The A380, shown here in a photo illustration, is the world's largest passenger jet. It has made a 3-hour flight powered by biofuels produced from waste fat and oil. (The small third engine was used to test hydrogen fuel.)

PHOTO: AIRBUS

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CAN BIOFUELS REALLY FLY?

To get the carbon out of air travel, industry and government are trying, again, to turn farm and food waste into fuel

By **Robert F. Service**

It's a painful truth for people who fly: Airplanes are climate killers. Air travel is among the most carbon-polluting human activities. A round trip from New York City to London emits nearly 1000 kilograms of carbon dioxide (CO_2) per passenger, more than an average person in Burundi, Nicaragua, or 47 other countries emits in a year. Annually, airplanes spew some 920 million tons of CO_2, accounting for roughly 3.5% of all greenhouse gas emissions worldwide.

Derek Vardon is hoping a yellowish, foul-smelling liquid will help change that. The fluid is a collection of short, chainlike molecules called volatile fatty acids (VFAs) from decaying food waste, such as chicken primavera and Greek salads. (The same types of molecules give manure its stench.) In a process he and colleagues developed, the VFAs are vaporized, then percolate over a bed of white, marble-size pellets of zirconium oxide, which knit the VFAs into longer chains called ketones. After condensing into a sweet smelling, clear liquid,

The A380, shown here in a photo illustration, is the world's largest passenger jet. It has made a 3-hour flight powered by biofuels produced from waste fat and oil. (The small rear engine was used to test hydrogen fuel.)

the ketones are piped to another reactor where gray platinum pellets link them together and strip off oxygen atoms to make kerosene, aka jet fuel.

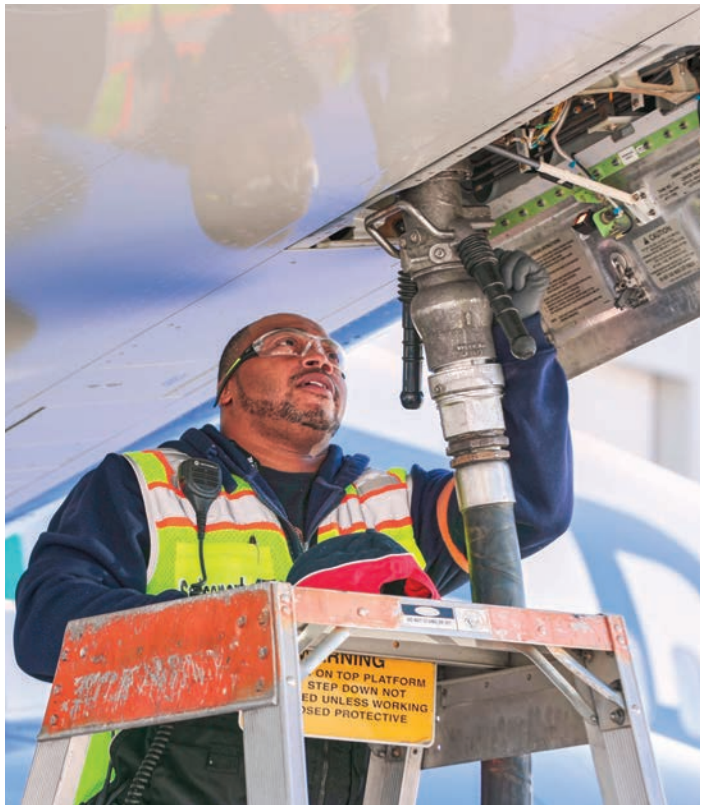
Vardon, a chemist who spent most of the past decade at the National Renewable Energy Laboratory (NREL), is betting this food-to-fuel process and others that convert different forms of waste "biomass" into fuel represent the future of air travel, and the world's best hope for dramatically reducing the greenhouse gases it generates. In March 2021, he and his colleagues detailed the technology in the *Proceedings of the National Academy of Sciences* along with calculations revealing the resulting jet fuel could be nearly as cheap as the petroleum-based version. Because the carbon it contains originated in plants, which drew it from the atmosphere, the net emissions from bio-based jet fuel would only be a fraction of those from fossil fuel.

In October 2021, Vardon bet on his technology, leaving NREL to become chief technical officer of Alder Fuels, a startup aiming to produce sustainable aviation fuels (SAFs). Alder is hedging its bets by developing another process as well: using high temperatures to convert wood waste to jet fuel. "We have a limited window to impact climate change," Vardon says. "I had to ask myself, 'Do I want to write more papers or try to take this solution and get it into the marketplace?'"

