

Whatever happened to cellulosic ethanol?

Technological immaturity, falling oil prices, overoptimistic investors, and regulatory uncertainty are blamed for the failure of a promising biofuel technology to perform as hoped.

Despite a decade and a half of big US federal investments in R&D and in pilot and demonstration plants, ethanol from noncrop biomass has yet to become a commercial reality in the US. Nor has that happened anywhere else in the world but Brazil.

Whether the technology can recover from the missteps of the past 15 years is an open question, but it has become ever more certain that sustainable biofuels are key to achieving global carbon neutrality by midcentury, according to the scientific consensus reflected in reports by the Intergovernmental Panel on Climate Change (IPCC) and other organizations.

"In order for biofuels to take their needed place in a sustainable world, the next decade has to be vastly more successful than the last," says Lee Lynd, an engineering professor at Dartmouth College who cofounded a failed cellulosic-ethanol startup named Mascoma. "We have got to do things differently, or from a climate change point of view, biofuels will have largely missed their opportunity."

Today, the US is by far the largest producer of ethanol, accounting for roughly 55% of global output. Nearly all of it is made from corn. The US renewable fuel standard (RFS), enacted in a 2005 statute and expanded two years later, requires petroleum refiners to blend ethanol into each gallon of the gasoline they sell. The RFS spurred the rapid growth of the corn-ethanol industry. Yet since the RFS for corn ethanol is capped at 15 billion gallons per year, there is little incentive for further expansion of the business. Another limitation on growth is the so-called blend wall, the 10% limit on the ethanol content of gasoline fuels that automakers have set for all but the small fraction of US vehicles that are flex-fuel, capable of burning ethanol content up to

85%. Ethanol advocates say the blend for conventional light-duty vehicles could be increased to 15% without harming drivetrains.

Roughly 40% of the annual US corn crop now goes to ethanol. Converting pasture or other lands to grow corn or other crops would result in the sudden release of large amounts of CO₂ from soils. That so-called carbon debt could take decades to pay back through photosynthesis by crops. The debt payoff time is debated in the scientific literature, but most analyses have identified that corn ethanol's life-cycle carbon intensity, including both CO₂ emissions and those associated with growing, is considerably lower than that of gasoline.

But John DeCicco, emeritus professor at the University of Michigan's Energy Institute, notes that the values that are assigned to land-use change in different models are arbitrary, and some studies have established a lower carbon-intensity value for gasoline.

The case for cellulosic

Cellulosic, or nonstarch, biomass—crop residues, wood waste, grasses, and other plant matter—has long been seen as a more sustainable raw material for ethanol production. Much of the biomass could come from lands unsuitable for agriculture, thus minimizing land-use impacts. Theoretically, cellulosic ethanol offers a much larger reduction in carbon intensity than corn ethanol—as much as 80% below gasoline's, depending on variables such as the feedstock used and the processing method, according to Argonne National Laboratory's Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies full-life-cycle emissions model. The GREET model calculates corn ethanol's carbon

intensity to be 44% below gasoline's.

In a series of 2016 studies collectively known as the "billion-ton report," the Department of Energy estimated that 500 million tons of nonstarch biomass could be harvested or collected annually in the US without adversely affecting ecosystems. DeCicco is skeptical of the finding, which he says is based on a lot of favorable assumptions. If cellulosic ethanol had actually taken off, he argues, it would have unleashed a wave of land-use conversions as large agribusinesses moved into the business of cultivating energy crops. "If they have an incentive to harvest biomass from switchgrass, miscanthus, or rapidly growing trees like aspens, they will seek to do that on the best land they can obtain."

The lignocellulose that composes the leaves and stalks of plants is considerably more difficult to break down to alcohol than the readily fermentable starch in corn; it requires specialized enzymes or thermochemical technologies. The 2007 RFS included a specific mandate for cellulosic ethanol, reaching 16 billion gallons by 2022. But lawmakers vastly overestimated the readiness of cellulosic





RAÍZEN'S PLANT in Piracicaba, Brazil, is the world's only commercial producer of cellulosic ethanol. Here, crushed sugarcane residue called bagasse is being loaded into the processing plant. Raízen plans to build 20 such plants by 2030.

technology, even as government and private money poured into R&D. The Environmental Protection Agency, which administers the RFS program, established a 2022 requirement for 630 million gallons of cellulosic biofuels.

