



Techno-economic, Feasibility, and Life Cycle Analysis of Renewable Propane

Final Report

Prepared by the National Renewable Energy Laboratory
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NOTICE

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Executive Summary

The Propane Education and Research Council (PERC) has engaged with the National Renewable Energy Laboratory (NREL) to develop information that is critical to understanding the current and future landscape for renewable propane (RP) and the value proposition for recovery of RP from existing and planned HEFA¹ biorefineries. The project has three main objectives:

- 1) quantify production of incremental renewable propane by increasing the severity of the hydroisomerization step in a HEFA biorefinery;
- 2) develop value proposition for recovery of renewable propane from existing and greenfield HEFA biorefineries;
- 3) survey the landscape for production of renewable propane from current and emerging biorefinery technologies and facilities.

In summary the following outcomes are identified from this study:

- 1) production of incremental RP by increasing the severity of the hydroisomerization step is insignificant to the overall propane yield from a HEFA biorefinery, however production of renewable butane (or LPG²) is quite significant thus suggesting alternate strategies for valorizing these fractions;
- 2) the value proposition for recovering RP and renewable LPG is quite strong, with capital recovery payback periods of 14 months for a small biorefinery producing 3.5 million gallons per year RP to as short as 2 months for a large biorefinery producing 87 million gallons per year RP. Paybacks for renewable LPG are as much as 50% shorter;
- 3) current and projected expansions of renewable diesel will greatly expand the potential availability of RP as a by-product. Several promising new pathways are under development but will not significantly increase production of RP for the next decade.

Introduction and Background

Due to concerns associated with global warming and the need to transition to a more sustainable industrial base, the demand for renewable gaseous and liquid transportation fuels is increasing. Due to the anticipated impact of electrification on light duty vehicles and the resulting decline in market for gasoline, biofuels production is currently focused on diesel and jet fuel (AKA sustainable Aviation fuel or SAF) where strong demand exists and electrification is generally not an option. This demand has spurred the use of technologies that seek to produce these fuels from abundant and renewable sources such as vegetable oils, animal fat and waste carbon (including biomass waste, municipal solid waste etc.). Chief among these is the HEFA process, where long-chain fatty acids obtained from renewable and waste feedstocks are processed to make drop-in diesel and jet blendstocks. The main product from the HEFA process is renewable diesel and, under normal processing conditions, only

¹ see Appendix A for acronyms, symbols, and abbreviations

² For purposes of this report, LPG (Liquified Petroleum Gas) is assumed to be a mixture of propane and butane that can be recovered from biorefinery process gasses by refrigeration and compression

about 15% of the total liquid product is SAF (Figure 1). Several pathways for producing SAF and Renewable Diesel (RD) are currently being practiced; Figure 1 summarizes the yield structure for six commercial technologies. **The need for plant infrastructure and yield loss due to additional processing means that SAF production is more expensive than the production of renewable diesel.** Stackable incentives from the Renewable Fuel Standard (RFS) and the Low Carbon Fuel Standard (LCFS, California and elsewhere) means that the economics favor production of RD – but the market pull for SAF is strongly incentivizing the biorefinery community to consider shifting production away from RD and to jet fuel blendstocks.

As can be seen, for five of the six pathways, production of “light ends” accompanies the production of RD and SAF. These light ends consist of naphtha and low molecular weight hydrocarbon gases in the range from methane to pentane. Naphtha produced is very low octane and is generally not suitable for use as a gasoline blendstock without further processing – but could be useful as a feedstock for production of renewable olefins in the plastics and petrochemicals industries. Propane and butanes (normal and iso) represent a significant fraction of the light ends and are the focus for this report.

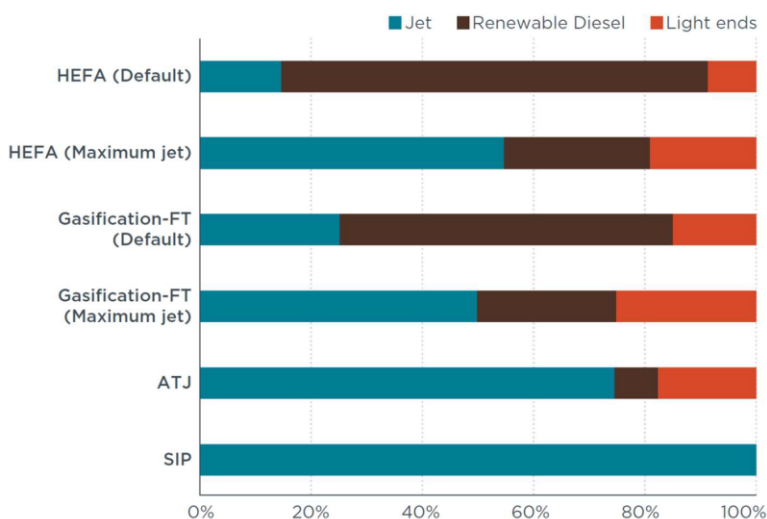


Figure 1. Yield structure for biorefineries producing RD and SAF (see Appendix A for list of acronyms, symbols, and abbreviations)

[Production of Incremental Renewable Propane from HEFA Biorefineries](#)

One of the principal objectives of this study was to quantify the possibility for producing ‘incremental’ renewable propane from HEFA biorefineries. Most biorefineries currently use a two-stage hydrotreating operation to produce renewable fuels from triglycerides (TAGs) found in fats, oils, and greases (FOGs); a simplified schematic is shown in Figure 2.

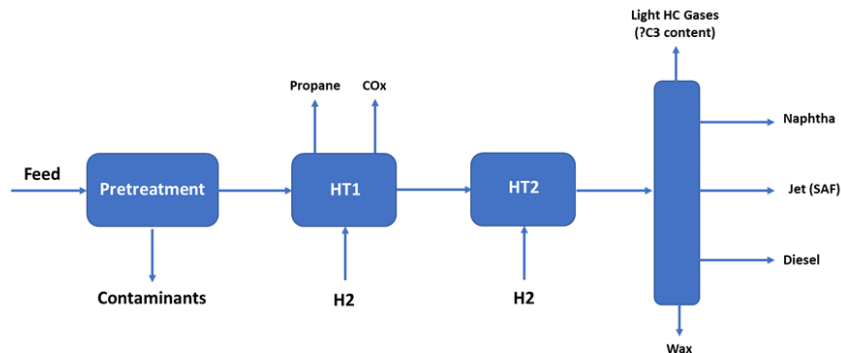


Figure 2. Simplified Schematic for HEFA biorefinery

The first hydrotreater (HT1) is where the primary TAG ‘propane cleave’ reaction (Figure 3) takes place; propane yield in this step is 5% by weight (see appendix A for calculation). It should be noted that FOG contains some materials that do not contain TAGs (such as waste cooking oil) hence this number is an upper bound for the renewable propane produced in HT1.

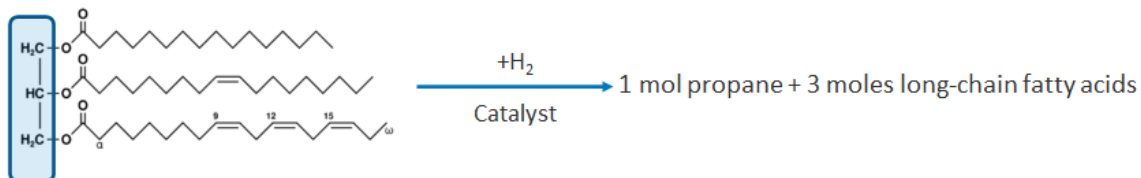


Figure 3. Reaction chemistry for production of propane from TAGs

The second hydrotreating step is for hydroisomerization of the products from HT1 in order to improve properties of the final fuels – principally to lower the freeze point and improve cold-flow properties for jet and diesel. This hydrotreating step also changes the ratio of SAF to RD, with higher severity³ operation favoring production of more jet and naphtha and less diesel. Primary reactions in HTs are isomerization (to lower freeze point) coupled with some hydrocracking. In the early stages of this project, we hypothesized that hydrocracking in HT2 could be a possible source of additional (AKA ‘incremental’) Renewable Propane (RP). Due to reaction chemistry, isomerization reactions will not produce incremental RP. We note that current economics favor production of RD as there is significant yield loss ($\approx 20\%$) associated with producing more SAF - however market pull is stronger for SAF and it could be assumed that the biorefinery operators will be shifting more capacity to SAF in the future.

Quantification of the amount of ‘incremental’ RP from HT2 was carried out by two means:

- 1) Stoichiometric modeling using reaction chemistry characteristic of HT2; and
- 2) Rigorous mass and energy balance modeling using an Aspen Plus[®] Hydrocracker model

For stoichiometric modeling, a reaction set for hydroisomerization and hydrocracking was utilized based on a NREL process model for production of SAF from FOG using HEFA technology. For purposes of this estimate, the feedstock to HT2 was assumed to consist of three long-chain hydrocarbons representing C_{15} , C_{17} , and C_{19} fragments from the primary TAG hydrotreating step (HT1). The reaction set and results of spreadsheet modeling for two cases are shown in Appendix 2:

³ Reaction severity is a combination of temperature, space time, and hydrogen treat rate with higher temperatures, longer space time, and higher hydrogen treat rates reflecting higher severity operation.

- Case 1 – low severity for HT2
- Case 2 – high severity for HT2

To vary severity, the stoichiometric coefficients for the cracking reactions were adjusted in order to vary the propane yield based on more or less hydrocracking in HT2.

Results show that incremental propane yields varied from 0.76 % (wt% based on feed to HT2) for low severity operation to 2.08% for high-severity operation. As a check to this result, rigorous modeling of HT2 was carried out by NREL’s analysis group using Aspen Plus⁴. Results of modeling for HT2 are presented in Figure 4.

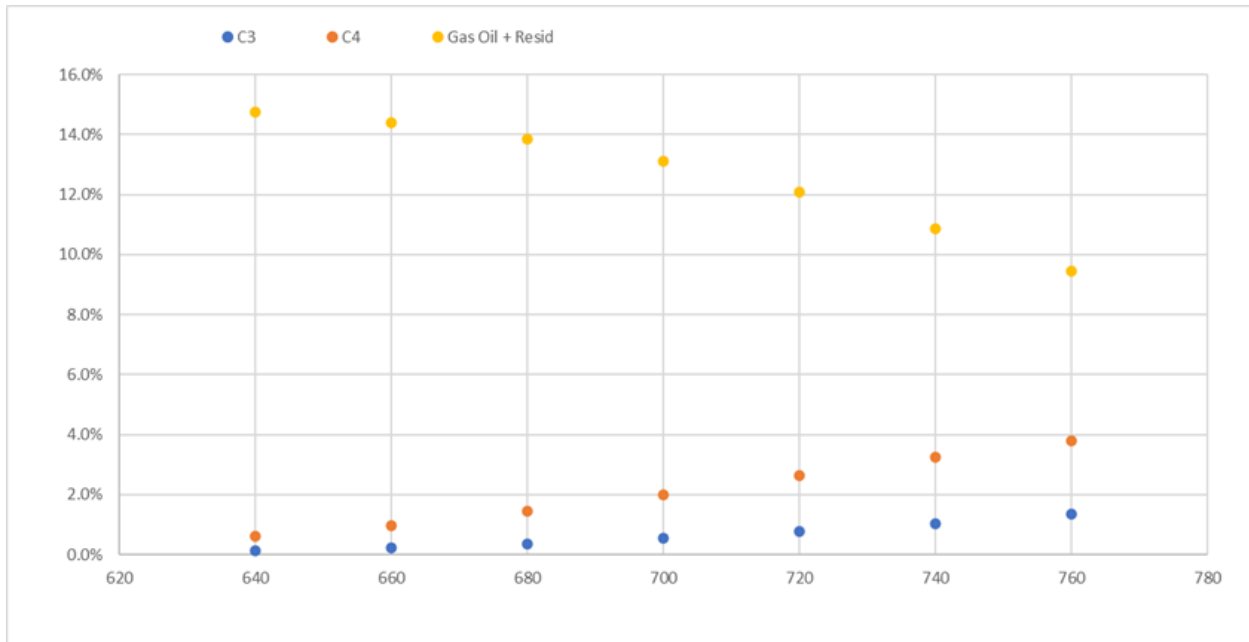


Figure 4. Incremental propane yield from HT2 by modeling in Aspen Plus; x-axis = reactor average temperature (°C), y-axis = wt% yield

In this case, reaction severity is reflected by the average reactor temperature (x-axis); yields for propane (blue circles) and butane (orange circles) are shown on the y-axis along with unconverted feedstock. While the agreement between the two analysis results is not perfect, what can be concluded is that the yield of incremental propane from HT2 is likely too small to be of economic interest to the biorefinery operator. However, there may be some economic value for recovering butanes from the process as higher severity of HT-2 can yield up to 4 wt% of butanes. Economics of recovery of propane from biorefinery process gases are discussed in the next section of this report, but generally this involves use of existing process equipment accompanied by extensive biorefinery infrastructure changes or installation of a new process train to recover propane at a purity required to meet HD-5 specifications, which limits the butane content to 2.5% by volume.

A somewhat surprising finding from the modeling exercise was that the yield of butane increases much more rapidly with reaction severity in HT2 than the yield of propane (see Figure 4).

Privileged conversations with biorefinery operators have confirmed that – in some cases –

⁴ Lead analyst was Mike Talmadge

the yield of renewable butane is twice that of renewable propane. This observation opens up opportunities for sales of renewable LPG that contains significantly higher amounts of butanes than is allowed for HD-5 spec-grade propane. The presence of iso-butane has also been reported which - if recovered - can be valorized for petrochemical uses.

Developing The Value Proposition for Renewable Propane

Renewable Fuel Standard (RFS) and Renewable Identification Number (RIN): A key driver for biofuel production and consumption in the U.S. is the Renewable Fuel Standard (RFS), which is a national program that requires transportation fuel sold in the U.S. to contain certain volumes of biofuels set by the EPA every year. The four renewable fuel categories under the RFS are:

- Biomass-based diesel
- Cellulosic biofuel
- Advanced biofuel
- Total renewable fuel

For a renewable fuel to be applied toward the volumetric obligation, it must be used for certain purposes (i.e., transportation fuel, jet fuel, heating oil⁵) and be approved by the EPA that certifies that the fuel meets certain environmental and biomass feedstock criteria. Among the criteria are specifications for biofuels that require the fuels to show a certain reduction (e.g., at least 50% reduction for advanced biofuels) in greenhouse gas (GHG) emissions as compared to a 2005 petroleum baseline (98.2 kgCO₂ eq/MMBtu or 93.1 gCO₂ eq/MJ for baseline gasoline and 97.0 kgCO₂ eq/MMBtu or 91.9 g CO₂ eq/MJ for baseline diesel). Obligated parties under the RFS program are refiners or importers of gasoline or diesel fuel. Compliance is achieved by blending renewable fuels into transportation fuel, or by obtaining credits (called “Renewable Identification Numbers”, or RINs) to meet an EPA-specified Renewable Volume Obligation (RVO).

