SUSTAINABLE AVIATION FUEL

Gevo's Alcohol-to-Jet Pathways Are Proven to Deliver Bio-Based, Drop-In Replacements as Low-Carbon Options for Travelers.

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Introduction

The aviation industry faces substantial challenges to reduce emissions of greenhouse gases and improve environmental sustainability in the face of rapid growth. The International Air Transport Association expects the number of flights in 2019 to be 40 million worldwide, with growth in jet-fuel demand estimated at 3 billion gallons per year. Simultaneously, the industry has declared a desire to freeze emissions and achieve carbon-neutral growth by 2020. The industry also has announced targets for a 50-percent reduction in carbon emissions (based on 2005 levels) by 2050.

The expected growth in flight volume indicates the aviation industry will explore new technologies to help reduce carbon emissions. While hybrid and electric vehicles are viable alternatives for other transportation needs, electric propulsion on planes appears to be several years away for air travel, and is currently limited to small aircraft and medium-range flights. The development of sustainable aviation fuel (SAF) will allow the use of existing aircraft, including long-range models, but with a substantial collective reduction of greenhouse gas (GHG) emissions.

SAF provides a reduced carbon footprint while adhering to the strict requirements that all aviation fuel must meet as laid out in the ASTM International (ASTM) D7566 standard. A variety of production methods produce SAF from a range of renewable feedstocks. Several pathways synthesize hydrocarbons to create renewable jet fuels and include alcohol-to-jet, oil-to-jet, syngas-to-jet, and sugar-to-jet. Each has challenges, including feedstock availability, process design and economics, life-cycle assessment (LCA) of GHG emissions, and commercial readiness. Feedstock availability and price, energy intensity of the process, and facility capital expenditure are significant barriers, but biomass-derived jet fuel could potentially replace a significant portion of the conventional jet fuel needed to meet commercial and military demand.

Fuel is the largest cost for the aviation industry, and while SAF is relatively new and now coming into real market conditions, its adoption will enable the airline industry to move away from the petroleum sources upon which the world has up to now relied. In addition, the United States Department of Defense has explored sources of sustainable biofuel to offset dependence on foreign energy sources.

This white paper will discuss the various methods of producing SAF, with a focus on alcohol-to-jet pathways as a standard for improving the sustainability of the supply chain and farming methods, while also having potential to offset and reduce production costs and capital expenditure in the ramp-up stage.

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Background

Alternative Jet Fuel Pathways

Seven SAF pathways have been certified by the ASTM D7566 process (initially reported January 2020, but still valid in 2022). The specifications laid out in D7566 limit drop-in fuels to certain blend rates, from 10 to 50 percent, depending on chemical composition (U.S. Department of Energy, *Sustainable Aviation Fuels: Review of Technical Pathways,* September 2020, and International Council on Clean Transportation (ICCT), *The Cost of Supporting Alternative Jet Fuels in the European Union*, by Pavlenko, Searle, Christensen, March 2019):

1. Hydro-processed esters and fatty acids (HEFA or HEFA-SPK): The HEFA pathway uses fatty feedstocks such as vegetable oils or waste fats, which first undergo a deoxygenation reaction followed by the addition of hydrogen in order to break down the fatty compounds into hydrocarbons, which can then be further refined into a mix of various liquid fuels. Can be blended up to 50 percent. [Also, according to the ICCT report, HEFA+ or high-freeze-point HEFA (HFPHEFA) is currently undergoing testing for ASTM certification. This variant of HEFA has a higher freeze point than standard HEFA fuel and would only be allowed to be blended up to 10 percent (Pavlenko & Kharina, 2018).]

2. Synthesis gas Fischer-Tropsch synthesized paraffinic kerosene (FT-SPK): This fuel conversion pathway includes the gasification of feedstocks into synthesis gas (i.e., syn-gas), a mix of CO and H2. The syn-gas is then combined with a catalyst in a reactor to generate a mix of hydrocarbons, which can then be refined into various liquid fuels. Can be blended up to 50 percent.

3. Power-to-liquids Fischer-Tropsch synthesized paraffinic kerosene (PtL FT-SPK): Similar to FT-SPK from bio-feedstocks, syngas is produced from hydrogen generated from the electrolysis of water (using renewable electricity) combined with captured carbon dioxide to generate a suitable feedstock for FT synthesis. Can be blended up to 50 percent.

