gevo®
FUELING THE FUTURE

THE CIRCULAR ECONOMY

Look at the whole picture, and the future can be powered with a sustainable system with fuels that use atmospheric carbon while employing natural systems that sequester carbon, add protein to the food supply, and improve the soil.
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303-858-8358

info@gevo.com

www.gevo.com

THE CIRCULAR ECONOMY

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Introduction

The entire premise of using renewable hydrocarbon fuels to reduce greenhouse gas (GHG) emissions is derived from the idea of using resources that are already engaged in the carbon cycle, rather than adding fossil-based carbon to the the cycle. Hydrocarbons are outstanding energy carriers, which is why they work so well in engines for transportation. When we refer to hydrocarbons, we're using a generic term for a chain of carbon atoms bonded to one another, with each carbon also bonded to hydrogen atoms. When hydrocarbons are burned they release a large amount of energy, and result in carbon dioxide being released to the atmosphere. The energy is not the problem, it's where we source the carbon that is. Carbon that is sequestered in the ground is not the problem, but when it is extracted as coal, petroleum, or natural gas, and then burned and released in the atmosphere, that's when that carbon threatens to knock the atmosphere out of balance. When fossil hydrocarbons—think fossil-based petroleum products like jet fuel, gasoline, and diesel fuel—are burned, they release carbon in the form of carbon dioxide into the atmosphere. That carbon dioxide would not have been released from its fossil entombment but for burning it as fuel.

Imagine we have a huge savings account in the bank—that's the carbon in the ground, oil and gas and coal reserves. But the good news is we also have a big wad of cash in our wallet, enough to cover any expense we could think of.

Renewable hydrocarbons are hydrocarbons made from the carbon dioxide in the atmosphere and as such, in essence, are recycling carbon in the atmosphere. Carbon dioxide in the atmosphere, because it is part of the carbon cycle, in the lingo of our industry, is called renewable carbon.

Think about carbon like it is money and it becomes easier to understand. Imagine we have a huge savings account in the bank—that's the carbon in the ground, oil and gas and coal reserves. But the good news is we also have a big wad of cash in our wallet, enough to cover any expense we could think of. Why would we go to the bank to make a huge withdrawal when we can pay in cash?

That's exactly what the world has done by using fossil fuels rather than drawing on the carbon already in circulation in the atmosphere. As a result, nature's system for pulling carbon out of the atmosphere can't keep up with our GHG emissions. Too much carbon in the atmosphere is widely believed to result in climate change, pushing the systems that sustain our world's ecology out of balance. Up to this point in our human history, we did not have the technology available to make drop-in hydrocarbon fuels from renewable carbon. Now that's changed with the advent of technologies that companies like us (and a select few others) are bringing to market.

In other words, technology has finally caught up and Gevo has been on the vanguard of evolving renewable fuel technology. These advanced fuels have enough energy to power cars, trucks, boats, and airplanes. They meet or exceed the standards set and upheld for petroleum-based fuels (standards written with petroleum-based fuels in mind), and if they meet those standards, they can be freely mixed and blended with those fuels with no impact on performance.

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Now we have the technology to reverse the cycle, and begin to turn back the clock to the days before the world was powered by fossil fuels. We need to use the carbon already in circulation, in combination with the world's existing system, to help our world keep functioning and, at the same time, begin to heal itself.