RINs are generated when eligible renewable fuels are produced and can be traded among parties. Obligated parties can buy gallons of renewable fuels with RINs attached and can also buy RINs on the market. At the end of the compliance year, obligated parties use RINs to demonstrate compliance by submitting all RIN generation information and other RIN transactions into the EPA Moderated Transaction System (EMTS).

Different renewable fuel types receive credit for specific numbers of RINs based on their estimated equivalence value relative to ethanol as determined by EPA40 (40 CFR 80.1415). The equivalence value (EV) is a number that is used to determine how many gallon-RINs can be generated for a physical gallon of renewable fuel, calculated using Eq.1.

$$EV = (R/0.972) * (EC/77,000) \quad (1)$$

Where:

- EV = Equivalence Value for the renewable fuel, rounded to the nearest tenth
- R = Renewable content of the renewable fuel; a measure of the portion of a renewable fuel that came from renewable biomass, expressed as a fraction, on an energy basis.
- EC = Energy content of the renewable fuel, in BTU per gallon (lower heating value).

⁵ Heating oils used to generate process heat, power and other functions are **not** approved for RIN generation. Fuel oil receives RIN only if it meets the applicable requirements such as use for interior spaces of homes or buildings to control ambient climate for human comfort (EPA, 2013).

EPA assigned EVs for a number of biofuels including denatured ethanol (with an EV of 1), biodiesel (with an EV of 1.5), non-ester renewable diesel (with an EV of 1.7). EPA assigned an EV of 1.1 to LPG, which means one physical gallon of LPG could generate 1.1 RINs. There is no assigned EV for renewable propane under the RFS because EPA has, to date, not received any petition requesting RIN credits for renewable propane⁶ as of March 2022 when the EPA responded to our inquiry. However, it is reasonable to expect that renewable propane will receive the same EV as LPG since the lower heating values of these two fuels are virtually identical⁷ (refer to Equation 1 above where EC is the lower heating value of a given renewable fuel).

RIN Price: The price of RIN credits fluctuates over time due to various factors such as agricultural market and trade, prices of biofuels and petroleum fuels, and mandated volumetric targets (Figure 5). Typically, the RIN price increases under two circumstances: 1) when the cost of a biofuel is higher than the petroleum fuel into which it is blended; and 2) when RFS volumetric mandates are higher than market-driven biofuel consumption.

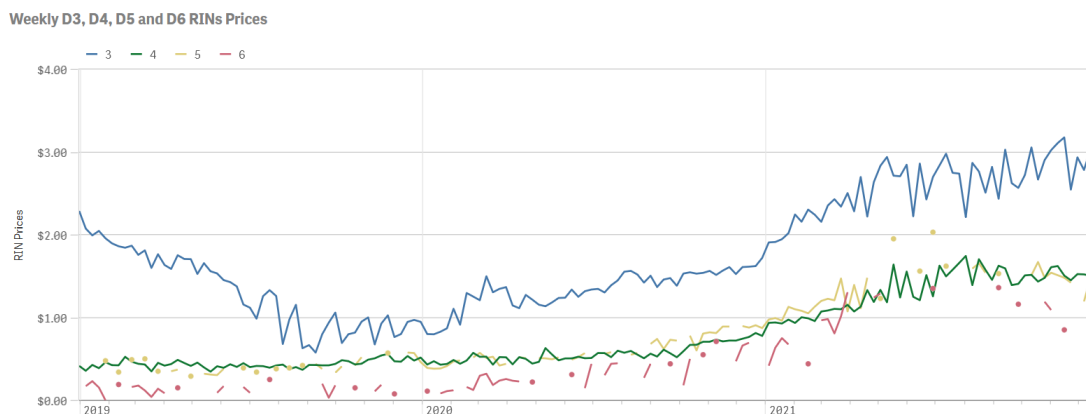


Figure 5: Weekly verified RIN prices for D3, D4, D5 and D6 from 2019-2021 (available from <https://www.epa.gov/fuels-registration-reporting-and-compliance-help/rin-trades-and-price-information>)

In 2021, RIN prices reached new high because of: 1) higher biofuel prices due primarily to increasing feedstock (corn, soybean) costs relative to the petroleum fuel prices; 2) tightened supply of RINs resulting from uncertainties around small refinery exemptions; and 3) recovery of gasoline and diesel demand from COVID-19, which subsequently increased the need to blend ethanol and biodiesel and therefore led to rising RIN prices.

RINs for Renewable Propane: Before a fuel can generate RFS RINs that fuel pathway must be approved by EPA; the process can take a considerable amount of time for some fuels (Congressional Research Service 2020)⁸. EPA reports it has approved over 100 facility-specific pathway petitions since 2010 (EPA 2020)⁹. **EPA has indicated that no renewable propane**

⁶ Private communication with EPA, March, 2022

⁷ The lower heating value of LPG is 84,950 Btu/gal or 89.6 MJ/gal whereas that of propane is 84,250 Btu/gal or 88.9 MJ/gal (data source: GREET 2020)

⁸ Congressional Research Service. 2020. The Renewable Fuel Standard (RFS): An Overview. Updated April 14, 2020. R43325.

⁹ EPA. 2020. Federal Register. Vol.85, No.25. February 6, 2020. Rules and Regulations.

pathway from a HEFA process has been approved under the RFS¹⁰. However, a number of pathways which produce renewable LPG (a mixture of propane with small amounts of butane and other components) from hydrotreating using eligible feedstocks have been approved by the EPA to generate D5 RINs. For example, in 2018 EPA approved a pathway for the generation of advanced biofuel (D5) RIN for LPG and naphtha through a hydrotreating process employed by the Renewable Energy Group (Geismar, Louisiana) which uses biogenic waste fats, oils and greases as feedstock (EPA 2018)¹¹.

Low Carbon Fuel Standard (LCFS): The LCFS in California is one of the key regulatory measures that aim to reduce GHG emissions. In 2018, California's Air Resources Board (CARB) approved the amendments to the LCFS, which require a minimum 20% reduction in carbon intensity (CI) of transportation fuel pool by 2030.

There are three ways to generate credits in the LCFS: fuel pathways, projects, and capacity-based crediting. Under fuel pathway-based crediting, a **transportation fuel** needs a life cycle carbon intensity (CI) score (typically in units of gCO_{2eq}/MJ) to participate in the LCFS. The providers of low carbon fuels used in California transportation generate credits by obtaining a certified CI and reporting transaction quantities on a quarterly basis. Credits are calculated relative to the annual CI benchmark and undergo verification post credit generation. California has an established market for credit transactions under the LCFS program. Entities with credits to sell can opt to pledge credits into the market and entities needing credits must purchase their pro-rata share of these pledged credits. CARB also publishes data on carbon credit price and credit volume on a regular basis. Although carbon credit price varies with time, CARB set price caps in the clearance market to prevent extreme market volatility. The price cap was set at \$200/metric ton CO_{2eq} in 2018. Adjusted for inflation, the price cap is \$221.67/metric ton CO_{2eq} in 2021.

As of January 2022, CARB has approved CIs for 9 renewable propane pathways, all of which use fats, oils and greases from various sources as feedstocks to produce renewable fuels (including renewable diesel, renewable naphtha) at the Renewable Energy Group's facility in Geismar, Louisiana. The varying CI for the LPG pathways results primarily from the differences in the CI of the feedstock used in the hydrotreating process (Figure 6).

¹⁰ personal communication with Aaron Levy, EPA, August 26 2021

¹¹ EPA. 2018. Renewable Energy Group, INC. Fuel Pathway Determination under the RSF Program. Office of Transportation and Air Quality. February 23, 2018.

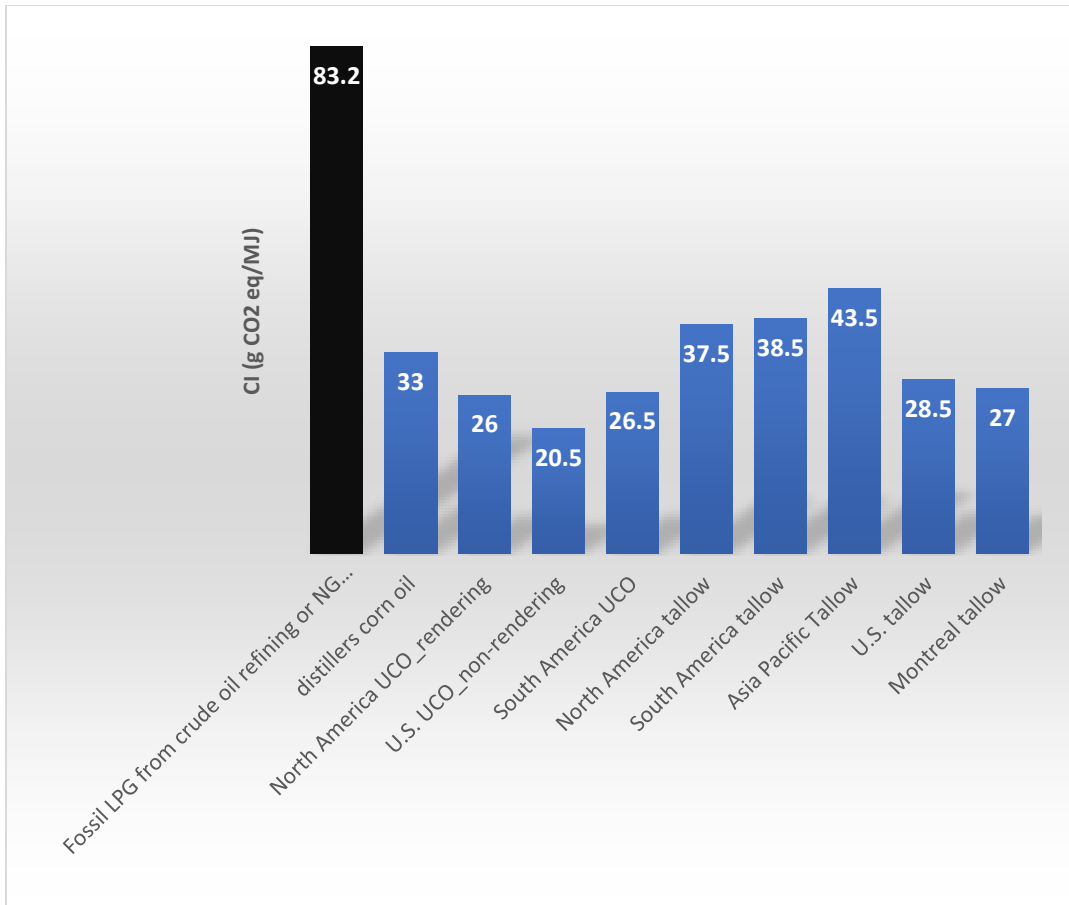


Figure 6: Carbon intensity of LCFS certified renewable propane (LPG) pathways (blue bars) in comparison to that of fossil LPG (black bar). UCO = used cooking oil. (available from <https://ww2.arb.ca.gov/resources/documents/lcfs-pathway-certified-carbon-intensities>)

Other jurisdictions are joining California, which is evident in the Pacific Coast Collaborative, a regional agreement between California, Oregon, Washington, and British Columbia to strategically align policies to reduce greenhouse gases and promote clean energy.

Oregon implemented the Clean Fuels Program (CFP) in 2016, which is similar to California’s LCFS. Oregon’s CFP set a declining target for the average CI of transportation fuels used in the state. The CFP incentivizes the deployment of emissions-reducing fuels and vehicles and can contribute toward economy-wide greenhouse gas reduction goals. The CFP requires annual CI reduction by 10% in the statewide fuel pool’s CI rating from 2015 levels by 2025. Oregon also has its own carbon clearance market. The average carbon credit price is about \$125.7/metric ton CO₂ eq. in 2021.

The Clean Fuels Program (CFP) in the State of Washington is designed to limit the carbon intensity of transportation fuel and will be linked to the existing CFP in Oregon and the LCFS in California, creating a West Coast market for biofuels and other low-carbon transportation fuels. The Clean Fuel Standard requires fuel suppliers to gradually reduce the carbon intensity of transportation fuels to 20 percent below 2017 levels by 2038. The program will begin in January 2023.

Other states/regions considering LCFS-like policies include:

- Midwestern Clean Fuels Policy Initiative, which aims to create a market specifically for regional clean fuel producers that simultaneously delivers environmental and economic benefits (Great Plains Institute 2020)¹².
- The governors of Massachusetts, Connecticut, and Rhode Island along with the mayor of the District of Columbia announced the Transportation and Climate Initiative Program, which will cut GHG from motor vehicles in the region by an estimated 26% from 2022 to 2032 (Transportation and Climate Initiative 2020)¹³. Delaware, Maryland, New Jersey, New York, North Carolina, Pennsylvania, Vermont and Virginia have the opportunity to join the program in the future.
- A 2020 report developed by the House Select Committee on the Climate Crisis recommends that “Congress develop a LCFS to build on the Renewable Fuel Standard. The standard should set a technology- and feedstock-neutral benchmark for liquid and non-liquid fuels tied to a life cycle assessment of the carbon intensity of the fuels” (p102, Select Committee on the Climate Crisis, 2020¹⁴)

It is worth noting that the credits provided by the RFS and LCFS predominantly favor the use of low carbon fuels in the transportation sectors while using these fuels in other markets such as residential and commercial sectors may not qualify for such credits.

Development of value proposition for producing renewable propane as a co-product: This section focuses on estimating the capital and operating and maintenance costs (CAPEX and OPEX) of recovering, storing, and handling renewable propane as a co-product from HEFA biorefineries. It should be noted that CAPEX will vary considerably depending on greenfield vs. brownfield circumstances. In the case of a new (greenfield) biorefinery, we assume that they will purchase and install new equipment to enable the recovery of renewable propane from the flue gas (or off-gas streams). For petroleum refinery conversion or biorefinery expansion projects the costs may be less as a typical petroleum refinery will have gas handling and recovery systems, and infrastructure conversion costs may be more modest for biorefinery expansion projects. Modifications may be required to achieve purity requirements or to add additional capacity, but CAPEX requirements will be less for conversion and expansion projects, while costs for storing and handling RP will be the same for either greenfield or brownfield operations. The following discussion assumes a greenfield operation with the associated CAPEX burdens on the plant.

Capital and O&M costs to recover propane

In estimating the CAPEX and OPEX, we leverage the TEA and process modeling work documented in an NREL report (2018)¹⁵ for a **baseline biorefinery, which has a capacity of processing 3,000 barrels of tallow per day to produce about 20 million (MM thereafter)**

¹² Great Plains Institute, A Clean Fuels Policy for the Midwest: A White Paper from the Midwestern Clean Fuels Policy Initiative, January 7, 2020.