In fall 2021, United Airlines committed to buying 5.7 billion liters of SAFs from Alder, the largest such aviation deal at that time. And Alder isn't alone. More than a dozen SAF startups have formed in recent years in the United States, China, Japan, Singapore, India, Finland, Sweden, Austria, and Canada. "The interest is global, and it is rapidly expanding," says James Spaeth, a biofuels expert with the U.S. Department of Energy's (DOE's) Bioenergy Technologies Office (BETO).

For now, SAF producers create just 100 million liters of fuel per year for an industry that consumed more than 360 billion liters in 2019, before the pandemic cut that in about half. By 2030, the market for SAFs may grow by 70-fold, to nearly $15.7 billion, according to Markets and Markets.

There is a shadow over the effort: the failed attempt, more than a decade ago, by a handful of companies to turn agricultural wastes into vehicle fuels. But this go around, success may be more likely, in part because companies are trying many approaches, and in part because airlines desperate to find ways to reduce their carbon footprint have few alternatives. Cars can run on batteries, but planes will likely always require liquid fuels, which carry much more energy in a given volume. "Nobody is going to be flying a battery-powered jet to Australia anytime soon," says Eric McAfee, CEO of Aemetis, a startup that turns wood waste and kitchen grease into biofuel.



In a first, United Airlines in 2021 used only biofuels to power a commercial flight. It carried passengers from Chicago to Washington, D.C.

Slowly and haltingly, the transition has already begun. In addition to United, more than a dozen airlines around the globe have committed to collectively buying some 21 billion liters of SAFs in coming years. SAFs were first mixed with fossil fuel–derived kerosene for an airline flight in 2008, and thousands of jetliners have burned such mixtures since then. But it was only in December 2021 that a United Airlines flight from Chicago to Washington, D.C., became the first passenger flight to fly on 100% SAFs.

BIOFUELS' FIRST TURN in the spotlight was a partial flop. Nearly every motorist has pumped some biofuel into their tank. In the United States that was ethanol made from corn kernels. Corn ethanol now supplies some 59 billion liters a year in the United States alone, but growing and harvesting the corn requires heavy use of fertilizer and other energy-intensive inputs, making its climate benefit marginal at best. "Cellulosic ethanol" made from corn stalks, forest debris, and other waste carbon was supposed to change that.

Billions of dollars went into the effort after Congress instituted the renewable fuels standard in 2005 to create a market for ethanol and other vehicle biofuels. A massive chemical plant that opened in 2014 in Emmetsburg, Iowa, in the middle of corn fields stretching toward the horizon, is one monument to its failure. The $275 million plant, dubbed Project Liberty, converted farm waste including decaying corn stalks and cobs into ethanol for blending into gasoline. The technology worked, but Project Liberty shut down in 2020, and in 2021, the Emmetsburg plant's owners shifted to producing hand sanitizer. Other cellulosic plants also went belly up within a few years. According to the Environmental Protection Agency (EPA), fewer than 1 million liters of cellulosic ethanol were produced in the United States last year.

The recipe for cellulosic ethanol seemed like a winner. Start with farm and forest waste that is so abundant it is essentially free, use microbial enzymes to convert it to sugars, let yeast ferment the sugar, and you've got a fuel you can sell. The climate case was equally compelling. Compared with fossil fuels, corn-derived ethanol reduces CO_2 emissions by 20% to 40%; ethanol made from waste biomass cuts emissions by 90%. For world leaders to have any shot of meeting their climate goals, such fuel is "just an absolute necessity," says Lee Lynd, an energy engineer at Dartmouth University. "In the future, the need for energy from biomass is greater than all the wind and solar combined."

PHOTO: UNITED AIRLINES

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expensive to truck to processing plants. The corn harvest only lasts about 1 month per year; stalks and other debris must be stored for the rest of the year to feed the biorefinery, further driving up costs. The biomass-degrading enzymes aren't cheap. And the spearlike corn stalks and other woody biomass often jammed machines designed to grind it up. "The chemical industry is built on handling liquids and gases," says Bruce Dale, a biofuels engineer at Michigan State University. "It's much harder with solids."

Chemist Derek Vardon is hoping to commercialize a process that converts food waste to aviation fuel.

Dale and others argue that companies, backed by grants from DOE, were too quick to try to scale up. Each step up in scale brings new challenges, such as getting farmers to agree to harvest crop wastes, rather than just crops. "The DOE declared victory way too soon" in trying to commercialize the technology, says Daniel Sperling, who directs the Institute of Transportation Studies at the University of California (UC), Davis. "As a result, R&D in the field just disappeared."

SAF BACKERS HOPE to prevent a repeat. In October 2021, President Joe Biden's administration outlined a Grand Challenge to produce 11.4 billion liters of SAFs annually by 2030 and enough to meet 100% of aviation fuel demand by 2050, projected to be about 160 billion liters. As part of that effort, BETO announced nearly $65 million for 22 projects to develop new biomass feedstocks and SAF technologies. Unlike cellulosic ethanol, which relied on a single basic recipe, the idea is to nurture multiple pathways, hoping some will succeed.

