

Theme 6/Air: “Air pollution emissions will be limited.”

Theme 7/Conservation: “CORSIA SAF will not be made from biomass obtained from areas that, due to their biodiversity, conservation value, or ecosystem services, are protected by the State having jurisdiction over that area, unless evidence is provided that shows the activity does not interfere with the protection purposes.”

“Low invasive-risk feedstock will be selected for cultivation and appropriate controls will be adopted to prevent the uncontrolled spread of cultivated alien species and modified microorganisms.”

“Operational practices will be implemented to avoid adverse effects on areas that, due to their biodiversity, conservation value, or ecosystem services, are protected by the State having jurisdiction over that area.”

Theme 8/Waste and Chemicals: “Operational practices will be implemented to ensure that waste arising from production processes, as well as chemicals used are stored, handled, and disposed of responsibly. ”

“Responsible and science-based operational practices will be implemented to limit or reduce pesticide use.”

“Operational practices will be implemented to prevent, minimize, and mitigate any damage from the unintentional release of fossil resources, fuel products, and/or other chemicals.”

Theme 9/Seismic and Vibrational Impacts: “Not applicable”

Theme 10/Human and Labor Rights: “CORSIA SAF production will respect human and labor rights.”

Theme 11/Land-Use Rights and Land Use: "CORSIA SAF production will respect existing land rights and land use rights, including indigenous peoples' rights, both formal and informal."

Theme 12/Water Use Rights: "CORSIA SAF production will respect the existing water use rights of local and indigenous communities."

Theme 13/Local and Social Development: "CORSIA SAF production will strive to, in regions of poverty, improve the socioeconomic conditions of the communities affected by the operation."

Theme 14/Food Security: "CORSIA SAF production will, in food insecure regions, strive to enhance the local food security of directly affected stakeholders."

Concerns About CORSIA Viability:

Questionable Quality of Credits: According to a study by the European non-governmental organization (NGO) Transport and Environment (T&E): "None of the offsetting programs approved under CORSIA meet all the required EU ETS criteria (and all have issues with double counting). A large share of existing projects are delivering emission reductions in sectors that are already covered by their respective country's current climate targets and double counted."

Low Price of Credits: According to a study by T&E: "CORSIA will have an oversupply of cheap (less than €1) carbon offset credits, worsened by ICAO's decision to change its baseline due to COVID-19, which implies the price signal faced by airlines under the scheme will never provide any financial incentives for them to reduce emissions. It is even cheaper to buy credits than using clean fuels and technology meaning there is no incentive to decarbonize."

See: https://www.transportenvironment.org/wp-content/uploads/2021/07/2021_03_Briefing_Corsia_EU_assessment_2021.pdf

Note: Not all the EU participants agree with T&E's interpretations, opinions, and foundation data.

As of November 2023, There Have Been Nine Conversion Processes Approved for Aviation Alternative Fuel Production by CORSIA:

- ASTM D7566 Annex 1 - Fischer-Tropsch hydroprocessed synthesized paraffinic kerosene (FT SPK)
- ASTM D7566 Annex 2 - Synthesized paraffinic kerosene from hydroprocessed esters and fatty acids (HEFA SPK)
- ASTM D7566 Annex 3 - Synthesized iso-paraffins from hydroprocessed fermented sugars (SIP)
- ASTM D7566 Annex 4 - Synthesized kerosene with aromatics derived by alkylation of light aromatics from non-petroleum sources (FT-SKA)
- ASTM D7566 Annex 5 - Alcohol-to-jet synthetic paraffinic kerosene (ATJ-SPK)
- ASTM D7566 Annex 6 - Catalytic hydrothermolysis jet (CHJ)

- ASTM D7566 Annex 7 - Synthesized paraffinic kerosene from hydrocarbon-hydroprocessed esters and fatty acids (HC-HEFA SPK)
- ASTM D-1655 - Co-hydroprocessing of esters and fatty acids in a conventional petroleum refinery
- ASTM D-1655 - Co-hydroprocessing of Fischer-Tropsch hydrocarbons in a conventional petroleum refinery.