¹³ Transportation and Climate Initiative. 2020. Transportation and Climate Initiative Program. Memorandum of Understanding. Available at <https://www.transportationandclimate.org/sites/default/files/TCI%20MOU%2012.2020.pdf>

¹⁴ House Select Committee on the Climate Crisis, Solving the climate crisis, Majority Staff Report. 116th Congress. June 2020, Available at <https://climatecrisis.house.gov/report>.

¹⁵ NREL. 2018. Bio-Propane: Production Pathways and Preliminary Economic Analysis. Final Report. January 2, 2018.

gallons/year of renewable diesel. At the design capacity, the biorefinery generates a fuel gas at a rate of 1 million standard cubic feet (MMSCF) per day; the process flow diagram (PFD) is shown in Figure 7. Although several commercial technologies are available for propane recovery from the gas mixture, a standard refrigeration technology is selected for estimating CAPEX and OPEX; **the validity of the use of these unit operations has been vetted by conversations with a number of biorefinery operators including World Energy and Global Clean Energy who currently are installing capacity for recovering RP.**

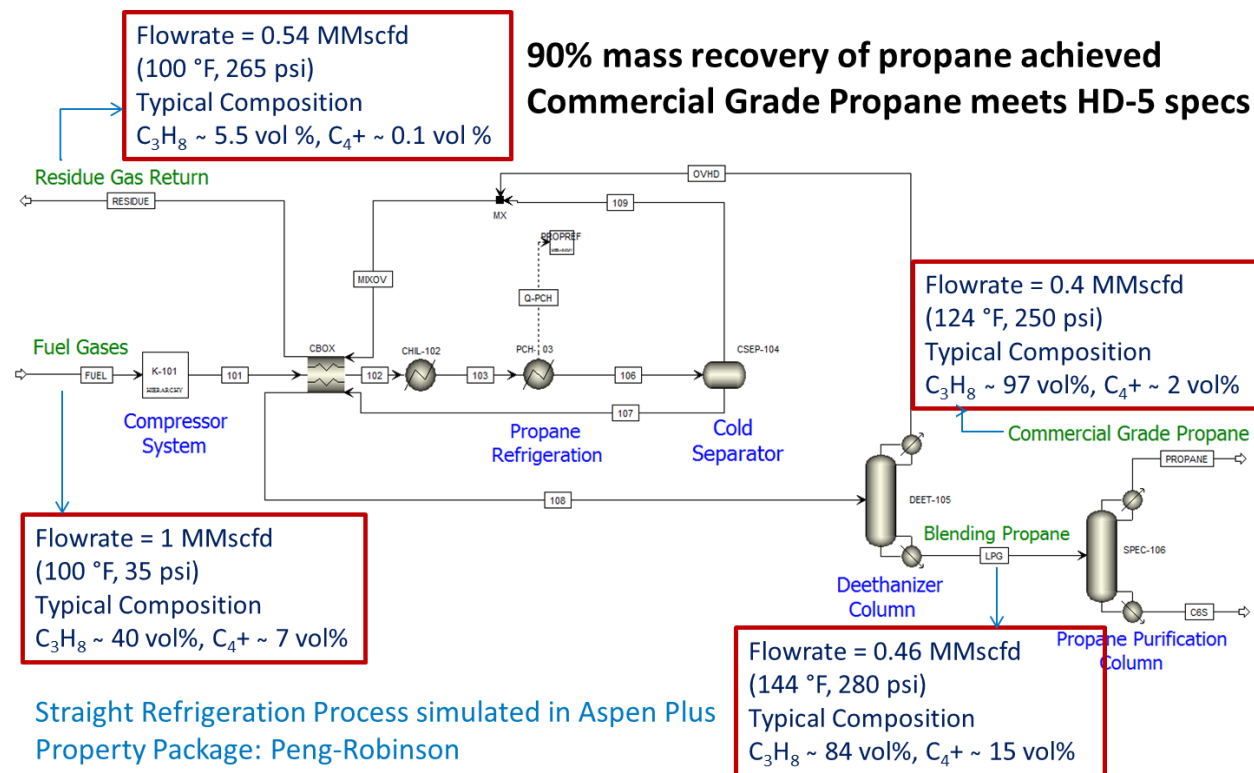


Figure 7. Separation scheme in refrigeration process for producing HD-5 spec renewable propane

The fuel gas is first compressed to approximately 400 psi followed by chilling in a series of exchangers to allow separation of the light gases in the cold separator. The liquid stream from the cold separator enters a multistage deethanizer column operating at reduced pressure from the cold separator. Overhead vapor containing light components (ethane, methane, and hydrogen) is combined with the vent stream from the cold separator and returned to the refinery as fuel gas. The liquid stream, labeled as LPG in Figure 3, enters the second fractionation column (i.e., propane purification column), which further separates the heavier hydrocarbons as bottoms, and the propane is recovered from the distillate stream. Based on the process model, up to 90% of the propane from the fuel gas header could be recovered. At this level of recovery and the fuel gas rate and composition modeled (NREL 2018), the baseline biorefinery could produce **3.5 MM gallons** of renewable propane per year. The propane can be used as a transportation fuel without further processing.

The total installed equipment cost for the propane recovery system is estimated at \$4.7MM (2020\$) for the baseline biorefinery. If the purification of propane is not needed to the HD-5 spec, the propane purification column is not needed, and the resultant CAPEX would be

\$4.3MM (2020\$). The LPG stream thus captures would have up to 84% propane and 15% butanes.

To understand how plant size impacts CAPEX, the techno-economic analysis in the NREL study from 2018 will be used; Table 1 shows these data. As can be seen, CAPEX does not scale linearly with plant size; due to economies of scale the CAPEX per unit of propane decreases as plant size increases.

OPEX for recovering renewable propane from the fuel gas includes both variable OPEX and fixed OPEX. Variable OPEX includes costs for incremental consumption of electricity, steam (low pressure steam, in particular), cooling water, chilled water, refrigerant replacement as well as make-up natural gas due to recovering propane from the fuel gas, which is otherwise used as a process fuel by the biorefinery. The fixed OPEX includes labor, maintenance, insurance, etc. Table 1 shows the OPEX for biorefineries, which generate fuel gas at rates between 1MMSCF and 25 MMSCF per day. The fixed and variable OPEX is estimated at \$3.51 MM per year for the baseline biorefinery, among which the make-up natural gas alone costs about \$1.31 MM/year, assuming an average natural gas price of \$3.5/MMBtu (NREL, 2018).

Plant Size (MM SCF/day)	1	2	5	10	25
Renewable Propane yield (MM gal/year)	3.5	7.0	17.5	35.0	87.5
Total installed cost (MM\$)	4.70	5.03	5.58	6.20	8.46
OPEX (MM\$/year)	3.51	5.19	10.30	18.43	43.31

Table 1: Total installed cost (TIC) and operation and maintenance cost (2020\$) for different plant sizes (derived from Table 6 in NREL, 2018¹⁶. TIC of equipment for renewable propane in Table 6 of NREL 2018 report was converted to 2020\$ by multiplying 1.07, the ratio of cost index of 2020 to that of 2015)

CAPEX and OPEX for storage system

Once renewable propane is recovered, it will be stored on-site in storage tanks before loading out for transportation (e.g., by rail). The CAPEX for the storage and handling system is estimated based on quotes provided by TransTech Energy (2022). The CAPEX shown in Table 2 includes design/engineering, truck loading, instrumentation, electric controls, storage tank, piping and installation, testing, etc. The total installed cost is estimated to be approximately \$2.8MM for a storage capacity of 90,000 gallons, which could store about 8 days of renewable propane produced from the baseline biorefinery. The CAPEX increases to about \$3.2MM if the desired storage capacity is doubled by including two 90,000 gallon storage tanks (TransTech Energy 2022)¹⁷, an increase of approximately 15% when compared to the single gallon system. The installed cost of a storage system with fifteen 90,000 gallon tanks (or a total of 1.35MM gallons) to allow 5 day storage of renewable propane generated from a biorefinery producing 25MMSCFD of fuel gas (i.e., the largest plant size shown in Table 1) is estimated at \$11.2MM. OPEX for operating the storage system is negligible (primarily electricity consumption for pumps and motors) and therefore is not explicitly estimated in the cost analysis.

¹⁶ NREL. 2018. Bio-Propane: Production Pathways and Preliminary Economic Analysis. Final Report. January 2, 2018.

¹⁷ TransTech Energy. Mark Wenik. Personal communications via emails. February 17, 2022 and January 25, 2022.

	Storage capacity (gallons)		
	90,000 (one 90,000 gal tank)	180,000 (two 90,000 gal tanks)	1,350,000 (fifteen 90,000 gal tanks)
Total installed cost (MM\$)	2.8	3.2	11.2

Table 2: Total installed cost for propane storage systems at three capacities (TransTech Energy, 2022)

Revenues from selling renewable propane: When selling renewable propane, the biorefinery could receive two revenue streams; one is the market value of renewable propane as a transportation fuel (for this analysis) and the other is incentives if the renewable propane meets the eligibility criteria. As discussed in the previous section, D5 RIN under the Renewable Fuel Standard and carbon credits provided by California’s Low Carbon Fuel Standard (when renewable propane is sold in California) are two incentives, for which the renewable propane could be eligible.

Market value of renewable propane: Data on wholesale and retail prices of renewable propane is not available in the public domain. Anecdotal information from one industrial source indicates that the premium for retail renewable propane is small when compared to the retail price and varies depending on market conditions (e.g., \$0.05 more per gallon for renewable propane)¹⁸. Due to the lack of publicly available information and the relatively small premium enjoyed by renewable propane, we use the conventional propane price published by EIA as a proxy to estimate the market value of renewable propane. As shown in Figure 8, propane price varied from a low of \$0.42 (in March 2020) to as much as \$1.63 (in October 2021) per gallon from 2019 to 2021 with an average wholesale price of \$0.89/gallon.

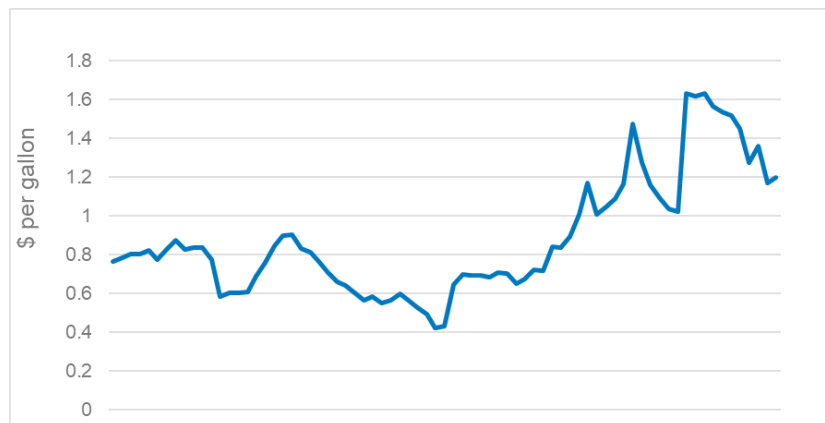


Figure 8: U.S. weekly propane wholesale price from 2019 – 2021. available from https://www.eia.gov/dnav/pet/pet_pri_wfr_dcus_nus_w.htm.

RIN credits under Renewable Fuel Standard: Renewable propane (referred to as renewable LPG by EPA as discussed earlier) produced as a co-product from the hydrotreating process could be eligible for D5 RIN credits if it meets the criteria (e.g., life cycle GHG reduction threshold of 50% relative to the benchmark) specified in the Renewable Fuel Standard. EPA publishes weekly RIN prices for various biofuel categories (e.g., D3, D4, D5, D6); both unverified and

¹⁸ Private communication from G. Vishwanathan, 2022

verified RIN prices are reported. For this analysis, we only use data which has been verified and is valid for compliance purposes under EPA’s Quality Assurance Plan (AKA Q-RINs). Figure 9 shows the weekly prices for each D5 RIN from 2019 to 2021. As can be seen, the prices varied from \$0.30 to \$2.04. The 3-year average over this same time period is \$0.84. As noted earlier, each physical gallon of renewable propane can receive 1.1 D5 RIN credits.



Figure 9: Weekly D5 RIN price from 2019 to 2021 (available from <https://www.epa.gov/fuels-registration-reporting-and-compliance-help/rin-trades-and-price-information>)

Carbon credits under California’s Low Carbon Fuel Standard (LCFS): Carbon credits generated from California’s LCFS are important factors, which influence the biofuel producer’s decision regarding whether it makes economic sense to produce and sell renewable propane as a co-product in the market. In developing the value proposition for renewable propane, it is logical to assume that biofuel producers are interested in selling renewable propane into California’s market to be eligible for carbon credits.

The LCFS requires fuel producers to meet annually **declining** carbon intensity (CI) benchmarks for the transportation fuels they sell into California. The monetary value of the carbon credit is estimated based on CI reduction relative to the benchmark CI of the baseline fuel (e.g., gasoline, diesel, conventional jet fuel) as well as the carbon credit price at California’s Carbon Clearance Market. Because the benchmark CI of the baseline fuel declines over time, the carbon credits a substitute fuel receives will decrease over time if the carbon price remains unchanged. In estimating the carbon credits, **we assume the renewable propane will be used as a substitute for gasoline fuel in light-duty vehicles or forklifts and 1 unit (e.g., MJ) of renewable propane displaces 1 unit of gasoline (i.e., an energy economy ratio of 1 as defined in the LCFS) i.e., the Energy Economy Ratio (EER) is 1.** Figure 10 shows the monthly carbon credit price from 2019 to 2021. The 3-year average is about \$193/metric ton of CO₂ with the highest price at \$206 and lowest \$174/metric ton of CO₂.

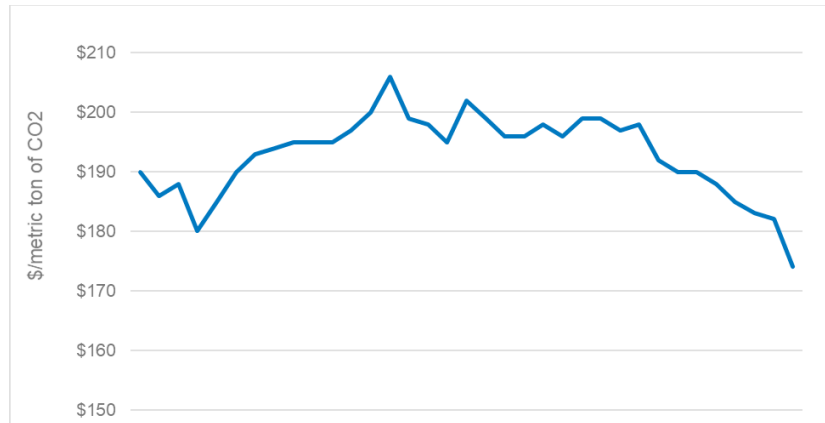


Figure 10: Monthly carbon credit price from 2019 to 2021 under the LCFS (available from <https://ww2.arb.ca.gov/resources/documents/weekly-lcfs-credit-transfer-activity-reports>)

Payback period – an example for the baseline biorefinery: To demonstrate the value proposition we use the payback period as a simple indicator to understand how long it may take the biorefinery to recoup its capital cost when investing in additional equipment to produce renewable propane. The average payback period is calculated by dividing the amount of initial capital cost by the annual net cash flow (eq. 2). Table 3 summarizes the key data used to estimate the initial capital cost and annual net cash flow for the baseline biorefinery, which produces 3.5 MM gallons of renewable propane per year.

$$\text{Payback period} = \frac{\text{Initial capital cost}}{\text{annual net cash flow}} \quad (2)$$

Based on the data and assumptions presented in Table 3, it is estimated that the baseline biorefinery, which produces and sells 3.5MM gallons of renewable propane per year, could recoup its capital cost in about 14 months.