4. Synthesized isoparaffins (SIP): Also called direct sugars-to-hydrocarbons (DSHC), this fuel conversion pathway converts sugary feedstocks through fermentation into farnesene (C15H24), a molecule with a carbon-chain length closer to distillate hydrocarbons than traditional alcohol fermentation products, followed by upgrading into farnesane (C15H32), via addition of hydrogen, which can be used as a drop-in fuel. Can be blended up to 10 percent.

While there are huge numbers of additional potential feedstocks available for carbohydrate-based technologies compared to HEFA or FT, the feedstocks for alcohol to jet need to be certified as sustainable and likewise show a low-carbon footprint.

5. Alcohol-to-jet synthesized paraffinic kerosene (ATJ-SPK): This fuel conversion pathway uses fermentation to convert sugars, starches, or hydrolyzed cellulose into an intermediate alcohol, either isobutanol or ethanol, which is then further processed and upgraded into a mix of hydrocarbons. Can be blended up to 50 percent.

6. Applied Research Associates Catalytic Hydrothermolysis Jet (ARA CHJ) was approved in January 2020 as a 50-percent blend. The fuel is produced from lipids using a supercritical hydrothermal process, creating a blendstock that contains all four hydrocarbon families: n-, iso-, and cyclo-alkanes and aromatics.

7. Synthesized paraffinic kerosene from hydroprocessed hydrocarbons, esters, and fatty acids (HC-HEFA) was approved in 2020 as a 10-percent blend. This is specifically for lipids from an B. braunii algae subjected to hydrocracking/hydroisomerization to remove all oxygen and saturate double bonds. The product is rich in iso-alkanes. This is the first approval through the fast-track process.

The Market for SAF

While the goal of the commercial aviation industry to cap GHG emissions and effectively reduce the carbon footprint of every passenger would seem pressing, many industrial, economic, regulatory, environmental, and social factors play a role in the market for SAF that may give some pathways advantages over others. The market potential for SAF is large, but the production capability needed to supply the market still needs to be developed. The production capability will develop if, and only if, reinvestment economics can be obtained in the selling price of SAF. Generally SAF is more expensive than petro-jet, given that new production capacity has to be deployed. SAF will not be widely available because production capacity will be built to contracts, not as a commodity, at least in the first decade or so.

Perceived Barriers to Establishing Production and Bringing SAF to Market

Scalability

SAF must be able to reach large volumes of production, and meet the required goals of sustainability and low carbon. Scalability depends

on producers being able to reach margins that encourage market development, having low-carbon feedstocks available in sufficient quantity and quality at a price that works for the production technology. HEFA technology uses vegetable oils as raw material. Raw materials such as used cooking oil (UCO) are not widely available because much of the available quantity has been used already for the diesel market, and there is not that much of a quantity available to begin with. For HEFA, other oilseeds can be used, but the beneficial sustainability aspects need to be further developed and communicated. FT has potential to use woody types of cellulosic feedstock that can be obtained from forests, or from a municipal solid waste (MSW) stream. Again, the overall sustainability profile and the carbon score will need to be proven, monitored, and tracked throughout the life cycle of the pathway as a fuel producer. For alcohol-to-jet pathways, generally any carbohydrate source could be used, including crops such as industrial corn, sorghum, beets, agricultural residues, such as straw, wood, wood residues, cellulosic MSW, certain food wastes, cane sugar, molasses, and other carbohydrate sources. While there are huge numbers of additional potential feedstocks available for carbohydrate-based technologies compared to HEFA or FT, the feedstocks for ATJ-SPK need to be certified as sustainable and likewise show a low-carbon footprint.

Issue: Feedstocks need to be available at a scale, quantity, cost, carbon footprint, and with a sustainability profile that enable large-scale production of SAF. In order to address the magnitude of the market in a meaningful way, all types of technology and feedstocks will likely be required.

Solution: Gevo has developed technology that works with and leverages existing fermentation industry infrastructure, specifically ethanol production.

Carbohydrate feedstocks are the most abundant and widely available throughout the world. Gevo is collaborating with farmers to help spread sustainable farming and growing practices with an emphasis on producing protein for the food chain and capturing carbon in the soil.

The farmers who supply Gevo have been shown to be capturing carbon in the soil at a rate of approximately two pounds of carbon per gallon of jet fuel because they use sustainable practices such as precision AG and conservation tillage.

At the same time, Gevo understands other feedstock sources will help ramp up production volume, so it continues to develop the production processes for cellulosic feedstocks internally and through partnerships.

In the US and other regions where ethanol production is established, the potential exists for Gevo to leverage several billion gallons of infrastructure. In other areas of the world, Gevo could use agricultural residues like rice straw, wheat straw, forestry residues, wood, or cellulosic MSW. In each system, Gevo would establish the requirements for carbon score and sustainability practices.