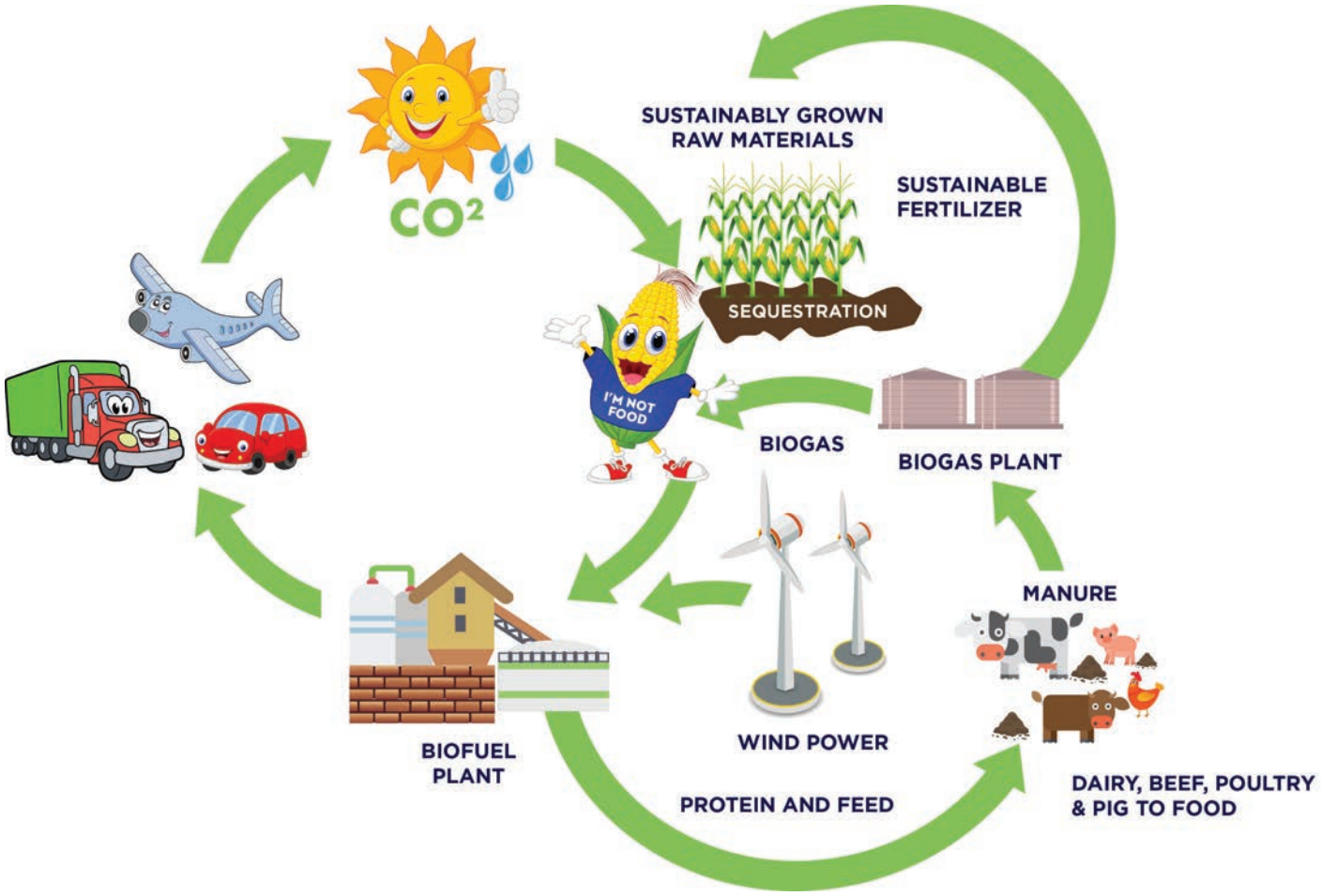
The Circular Economy

PART 1: DOWN ON THE FARM

The process begins in America's Heartland, where No. 2 dent corn is raised in huge quantities by farmers who have been stewards of the land for generations. These farmers know their plots, and they understand how to get more corn out of each acre. Their land is their future. It is their asset to make money. Anyone thinks a farmer doesn't care about his or her land is simply out to lunch.

As far as the corn goes, people do not eat this corn—it's inedible to humans and is not sold in grocery stores. There's a different kind of corn that can be eaten directly. The variety of corn in our area of the Midwest is grown primarily for its nutrional protein content, i.e., animal feed. About one third of each bushel of corn is protein, with two-thirds being carbohydrate. Animals use the corn protein to meet their nutritional need. The animals that eat this corn are living machines that convert the protein in each kernel into meat. Those animals play a critical role in the circular economy as well, both economically and nutritionally. We've all heard about cows and their emissions. It turns our that when cows eat too much corn, the carbohydrate portion of the corn gets converted to gas, and they burp. If the carbohydrate is removed, then they burp less. At our production plant in Luverne, Minnesota, we remove the carbohydrates from the corn, leaving the nutritious protein for feed. Better for the cows, and we need the carbohydrates as the feedstock for fuel production—more on this later.