Initial capital cost (MM\$)	
Propane recovery system	4.7
Propane storage and handling (one 90,000 storage tank)	2.8
Annual revenue and cost (MM\$/Year)	
Revenue1 - Sales of renewable propane at \$0.89/gallon (3-year average wholesale price from 2019 to 2021)	3.1
Revenue 2 - RIN credits at \$0.86 per D5 RIN (\$0.95/gal) (3-year average D5 RIN price, 2019 to 2021. 1 gallon receives 1.1 D5 RIN)	3.3
Revenue 3- Carbon credits at \$193/metric ton of CO ₂ under LCFS (3-year average carbon price from 2019 to 2021. CI of 28.5 g CO ₂ /MJ for renewable propane*)	Year 1 (2022): 3.7 Year 2 (2023): 3.6 Year 3 (2024): 3.5
Cost 1 – Fixed and variable OPEX cost	3.5
Estimated annual net revenue (MMS\$/year)	
Annual net revenue = ΣRevenue – ΣCost	Year 1 (2022): 6.6 Year 2 (2023): 6.5 Year 3 (2024): 6.4

Table 3: Capital cost and annual cash flow for producing renewable propane from a baseline biorefinery. Note: *CI is based on CARB’s estimate for REG’s RP produced from U.S. tallow. Carbon credits per gallon of renewable propane = (CI_{propane} – CI_{gasoline})*Carbon price*renewable propane output*LHV_{renewable propane}/1,000,000 where LHV_{renewable propane} = 88.88 MJ/gallon (GREET 2021), CI_{gasoline} = 89.5 (2022) or 88.25 (2023) or 87.01 (2024), all in g CO₂ eq/MJ.

As noted earlier, recovering renewable propane from the fuel gas will require the biorefinery to purchase supplement natural gas to meet the demand by the internal conversion process. We estimated the annual revenues from selling renewable propane as well as the fuel cost savings if the biorefinery substitutes natural gas for propane for internal process at two natural gas prices, i.e., \$3.5/MMBtu and \$5/MMBtu. For the baseline biorefinery (1MMSCF per day), the annual savings range between \$1.2 and \$1.8MM if the biorefinery sells renewable propane and purchases supplement natural gas for internal process. The largest facility (25 MMSCF per day) could realize an annual saving of \$31.1MM at a natural gas price of \$5/MMBtu. The annual saving goes up to \$45.1MM at a natural gas price of \$3.5/MMBtu (Figure 11).

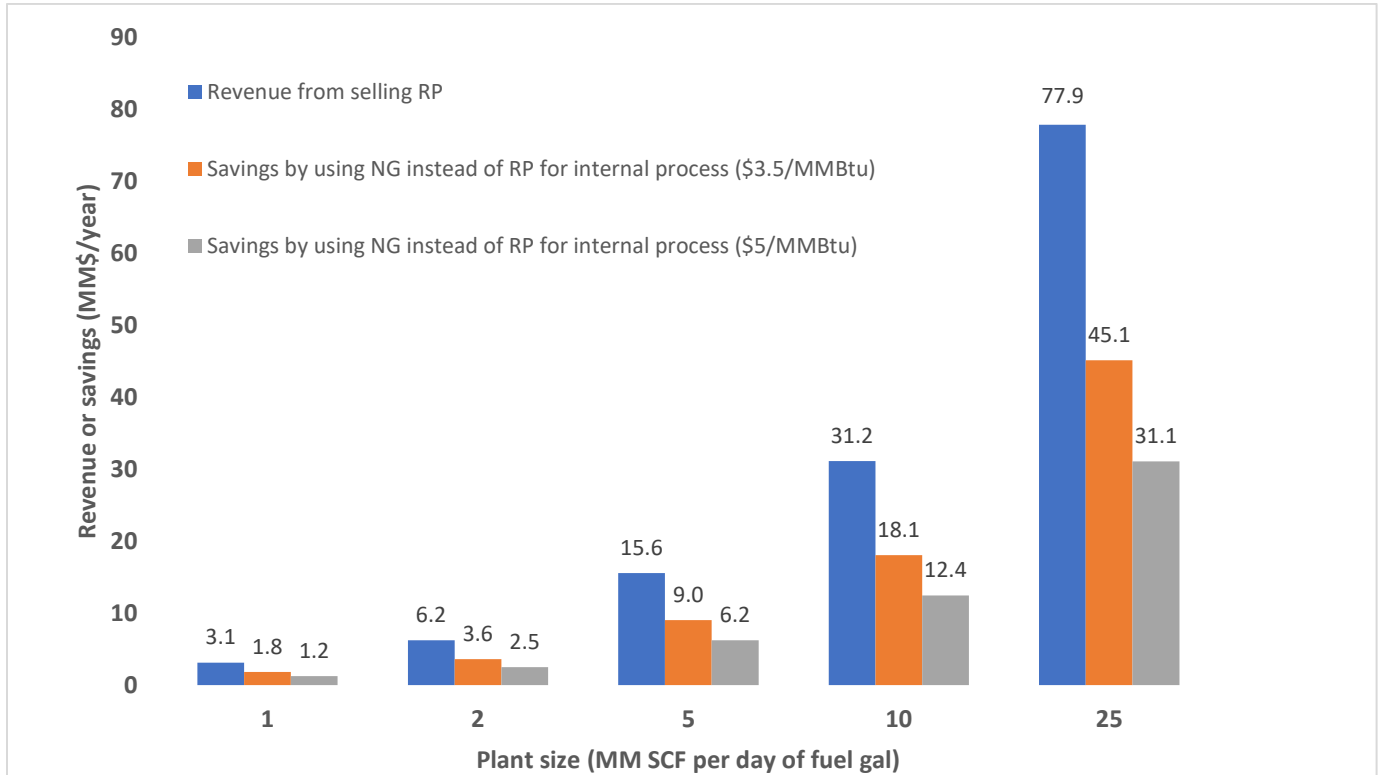


Figure 11. Revenue from selling renewable propane and savings in fuel costs at two natural gas prices (i.e., \$3.5 and \$5/MMBtu) for biorefineries at various sizes.

Sensitivity analysis on payback period: Because of the uncertainties or variations in a number of data/assumptions used to estimate the payback period in the example illustrated in the prior section, we performed a sensitivity analysis on six parameters, including 1) plant size, 2) total installed cost to recover renewable propane (excluding storage cost), 3) annual fixed and variable OPEX, 4) RIN price, 5) carbon price under the LCFS, and 6) carbon intensity of renewable propane produced. Table 4 shows the range of these parameters used in the sensitivity analysis.

	Lower bound	Baseline	Upper bound
Plant size (MMSCF per day of fuel gas)	1	1	25
Total installed cost to recover propane (\$MM)	2.35 (-50% of baseline)	4.7	7.05 (+50% of baseline)
Annual fixed and variable OPEX (\$MM/yr)	1.76 (-50% of baseline)	3.51	5.27 (+50% of baseline)
RIN price (\$/D5 RIN)	0 (assuming that RP from soybean oil does not generate RIN)	0.86 (3-year average, 2019 - 2022)	2.04 (highest price, 2019 - 2022)
Carbon price under LCFS (\$/metric ton of CO ₂)	174 (lowest price, 2019 - 2022)	193 (3-year average, 2019 - 2022)	206 (highest price, 2019 - 2022)
Carbon intensity of renewable propane (g CO ₂ eq./MJ)	0 (CI when using very low CI feedstock such as camelina)	28.5 (One of CARB approved RP pathways; tallow feedstock)	43.5 (Highest CI among 9 CARB approved RP pathways)

Table 4: Ranges in selected parameters used for sensitivity analysis

The results for the single point sensitivity analysis are shown in Figure 12. A number of observations are relevant to this Figure: **1)** Because of the wider range in RIN prices, RIN credits could significantly impact the payback period. Under a worst case, we assume that the renewable propane does not receive RIN credits; losing the revenue from RIN credits (~\$3.3 MM per year in the base case) increases the payback period by 13.7 months. Conversely, the payback period decreases by 5 months if D5 RIN is worth \$2.04 and each gallon of renewable propane receives \$2.24 RIN credits (1.1 times of D5 RIN for each physical gallon of renewable propane). **2)** The economy of scale favors larger biorefineries. Therefore, increasing the plant size from 1MM SCFD per day (baseline fuel gas flowrate) to 25MM SCF per day reduces the payback period by 12.6 months. In other words, the biorefinery could recoup the capital investment in less than 2 months. **3)** Varying CAPEX and annual OPEX required for propane recovery by $\pm 50\%$ also affects the payback period noticeably. The payback period increases by 4-5 months if the CAPEX and the OPEX go up by 50%. **4)** If the renewable propane has a carbon intensity of 0 g CO₂ eq./MJ, it could shorten the payback period by about 3 months. If the carbon intensity increases from 28.5 (baseline) to 43.5 g CO₂ eq./MJ, the payback period increases by 2 months. **5)** The impact on the payback period of carbon price under the LCFS does not appear to be significant within the stated range because the variations are relatively small (from \$174 to \$206/metric ton of CO₂).

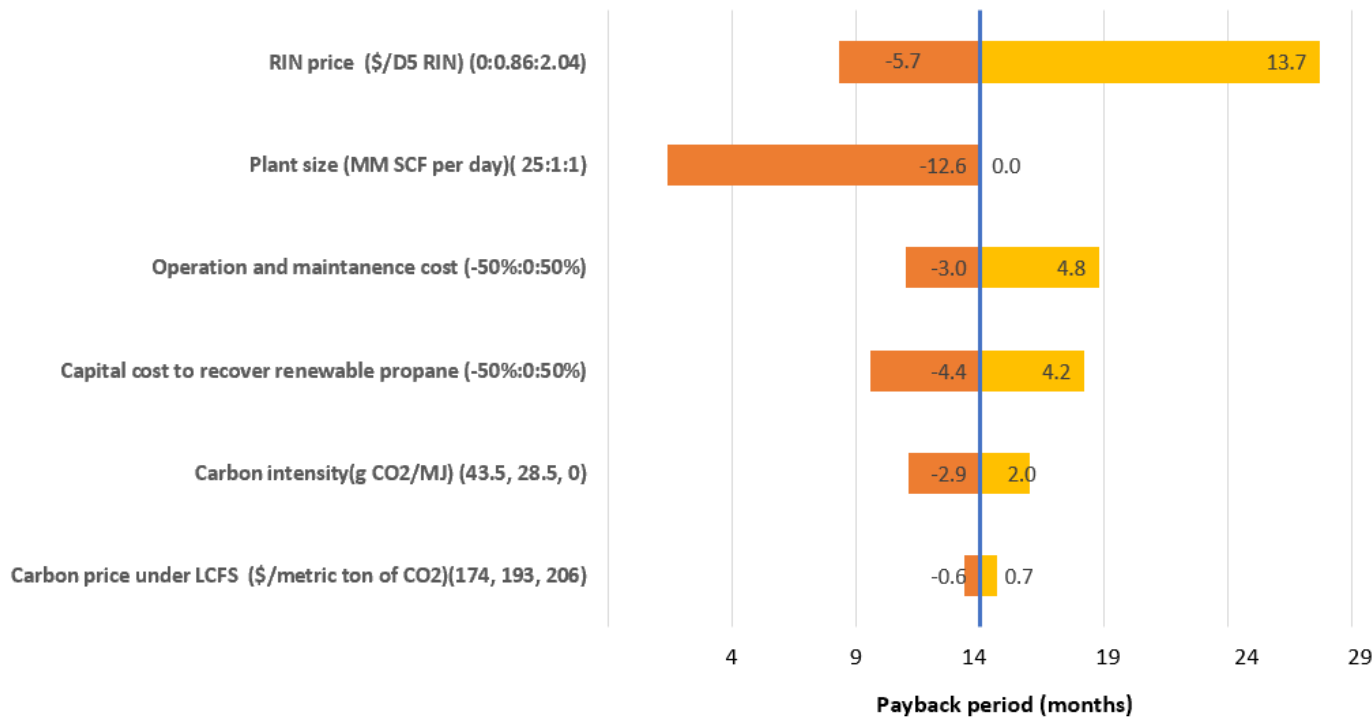


Figure 12. Single point sensitivity analysis results on payback period for renewable propane production. Baseline biorefinery payback is 14 months; orange bars represent shorter payback, yellow bars represent longer payback periods

Conclusions from sensitivity analysis:

- Best case pay back is less than 2 months (for a large biorefinery which produces 25 times fuel gas in comparison to the base case biorefinery) and worst case is 28 months if the renewable propane does not receive RIN credits.
- In order for renewable propane to qualify for RIN credits under the current Renewable Fuel Standard, it needs to have a life cycle carbon intensity below 45 g CO₂ eq/MJ.
- Recovery of LPG irrespective of the volume percentage of butane has a much shorter payback and could prove to be lucrative for the biorefinery.

Impact of Producing Renewable LPG: As mentioned in Part 1 of this report, an important finding is that HEFA biorefineries produce significant quantities of renewable butanes (normal plus iso-) – depending on feedstock and processing conditions up to 2X the renewable propane yield. This finding suggests that marketing renewable LPG could represent a very strong value proposition for the biorefinery operator. While a comprehensive analysis of the impact of recovering and selling renewable butane is beyond the scope of this study, the following general aspects are noted here:

- 1) Producing renewable butane rather than spec-grade propane could result in significant savings in CAPEX for the installed cost of the unit operations by eliminating the propane purification column (see Figure 3). This will, however, possibly increase costs for storage and handling.

- 2) Recovery of butane will in addition provide increased revenue due to the volumes of this material produced. However, this may also increase the need for make-up natural gas and might require approval of CI score for the fuel product from regulatory agencies.
- 3) Butanes from HEFA biorefineries may be rich in iso-butane, which is a very valuable petrochemical intermediate. Recovery and sale of renewable iso-butane could present an extremely strong value proposition to the biorefinery operator.

