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WHITE PAPER

The Feedstock Conundrum for Renewable Diesel and Sustainable Aviation Fuel

Refiners are expanding their interests beyond renewable diesel into the sustainable aviation fuel marketplace. While feedstock availability continues to be a concern, another pathway has opened that may provide some temporary relief.

From 2018 to 2020, there were many renewable diesel project announcements, and renewable diesel established itself as a new campaign in the oil refining sector. Many industry players focused on leveraging government incentives from the national Renewable Fuels Standard (RFS) and California's Low Carbon Fuel Standard (LCFS) by processing triglyceride feedstocks to produce renewable diesel. In 2021, conversations among refiners shifted from the prospects of renewable diesel to sustainable aviation fuel (SAF). This market shift is driven primarily by interest from airlines and lobbying groups to decarbonize the aviation sector via the use of future SAF credits. Many studies have been commissioned on existing or planned renewable diesel facilities to evaluate what additional capital investment would be required to produce low, medium and/or high quantities of SAF coproduct.

Meanwhile, an elephant in the room surfaced, summarized by this question: How will we provide the feedstock? Those invested into the renewable fuels market are already familiar with the limited volume of triglyceride feedstock available today. Now they must more seriously consider alternative feedstocks to meet the growing demand for renewable fuels.

Market Potential

Answering questions surrounding feedstocks requires some basic understanding of the potential size of the markets. As depicted in Figure 1, the U.S. jet fuel market totals 24 billion gallons, and the diesel market is over twice that volume.

Current supplies of soybean oil — one of the primary feedstocks for renewable diesel or SAF — can only meet a fraction of this volume. Only 6.3 billion gallons of soybean oil is potentially available within all current U.S. soybean production. Of that total only 3.4 billion gallons is produced from crushing and only 1.1 billion gallons of this volume is devoted to renewable fuels (see Figure 2). Today soybean oil represents approximately 55% of the feedstock that is routed to bio-based diesel, according to the latest marketplace analysis by The Jacobsen. The balance of the feedstock includes canola oil, distillers corn oil, beef tallow, white grease, poultry fat, yellow grease and used cooking oil. Keep in mind, however, that this only presents the domestic picture of triglyceride feedstocks. There is an international market that can supply the U.S. as well.

Clearly, the triglyceride markets will be challenged to provide even 5 billion gallons of renewable fuel, a volume that falls below the 83 billion gallons of jet fuel and diesel demand that we see today. There are, however, some alternative feedstocks that have been proposed:

1. **Cover crops** — Pennycress and camelina cover crops can be grown outside of the normal planting season to yield more oil per acre. To date, cover crops are typically grown only to prevent soil erosion. However, we are beginning to see small crushing facilities built for the purpose of extracting oil from these crops.
2. **Waste grease** — Besides used cooking oil, which is already being processed extensively, brown grease or trap grease can potentially be recovered from wastewater systems and processed into renewable fuels. However, these feedstocks are difficult to collect and treat in large quantities.
3. **Algae oil** — While the process of producing oil from algae has been researched for some time, no facility for large-scale production is in operation to date.

These pathways are promising, but it still appears obvious that more feedstock is needed. Triglycerides alone are not going to support the rapid expansion of bio-based diesel and SAF, particularly not at the rate we have seen over the past few years.

Elevated Feedstock Prices

The market agrees with the assessment that there is not enough supply, and the result is elevated prices in the fats and oils market (see Figure 3). Soybean oil, distillers corn oil and used cooking oil prices are 60%- 100% higher than prices in the fall of 2020. While there are other factors at play, it is widely suspected that the surge in renewable diesel project starts has played a significant role. Many more of those projects will come online in the next few years, likely leading to an even tighter market.

Ethanol as an Alternative Feedstock

New interest has arisen in ethanol as a bio-based renewable feedstock that could potentially serve as an alternative for production of sustainable aviation fuel, via the ATJ-SPK (alcohol-to-jet synthetic paraffinic kerosene) route. This is one of seven pathways approved by ASTM International (formerly the American Society for Testing and Materials).

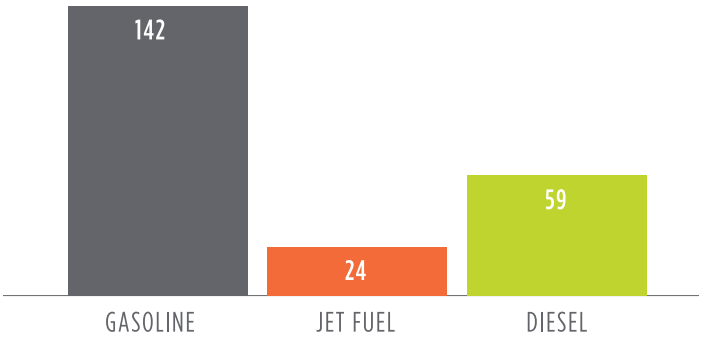

Figure 1. U.S. consumption of refined products (in billions of gallons) as of 2021.