Issue: All bio-based SAF are made via plant matter, from something that grows. If land is used, then a priority needs to be given to food. Raw materials used in the production of SAF should not impact the food chain in a negative way. A raw material for SAF should not negatively impact forests. A raw material, even if coming from bio-based MSW, should not negatively impact food or land use, nor should it encourage non-sustainable practices.

Solution: When Gevo uses sustainable corn as a feedstock, our process also produces ten pounds of high-protein animal feed for every gallon of fuel produced. This is not a byproduct, but a coproduct that has a market in close proximity to the facility. This adds more protein into the food chain, and also results in healthier livestock.

The farmers who supply Gevo have been shown to be capturing carbon in the soil at a rate of approximately two pounds of carbon per gallon of jet fuel because they use sustainable practices such as precision AG and conservation tillage. They optimize the chemicals applied to the land for the benefit of the soil by using low-tillage and no-tillage practices, by protecting groundwater run-off with drain tiles, and by using manure rather than synthetic nitrogen. Additionally, there are several technologies being developed that could increase this carbon capture by an order of magnitude or more by enhancing soil quality and root-system growth.

When using cellulosic feedstocks, Gevo plans to establish a sustainable and certified procurement system to ensure that the objectives of carbon score and sustainability are being met.

Transportation

SAF must be competitive both technically and economically, and it must behave as traditional jet fuel. SAF has already been shown to be able to be economically transported through pipelines, stored in tanks, and blended with petro-jet. It may be that as SAF grows in volume, new blending tanks may need to be added in certain regions if the capacity doesn't exist. But because SAF must meet ASTM standards, the issues around transportation are insignificant once blended—it is the same and fungible.

Issue: For biofuels to gain acceptance quickly, they need to work seamlessly with the infrastructure that delivers fossil fuels, and will continue to be used.

Solution: Gevo's alcohol-to-jet pathways meet ASTM standards, and therefore can be blended into traditional petro-jet fuel. Gevo has already demonstrated the efficacy of this approach in numerous airports around the world. Not all types of biofuel work with infrastructure as seamlessly.

Public acceptance of low-carbon SAF may soon outstrip that of fossil jet fuel as air travelers gain a fuller understanding of climate change and realize that they have a choice, and we will be positioned to capitalize on that moment.

Pricing

The market may accommodate some pricing flexibility in exchange for the reduction in carbon emissions. As countries develop their strategies for incorporating SAF, the cost of producing biojet is estimated to be two to seven times greater than conventional jet fuel for the foreseeable future. Governments can use levies and tax policy effectively to help achieve parity of prices, but taxes designed to encourage green initiatives could also be seen as siphoning money from companies that may be inclined to invest in still more efforts to reduce GHG emissions (U.S. Department of Energy, *Alternative Aviation Fuels: Overview of Challenges, Opportunities, and Next Steps,* 2016).

Issue: Fossil-fuel producers, as the established segment in the market, have the advantages of lucrative offtake contracts, standards written with their product in mind, existing production infrastructure set up and amortized over decades of delivery, and consistent product with wide public acceptance. Biofuels have none of those advantages and expensive ramp-up to minimal commercial production levels.

Solution: Gevo's production technology is very efficient in terms of yield and energy. Because Gevo has to build new production capacity, the selling price at the factory gate for SAF will be higher than petro-jet. However at the airport or customer gate, the realized price to customer is expected in the near term to be only a relatively small premium because of policies, such as renewable fuel standards (RFS), low carbon fuel standards (LCFS), and tax credits, which give value for renewable SAF. As oil rises in price over time, as carbon value incrementally increases, and as production reaches optimized economies of scale, it is possible to see that SAF could actually become incrementally less expensive than petro-jet, even though SAF has to pay for the returns on its new production capacity. Gevo believes that carbon value will likely increase and become more highly valued. Public acceptance of low-carbon SAF may soon outstrip that of fossil jet fuel as air travelers gain a fuller understanding of climate change and realize that they have a choice, and we will be positioned to capitalize on that moment. At the same time, we are also positioned to market our isobutanol, isooctane, and diesel fuels.

Infrastructure

New industries traditionally face other challenges, such as the ramp-up of the infrastructure to produce SAF. Many of these facilities still need to be built, and construction will have upfront costs that will not be amortized for years. Even when these challenges are overcome and the facility is constructed, production capacity will typically be at a demonstration or pilot level to prove process viability, and additional, expensive facilities will need to be built to realize commercial-level production. Still other factors include the location: To reduce carbon footprint and transport costs to get feedstock into the facility, each should be situated in close proximity to sources.