LCA data for these pathways, using many different feedstocks, are reported in the “CORISIA Supporting Document CORISIA Eligible Fuels – Life-Cycle Assessment Methodology Version 4 – November 2021” for a summary of the required LCA assessment methodology.

For Additional Information on Eligible SAFs and Feedstocks: See “CORISIA Supporting Document CORISIA Eligible Fuels – Life-Cycle Assessment Methodology Version 4 – November 2021” for a summary of the required LCA assessment methodology. (164 pages)

https://www.icao.int/environmental-protection/CORISIA/Documents/CORISIA_Supporting_Document_CORISIA%20Eligible%20Fuels_LCA_Methodology_V4.pdf

This document covers:

- Default core LCA values for all eligible fuels (using GREET and E3 models).
- Calculation of ILUC values.
- Default ILUS emission intensities.
- Approved SAF production pathways.
- Approved feedstocks.

Credits Eligibility Criterion: “Carbon offset credits must be quantified, monitored, reported, and verified. Emissions reductions should be calculated in a manner that is conservative and transparent. Carbon offset credits must have a clear and transparent chain of custody within the offset program. Offset credits should be assigned an identification number that can be tracked from when the unit is issued through to its transfer or use (cancellation or retirement) via a registry system(s).”

- Scope of eligibility: ACR Emission Reduction MT (ERTs), including any additional certifications, and with the exclusion of the following activity and/or unit types, methodologies, program elements, and/or procedural classes: California Registry Offset Credits (ROCs).
- California Early Action Offset Credits (EAOs).
- ERTs issued to all activities that are developed in REDD+ countries and utilize methodologies in the program’s sectoral Scope 3 (land use, land use change, and forestry) category and are estimated to generate greater than 7,000 ERTs/annum individually or grouped.

Figure 12.1: Pathways Analyzed to Date Under CORSIA



Section 13: Appendix C: Comparison of Jet Fuel Specifications

SAF is considered a “drop-in” fuel, meaning that once blended with conventional jet fuel, the fuel blend is fully compatible with existing infrastructure, including jet engines and airport fueling infrastructure.

Table 13.1: Comparison of Jet Fuel Specifications

	Petroleum-Based Jet Fuel	SAF: SPK Types (1,2)
General Composition	n-alkanes, iso-alkanes, cycloalkanes, and aromatics	n- and iso-alkanes
Sulfur Level	0.3 wt% max	Very little or none detectable
Meets ASTM D1655 Specs? (3)	Yes	Yes
Feedstock(s)	Crude oil and hydrogen	Synthesis, gas, animal fats, seed oils, used cooking oils, sugars, alcohols, and hydrogen

– EcoEngineers and ASTM

Notes

1. Synthetic paraffinic kerosenes (SPK), which consist of n- and iso-alkanes constituted the first alternative SAF and RD-type fuels approved and they came from four sources: synthesis gas (syngas), lipids (fats, oils, greases), sugars, and alcohols.
2. To date, no alternative fuel SAF is approved for greater than 50% blending with conventional jet fuel. Current allowed blend levels range from 10% to 50%, depending on the feedstock and how the fuel is produced.
3. This is the standard specification for aviation turbine fuels. Key elements of the spec are freeze point, flash point, initial and final boiling points, distillation residue, max aromatics level, max sulfur level, viscosity, acidity, and density.

