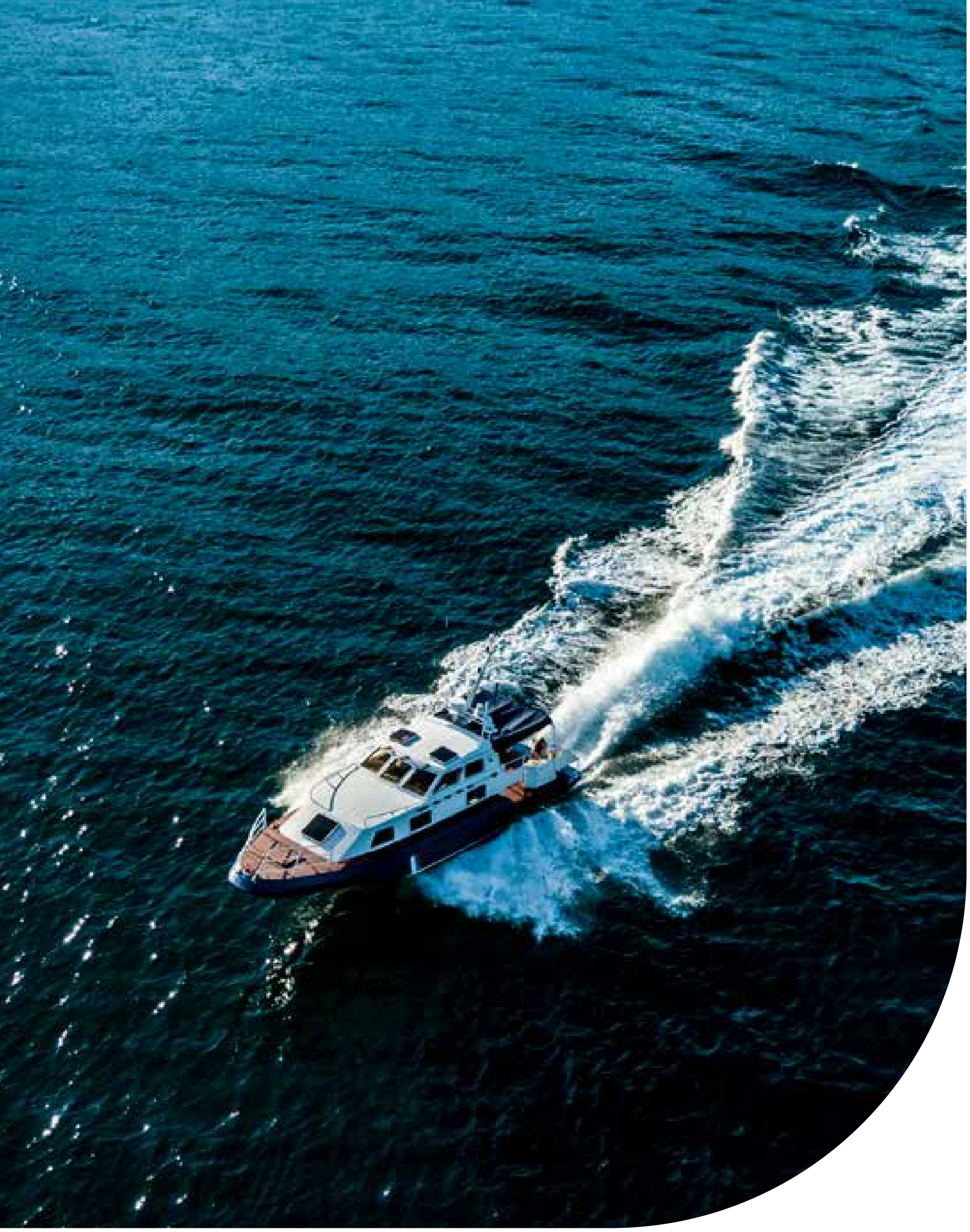

AN OVERVIEW OF GEVO'S BIOBASED ISOBUTANOL PRODUCTION PROCESS

Gevo ferments residual starches and sugars to make Isobutanol, a useful building block to make energy-dense liquid hydrocarbons and renewable chemicals, and our process is a scalable, adaptive pathway to a variety of markets.