Locations for industrial chemical-production plants face similar challenges to other industries, including zoning questions and the NIMBY factor, where neighbors are often leery of chemical processes they don't fully understand and fear explosions, clouds of poisonous gas escaping, or odors changing the overall surroundings permanently.

Facilities that aim to process MSW may need to be sited at landfill locations, requiring ground-up new construction, or will have to deal with public comment periods and planning and zoning meetings when word gets out that truck after truck of garbage will be delivered there daily.

Issue: New biofuel factories take time and money to build, driving up the price of their offtake once they get online and hampering their ability to reach the critical mass of profitability.

Solution: Gevo's alcohol-to-jet fuel (ATJ) is made from ethanol and isobutanol that can be manufactured in existing ethanol plants. These plants are already sited in proximity to feedstock production, surrounded by a resident population of skilled workers who may have recently been idled due to government policies that have made ethanol a challenging market. Using existing facilities further enhances our strategy of reducing the carbon footprint of the entire process—there are no fossil-fuel-powered bulldozers arriving for site prep and no building materials and cement trucks creating greenfield facilities.

We are minimizing the carbon footprint at our development facility and biorefinery by incorporating wind power, structuring a deal where wind turbines provide optimal sustainable power.

Energy Use for Production

All pathways use energy throughout the production process, from hauling feedstock to the production facility to keeping the lights on and maintaining a safe and healthy work environment, to the power required to effect the physical, biological, and chemical processes in the facility on an industrial scale, to delivering the completed fuel product to the distribution infrastructure. Because much of the electricity from the grid is produced in coal-fired plants, alternatives should be explored to reduce dependence on those sources. In order to have a true image of the carbon footprint of each gallon of SAF produced, all of these factors must be tracked, monitored, and certified.

Issue: Energy use in creating biofuels and alternative jet fuel adds carbon intensity (CI) back into the process even if carbon is reduced when comparing the final product to its fossil-fuel analog. This additional carbon footprint should be tracked, measured, and included in the LCA, which all biofuel producers should review and share to give an accurate accounting of their products' CI.

Solution: Gevo is focused on decarbonization in every step of the production process. It starts with the farmers who supply the feedstock. They use enhanced agriculture techniques to improve carbon sequestration in the soil, including zone-tilling. The farmers employ land-use methods that provide measurable carbon sequestration and conservation of resources. These advances are good for our process, but they also make economic sense for the farmer, improving yields and reducing expense, such as costs for additional synthetic fertilizer.

In addition, we expect to minimize the carbon footprint at our ethanol and isobutanol production facilities and biorefineries by incorporating wind power, structuring deals where wind turbines provide optimal sustainable power. By adding the wind turbines, we use less electricity from the coal-fired electrical grid to power our ethanol and isobutanol production.

Also, Gevo works with livestock farmers, some of whom buy our high-protein animal feed. We have developed a system where we will construct anaerobic digesters on their property, and these digesters will biochemically process manure to capture methane. The methane will then be converted to renewable natural gas, which will further reduce our use of fossil-fuel energy. Because this captured methane will not be introduced to the atmosphere, the farmers will reduce their emission of this particularly potent greenhouse gas—methane retains 80 times more atmospheric heat than carbon dioxide. This helps lower the carbon rating for the entire process, thanks to its negative-200 carbon score. The

digested manure can serve as fertilizer, putting valuable nutrients back into the soil.

All of these factors are expected to combine to drive down the CI of Gevo's process. It's all by design, and each step fits into our plan to push down our carbon rating as low as it will go.

Benefits of Alcohol-to-Jet Synthetic Paraffinic Kerosene

The ATJ Process and Results Meet the Highest Standards

The alcohol-to-jet process gets its start with ethanol and isobutanol. At dry-mill corn ethanol plants, the corn mash stream coming out of the front end of the process that feeds the ethanol fermentation. This is the same stream that can also be used for isobutanol fermentation. This stream is prepared for fermentation and then added to large non-sterile fermentation tanks, where proprietary yeast is added to convert the sugars to isobutanol.

Ethanol and isobutanol must then go through additional steps at a biorefinery, where they can be refined into SAF. To make drop-in alternative fuel from alcohols, the refinery must minimize differences in the alcohol-derived fuels and conventional fuels in physical and chemical properties. The three steps in the process include alcohol dehydration, oligomerization, and hydrogenation. These steps are already in use on a commercial scale.