Farming uses technology, and it has been advancing substantially. In agriculture, science and technology are key to improving the yield of each acre of farmland. Farmers use satellite imagery to target problem areas in fields where insects, drainage problems,



and other factors have a negative impact. They program their tractors and harvesters with GPS-controlled precision. Farmers have a deep understanding of the fields they work, and they know the soil is their key resource to make each year a success. That soil is made up of a combination of mineral and organic matter, and farmers don't just take away from the fields, they must replenish to keep producing year after year.

How do they do that? Well for one thing they use what's known as strip-tilling or zone-tilling, which only tills a four-inch-wide strip of soil, planting the seeds in rows and fertilizing directly in the strip where it can do the most good. This process keeps the soil in place. Even better, the farmers till these strips between the rows of last year's corn, leaving the root structure of the previous year's crop to decay and become that organic matter in the soil. Remember your middle-school science classes that said matter cannot be destroyed? The same is true here, the nutrients still contained in the root and stalk of the corn left in the field after harvest get into that soil and stay there, building that healthy soil that will help next year's plants grow better, and need less fertilizer to do it. It happens every year.

Best of all, that organic matter that goes into the dirt also contains carbon that is being sequestered in the soil. As Gevo makes sustainable aviation fuel, it captures anywhere from 0.8 to 4 kilograms of carbon dioxide in the soil for every gallon of jet fuel produced. Increasing carbon in the soil offsets the impact of fossil fuels, but also increases feed and food production for a growing global population. The use of this natural storehouse could allow us to sequester an additional 1 billion to 3 billion tons of carbon annually. That's equivalent to roughly 3.5 billion to 11 billion tons of carbon dioxide emissions. Most of the biomass used to produce Gevo's advanced fuels comes from sources that use farming techniques that build soil organic carbon.

PART 2: FERMENTING FUEL AND FEEDING LIVESTOCK

Gevo takes that corn and brings it to its converted ethanol plant in Luverne, Minnesota. That plant has been fitted out with the equipment to make next-generation fuels. Instead of just fermenting the corn to make ethanol—a two-carbon alcohol that can still be produced there—Gevo also makes isobutanol as an intermediate, a building block to create isooctane and sustainable aviation fuel.

As with any alcohol fermentation, isobutanol has a stress effect on yeast as the fermentation proceeds and the concentration increases. Unlike ethanol, isobutanol is much more stressful on the fermentation organism, which typically would result in a reduced fermentation rate and/or reduced batch size. Gevo has solved this issue by using its GIFT® process (Gevo Integrated

Fermentation Technology) for continuously removing the product during fermentation.

The GIFT process maintains the isobutanol concentration in the fermenter at target levels to optimize process rates and cost by removing isobutanol continuously during fermentation, despite the fact that isobutanol's boiling point is eight degrees celsius higher than water. Isobutanol-water is azeotropic, meaning the vapor has the same composition as the liquid. The fermentation broth is circulated through the GIFT process where it is subject to low-pressure evaporation. Isobutanol flashes off the broth, resulting in a vapor concentration nearly twenty times greater than what was in the fermenter. When the vapor is condensed, the concentration of isobutanol is now above its solubility limit in water and phase separation occurs, leaving a relatively pure isobutanol-rich phase and a water-rich phase. The isobutanol-rich phase is sent to a purification step and the water-rich phase goes to a stripping distillation step where residual isobutanol is removed and the water returned to the fermenter. All of the biomass and yeast remain in the fer-

menter-GIFT system and production occurs until all of the carbohydrates are eaten by the yeast.

A Word About Sustainability

Gevo's process to manufacture isobutanol and ethanol is more energy-efficient than other biofuel-production methods, but it still takes energy, meaning electricity and energy sources for heat in the production process. This adds to the carbon footprint of Gevo products. The smaller the fossil footprint, the better. We want to keep the fossil footprint out of our business system as much as we practically can. All of this is a key aspect of the Circular Economy—economizing that currency of carbon to keep it out of circulation and in the bank.