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ISOBUTANOL PRODUCTION PROCESS

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Introduction

As the ethanol industry evolves, more production plants are seeking ways to add additional products to their production capability and are exploring ways to increase margin at their site. After all, ethanol producers are inextricably linked to a single product—gasoline. So if demand falters due to travel restrictions or climbing prices, their business suffers.

At Gevo, we have learned valuable lessons from seeing how a product with a single market can put an entire business model in danger. Instead we have devised a pathway to create isobutanol, a product that is, by its very nature, able to adapt to the whims of the marketplace. Using advances in synthetic biology and industrial chemistry to develop our proprietary GIFT® (Gevo Integrated Fermentation Technology) Process, Gevo has introduced a scalable method to produce isobutanol, a four-carbon alcohol that can serve as a building block to create a range of renewable fuels and chemicals, including renewable premium gasoline, sustainable aviation fuel, and renewable diesel. These are drop-in liquid hydrocarbons that are built from the ground up using isobutanol. Our renewable fuels work in today's engines with no modification, and can be added—and blended with petroleum-based fuels, as needed—into the established fuel-delivery infrastructure, whether it's pipelines, pumps, or storage tanks. Our fuels act just like their fossil-based analogs because they are those fuels, on a molecular level. Our sustainable aviation fuel is aviation fuel. Our renewable premium gasoline is gasoline. On their own, our fuels eliminate many of the 4,000 or so chemicals that fossil-based fuels release when burned. Many of these chemicals are considered very undesirable to release into the atmosphere, and several are considered carcinogenic or otherwise detrimental to human health.

With attention to true sustainability, Gevo developed its process with the idea of making the most of every acre of farmland, using the corn's protein to produce high-protein animal feed, and using the residual starch from the same kernels, to yield another product from the residual starch, isobutanol. And there's the real difference—the carbon in our fuels comes from corn, which uses the sun's energy to draw carbon dioxide out of the atmosphere.

Background

Proprietary Technology

Gevo has developed technology for producing isobutanol from renewable feedstocks. This is accomplished using two pieces of proprietary technology: a yeast that has been developed to produce isobutanol and a product-recovery technology that continuously removes isobutanol as it is formed. Gevo's proprietary yeast has been developed using the world's latest biotechnology tools to achieve commercially attractive yields and rates. Moreover, the yeast is safe for use

PRODUCTION OF BIOBASED ISOBUTANOL IN THE LUVERNE, MINNESOTA, FACILITY YIELDS ACCESS TO MARKETS FOR SPECIALTY GASOLINE BLENDSTOCK AND SPECIALTY CHEMICALS AND SOLVENTS, WHILE ISOBUTANOL BROUGHT TO THE SILSBEE, TEXAS, BIOREFINERY PRODUCES SUSTAINABLE AVIATION FUEL AND ISOOCTANE.

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in animal feed, which is a key product Gevo produces and a source of revenue.

Isobutanol is a colorless liquid with a sweet odor that is found naturally in fruits and in commercial ethanol fermentations and in distilled spirits like whiskey. In contrast to ethanol, isobutanol has low water solubility and properties more like a hydrocarbon due to its chemical structure.

Markets

Isobutanol is commercially attractive because of the numbers of chemicals and fuels markets it can serve and the value it has in those applications. The traditional market for isobutanol is solvents, coatings, and chemical intermediates.

Isobutanol can also be chemically converted, using conventional, commercial-unit operations, in the production of isobutylene which is a building block for isooctane, jet fuel, plastics, rubber, lubricants, and other hydrocarbons already in use in the petrochemical industry. The introduction of biobased products made from renewable raw materials is of increasing importance to companies looking to reduce their dependence on petroleum and to improve the sustainability of their chemical business system. This approach provides for a true drop-in product rather than having all downstream processes and industries change their assets and business models to adapt to a new molecule.