Through dehydration, isobutanol is turned into isobutylene, a C4 building block, in a chemical process by stripping away the oxygen as water. Oligomerization turns the isobutylene into C8 and C12 olefins. The olefins have only one double bond and are readily hydrogenated to hydrocarbons. The resulting hydrocarbons are distilled to ATJ and isooctane products. Isooctane is another marketable product, further diffusing the risk of investment in the process of producing ATJ.

The resulting ATJ meets or exceeds the standards in ASTM D1655 specification. For flash point, the standard stipulates a 38 degrees C minimum, and both typical Jet A-1 and ATJ are well within acceptable range at 48 degrees C, and both also pass the standard for thermal oxidation stability. For freezing point, the standard requires -40 degrees C maximum for Jet A and -47 degrees C for Jet A-1, and Jet A-1 complies with -50 degrees C, while ATJ is -80 degrees C. The energy density standard is 42.8 MJ/kg minimum, and Jet A-1 complies with 42.9 MJ/kg, while ATJ has 43.2 MJ/kg. The total sulfur content standard is 0.3 percent max, while Jet A-1 comes in at 0.05 percent and ATJ rates are at less than 0.01 percent.

Independent, global, multi-stakeholder organizations, including the International Sustainability and Carbon Certification System and the Roundtable on Sustainable Biomaterials, ensure supply chains implement and uphold carbon and sustainability standards through review and certification.

Jet Fuel Tests	Units	Specification ASTM D1655/7566	Gevo Alcohol to Jet
Freezing Point	°C	< -40	< -78
Flash Point	°C	> 38	45-50
Distillation (D86) T90 – T10	°C	> 22	25-70
Energy Density	MJ/kg	> 42.8	44.0
Density @ 15°C	kg/L	0.73-0.77 (SPK)	0.76
Aromatics	%	< 0.5	0
Sulfur	%	<0.0015	0
JFTOT Breakpoint	°C	> 325	> 350

Feedstocks

Ethanol and isobutanol can be derived from any number of sugar feedstocks, including sugar beets, sugar cane, and molasses, as well as cellulosic sources such as bagasse (sugar cane waste), wood slash (forestry waste), and rice straw.

Rice straw is a particularly interesting feedstock, since it has long been burned as waste in several Asian countries, including India and Vietnam, and only now is the promise of turning this biomass from a pollutant to a renewable energy source changing the thinking.

Beneficial Byproducts from the Inedible Corn Feedstock

Gevo's production of ethanol and isobutanol adds protein to the byproduct. The result is production of a high-protein animal feed product that is sold commercially and is an important product out of the biorefinery. For each gallon of ethanol and isobutanol produced, the process yields a substantial amount of this animal feed. Protein is grown during the fermentation process, and all of the nutrients in the corn end up in the animal feed. When livestock eat high-protein animal feed they don't get the starch that they can't digest effectively, so they're healthier and produce better meat.

Decarbonization at Every Step

To truly reduce the carbon intensity of every gallon of SAF as much as possible, every stage of the life of the feedstock and fuel products (and co-products) should be followed and tracked. Converted ethanol plants are already built and placed in the midst of the feedstock source. The facilities can be operated on renewable natural gas and wind power. The feedstock yields high-protein animal feed that can be sold to the surrounding farms—rather than shipped all over the country or overseas. And the finished fuel products have the ability to be transferred either as blended fuel or blendstock via pipeline—this is a valuable asset: Fewer carbon-intensive trucks mean less carbon going to the LCA bottom line.

Today's understanding of growing techniques allows further decarbonization. Collaborating with farmers, who are stewards of the land, Gevo researches the advanced techniques they use to achieve better yields, and how they use (and reuse) available nutrients occurring naturally in the cycle in lieu of synthetic fertilizers.

Independent, global, multi-stakeholder organizations, including the International Sustainability and Carbon Certification System and the Roundtable on Sustainable Biomaterials, ensure supply chains implement and uphold carbon and sustainability standards through review and certification.

Conclusion

While the aviation industry has set the goal of continued growth without increasing its carbon footprint, the roadmap to achieving these goals shows many paths. To effect immediate change, the existing infrastructure and equipment can be employed with minimal service interruption and varying degrees of success in reducing the industry's carbon footprint. While some SAF options show promise, the ramp-up to realistic levels of commercialization is expensive and time consuming. Gevo has developed an innovative process for producing alcohol to jet that has the advantage of working within established infrastructure and is ready to scale up with reasonable investment and a relatively short time horizon, and with a resulting product that outperforms the conventional jet fuel in many standard categories.