Some may not, SAF backers concede. "I am hopeful this technology will get over the finish line," says Daniel Sanchez, a bioenergy expert at UC Berkeley. "But what isn't clear is how many projects will fail first."

McAfee is betting Aemetis won't be among them. He's building a large chemical facility in the middle of Northern California's almond orchard country. Almond farmers typically replace their trees every 15 to 25 years. That creates more than 2 million tons of agricultural waste per year. Farmers used to burn it, but the practice is being phased out to improve the region's air quality. Aemetis has now contracted to buy much of that waste at $20 per ton and will use a high-temperature process called gasification to extract hydrogen from it. The waste CO_2 from the process will be captured and sequestered underground, McAfee says.

The company will use the hydrogen to chemically treat vegetable oils and animal fats. This "hydrotreatment" breaks the oil molecules—typically hydrocarbons with three or more branches—into chains with just a single branch. A second reaction, called hydroisomerization, then rearranges these chains into the mix of hydrocarbons that make up standard jet fuel, also known as Jet A.

Other routes to making SAFs are springing up as well. LanzaJet is converting municipal garbage, wood waste, and waste industrial gases to ethanol and then upgrading that to jet fuel. First water molecules are stripped from the ethanol, turning it into ethylene. Multiple ethylene molecules are then spliced together to make short hydrocarbons called olefins. Another reaction with hydrogen turns the olefins into an array of hydrocarbons, including kerosene, which is refined into fuel in a final step.

Colorado-based Gevo is converting corn stalks and other agricultural wastes to a different alcohol, isobutanol, which the company then chemically upgrades to aviation fuel. And Canada-based Enerkem is partnering with Shell to use heat and steam to convert municipal garbage and other feedstocks into syngas—a mix of hydrogen and CO_2 that it then purifies and converts into SAFs using a century-old process called Fischer-Tropsch technology.

All of these pathways have already been tested and approved for making jet fuel that can be blended into Jet A by the American Society for Testing and Materials, the standards agency responsible for aviation fuel blends. The variety of waste feedstocks they rely on is a strength, engineers say, allowing companies to take advantage of whatever local waste is cheapest.

The diversity of feedstocks should also help SAF producers meet the demand from airlines. According to Vardon, wet wastes, including food leftovers, could provide raw material for up to 15 billion liters of SAFs per year. Another 19 billion liters could come from treating fats, oils, and greases with hydrogen. And likely billions more from converting municipal garbage and farm waste to fuel. The market for aviation fuels is so large, "all technically and economically viable pathways to produce chemicals and fuels from waste carbon will be needed," Laurel Harmon, a chemist who is

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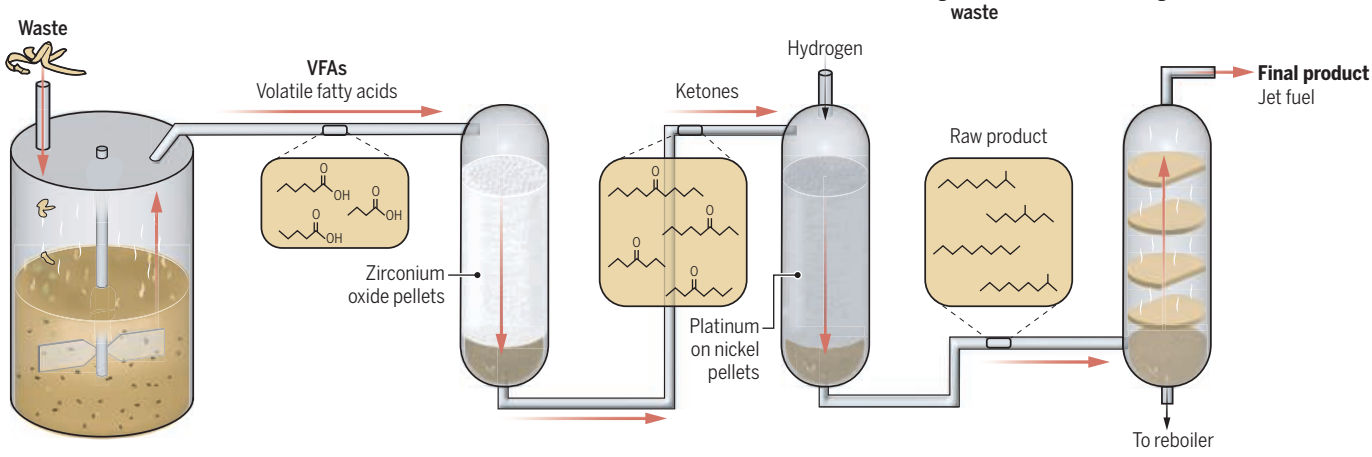
PHOTO: WERNER SLOCUM/NREL

From garbage to Jet A

Companies are turning waste carbon sources, such as food waste and municipal garbage (right) to jet fuel. Because this fuel is made from plants that remove carbon dioxide from the air, its climate impacts would be lower than that of conventional fuel. The graphic depicts one process, from Alder Fuels.