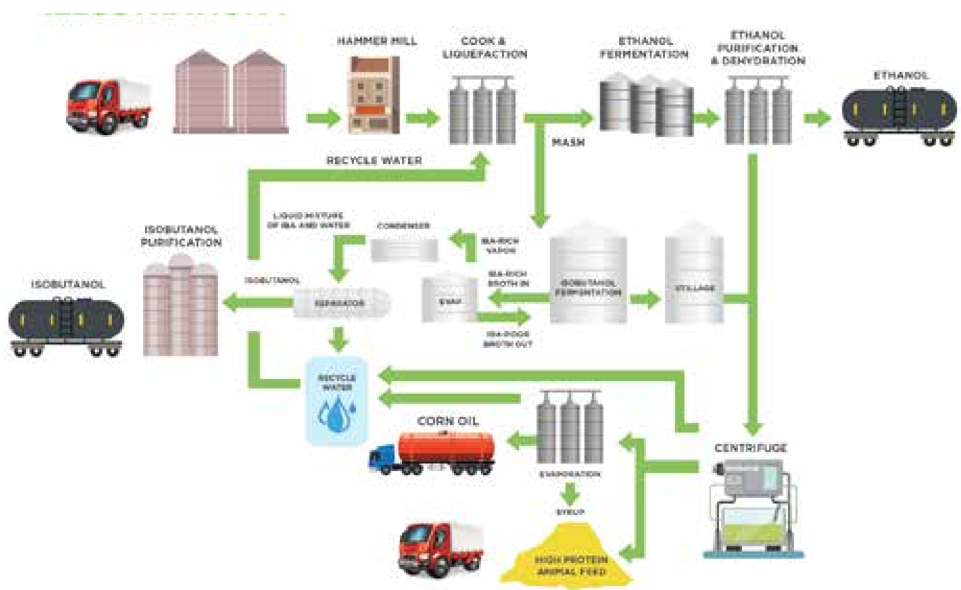
At South Hampton Resources, a company with a site in Silsbee, Texas, Gevo converts isobutanol to isobutylene to isooctane, isooctene, and jet fuel (isoparaffinic kerosene). Gevo has been producing and selling alcohol-to-jet fuel (ATJ) derived from isobutanol since 2011 where the fuel was used in certification tests, including test flights with the U.S. Air Force, U.S. Army, and U.S. Navy. Since receiving its ASTM certification in 2016, Gevo's ATJ fuel has been used in commercial flights around the world. Gevo is working toward commercializing this ATJ production process. Isooctane made from renewable isobutanol at this same site has been sold into specialty fuels applications including supplying Total with isooctane that they used to formulate Formula One racing fuels.

The Production Process

The isobutanol production process begins with biomass containing any fermentable sugars. At an existing dry-mill corn ethanol plant, the corn mash stream coming out of the front end of the process that feeds the ethanol fermentation is the same stream used for isobutanol fermentation. This stream is prepared for isobutanol fermentation, added to large non-sterile fermentation tanks (approximately 1 million liters at our Agri-Energy site) and Gevo's proprietary yeast is added to convert the sugars to isobutanol. As with any alcohol fermentation, isobutanol has a stress effect on yeast as the fermentation proceeds and the isobutanol concentration increases. Unlike ethanol, butanol is much more stressful on the fermentation organism, which typically would result in reduced fermentation rate and/or reduced batch size, however, Gevo has solved for this issue by using its GIFT® (Gevo Integrated Fermenta-

Our approach provides for a true drop-in product rather than having all downstream processes and industries change their assets and business models to adapt to a new molecule.

THIS PROCESS SCHEMATIC DEPICTS THE ISOBUTANOL-ETHANOL SIDE-BY-SIDE DRY-MILL PROCESS.



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tion Technology) process for continuously removing the product during fermentation.