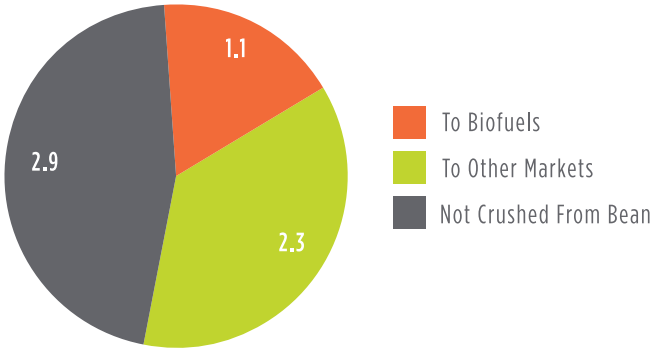

Figure 2: Soybean production (in billions of gallons) allocated by market as of 2021.

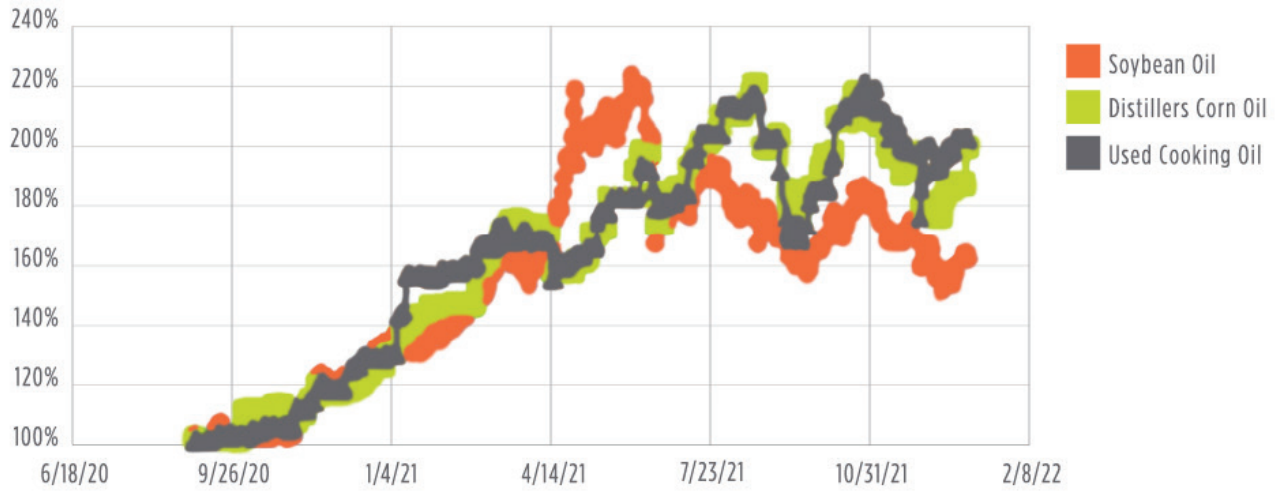

Figure 3: Triglyceride feedstock prices are rising.

Although most of the ethanol in the United States is routed to gasoline production, it is anticipated that electric vehicles will reduce gasoline demand over time. In fact, the U.S. Energy Information Administration (EIA) anticipates that motor gasoline production will decline by an average of approximately 0.3% per year through 2050. Since ethanol demand follows gasoline demand due to the 10%-by-volume mandate, this is expected to hamper ethanol growth. To keep demand for the world's most prolific biofuel increasing, ethanol producers will likely need to find another large outlet for their product.

Though the ethanol-based SAF product is chemically similar to SAF produced by triglycerides via the HEFA (hydroprocessed esters and fatty acids) process, production of SAF from ethanol requires a completely different flow scheme (see Figure 4).

Ethanol is first converted to ethylene via the dehydration loss. Although significant mass is lost to the water byproduct, most of the heating value is retained since the oxygen lost to water does not have heating value. In the second phase of this process, ethylene is oligomerized into mostly jet molecules in the C12 range. Finally, hydrogen is used to saturate the olefins in order to meet jet fuel specifications. Each of the processes is already commercially proven. Oligomerization and hydrogenation are processes already familiar to the oil refining industry, while ethanol dehydration has recently been commercialized as a low-carbon pathway to make ethylene.

Comparison of Ethanol and Triglycerides as Feedstocks

Though ethanol provides a compelling production pathway, it's worth assessing how it compares to the conventional triglyceride pathway. The advantages and disadvantages of ethanol and triglycerides as feedstocks are summarized as follows:

Ethanol

- Ethanol has more volume potential for producing SAF than triglycerides:
  - 14.6 billion gallons of ethanol could produce 8.1 billion gallons of SAF if all ethanol produced today were diverted to SAF.
  - 3.4 billion gallons of soybean oil could produce 2.6 billion gallons of SAF if all soybean oil produced today in the U.S. were diverted to SAF.
  - Assuming soybean oil is 55% of available triglycerides, the pool of available triglycerides including soybean oil, distillers corn oil, used cooking oil, and other feedstocks could produce 4.7 billion gallons of SAF.
  - See Figure 4 for a visual representation.
- Ethanol prices are $2 per gallon lower than soybean oil (as of December 2021). The other triglyceride feedstocks are also substantially more expensive than ethanol.
- Ethanol is a feedstock that is currently untapped for SAF, while triglycerides are already suffering supply constraints due to the maturity of the recent renewable diesel campaign.