Value proposition for producing renewable LPG as a co-product

To understand how recovering and selling LPG in lieu of renewable propane may influence the economics, we updated the CAPEX by removing the propane purification column and OPEX by adjusting the utility costs. Compared to producing renewable propane, recovering LPG reduces the base-case CAPEX by ~\$0.4MM and reduces the variable OPEX by about ~\$0.4MM/year due to lower steam and cooling water needs (Singh 2022¹⁹) in 2020\$. The total output of LPG is estimated to be 5.0MM gal per year. Table 5 summarizes the economics of producing LPG as a co-product instead of renewable propane. The estimated payback period is about **5 months** if LPG is produced and sold as a co-product, about 9 months shorter than the payback period when producing renewable propane. It should be noted that no renewable LPG pathways are listed in CARB’s database under the LCFS program. The biorefinery operators will need to verify the CI score and carbon credits with CARB before deciding to produce and sell renewable LPG as a transportation fuel in California.

Initial capital cost (MM\$)	
LPG recovery system	4.3
LPG storage and handling (one 90,000 storage tank)	2.8
Annual revenue and cost (MM\$/Year)	
Revenue1 - Sales of renewable LPG at \$0.89/gallon (3-year average wholesale price from 2019 to 2021)	4.5
Revenue 2 - RIN credits at \$0.86 per D5 RIN (\$0.95/gal of LPG) (3-year average D5 RIN price, 2019 to 2021. 1 gallon receives 1.1 D5 RIN)	4.7
Revenue 3- Carbon credits at \$193/metric ton of CO ₂ under LCFS (3-year average carbon price from 2019 to 2021. CI of 28.5 g CO ₂ /MJ for LPG*)	Year 1 (2022): 5.3 Year 2 (2023): 5.2 Year 3 (2024): 5.1
Cost 1 – Fixed and variable OPEX cost	3.1
Estimated annual net revenue (MM\$/year)	
Annual net revenue = ΣRevenue – ΣCost	Year 1 (2022): 11.3 Year 2 (2023): 11.2 Year 3 (2024): 11.1

Table 5: Capital cost and annual cash flow for producing LPG from a baseline biorefinery. Note:
 *CI is based on CARB’s estimate for REG’s renewable propane produced from U.S. tallow. We assume the CI for LPG is identical to that for renewable propane. Carbon credits (under LCFS) per gallon of LPG = (CI_{LPG} – CI_{gasoline})*Carbon price*LPG output*LHV_{LPG}/1,000,000 where LHV_{LPG} = 89.6 MJ/gallon (GREET 2021), CI_{gasoline} = 89.5 (2022) or 88.25 (2023) or 87.01 (2024), all in g CO₂ eq/MJ.

Renewable Hydrogen from Renewable Propane and LPG: Renewable hydrogen can be produced by steam reforming of light hydrocarbons like propane and butane and mixtures of C3/C4 compounds. A typical steam reforming reactor is shown in Figure 13.

¹⁹ Personal communication with Avantika Singh, who adjusted the costs, LPG throughput, etc. based on the bio-propane ASPEN model developed for the 2018 NREL report (April 2022).

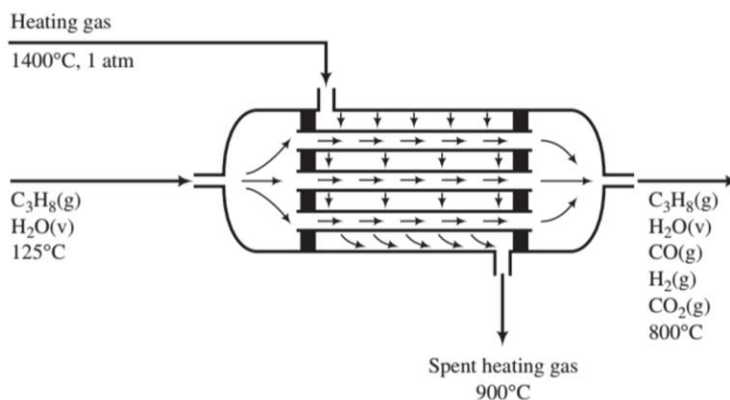


Figure 13. Steam reforming reactor

The reaction is carried out over a nickel-based catalyst in the tubes of a shell-and-tube reactor. Feed to the reactor consists of steam and hydrocarbon in a 6:1 molar ratio. The reactor is heated using waste gas from a boiler and products exit the reactor at 800 °C. Hydrogen is produced from 2 reactions (shown for propane):

- 1) Steam reforming reaction: $C_3H_8 + 3H_2O \rightarrow 3CO + 7H_2$
- 2) Water-gas shift reaction: $CO + H_2O \rightarrow CO_2 + H_2$

One option facing the biorefinery operator is to use renewable propane or LPG to produce renewable hydrogen for sale. Markets for hydrogen as a transportation fuel are extremely limited at this point in time and distribution networks - pipelines for example - that would be needed to move the fuel from the biorefinery to a fueling station are similarly lacking. Accordingly, the following discussion will focus on use of renewable hydrogen as an industrial chemical for hydrotreating, which is an important and emerging market. Renewable hydrogen can be used to lower the carbon intensity of fuels produced either in the biorefinery (where hydrotreating is required as a fuel finishing step) or in a conventional fossil petroleum refinery. Hydrogen used in the biorefinery for hydrotreating can be produced by a variety of technologies including:

- steam reforming of fossil natural gas (methane) with or without carbon capture and sequestration (CCS)
- water electrolysis
- steam reforming of biorefinery process gases with and without CCS

Economic Comparisons: Current estimates for the cost of green hydrogen from water electrolysis range from \$8/kg to \$10/kg. DOE is sponsoring the Hydrogen Earth Shot program that aims to develop renewable hydrogen at \$1/kg - but progress towards this goal is just starting. For purposes of reference, the cost for producing hydrogen from fossil natural gas via methane steam reforming in large world-scale facilities is between \$1.25/kg to \$2/kg depending on the cost of feedstock and plant size; costs range from \$3/kg to \$5/kg for small plants. The feedstock for these facilities is natural gas, which is currently trading at \$4.00/MM BTU or about 19¢/kg²⁰. The 2019 - 2021 2-year average selling price for propane is 89¢/gal which equates to about 42¢/kg. It is important to keep in mind that there are currently no economic incentives such as RIN or LCFS credits for hydrogen as an industrial chemical so economics for producing

²⁰ Taking the heating value of natural gas as 23,811 BTU/lb

hydrogen basically come down to a head-to-head comparison of feedstock costs. Since the cost of renewable propane is 2X the cost for natural gas, it is difficult to see why a producer of industrial hydrogen would be interested in using this as a feedstock.

Further, it is technically infeasible to use an existing methane reformer to process propane. The hydrogen yield from propane is 7/3 (factor of 2.33) that of methane so just keeping the feedrate the same and switching from methane to propane produces dramatically higher volumes of hydrogen; downstream separation and gas cleaning and processing unit operations will not be adequately sized to handle the increased capacity necessitating expenditure of additional CAPEX for equipment replacement and OPEX (specifically, energy costs for compression). If the hydrogen production rate is maintained at the same level by reducing the feedrate, the reforming reactor will not work properly as it is designed to operate at a specific space velocity based on the C1 feed material. So the reactor will either have to be re-designed or replaced – again with significant CAPEX penalties.

Impact of Low-Carbon Hydrogen on Carbon Intensity of Fuels: One possible incentive that could change the economic picture for manufacture of hydrogen from a renewable feedstock (like RP) is the change in carbon intensity of the final product that results from using renewable hydrogen rather than fossil-based hydrogen in hydrotreating. This is an extremely complex issue, but confidential conversations with officials at CARB suggest that the CI impact from switching from fossil-derived hydrogen to bio-derived hydrogen is as simple as the difference in emissions from the two pathways for making hydrogen. In this regard, the carbon intensity of bio-derived hydrogen is key. Data from the California Air Resources Board (CARB) on carbon intensity of hydrogen produced by several processes are shown in Table 3. As can be seen, switching from fossil sources for hydrogen to renewable sources (like landfill gas) has a surprisingly small impact on the carbon intensity of hydrogen produced via steam reforming. Getting very low CI scores for hydrogen requires use of hydrogen from water electrolysis or from very constrained sources such as dairy farm waste where negative CI scores for hydrogen are common due to avoided methane emissions. There are no current CARB pathways that present a quantitative assessment of the impact of switching from fossil hydrogen to renewable hydrogen for biorefinery products, but it could be inferred from the data in Table 6 that the changes will be modest and hence impacts on carbon credits such as the LCFS will be minimal.

Fuel Pathway Code	Pathway Description	Total CI gCO ₂ e/MJ
HYF	Compressed H ₂ produced in California from central SMR of North American fossil-based NG	117.67
HYFL	Liquefied H ₂ produced in California from central SMR of North American fossil-based NG	150.94
HYB	Compressed H ₂ produced in California from central SMR of biomethane (renewable feedstock) from North American landfills	99.48
HYBL	Liquefied H ₂ produced in California from central SMR of biomethane (renewable feedstock) from North American landfills	129.09
HYEG	Compressed H ₂ produced in California from electrolysis using California average grid electricity	164.46
HYER	Compressed H ₂ produced in California from electrolysis using solar- or wind-generated electricity	10.51

Table 6. Hydrogen carbon intensities (CARB)

Thus, it is inferred from the above cursory analysis that the value proposition offered by the sale of renewable propane for transportation and forklift markets, with suitable incentives such as EPA RINs and CARB LCFS, will be far better than using renewable propane as either a process gas or feedstock for producing renewable hydrogen.

Alternative sources of renewable propane

The HEFA process is a pathway to sustainable aviation fuel and renewable diesel with renewable propane as a byproduct, but HEFA biorefineries alone cannot meet the projected demand for propane. **Existing HEFA plants and planned expansion could potentially provide several hundred million gallons of renewable propane per year, but this is far short of the 10B GPY that is currently being used in the US; other technologies will be needed to meet medium- and long-term need.**

There are several emerging stand-alone technologies that could be used to make renewable propane from sustainable feedstocks, including:

- Cool LPG
- Methanol-to-Olefins (MTO) with hydrogenation of olefins
- Catalytic conversion of sugars (Virent and others)

In the short term, it is unlikely that significant quantities of renewable propane will be produced by single-purpose stand-alone or dedicated processes since the value proposition for renewable propane as a transportation fuel is not as well developed as is the case for other fuels such as diesel and jet. What is likely however is that propane will be produced as a by-product from biorefineries producing other renewable transportation fuels; ***accordingly, this section of the report will focus on technologies that enable production of renewable propane as a by-product or co-product.*** Table 7 shows a collection of current and emerging biofuels production pathways that either are or could be producing propane as a by-product. The pathways in the table are

listed by the Technology Readiness Level²¹ (TRL) with those that are closest to commercialization (TRL 8-9) at the top and those being investigated by laboratory research (TRL 1-2) at the bottom. As a cautionary note, the data in this table for ‘Potential RP’ assume that the required feedstocks will be available at the levels shown in the column labeled ‘Feedstock Supply’. In reality the supply of feedstock – particularly FOG – will be limited due to competition between existing and emerging biorefineries in the USA. Thus, the numbers for ‘Potential RP’ need to be considered as *hypothetically available* given no constraints in feedstock availability.

In the following section of this report, we will discuss the state of these technologies, their potential for producing renewable propane and their carbon intensity. As with the table, we will discuss the technologies in order of their stage of development.

²¹ TRL is a measure of technology maturity, with TRL = 9 a commercial process and TRL = 1 still in the early R&D stage

Table 7. Overview of technologies for producing renewable diesel and sustainable aviation fuel

	Technology	Companies	Feedstock	Feedstock Supply TPY	Potential RP GPY	CI gCO ₂ eq/MJ
Existing commercial plants	HEFA	REG, Valero, etc.	FOG	5.7 M	0.2 B	22 – 44
Planned commercial plants	Gasification/FT	Velocys, Red Rocks Biofuels	Forest Resources	97 M	1.9 B	6 – 13
	Gasification/FT	Fulcrum	Waste	142 M	2.7 B	52 – 56
Commercial technology for some steps	Gasification/MTG	Arbor/Haldor Topsoe	Forest Resources	97 M	0.8 B	6 – 13
	Ethanol to iet	LanzaJet	Ag Residue	176 M	8.5 B	22 – 71
	Fermentation to butanol + hydrotreating and cracking	GEVO	Agricultural residue	176 M	18.9 B	22 – 71
	Glycerin from biodiesel + hydrotreating	Biofuels Solution, REG	FOG	5.7 M	0.2 B	22 – 44
	Pyrolysis + FCC	Ensyn	Forest Resources	97 M	3.1 B	22
Pilot scale	Catalytic pyrolysis	Anellotech	Forest Resources	97 M	1.0 B	22
	Hydrocatalytic fast pyrolysis	GTI/Shell (IH2)	Forest Resources	97 M	5.2 B	9
	Aqueous phase reforming	Virent	Ag Residue	176 M	3.7 B	22 – 71
	Ethanol to Jet	Vertimass	Ag Residue	176 M	8.5 B	22 – 71
Laboratory Research	Fermentation to butyric acid + decarboxylation	NREL	Ag Residue	176 M	4.7 B	22 – 71
	Nonthermal conversion of RNG	Plasmerica	Waste	142 M	1.5 B	N/A

Feedstock Availability

Production of renewable fuels with HEFA is limited due to availability of fats, oils, and greases (FOG) and other conversion processes should be considered that rely on more abundant biomass feeds. The production of FOG in the US is currently about²² 5.7Mt/y and is not likely to grow much further. This is not enough material to meet the demands for SAF, RD and renewable propane. If all this feedstock was used to produce SAF and the yield of propane was 6% from the HEFA process, then the total yield of renewable propane would be about 180M GPY, far short of the current consumption. Further, there will be competition from food production for some of the FOG that is produced and some of the fats are not practical for biofuels production. Clearly other processes are required to meet the demand for renewable propane. Technologies that rely on biomass or waste as a feedstock are much more robust and will be better suited to meet the renewable propane yield. For instance, forestry resources, waste and agricultural residues could supply 97, 140 and 149 Mt/y of feedstock²³ (Table II). Depending on the yields of propane from the process shown, the potential production of renewable propane can be significant from these feedstocks.

Feedstock	2017	2022	2030	2040
	Million dry tons			
Currently used resources				
Forestry resources	154	154	154	154
Agricultural resources	144	144	144	144
Waste resources	68	68	68	68
Total currently used	365	365	365	365
Potential: Base-case scenario				
Forestry resources (all timberland) ^{a,b}	103	109	97	97
Forestry resources (no federal timberland) ^{a,b}	84	88	77	80
Agricultural residues	104	123	149	176
Energy crops ^c		78	239	411
Waste resources ^d	137	139	140	142
Total base-case scenario potential (all timberland)	343	449	625	826
Total base-case scenario (currently used + potential)	709	814	991	1,192
Potential: High-yield scenario				
Forestry resources (all timberland) ^{b,e}	95	99	87	76
Forestry resources (no federal timberland) ^{b,e}	78	81	71	66
Agricultural residues	105	135	174	200
Energy crops ^{c,f}		110	380	736
Waste resources ^d	137	139	140	142
Total high-yield scenario potential (all timberland)	337	483	782	1,154
Total high-yield scenario (currently used + potential)	702	848	1,147	1,520

Note: Numbers may not add because of rounding. Currently used resources are procured under market prices.