Despite the fact that isobutanol's boiling point is 8°C higher than water, the GIFT process is able to remove isobutanol continuously during fermentation to maintain its concentration in the fermenter at target levels to optimize process rates and cost. This is accomplished by taking advantage of the azeotropic properties of isobutanol-water. The fermentation broth is circulated through the GIFT process where it is subject to low-pressure evaporation and isobutanol flashes off the broth, resulting in a vapor concentration nearly 20X 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 remains in the fermenter-GIFT system thereby greatly simplifying purification of the isobutanol.

Food Before Fuel: High-Protein Animal Feed

In a typical ethanol plant, all of the isobutanol-water recycle operations and animal-feed operations can be shared with the ethanol side of the process thereby minimizing capital for adding isobutanol capability. The spent fermentation broth from isobutanol production can be combined with spent broth from ethanol production to send the two streams through one set of decanters already in use in an ethanol process. The solids, which contain all the nutrients originally in the corn plus additional protein, can be processed through an existing animal feed dryer while the liquids are processed through a shared evaporation process. The evaporation process yields a high-protein syrup, which is added to the animal feed, and an overhead stream of water for recycle in the plant.

Many growers are using more advanced means of farming, which can lead to higher yields and lower inputs than conventional practices.

The high-protein animal feed product, being sold commercially, is an important product out of the biorefinery. For each gallon of isobutanol produced, the process yields approximately 9 pounds of high-protein animal feed. That's 20 percent more protein than comes into the process with corn feedstock. That's because protein is grown during the fermentation process. All of the nutrients in the corn end up in the high-protein animal feed.

The Feedstock

The feedstock is #2 yellow dent corn which represents about 99% of corn grown in the U.S. and is currently used for animal feed and industrial uses. None of this corn would ever be used for direct human consumption.

Many growers are using more advanced means of farming which can lead to a higher yields and lower inputs than conventional practices. A University of Minnesota study that assessed farm practices for a variety of growers near Gevo's Luverne, Minnesota, production facility concluded that the corn grown by those farmers had on average 50 percent of the carbon footprint, in terms of gram CO_2 equivalents/kg grain, as the 'U.S. average' as

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reported by Argonne National Laboratory's Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model. This is due to the high yields (188 bu/acre in 2015) and relatively low inputs. In fact, farms that use sustainable agricultural practices, like no-till and low-till techniques and employing nutrient-rich manure in place of chemical inputs, were shown to be carbon negative. Farmers that had the lowest carbon footprint used no-till farming and applied manure in place of some of the synthetic nutrient inputs used on the field.

Gevo has seized on a great opportunity, collaborating with these forward-thinking farmers, sharing information with them about techniques and soil amendments. The result? Farms capture more carbon from the atmosphere and improve their corn yield. Gevo, in turn, rewards those farms by paying premium prices for sustainably grown corn. As in everything Gevo does, this decarbonization of the feedstock has become a key factor in the reduced carbon of our business system.

Key Isobutanol Production Process Features

• Continuous removal of product enables long fermentation times and large batches.
• Product recovery technology can be applied to C3-C6 alcohols.
• Can use any fermentable sugars in their unpurified form thereby reducing capital and operating costs, as well as the carbon footprint of energy use associated with sugar purification.
• Can use conventional dry milling/starch feedstock with conventional process conditions, enzymes, and unit operations.
• High-protein coproduct feed is safe for animals and provides a significant revenue stream. In fact, in a dry mill operation, this process produces approximately 20 percent more protein than what enters the process with the feedstock.
• Robust yeast fermentation with no risk of phage infection, common in industrial bacterial fermentations.

Additional Considerations

The dry-mill-based production process in operation in Luverne, Minnesota, is now being adapted to sugar mills for use around the world in a collaboration between Gevo and Praj. Also, the process has been adapted and demonstrated for use with woody feedstocks in a consortium funded by the United States Department of Agriculture (USDA) called the Northwest Advanced Renewables Alliance (NARA).

While Gevo will continue to produce isobutanol at its Luverne facility, licensing of this isobutanol technology is expected to be the key driver of production growth in the future.

Gevo's ability to convert sugars from multiple renewable feedstocks makes isobutanol a global opportunity.