DOE in 2007 established three bioenergy research centers at its national labs. A fourth center, headed by the University of Illinois at Urbana-Champaign, was added in 2017. In 2007, BP pledged \$500 million over 10 years to fund an Energy Biosciences Institute, headquartered at the University of California, Berkeley. Chris Somerville, the institute's former director, says interest in biofuels fell in concert with plunging oil prices in 2014. "The bottom line is that to disrupt a cheap commodity business one needs to pay attention to all the sources of value. And to do that requires quite a lot of technical knowledge and know-how," he says. Large integrated oil companies such as BP could accomplish that, but "it will remain very challenging for

startups to assemble the funds and technical abilities to do it."

DuPont, Poet-DSM, and Abengoa built commercial-scale cellulosic-ethanol plants in the mid 2010s with DOE cost-shared funding and loan guarantees. None remain in operation. One was mothballed, and two were sold and converted to produce biogas. As domestic production failed to materialize, the EPA has had little choice but to annually waive the cellulosic RFS requirement.

"DOE, who was sponsoring projects, was pushing very hard for them to be big," says Dartmouth's Lynd. "Technology providers had a very strong interest in saying, 'Look, the future is here, and we're ready to go today.'"

In the case of startups such as Mascoma, venture capitalists must share blame, Lynd says, for "inflating expectations way beyond the probable." During one meeting with investors, he recalls, "I stood up and said that what we're doing is not that different and not that good.

Their response was, 'It doesn't have to be different or good—it just has to be first.' And the assumption was that the world would remain really excited about biofuels, and by God it was going to happen somewhere, and you just had to get there. But the world didn't remain that enthusiastic about biofuels."

The cellulosic-ethanol field, he says, "got overheated because each of the parties—the sponsors, technology providers, and investors—were all saying, 'Let's go big or go home,' and we ended up going home."

Bruce Dale, a chemical engineer at Michigan State University, says the challenges of gathering and processing the cellulosic feedstocks were seriously underestimated. "You have to have a guaranteed supply chain set up, know what kind of cellulosic material you're going to use, and know how much you're going to pay for it. In the US, we had sort of a technology, but no supply chain set up. There was no way to get large amounts of biomass delivered at defined qualities to the biorefinery."

Cellulosic material is inherently combustible, difficult to gather, and uneconomical to transport over distances greater than 80 kilometers, Dale says. It's also contaminated with rocks, soil, and other extraneous matter that tends to clog up machinery at the refinery. Fires in storage facilities were a regular occurrence.

Brian Davison, chief science officer at the Center for Bioenergy Innovation at Oak Ridge National Laboratory, says regulatory uncertainty also helped doom the commercial ventures. Poet-DSM blamed the instability of the RFS and other low-carbon credits such as California's Low Carbon Fuel Standard for the mothballing of its plant. "There was a year when the actual final value of the RFS wasn't announced until 18 months after the year began," he says. "It generally came in at a decent value, but the uncertainty was problematic. And the RFS would typically come up for a vote in Congress every year or two."

A success story

Brazil, with 27% of the global ethanol output, is the world's second-largest producer. There, sugarcane is the raw material; roughly half of Brazil's annual sugarcane crop is converted to ethanol each year. Vehicles in Brazil run either on a 25% ethanol mix or pure ethanol fuel. Raízen,

a joint venture of Shell and Cosan, a Brazilian conglomerate, operates 26 plants producing sugar, ethanol, and biogas, and manufactured approximately 2.5 billion liters of ethanol and 3.8 million tons of sugar in the 2019–20 crop year. It began making cellulosic ethanol commercially in 2014, using sugarcane straw and bagasse, the pulp that remains once the juice is squeezed from the cane.

Mateus Schreiner Garcez Lopes, Raízen's global director for energy transition and investments, says that the plant uses technology licensed from Canada's Iogen and, after overcoming some challenges, has achieved production targets for the last three years. The company expects to open its second cellulosic facility next year, and it has committed to build a total of 20 such plants by 2030. Raízen recently completed an initial public offering to help finance its cellulosic expansion. "At this point, our bottleneck is the ability to build new plants," Garcez Lopes says.