The LCA is widely considered to be the best yardstick of true carbon intensity in fuels and chemicals produced to replace fossil fuels, because this metric takes into account the full range of carbon emissions and sequestration from all steps of the process.

It doesn't do any good to invest in the research and science of taking the fossil fuels out of isobutanol, isooctane, and aviation fuel if the facility has to draw electricity off the coal-burning electrical grid to run our processes. To reduce that factor, Gevo has secured a partnership with wind turbine company Juhl Energy to provide renewable electricity through wind power at the Luverne, Minnesota, facility. Juhl sells power to Missouri River Energy Services (MRES), which is the area utility that supplies Luverne. Gevo buys the power from Luverne, but the actual electricity comes directly to the plant, and Gevo buys the renewable energy credits from Juhl directly. The transmission wire from the wind turbines goes directly to the plant, so it meets all the requirements for counting toward sustainability.

By taking carbon out of every step of the process, Gevo reduces the carbon footprint of every gallon of advanced fuel it produces. It passes the carbon savings along to every consumer as everyone does their part to reduce GHG emissions.

PART 3: POWER TO THE PEOPLE

The fuels produced by Gevo go to the market and power the world. Each gallon of next-generation fuel that enters the market replaces a gallon of fossil fuel that would otherwise be burned in a jet, or city bus, or car, or boat, or lawnmower.

Isobutanol is the building block for other fuels that we produce and market, but it's a product in its own right, born of our synthetic biology to create a yeast that manufactures it in our proprietary fermentation methods. Isobutanol is a blendstock oxygenate for gasoline and works well in marine and small engines.

Sustainable Aviation Fuel (SAF): While there are five different pathways to creating renewable jet fuel, Gevo uses the Alcohol-to-Jet synthesized paraffinic kerosene or ATJ-SPK method to create the necessary 12-carbon chain from its isobutanol.

Isooctane: This gasoline replacement is already in use in Formula 1 racing in Europe and for packaged fuels. Gevo uses its isobutanol as a base to create the eight-carbon chain found in the fuel cells of the fastest racecars.

Renewable Gasoline: Gasoline blended from isooctane made from corn or other renewable feedstocks, and blended with isobutanol or other renewable oxygenate will have low carbon intensity and a reduced carbon footprint. Gevo already makes the components, and as costs fall, this may be the fuel of the future for personal transportation.

Renewable Diesel: Diesel drives much of the freight hauling and human transportation around the world, and to have a renewable replacement would reduce a large part of the world's transportation carbon footprint and attendant GHG emissions. Gevo has developed a way to make biodiesel from isobutanol and fusel oils, natural waste byproducts of the fermentation process.

Ethanol: It's the original fermented fuel blendstock, made from corn and lignocellulosic feedstock.

Life-Cycle Assessment

GHG emissions for biofuels are most commonly evaluated through a life-cycle assessment, which calculates the amount of greenhouse gases that are released per unit of fuel, including emissions and carbon sequestration. Emissions reductions are higher for advanced biofuels. (Environmental Energy and Study Institute, "Biofuels Vs. Gasoline: The Emissions Gap Is Widening," September 2016). Gevo's product line focuses on decarbonization of the process to give each of its biofuels, chemicals, and co-products the lowest carbon life-cycle assessment (LCA) possible. The LCA is widely considered to be the best yardstick of true carbon intensity in fuels and chemicals produced to replace fossil fuels, because this metric takes into account the full range of carbon emissions and sequestration from all steps of the process.

Using advanced bio-based fuels releases carbon into the atmosphere. That's a fact of using internal combustion engines to burn hydrocarbon fuels to create power. But the carbon that's released into the atmosphere is coming from the carbon-stuffed

wallet, not from that bank account of fossil-fuel carbon. And every gallon of Gevo advanced fuel coming from sustainably grown corn sequesters more carbon in the soil, putting it in the bank.