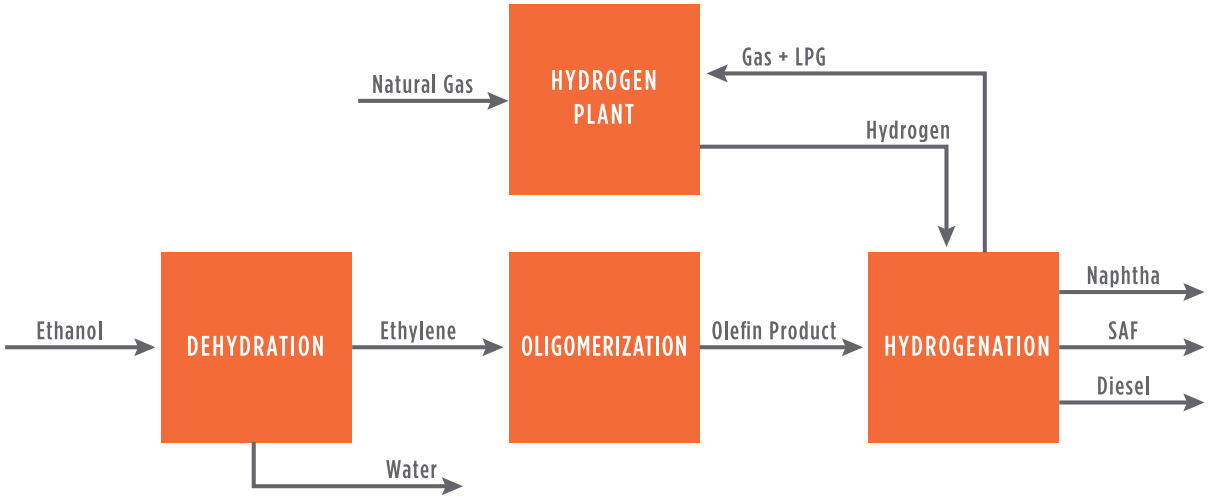

Figure 4: The ethanol to SAF process flow.

- Ethanol plant capacity often outpaces the market, resulting in plant idling. Thus, there is ethanol plant capacity available to support the ethanol-to-jet campaign.
- Ethanol supplies may become more available in the future, due to flat or declining growth in gasoline demand.

Triglycerides

- Triglycerides contain only about 12 wt% oxygen, versus 34.7 wt% oxygen for ethanol. This contaminant has no value in the SAF market.
- The technology for triglycerides-to-SAF via the HEFA process is more mature and has been commercially demonstrated.
- Triglycerides can produce higher SAF yields than ethanol — 80% for full conversion processes and higher when coupled with renewable diesel as a coproduct. Ethanol-based SAF yields only about 60% jet plus diesel by volume.
- Triglycerides feedstocks on average have lower carbon intensity pathways compared to ethanol. However, this may be offset in part by carbon capture, which is relatively low cost to employ at a corn ethanol facility.
- Triglycerides already established RIN pathway and LCFS pathway. Ethanol-to-jet fuel does not have a pathway.

Conclusion

Current market conditions indicate that the primary advantages of ethanol over triglycerides as feedstock are availability and feedstock price.

Energy companies will continue to look for low-carbon fuels to maintain their relevance as well as meet their long-term environmental, social and governance (ESG) goals. The transportation market has been largely dependent on the slow-growing electric vehicle market along with renewable diesel, but growth has been slow and the effort has been primarily confined to California. More pathways need to be uncovered. In 2022 and beyond, ethanol-to-SAF is a viable pathway that is worth considering among the menu of options available to help achieve sustainability goals.

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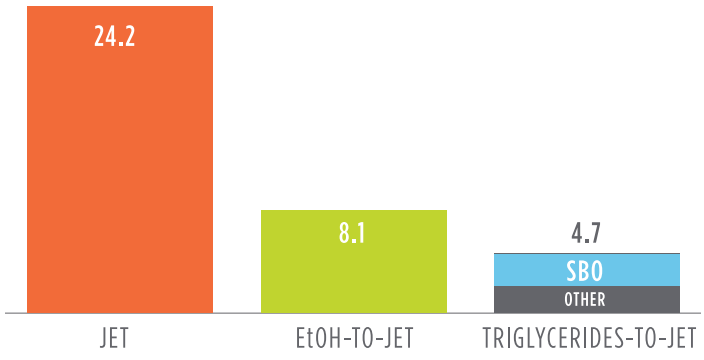

Figure 5: Ethanol can potentially produce more SAF (in billions of gallons) than triglycerides.

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