Fermentation and separation
Alder Fuels uses microbes to convert food waste to short hydrocarbons called VFAs.

Ketonization reactor
The fatty acids flow through zirconium oxide catalyst pellets, which knit VFAs into ketones.

HDO-ISO reactor
Ketones flow through catalyst pellets made from nickel coated with platinum, which link the ketones plus added hydrogen into larger hydrocarbons and strip off oxygen atoms.

Distillation
The hydrocarbons are then separated by their length and weight, with the lightest batch making up jet fuel.

LanzaTech's vice president of government relations, told a U.S. House of Representatives committee looking into SAFs.

The activity extends beyond industry to a consortium of nine U.S. national labs, which BETO has funded to come up with technologies that could aid many different SAF pathways. Among the projects: developing artificial intelligence to find combinations of enzymes and catalysts that break down waste at lower temperatures than existing versions and exploring whether converting municipal solid waste to tiny pellets will simplify processing steps.

Other ideas are emerging as well. Dale argues that having farmers and other feedstock collectors convert their biomass onsite to a form of "biocrude"—either granules, liquids, or gases—could allow the emerging SAF industry to use existing infrastructure. Trucks or pipes could carry that biocrude to regional biorefineries, or even conventional petroleum refineries, to be made into jet fuel, Dale says.

Still, SAFs are currently three times as expensive as petroleum-derived kerosene, according to the Intergovernmental Panel on Climate Change, and better technologies and economies of scale can bring down the price only so much. Zia Abdullah, NREL's biomass laboratory program manager, notes that converting solids into fuel simply requires a lot more handling and processing than making it from liquid petroleum. As a result, he says, "I don't think that it's possible to make SAFs completely cost competitive with fossil Jet A."

Airlines may be unwilling to accept the added expense of cleaner fuels, despite their climate pledges, given that fuel now accounts for about 30% of the cost of air travel. Still, the International Air Transport Association, which includes 290 airlines around the globe, has committed to adopting SAFs as part of their commitment to having the industry produce net zero carbon emissions by 2050. But to keep SAFs from withering and dying as the cellulosic ethanol plants did before them, governments may have to step in, says Lauren Riley, United's chief sustainability officer.

SOME MEASURES appear to be on the horizon. In July 2021, the European Commission proposed a rule that would require fuel suppliers to blend SAFs into their jet fuel, with the proportion rising from 2% in 2025 to 63% by 2050. A final vote on the proposal could come this year. But a coalition of more than a dozen aircraft manufacturers, airports, and fuel suppliers argues that mandates alone won't be enough and that government incentives will be needed for SAF makers to flourish.

The United States is already exploring incentives. California's 13-year-old Low Carbon Fuel Standard (LCFS) uses a credit trading scheme to effectively pay fuelmakers $150 for every ton of CO_2 emission they prevent, compared with a fossil fuel benchmark. (The amount emitted by benchmark fuels is then lowered annually, making the carbon reduction criteria more stringent over time. The LCFS is already giving a major boost to biofuel producers, Sanchez says. Because it gives higher incentives to diesel than aviation fuels, however, most alternative fuel producers have been making renewable diesel.

Changes could be coming nationwide. Last year, U.S. House members introduced two bills to support SAFs. One would grant fuel producers a $1.50 tax credit for each gallon of SAF blended into aviation fuel as long as it cut greenhouse gas emissions by at least 50% compared with fossil jet fuel; in October, Biden praised the bill. The other would authorize up to $1 billion to support SAF plant construction and require EPA to create a national LCFS-like program for aviation fuels. Related bills have advanced in the Senate. So far, however, these bills remain stalled in Congress.

Whether SAFs succeed is going to come down to a combination of chemistry, logistics, and governmental policy. At stake is not only investors' cash, but also the prospects of reconciling jet travel, critical in our interconnected world, with the need to prevent irreversible and catastrophic climate change.

Like many others, Spaeth remains optimistic. "It just feels different to me than it did 10 to 15 years ago with the cellulosic ethanol industry," he says. If he's right, in a few years, future flights may come with less baggage for the planet. ■

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Science

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Science, 376 (6600), • DOI: 10.1126/science.add5097

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