The carbon dioxide that's released as GHG emissions is consumed by the corn fields as millions and millions of corn stocks grow from seed to more than six feet tall, storing energy in stalk and root, leaves, and most importantly, corn. And they draw more carbon from the atmosphere as new seed is planted each spring and stalks grow to maturity each year.

A Word About Tracking Sustainability

While it's great to beat the drum of sustainability, it must be tracked and certified to be an effective way to combat GHG emissions. Distributed Ledger Technology, or DLT, is an immutable tool that allows tracking of data with a product and the transactions associated with the product. Originally developed as an underlying branch of blockchain technology, DLT will let Gevo attach the key metrics for sustainability to each gallon of fuel, and therefore enable a "sustainability" assurance that has not yet been seen. The data associated with certain key metrics for measuring sustainability are suitable for being digitized through blockchain, and could lead to tokenization of those attributes. DLT will enable Gevo to sort out what is truly valuable in the end market, assign the correct value to it, and then set up market mechanisms to share value upstream in the value chain. Eventually, this will help create a system that rewards the value chain for improving sustainability.

PART 4: FUEL AND FOOD AND MORE FUEL

Biofuel production at Gevo does not use the entire kernel of inedible corn that is the primary feedstock for our isobutanol plant. The process uses the starch, and that leaves Gevo with plenty of protein from the corn. The protein the company captures—and there is a lot of it—is turned into animal feed, to the tune of about 10 pounds (around 5 kilograms) per gallon of isobutanol produced. On a tonnage basis, Gevo produces more animal feed than fuel at the Luverne, Minnesota, plant.

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Protein is critical to the food supply, and meat is cited by studies as the source for 18 percent of the world's protein consumption, and meat consumption has grown by 60 percent between 1990 and 2009 (Henchion M., McCarthy M., Resconi V.C., Troy D., "Meat Consumption: Trends and Quality Matters," Meat Sci. November 2014).

Animal feed is more than just a byproduct of biofuel production at Gevo, it's a co-product that is something else to sell. Because this feed creates an additional revenue stream for the company, it helps to offset the cost of producing isobutanol.

Farmers who keep livestock as a complement to growing corn have a natural source of inexpensive fertilizer from manure that keeps the nutrients from the corn on the farm, without trucking in synthetic fertilizers.

High-protein animal feed is considered to be better for livestock and some results in healthier livestock that produce better meat. Gevo's goal of reducing GHG emissions means there are additional benefits. First, Gevo sells its animal feed to farmers in the area around the Luverne, Minnesota, facility, so the feed is not trucked over long distances.

High-protein animal feed reduces methane emissions from livestock. Methane is a greenhouse gas that is widely understood to retain atmospheric heat more effectively than carbon dioxide.

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The manure also can be placed in digesters that use natural yeasts to break down the manure, releasing methane which can then be captured and used for energy as renewable natural gas—called biogas. Gevo is planning to install these digesters at area farms and use the biogas to offset even more of the energy use at the plant, making the most of this renewable resource.

Conclusion

The Circular Economy follows the path of carbon atoms that are released from advanced, bio-based fuel into the atmosphere. As they are consumed by the biomass of a cornfield that yields corn to be used in making advanced fuels, these carbon atoms go back through the process and get used again and again. The benefits of taking this carbon from renewable sources keep the fossil carbon in the ground, where it belongs, while sequestering even more carbon in the soil. Once the carbon levels in the atmosphere begin to return to sustainable levels, the Earth's temperatures will normalize as GHGs regulate the temperature properly. When the carbon level in the atmosphere drops, oceans will begin to cool and reverse their carbon absorption, which is thought by many to cause acidification. The cycles that have preserved life on Earth for millions of years will again be in balance.

The Circular Economy is properly named because it is the economic forces of human existence that drive it. Gevo uses the power of economics to drive the use of sustainable fuels. The production of isobutanol can be directed to a variety of fuel types, to meet market demand. High-protein animal feed can be sold to offset the costs of production. And farmers who work with Gevo benefit from their farm research to derive best practices that result in improved yield.

As economic factors from climate change and population growth add to the equation, sustainability will become even more economically feasible and desirable. And Gevo will be on the leading edge.