



AN OVERVIEW OF GEVO'S BIOBASED ISOBUTANOL PRODUCTION PROCESS

The isobutanol-ethanol side-by-side dry-mill production process is a scalable pathway to a variety of renewable biofuels and chemicals and their markets.

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ISOBUTANOL PRODUCTION PROCESS



Introduction

As the ethanol industry evolves, more production plants are seeking ways to add additional products to their production capability and ways to increase margin at their site. One of those options is production of isobutanol and its derivatives including octane, jet-fuel blendstock, and other drop-in hydrocarbons. Commercial production of biobased isobutanol, alongside ethanol, has been in operation since 2014 at Gevo's Luverne, Minnesota, facility in a side-by-side operation where various streams in the plant are shared between the operations to minimize capital and operating cost. By operating in side-by-side mode, the isobutanol process and ethanol can share common feedstock handling and preparation operations, animal-feed process operations, and water-recycle systems. Doing this allows a capital-efficient deployment of isobutanol production at any ethanol plant.

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 in animal feed, which is a key by-product and 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. But because biobased isobutanol has unique fuel properties and qualifies under the Renewable Fuel Standard for a Renewable Identification Number (RIN), there is demand and value in the fuels market. For example, due to isobutanol's low water solubility, high octane and low vapor pressure, there has been overwhelming response from the marine market to isobutanol-gasoline blends. Gevo's bio-based isobutanol has been officially endorsed by the National Marine Manufacturers Association (NMMA) as a drop-in fuel for marine and recreational boat engines.

Isobutanol can also be chemically converted, using conven-



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.

tional, 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

ISOBUTANOL PRODUCTION PROCESS



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

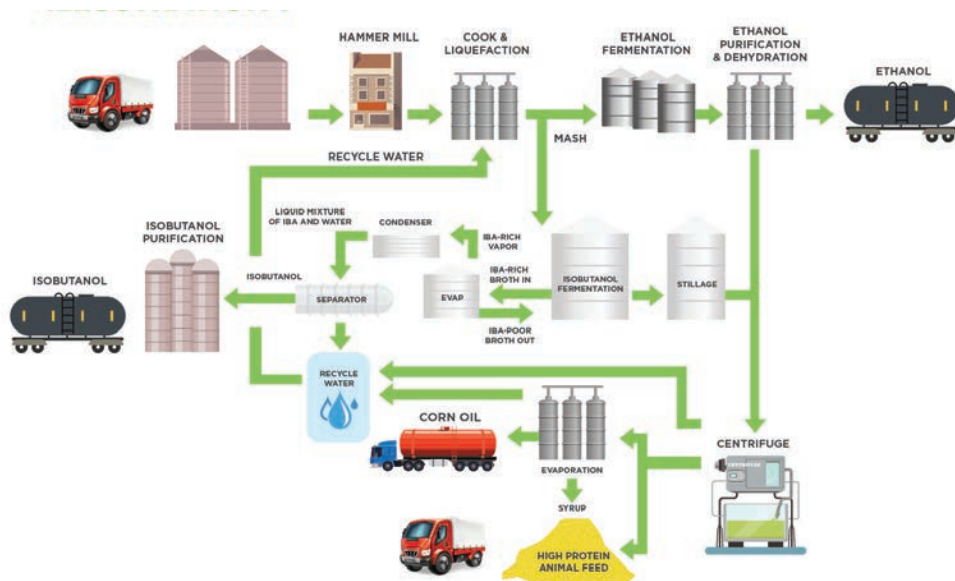
The isobutanol production process begins with biomass containing any fermentable sugars. At an existing dry-mill corn ethanol plant, the corn mash stream coming out of the front end of the process that feeds the ethanol fermentation is the same stream used for isobutanol fermentation. This stream is 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 Fermentation 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

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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 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.

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



ISOBUTANOL PRODUCTION PROCESS



Coproduct: 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.

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 10 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 is 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 which 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% of the carbon footprint, in terms of gram CO₂ equivalents/kg grain, as the 'U.S. average' as reported by Argonne National Laboratory's Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model. This is due to

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the high yields (188 bu/acre in 2015) and relatively low inputs. In fact, farms that use more sustainable agricultural practices, like no-till and manure in place of chemical fertilizer, were shown to be carbon negative. There is a great opportunity to collaborate with farms to capture more carbon from the atmosphere and reward those farms in a low carbon fuel business system. Farmers that had the lowest carbon footprint used no-till farming and used manure in place of some of the nutrients used on the field.

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 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% 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. There are two key approaches to be used depending upon the licensing partner:

Side-by-Side: This approach allows an alcohol plant owner to add isobutanol production capacity to an existing site, while leveraging infrastructure and operational efficiencies. These Side-by-Side plants would produce isobutanol, ethanol, and animal feed, which would be expected to provide additional revenue and margin opportunities to the plant owner.

Retrofit: Alternatively some ethanol plant owners might choose to switch all of their fermentation capacity to isobutanol and cease production of ethanol.

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