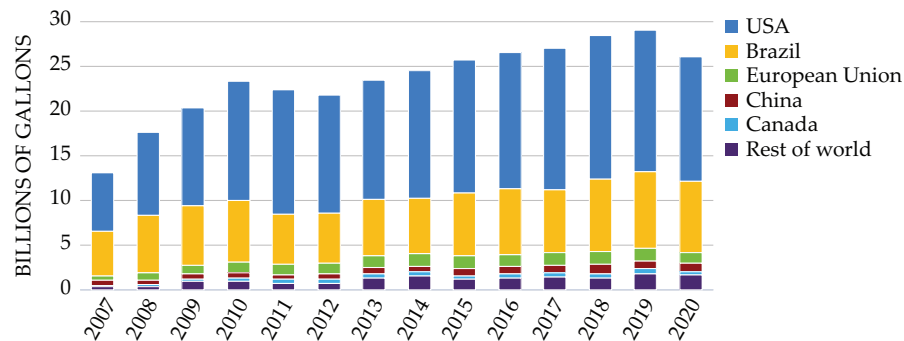
Raízen has an inherent advantage over US cellulosic-ethanol aspirants: Brazil's method of harvest brings the cellulosic feedstock together with the cane to the sugar mill. In the US, only the corn kernel is harvested; the remainder of the plant, known as stover, is left behind. Gathering and baling stover or other crop residues from the farm requires a separate harvest.

Lynd says the lower cost and pre-established supply chain for bagasse more than trumps the easier convertibility of corn stover. "And if you succeed at one plant in the US, you've still got to line up your feedstock for a second plant. In Brazil, if you succeed at one plant, there's 100 other plants you could do this at."

Raízen's entire output of cellulosic ethanol is exported to the US and Europe, where it fetches higher prices due to various RFS incentives. Though it's currently more costly to produce than conventional ethanol, Garcez Lopes says he expects that differential will disappear.

A bright future?

Some people have a perception that more ethanol won't be needed as electric vehicles become predominant, says Lynd. But that argument ignores the one-half of energy use in the transportation sector that can't be easily electrified: in aviation, heavy-duty trucks, and maritime shipping. "If you look at IPCC and [Inter-



GLOBAL ETHANOL PRODUCTION. (Courtesy of the US Department of Energy, based on Renewable Fuels Association data.)

national Energy Agency] reports, biofuels are still a significant fraction, 10–20%, of the energy we need for 2050," says Davison. In fact, the median scenario of all 85 possible pathways considered by the IPCC to hold the global temperature increase to 1.5 °C above preindustrial levels by 2050 foresees a bigger role for biofuels than for wind and solar energy combined.

Ethanol can't be used directly for aviation fuel; more complex hydrocarbons are required. But ethanol can be an intermediate step for catalytic conversion to renewable aviation fuels. At least two US companies, LanzaTech and Vertimass, are nearing commercialization of sustainable aviation fuels derived from ethanol. LanzaTech licensed a process developed at Pacific Northwest National Laboratory; Vertimass licensed its technology from Oak Ridge National Laboratory, where it was codeveloped by Davison.

Other so-called drop-in fuels, such as renewable fuel oil for ships, and hydrogen production are potential growth areas for ethanol, says Garcez Lopes. The need is vast: Demand for aviation fuels will reach 400 million tons in 2030, he says, requiring five times the current global ethanol production.

"We are still very much interested in lignocellulosic conversion into biofuels," says a DOE official who declined to be identified. "The industry will take off in the very near future." There aren't many other good options for decarbonizing aviation fuel and other economic sectors that can't be electrified, he says.

Aviation fuels have been the focus of recent requests for proposals from DOE's Energy Efficiency and Renewable Energy office. On 1 June, DOE announced a \$59 million solicitation for biorefinery and feedstock-development projects in support of sustainable avia-

tion, diesel, marine, and rail fuels.

Lynd predicts that carbon dioxide removal will soon become the biggest driver of cellulosic ethanol and other biofuels. Photosynthesis in one form or another is the best way to remove CO₂ from the air, he says, and "the potential for biofuels in this capacity has been radically underestimated."

In biofuels that are produced efficiently, Lynd explains, 50–70% of the carbon content of the raw material is released and available for capture at the production site. Yet 40–70% of the feedstock's energy content remains in the fuel that's delivered to a vehicle. He cites a friend telling him that "biofuels are the only way we've figured out to have negative emissions and something other than negative-emissions [credits] to sell."

Dale is less optimistic about cellulosic biofuel's future. Biomass, he notes, can also readily produce methane. The existing natural-gas infrastructure and markets mean that incentivizing farmers to produce methane through anaerobic digestion of manure will be easier than motivating them to gather up crop stubble. While cellulosic ethanol wallows, biogas is already thriving, he says. "California is buying all it can get."

Dale, whose research currently focuses on sustainable agriculture, says US farmers could follow the example of counterparts in Italy who grow cover crops such as grasses after harvesting their grain or soybeans. In the spring, they harvest the grass, compress it, and allow it to ferment, producing biogas they burn to generate electricity. But in the US, he laments, "people are interested in these ideas, cover crops and so forth, but they don't think about harvesting them to make something farmers could sell."

David Kramer