^a Forestry baseline scenario.

^b Forestry resources include whole-tree biomass and residues from chapter 3 in addition to other forest residue and other forest thinnings quantified in chapter 5.

^c Energy crops are planted starting in 2019. Note: BT2 assumed a 2014 start for energy crops.

^d The potential biogas from landfills is estimated at about 230 billion ft³ per year as shown in table 5.12.

^e Forestry high-housing, high biomass-demand scenarios.

^f The high-yield scenario assumes 3% annual increase in yield.

Table 8. Biomass feedstocks from Billion Ton study

²² <https://www.ers.usda.gov/data-products/u-s-bioenergy-statistics/>

²³ 2016 Billion-Ton Report, Oak Ridge National Laboratories, 2016.

The geographic location of biomass in the US is an important consideration for biomass conversion processes because transportation costs of biomass can be significant. Figure 14 shows plots of the distribution of two key biomass sources in the US, agricultural residues and forest residues. As can be seen, agricultural residues are centered in the Midwest, while forest residues are located in the south, northwest and other northern states.

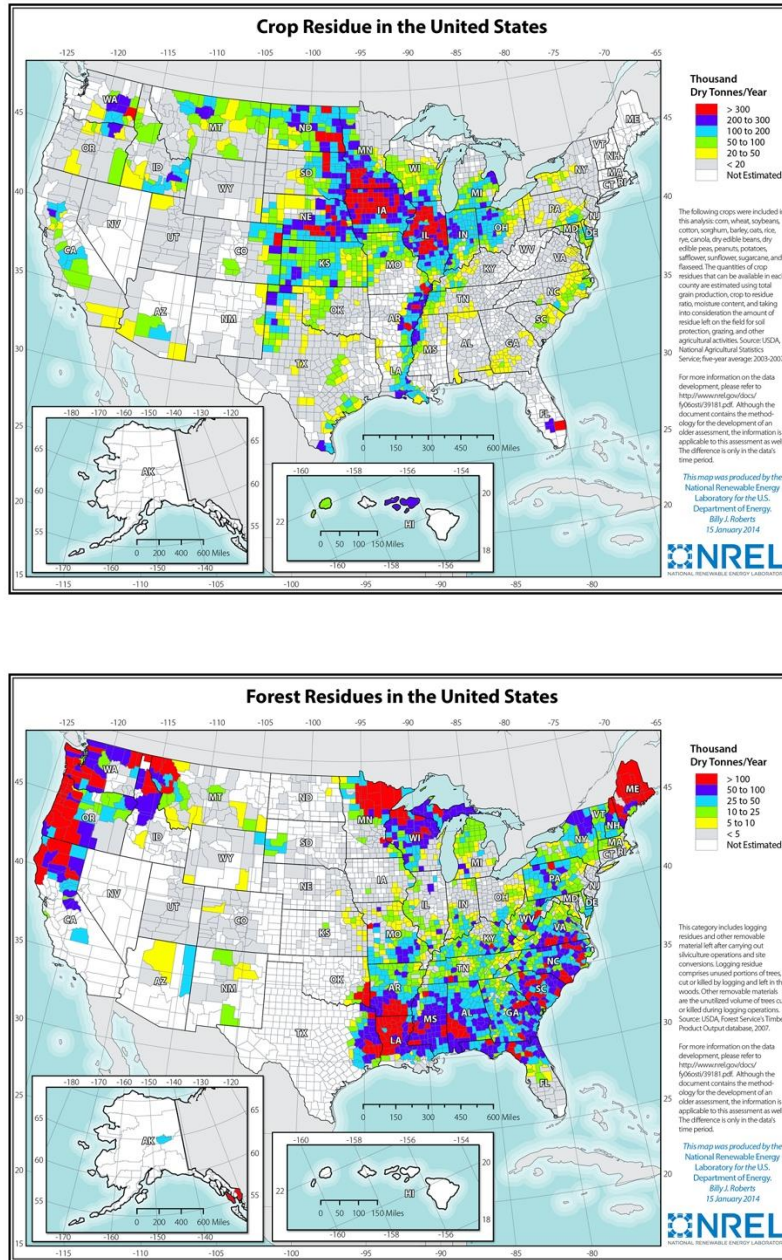


Figure 14. Distribution of biomass resources²⁴ in the US.

²⁴ <https://www.nrel.gov/gis/biomass.html>

Commercial plants planned

Several commercial biofuels plants using technologies other than HEFA are being planned or constructed to produce sustainable aviation fuel (SAF) or renewable diesel. Renewable propane could be a co-product in these plants depending on the technology. Table 1 lists four plants that will use gasification and Fischer-Tropsch synthesis or ethanol-to-jet technologies to produce hydrocarbons in the jet or diesel fuel range.

Gasification and Fischer-Tropsch: The gasification/Fischer-Tropsch (FT) synthesis pathway involves heating biomass to high temperature (700 – 1000°C) to produce synthesis gas (a mixture of carbon monoxide and hydrogen) followed by gas clean up and conditioning and catalytic conversion of syngas (FT) to hydrocarbon products. The FT technology can produce naphtha, jet and diesel fuel with higher molecular weight hydrocarbons being produced at lower temperatures. Hydrocracking or hydrotreating may be required to optimize fuel properties. Both gasification and FT technologies are well established for fossil fuels (dating from the early 1900s) but coupling gasification to FT synthesis in a commercial operation is only currently practiced at large scale in South Africa²⁵. The feedstock for these plants was primarily coal but has been shifting to natural gas. For biomass gasification, only one plant is operational in the world – the Enerkem Alberta Biofuels facility²⁶ in Edmonton, Alberta, Canada, which is producing bio-methanol, bio-ethanol and other chemicals. No commercial biomass-based gasification/FT plant exists, but the technology is mature, and several commercial plants are in planning or construction. The yield of propane from FT can be estimated from the plot of products shown in Figure 15, which shows the products as a function of the alpha value from the Anderson-Schulz-Flory theory. The alpha value is the ratio of the propagation rates to the sum of the propagation and termination rates and is dependent upon the reaction temperature, catalyst type and hydrogen-to-carbon ratio. The preferred feedstock for gasification is woody biomass because of the low ash content. High ash feedstocks such as herbaceous biomass (agricultural resources) can present slagging problems in the gasifier and gas clean up problems.

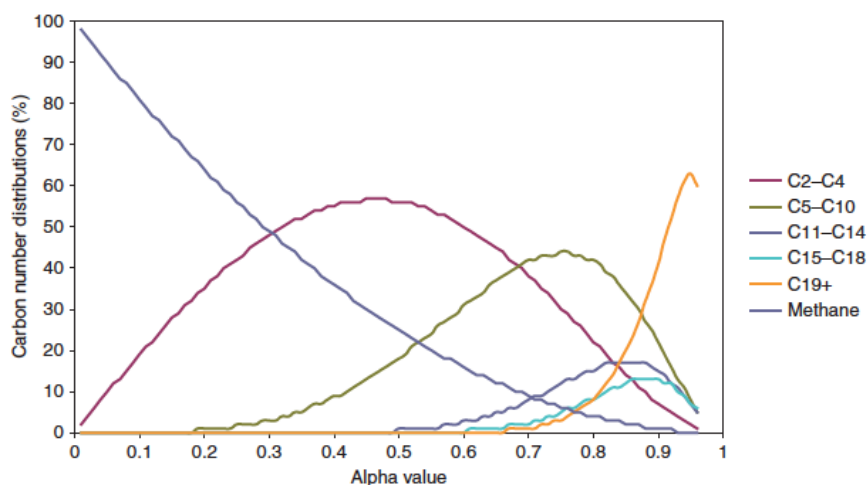


Figure 15. Distribution of products from Fischer-Tropsch synthesis²⁷ as a function of alpha value.

²⁵ <https://www.netl.doe.gov/research/Coal/energy-systems/gasification/gasifipedia/sasol>

²⁶ <https://enerkem.com/>

²⁷ Evans, G., and C. Smith. "Biomass to liquids technology." (2012): 155-204.

Velocys: Velocys has developed an FT synthesis reactor that can be employed with other demonstrated gasification, purification and hydrocracking technologies to produce renewable diesel and jet fuels. They claim an alpha value²⁸ of about 0.9, suggesting that the yield of LPG is about 7% from the plot in **Figure 2**. The yield of diesel from the FT process has been estimated²⁹ to be about 13% and thus the calculated potential for renewable propane from this technology is about 1.9B GPY. Actual yields may be much lower than this depending on their operating conditions. Private conversations have indicated that the yields may be closer to 3%. The carbon intensity for gasification/FT using biomass is calculated³⁰ to be low (6 – 13 gCO₂eq/MJ).

Development: Velocys is working on two projects, a 20M GPY plant in Immingham, UK and a 25M GPY plant in Natchez, MS. They also just signed a collaborative agreement with Toyota to build a biofuels plant in Japan.

Reference: <https://www.velocys.com/>

Red Rock Biofuels: Red Rock's initial plant (under construction) is located in Lakeview, Oregon and will use waste woody biomass for gasification and FT synthesis. They use FT technology developed by Velocys³¹ and should have a similar yield of renewable propane. They will use forestry residue to produce their biofuels and should have a low carbon intensity³² (6 gCO₂eq/MJ).

Development: Their plant at Lakeview OR is under construction and will produce 10M GPY SAF. Construction on the plant has apparently halted because Red Rock Biofuels recently parted with their financial partners and is searching³³ for a new financial partner.

Reference: <https://www.redrockbio.com/>

Fulcrum Bioenergy: Fulcrum is building a FT plant in Storey County, Nevada 20 miles east of Reno that will use municipal solid waste (MSW) from the nearby Lockwood Regional Landfill. According to the EPA and information from Enerkem, 20 – 50 % of the carbon in MSW is from anthropogenic sources, primarily plastics, which limits the reduction in GHG relative to petroleum-based diesel. Fulcrum will gasify the MSW and convert it to a FT-wax syncrude that will be further processed by Marathon Petroleum into transportation fuel. It is not clear if the syncrude will be processed separately or mixed with petroleum and processed in a conventional petroleum refinery. Due to the scale of the plant, the latter is more likely. This would also reduce the amount of biogenic carbon in the fuel, depending on the mixing ratio. We have used the same yield numbers as for Velocys and this technology has the potential to produce 2.7B GPY given the amount of waste available. However, since the waste contains about 50% anthropogenic carbon the carbon intensity could be high (52 – 56 gCO₂eq/MJ), assuming that the carbon intensity from anthropogenic waste is the same as petroleum feed.

Development: Fulcrum is building a plant near Reno NV that will produce 10M gallons per year (GPY) when completed and they have plans for three other plants with output ranging from 20 to

²⁸ LeViness, Top Catal (2014) 57:518–525

²⁹ de Jong, Biofuels, Bioprod. Bioref. 9:778–800 (2015)

³⁰ de Jong et al. Biotechnol Biofuels (2017) 10:64

³¹https://www.energy.gov/sites/prod/files/2019/04/f61/Woody%20Biomass%20Biorefinery%20Capability%20Development_EE000DPA2.pdf

³² de Jong et al. Biotechnol Biofuels (2017) 10:64

³³ <https://www.businesswire.com/news/home/20220214005150/en/Red-Rock-Biofuels-Begins-Search-to-Source-Development-Partner>

33M GPY. It is not clear if these other plants will use MSW as a feed or if the crude will be further processed with petroleum in a petroleum refinery.

Reference: <https://fulcrum-bioenergy.com/>

Gasification + Methanol to Gasoline: In this process, biomass is gasified, and the syngas is used to synthesize methanol, which is then used in a methanol to gasoline (MTG) process. The MTG process has been commercialized by Haldor Topsoe (TIGAS) and ExxonMobil and has been used for syngas generated from natural gas or coal. **This process yields about 12% LPG and could be used as a source of renewable propane if biomass was used as the source of syngas.** There are no biomass gasification/MTG refineries in operation, but Arbor Renewable Gas is planning to build such a refinery.

Arbor Renewable Gas: Arbor plans to build a gasification/MTG plant using the TIGAS MTG process developed by Haldor Topsoe. They will be using waste wood as a feedstock and the carbon intensity should be low (6 gCO₂eq/MJ), assuming that the CI is similar to gasification/FT. The yields of LPG from this process³⁴ (9.3 ga/ton biomass) results in a potential of 0.8 B GPY.

Development: Arbor is planning a 15M GPY facility in Beaumont, TX and claimed in 2019 that they would start construction in 2022. There have not been any press releases since November, 2019.

Reference: <https://www.arborgas.com/>

Ethanol to Jet: The ethanol to jet (ETJ) process converts ethanol to paraffins through a process that involves dehydration of the alcohol to olefins, oligomerization of the olefins, and hydrotreating of the resulting long chain olefins to paraffins. Propane or LPG can be produced as a by-product from the hydrotreating or coupling reactions. This technology builds on the well-established ethanol industry that grew rapidly during the last twenty years but has run into a blend wall (maximum blend of 10% ethanol in gasoline). As a result of this and declining gasoline sales the industry is looking for new markets. ETJ provides such a market and the first commercial plant using this technology is being built. However, there is concern about the impact of this technology on GHG reduction. All the commercial ethanol industry in the US relies on sugars that are derived from plant starch (corn starch), which is cheaper than sugars derived from plant cellulose³⁵. Unfortunately, starch-based ethanol production provides a much lower reduction in GHG reduction compared to cellulosic ethanol. For instance, the GHG reduction for cellulosic ethanol from switchgrass is 80% relative to gasoline while it is only 25% for ethanol from corn starch (Figure 16). The source of the ethanol should be considered for the ETJ, due to this concern. The preferred biomass feedstock for cellulosic ethanol production, which is the source for ETJ, is herbaceous biomass such as corn stover (agricultural resources).

³⁴ Phillips *et al.*, NREL technical report, NREL/TP-5100-47594, 2011

³⁵ Cheng, M. H.; Huang, H.; Dien, B. S.; Singh, V., The costs of sugar production from different feedstocks and processing technologies. *Biofuels, Bioproducts and Biorefining* **2019**, *13* (3), 723-739.