Section 14: Appendix D: The Aviation GHG Footprint

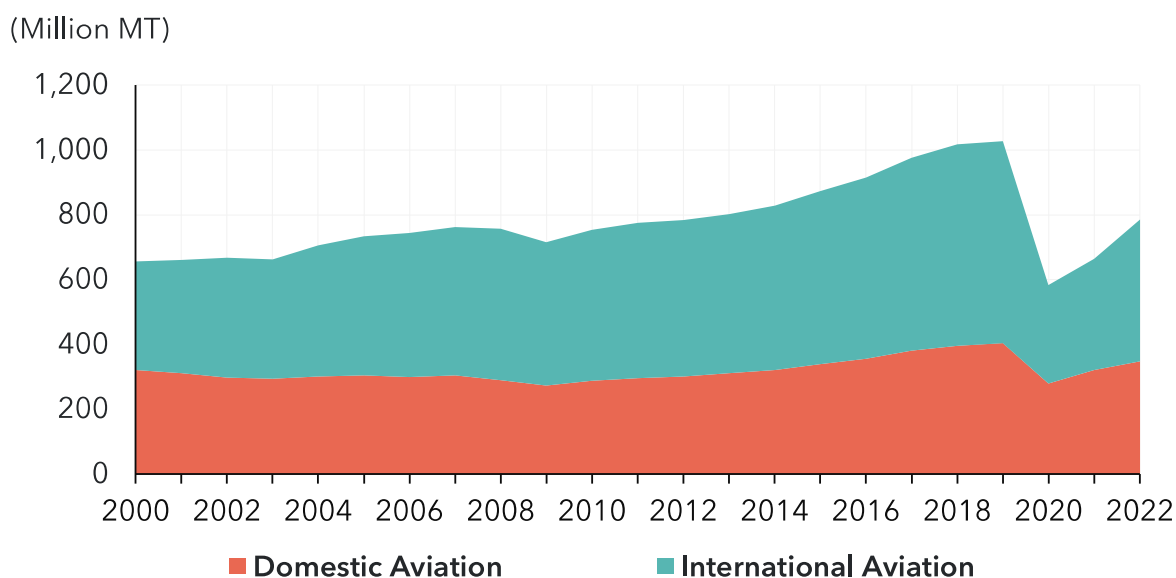
Aviation-related CO₂ emissions rose in 2022 to reach nearly 80% of their pre-pandemic peak.

As demand from air passengers recovered in 2022, emissions increased in all global regions, except for China (due to the zero-COVID policy) and Russia (due to the invasion of Ukraine), reaching almost 800,000 MT CO₂.

At current rates of growth, aviation CO₂ emissions will surpass 2019 levels by 2025.

The aviation CO₂ emissions level in 2019 was approximately 2.5% of the total year 2019 global CO₂ emissions.

Figure 14.1: Historical Worldwide CO₂ Emissions Due To Aviation



– IEA

Section 15: Jet Fuel and SAF Background

Liquid Jet Fuel - The Great Enabler: Liquid fuels with high energy density manufactured from widely available petroleum enabled the initial development of piston-engine airplanes and then turbine-engine jets during the period between 1900-1940.

During the initial development of turbine jet engines in the 1930s, the new engine developers wanted a fuel that was safer to handle than aviation gasoline (avgas). They wanted a fuel that had a higher flash point and that didn't vaporize easily.

Flashpoint refers to the temperature at which the vapor above the liquid fuel catches fire when a flame or spark is present. For avgas, this temperature is very low, less than minus 30 degrees C (minus 22 degrees F), making it quite hazardous if spilled and a vapor cloud

forms. Jet fuel, on the other hand, must be heated to greater than 38 degrees C (100 degrees F) for the vapor to burn under ambient conditions.

Diesel fuel was the first choice for early jet engine developers as it was readily available and had a higher flashpoint than gasoline. However, there were often problems when refueling jets with diesel fuel. Carbon deposits sometimes block vaporizers and coated flame tubes, causing local overheating and power instability. Another disadvantage with diesel fuel was that at low temperatures it sometimes froze or formed wax crystals, blocking filters and stalling engines.

The early jet engine developers required a fuel that did not form deposits and that would allow aviators to fly at high altitudes under extremely cold conditions. A new type of jet fuel (also known as "jet kerosene") was developed and manufactured to keep flowing under low-temperature conditions. It can also serve as a foul-resistant coolant for jet engine oil and maintain clean injector nozzles, avoiding carbon deposits on surfaces that perform at extremely high temperatures in modern turbine jet engines.

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