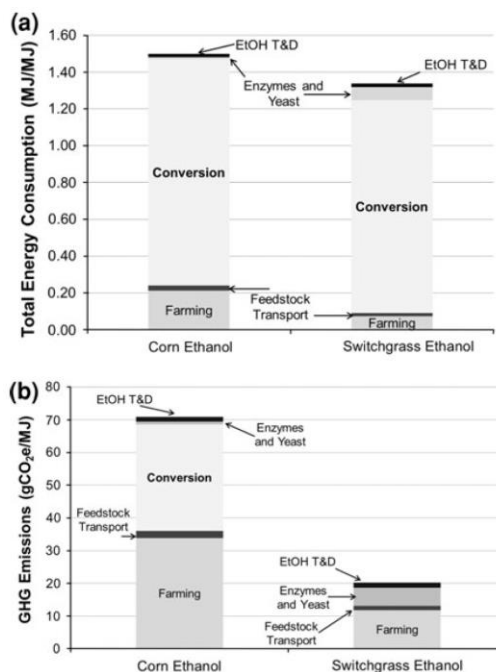


Figure 16. Comparison³⁶ of ethanol production from starch (corn) and cellulotics (switchgrass). Gasoline life cycle emissions are 93.5 gCO₂/MJ.

LanzaJet: The LanzaJet process for making jet and diesel fuel relies on the three-step process (Figure 17) where ethanol dehydration, oligomerization and hydrogenation are done in three separate steps. The LanzaJet process is supported by work from the Pacific Northwest National Lab (PNNL) and produces a mixture of C₈ – C₂₂ paraffins that fits into both the jet (C₈ – C₁₆) and diesel (C₁₀ – C₂₂) range. The current technology includes recycle of propane: after the dehydration/oligomerization step, C₂ – C₄ products (including propane) are recycled back to the feed stream. The LPG in this stream is about 9% of the total yield and could be diverted for renewable propane. **Ethanol produced from corn stover would result in a carbon intensity of about 22 gCO₂eq/MJ, but this would climb to 71 gCO₂eq/MJ for ethanol produced from corn starch.**

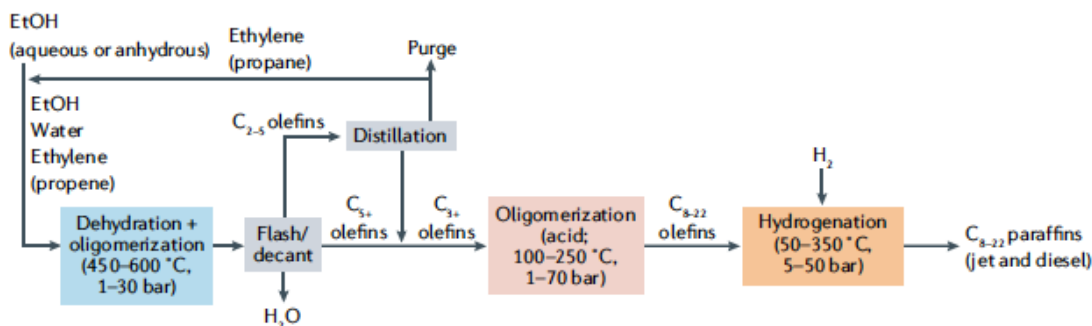


Figure 17. Three step process for producing hydrocarbons from ethanol.³⁷

³⁶ Dunn, J. B.; Mueller, S.; Wang, M.; Han, J., Energy consumption and greenhouse gas emissions from enzyme and yeast manufacture for corn and cellulosic ethanol production. *Biotechnology Letters* **2012**, *34* (12), 2259-2263.

³⁷ Eagan, N. M., Kumbhalkar, M. D., Buchanan, J. S., Dumesic, J. A. & Huber, G. W. Chemistries and processes for the conversion of ethanol into middle-distillate fuels. *Nature Reviews Chemistry* **3**, 223-249, doi:10.1038/s41570-019-0084-4 (2019).

Development Status: Lanzajet has received backing from Suncor, Mitsui and the Microsoft Climate Innovation Fund and is planning a 10M GPY plant at their Freedom Pines facility in Soperton, GA that is scheduled³⁸ to come online in 2022.

Reference: <https://www.lanzajet.com/>

Partially Commercialized Process Pathways

For the following processes at least one step in the process has been commercialized, but other steps are still in the exploratory stage.

Sugar fermentation: Converting sugars to fuel hydrocarbons encompasses several technologies that are being researched with a limited amount of commercial development. Sugars can be sourced either from starch sources (lower cost, higher GHG emissions) or lignocellulosic biomass (high cost, low GHG emissions). Lignocellulosic sugars often require multiple steps (pretreatment, hydrolysis), which increases cost, but utilizes larger amounts of the plant biomass. Herbaceous biomass is typically the preferred feedstock for these pathways. Fermentation typically produces oxygenated intermediates, that can be converted into hydrocarbon using conventional processes (coupling, hydrotreating). Opportunities for producing LPG arise in these downstream processes.

Gevo: Gevo has developed a process that ferments sugars to produce isobutanol, which can be converted to aviation fuel using a similar process to the ETJ process but can also be directly converted to LPG. This process is particularly well suited to jet fuel because the branched alcohol feed leads more readily branched paraffins that are ideal for aviation fuel. The butanol can be diverted to making LPG by hydrotreating and cracking, though this has not been discussed by GEVO. Producing propane will have to compete with production of propylene, which is much more valuable. However, if the butanol could be diverted to LPG, there is a very high potential output. Up to 18.9B GPY could be produced. As with ethanol, the source of the sugars contributes to the cost of the fuel and the carbon intensity. We assume that the CI would be the same for ETJ depending on feedstock; 22 gCO₂eq/MJ for cellulosics and 71 gCO₂eq/MJ for starch-based sugars.

Development Status: Gevo is planning to build a plant at Lake Preston, SD, which is close to their facility in Luverne, MN. They are planning to produce 45M GPY of gasoline and jet fuels.

Reference: <https://gevo.com/>

Glycerin Dehydration/hydrogenation: Glycerin is a byproduct from the production of biodiesel (transesterification of triglycerides or fatty acids) and could be used as a source of renewable propane. The glycerin could be converted into propane by hydrodeoxygenation, which has been reported³⁹ in the literature and studied at the pilot scale⁴⁰. The biodiesel market is well developed and produces about 1.8B GPY, but there is no known commercialized process for producing propane from the resulting glycerin, which is a low value product. **Bio-fuel Solution** (<https://www.biofuel-solution.com/>) claims to be pursuing this pathway but there has been no activity on their website since 2012. **REG** is a large producer of biodiesel, but they appear to be selling the glycerin without upgrading. They produce renewable propane, but that comes from

³⁸ <https://www.suncor.com/en-ca/newsroom/news-releases/2042333>

³⁹ Brandin, *et al.*, "Bio-Propane from glycerol for biogas addition" SGC report 198•1102-7371, 2008

⁴⁰ Hultberg, *et al.* "Demonstrating Renewable Propane" Energiforsk, report 2018:538, 2018.

their HEFA process. Renewable propane from biodiesel suffers from the same limitations as HEFA in that there is a limited availability of feedstocks for biodiesel, which is essentially the same as for HEFA. The maximum production of propane from this pathway is 0.2B GPY as discussed above. However, there are potential routes for producing glycerin from directly from biomass⁴¹, which could produce propane on a much larger scale. This would be a multistep process and would likely be very expensive. We estimate that renewable propane as a coproduct from biodiesel production would have the same carbon intensity as HEFA⁴², 22 – 44 gCO₂eq/MJ.

Pyrolysis: Biomass pyrolysis produces high yields (up to 70%) of a liquid biocrude that could potentially be upgraded to hydrocarbons for transportation fuel and potentially propane. The biocrude contains 40% oxygen and up to 30% water that must be removed, and hydrogen must be added to produce paraffins. Three pathways to renewable transportation fuel have been proposed: 1) hydrotreating pure biocrude; 2) co-feeding the biocrude with petroleum feeds into a refinery hydrotreater, or; 3) co-feeding the biocrude in a refinery Fluid Catalytic Cracker (FCC). Hydrotreating pure biocrude has proven to be difficult because of fouling of the catalyst. Co-feeding the biocrude into a petroleum refinery hydrotreater or an FCC would likely be done with low concentrations of the biocrude because of the difference in scales for biocrude production and petroleum refining and because of the low solubility of biocrude. For instance, 5 – 10% biocrude would be introduced into a petroleum stream and as a result, the amount of renewable carbon in the fuel would be low. Introduction into the FCC is also problematic because this operation typically produces gasoline range fuels. Commercial scale co-feeding of biocrude into a refinery hydrotreater has not been reported. The preferred feedstock for pyrolysis is woody biomass (forest resources).

Ensyn: Ensyn uses a technology that they call Rapid Thermal Processing (RTP), in which the biomass is heated in an entrained flow reactor and the vapors are condensed into a biocrude. This biocrude has largely been used as a fuel for heat or electricity generation. Recently, Ensyn has been working with other partners (Honeywell UOP, Chevron, Petrobras) to co-feed their biocrude into FCC reactors with petroleum feeds such as vacuum gas oil (VGO). This operation largely produces gasoline and some LPG. They report producing 8 – 12% LPG with 5 – 10% cofeeding of biocrude with VGO. Based upon this and the yield of pyrolysis oils (60%), we estimate that the potential for renewable propane from this source is high, about 3.1B GPY. The carbon intensity for this pathway should be lower than pyrolysis with hydrotreating⁴³ (22 gCO₂eq/MJ). However, the biogenic carbon will be diluted with anthropogenic carbon and demonstrating the yields of biogenic propane will be required to obtain renewable carbon credits.

Development Status: Ensyn has a 70 ton/day commercial pyrolysis facility in Renfro, Ontario and has completed construction of a 200 ton/day commercial plant in Port-Cartier, Quebec, which produces 10.5M GPY of biocrude. No commercial development of FCC conversion of these oils has been reported.

Reference: <http://www.ensyn.com/>

⁴¹ Hulteberg, *et al.* “Demonstrating Renewable Propane” Energiforsk, report 2018:538, 2018.

⁴² de Jong *et al.* *Biotechnol Biofuels* (2017) 10:64

⁴³ de Jong *et al.* *Biotechnol Biofuels* (2017) 10:64

Pilot plants

These processes have been demonstrated at a pilot scale, primarily with a focus on transportation fuel (naphtha, aviation and diesel)

Catalytic Pyrolysis (CP): With this process, pyrolysis vapors are catalytically upgraded to reduce the oxygen content of the resulting crude, which may need additional hydrotreating to produce fuels and renewable propane. There are a variety of approaches for making hydrocarbons using this technology. Hydrogen can be added to the process to facilitate the removal of oxygen and there are several types of catalysts that have been used to improve the yields and properties of the biocrude. The improved ability to hydrotreat the oil significantly improves the economics of the overall biofuel production and CP is considered a viable route to hydrocarbons. Anellotech is using CP to produce aromatic molecules as chemical products, but under. GTI's process (IH2) is a high pressure (10 – 35 Bar) containing hydrogen but is primarily focused on transportation fuel. As with pyrolysis, woody feedstocks are preferred.

Anellotech: Anellotech uses catalytic pyrolysis with a metal modified zeolite catalyst to convert biomass pyrolysis into an aromatic stream for sales as a chemical product and a stream that can be hydrotreated to produce a transportation fuel. They produce significant amounts of light gas from the process, including about 10% hydrocarbons⁴⁴. Given this yield the potential for this process is about 1B GPY of propane. We assume a similar carbon intensity as for pyrolysis⁴⁵, 22 gCO₂eq/MJ. Development Status: Anellotech has built and operated a pilot plant for 5,000 hours based upon their technology. They are looking for funding to build a commercial plant that could process 150 tonnes biomass/day.

Reference: <https://anellotech.com/>

GTI/Shell: GTI, a research and development company, developed the IH2 process, which is a catalytic pyrolysis process in the presence of high-pressure (10 – 35 Bar) hydrogen. They licensed the technology to Shell, who is trying to commercialize it. They claim⁴⁶ a 10% LPG yield, which suggests that the potential yield of renewable propane from this pathway could be 5.2B GPY. They claim a 90% reduction in GHG with this process compared to fossil fuel, suggesting a carbon intensity of about 9 gCO₂eq/MJ.

Development Status: GTI conducted 50 kg/d experiment pilot scale experiments of the IH2 process and Shell has built a 5 tonne/d demonstration plant in India.

Reference:<https://www.shell.com/business-customers/catalysts-technologies/licensed-technologies/benefits-of-biofuels/ih2-technology.html>

Aqueous phase reforming: The aqueous phase reforming process encompasses a series of reactions in which sugars are converted into hydrocarbon using in-situ generated hydrogen. Products from the process include naphtha, jet and diesel range hydrocarbons as well as LPG. Typically, the LPG is burned for process heat, but could be diverted for renewable propane.

⁴⁴ Jae *et al.* ChemicalEngineeringScience 108(2014)33–46

⁴⁵ de Jong *et al.* Biotechnol Biofuels (2017) 10:64

⁴⁶ Chen *et al.* Energies 2021, 14, 3916.

Virent: Virent is a subsidiary of Marathon and is the only known company pursuing aqueous phase reforming using a process that they call Bioforming⁴⁷, which they have tested at the pilot scale. The technology can use sugars from plant starch or by pretreating lignocellulosic biomass. Typically, the feedstocks used for this technology are agricultural residues. Figure 18 shows a typical distribution of hydrocarbon products from Bioforming. As can be seen, 26% of the carbon is found in the C1 – C4 range and if we assume that 50% of this is methane⁴⁸, then the LPG yield is about 13%. As a result, this pathway has a high potential for production of renewable propane, up to 3.7B GPY. The carbon intensity of this process can be assumed to be similar to fermentation processes or alcohol to jet⁴⁹, 22 gCO₂eq/MJ for lignocellulosic sugars and 71 gCO₂eq/MJ for starch sugars.

Development Status: The Virent technology is at TRL 7-8 and is ready for commercial license.

Reference: <https://www.virent.com/>

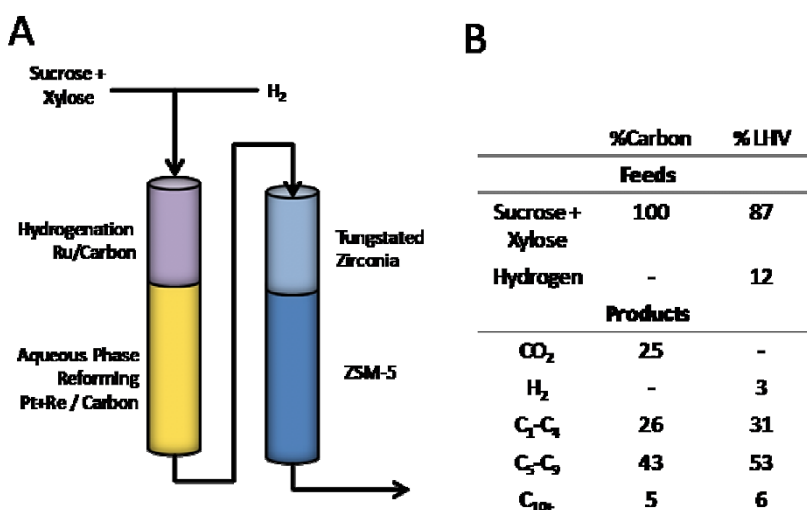


Figure 18. Schematic of the Bioforming process and product yields.

Ethanol to Jet (single stage)

Vertimass: The Vertimass process is similar to the Lanzajet process, except the dehydration, oligomerization and hydrogenation steps are combined into a single unit operation, which can reduce the cost of the fuel (Figure 19). The process is called consolidated alcohol dehydration and oligomerization (CADO), which has been tested at the pilot scale. As with the Lanzatech process, light gases are produced from the dehydration and oligomerization. We assume that the yields are similar to the Lanzatech process and that the potential for renewable propane is high; up to 8.5B GPY. We also assume that the carbon intensity would be the same as for the Lanzatech process 22 – 71 gCO₂eq/MJ, depending on the source of sugars.

Development Status: Vertimass has demonstrated their technology at the pilot-plant scale and are actively seeking scale-up partners. They have partnered with UGI to develop a commercial plant

⁴⁷ Blommel and Cortright, “Production of Conventional Liquid Fuels from Sugars”, 2008.

⁴⁸ Coronado *et al.* Int. J. Hydro. En., 41, (2016) 11003 – 11032.

⁴⁹ de Jong *et al.* Biotechnol Biofuels (2017) 10:64

in 2024 with a production of 50 GPY. (<https://www.ugicorp.com/news-releases/news-release-details/ugi-and-vertimass-enter-agreement-produce-renewable-fuels-us-and>)

Reference: <https://www.vertimass.com/>

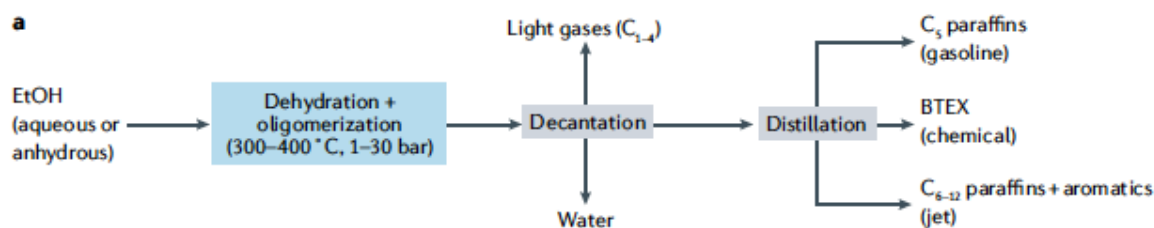


Figure 19. One step process for making hydrocarbons from ethanol.⁵⁰

Laboratory Research

Although there are likely numerous potential biomass conversion pathways being explored at a laboratory scale that could lead to the production of renewable propane, we will only provide information about two. This is not meant to be an exhaustive investigation, but just to provide a flavor of some technologies. For these processes, additional research is needed before they can be scaled up.

Lignocellulosics to butyric acid for SAF: Sugars from lignocellulosic biomass or from plant starch can be fermented into butyric acid, which can be condensed using ketonization into longer chain carbonyls that can be hydrotreated to transportation fuel range hydrocarbons. However, the butyric acid can also be directly converted into propane using decarboxylation, without the need for added hydrogen. This approach to propane synthesis⁵¹ from butyric acid was attempted in 2010 by a small company named C3 Bioenergy, but the company was not successful and quickly dissolved. In spite of their failure, others have investigated this decarboxylation⁵² and have reported yields near 50%. The production of butyric acid has been explored by NREL and has been discussed in technical reports⁵³. The yields of butyric acid from fermentation are greater than 10% (based upon dry biomass – agricultural residues) and the potential for renewable propane is high. Up to 4.7B GPY. The carbon intensity of this process should be similar to other fermentation processes; 22 – 71 gCO₂eq/MJ.

Non thermal conversion of methane: In this process methane of natural gas is converted to propane or other hydrocarbons in a low temperature, low pressure plasma process. Methane could be produced from biomass or waste (bio-gas) and so this could be a pathway to renewable propane. **PlasMerica** is pursuing this pathway.

Reference: <https://www.plasmerica.com/>

⁵⁰ Eagan, N. M., Kumbhalkar, M. D., Buchanan, J. S., Dumesic, J. A. & Huber, G. W. Chemistries and processes for the conversion of ethanol into middle-distillate fuels. *Nature Reviews Chemistry* **3**, 223-249, doi:10.1038/s41570-019-0084-4 (2019).

⁵¹ Fischer *et al.* *Ind. Eng. Chem. Res.* 2011, 50, 4420–4424

⁵² Razak, *Energies* 2021, 14, 3316.

⁵³ Davis *et al.* “Biochemical Conversion of Lignocellulosic Biomass to Hydrocarbon Fuels and Products: 2019 State of Technology and Future Research”, NREL/TP-5100-76567, 2020

Related Development in the UK; Coryton: Coryton is a small UK fuel development company (50 employees) that works with other industry partners to develop and test sustainable fuels. They have conducted research on an ethanol-to-fuel process, which is similar to the ethanol-to-jet process being developed by Vertimass, though they are also focused on producing gasoline. They are also investigating a methanol-to-gasoline process like the Arbor process. For both of these processes, Coryton lists renewable LPG as a co-product, but we could find no description of yields. We also could find no description of plans to scale up either process, which would likely require the assistance of other companies. It appears their work is conducted at a laboratory scale, though they have produced enough fuel for engine tests.

References:

<https://www.zemo.org.uk/assets/presentations/Zemo%20Advanced%20Renewable%20Gasoline%20Session%201.pdf>

<https://coryton.com/latest/the-opportunity-for-sustainable-fuels-in-high-performance-engines/>

Appendix A
List of Acronyms and Abbreviations

ATJ: Alcohol to Jet
CARB: California Air Resources Board
CAPEX: Capital Expenditures
CP: Catalytic Pyrolysis
CFP: Catalytic Fast Pyrolysis
CI: Carbon Intensity
ETJ: Ethanol to Jet
FOG: Fats, Oils, and Greases
GTI: Gas Technology Institute
FCC: Fluid Catalytic Cracking
FT: Fischer-Tropsch
GHG: Green House Gas
GPY: Gallons per Year
GREET: Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies
HEFA: Hydrogenated Esters and Fatty Acids
LCFS: Low Carbon Fuel Standard
LPG: Liquefied Petroleum Gas
MSW: Municipal Solid Waste
MTG: Methanol to Gasoline
NREL: National Renewable Energy Laboratory
OPEX: Operating Expenses
PERC: Propane Education and Research Council
REG: Renewable Energy Group
RD: Renewable Diesel
RIN: Renewable Identification Number
RP: Renewable Propane
SAF: Sustainable Aviation Fuel
SCF: Standard Cubic Foot
SIP: Sugars to Synthetic Isoparaffins
TAG: Triglyceride
TIC: Total Installed Cost
VGO: Vacuum Gas Oil

Appendix B
Calculation of Renewable Propane Yield in HT1

TAG Average Molecular Weight, Soybean Oil⁵⁴ = 872.33 g/mol

Basis: 1 metric tonne (MT) of feedstock (assume 100% TAGs)

1,000 kg/MT x kmol TAG/872.33 kg = 1.15 kmol TAGs = 1,150 gmol TAGs

From reaction chemistry; cracking of 1 mol TAG yields one mol propane

∴ 1,150 gmol TAG → 1,150 gmol propane in HT1

1,150 gmol propane x 44 g/gmol = 50,600 g propane

(50,600 g propane/1,000,000 g TAG) * 100% = 5% (weight %) yield propane based on TAG feedstock

⁵⁴ <https://www.Biodieseleducation.org>

Appendix C
Stoichiometric Modeling for Incremental Propane from HT2

Low Severity Cracking Reactions

**C15
Cracking**

Products	MW	FracConv	stoich	Kmoles/hr	kg/hr
CH4	16	0.000667	15	0.01573	0.251673
C2H6	30	0.001333	7.5	0.015718	0.471533
C3H8	44	0.008033	5	0.063146	2.778433
C4H10	58	0.050493	3.75	0.297688	17.26593
C5H12	72	0.066396	3	0.313157	22.54733
C6H14	86	0.079612	2.5	0.312909	26.91017
C7H16	100	0.092806	2.14286	0.312658	31.26578
C8H18	114	0.105979	1.875	0.312407	35.61438
C9H20	128	0.119131	1.66667	0.312158	39.95617
C10H22	142	0.132262	1.5	0.311907	44.29086
C11H24	156	0.145371	1.36364	0.311657	48.6185
C12H26	170	0.15845	1.25	0.311388	52.93594
C13H28	184	0.032324	1.15385	0.058637	10.78926
C14H30	198	0.007143	1.07143	0.012032	2.382369
		1			336.0783

**C17
Cracking**

Products	MW	FracConv	Stoich	Kmoles/hr	kg/hr
CH4	16	0.000583	17	0.013764	0.220222
C2H6	30	0.002331	8.5	0.027516	0.82548
C3H8	44	0.007699	5.66667	0.060588	2.66587
C4H10	58	0.048946	4.25	0.288888	16.75553
C5H12	72	0.065096	3.4	0.307367	22.13043
C6H14	86	0.076915	2.83333	0.302644	26.0274
C7H16	100	0.089734	2.42857	0.302644	30.26438
C8H18	114	0.102554	2.125	0.302646	34.5017
C9H20	128	0.115373	1.88889	0.302646	38.73869
C10H22	142	0.128192	1.7	0.302645	42.97563
C11H24	156	0.141011	1.54546	0.302646	47.21276
C12H26	170	0.15383	1.41667	0.302645	51.44969
C13H28	184	0.037875	1.30769	0.068783	12.65608
C14H30	198	0.008158	1.21429	0.013757	2.723926
C15H32	212	0.00874	1.13333	0.013756	2.91627
C16H34	226	0.009323	1.0625	0.013757	3.108974
		0.99636			335.173

**C19
Cracking**

Products	MW	FracConv	Stoich	Kmoles/hr	kg/hr
CH4	16	0	19	0	0
C2H6	30	0.001048	9.5	0.012382	0.371455
C3H8	44	0.006285	6.33333	0.049504	2.178164
C4H10	58	0.011668	4.75	0.068927	3.997777
C5H12	72	0.030903	3.8	0.146044	10.51519
C6H14	86	0.037084	3.16667	0.146046	12.55996
C7H16	100	0.043265	2.71429	0.146047	14.60473
C8H18	114	0.049445	2.375	0.146045	16.64912
C9H20	128	0.055626	2.11111	0.146046	18.69387
C10H22	142	0.061807	1.9	0.146047	20.73863
C11H24	156	0.067987	1.72727	0.146045	22.78302
C12H26	170	0.074168	1.58333	0.146046	24.82775
C13H28	184	0.078306	1.46154	0.142333	26.18931
C14H30	198	0.084329	1.35714	0.142332	28.18171
C15H32	212	0.090353	1.26667	0.142333	30.17466
C16H34	226	0.096377	1.1875	0.142334	32.1674
C17H36	240	0.1024	1.11765	0.142333	34.15997
C18H38	254	0.108424	1.05556	0.142334	36.15285
		0.999475			334.9456

Results:

wt% Propane	0.762247
wt% Yield Loss (C1-C4)	4.778207
wt% Naphtha (C5-C6)	12.06905
wt% C7-C18	83.77244
TOTAL	100.6197

RP production (kg/hr)	7.622467	0.76%
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High Severity Cracking Reactions

C15 Cracking

Products	MW	FracConv	stoich	Kmoles/hr	kg/hr
CH4	16	0.000667	15	0.01573	0.251673
C2H6	30	0.001333	7.5	0.015718	0.471533
C3H8	44	0.02	5	0.157217	6.917547
C4H10	58	0.050493	3.75	0.297688	17.26593
C5H12	72	0.066396	3	0.313157	22.54733
C6H14	86	0.079612	2.5	0.312909	26.91017
C7H16	100	0.092806	2.14286	0.312658	31.26578
C8H18	114	0.105979	1.875	0.312407	35.61438
C9H20	128	0.119131	1.66667	0.312158	39.95617
C10H22	142	0.132262	1.5	0.311907	44.29086
C11H24	156	0.145371	1.36364	0.311657	48.6185
C12H26	170	0.15845	1.25	0.311388	52.93594
C13H28	184	0.032324	1.15385	0.058637	10.78926
C14H30	198	0.007143	1.07143	0.012032	2.382369
		1.011967			340.2174

C17 Cracking

Products	MW	FracConv	Stoich	Kmoles/hr	kg/hr
CH4	16	0.000583	17	0.013764	0.220222
C2H6	30	0.002331	8.5	0.027516	0.82548
C3H8	44	0.007699	5.66667	0.060588	2.66587
C4H10	58	0.048946	4.25	0.288888	16.75553
C5H12	72	0.065096	3.4	0.307367	22.13043
C6H14	86	0.076915	2.83333	0.302644	26.0274
C7H16	100	0.089734	2.42857	0.302644	30.26438
C8H18	114	0.102554	2.125	0.302646	34.5017
C9H20	128	0.115373	1.88889	0.302646	38.73869
C10H22	142	0.128192	1.7	0.302645	42.97563
C11H24	156	0.141011	1.54546	0.302646	47.21276
C12H26	170	0.15383	1.41667	0.302645	51.44969
C13H28	184	0.037875	1.30769	0.068783	12.65608
C14H30	198	0.008158	1.21429	0.013757	2.723926
C15H32	212	0.00874	1.13333	0.013756	2.91627
C16H34	226	0.009323	1.0625	0.013757	3.108974
		0.99636			335.173

**C19
Cracking**

Products	MW	FracConv	Stoich	Kmoles/hr	kg/hr
CH4	16	0	19	0	0
C2H6	30	0.001048	9.5	0.012382	0.371455
C3H8	44	0.006285	6.33333	0.049504	2.178164
C4H10	58	0.011668	4.75	0.068927	3.997777
C5H12	72	0.030903	3.8	0.146044	10.51519
C6H14	86	0.037084	3.16667	0.146046	12.55996
C7H16	100	0.043265	2.71429	0.146047	14.60473
C8H18	114	0.049445	2.375	0.146045	16.64912
C9H20	128	0.055626	2.11111	0.146046	18.69387
C10H22	142	0.061807	1.9	0.146047	20.73863
C11H24	156	0.067987	1.72727	0.146045	22.78302
C12H26	170	0.074168	1.58333	0.146046	24.82775
C13H28	184	0.078306	1.46154	0.142333	26.18931
C14H30	198	0.084329	1.35714	0.142332	28.18171
C15H32	212	0.090353	1.26667	0.142333	30.17466
C16H34	226	0.096377	1.1875	0.142334	32.1674
C17H36	240	0.1024	1.11765	0.142333	34.15997
C18H38	254	0.108424	1.05556	0.142334	36.15285
		0.999475			334.9456

Results:

wt% Propane	2.077409
wt% Yield Loss (C1-C4)	6.093369
wt% Naphtha (C5-C6)	12.06905
wt% C7-C18	83.77244
TOTAL	101.9349

RP production (kg/hr)	20.77409	2.08%
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