Sustainable Aviation Fuel State-of-Industry Report: Hydroprocessed Esters and Fatty Acids Pathway

NREL/TP-5100-87803 • July 2024

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Suggested Citation: Rosales Calderon, Oscar, Ling Tao, Zia Abdullah, Michael Talmadge, Anelia Milbrandt, Sharon Smolinski, Kristi Moriarty, et al. 2024. *Sustainable Aviation Fuel State-of-Industry Report: Hydroprocessed Esters and Fatty Acids Pathway*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5100-87803. https://www.nrel.gov/docs/fy24osti/87803.pdf.

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This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Bioenergy Technologies Office. The views expressed herein do not necessarily represent the views of the DOE or the U.S. Government.

Acknowledgments

We thank the U.S. Department of Energy's Bioenergy Technologies Office for funding and supporting this work. We also thank the interviewed industry stakeholders for providing their expert perspectives related to ramping up sustainable aviation fuel (SAF) production to meet the SAF Grand Challenge goals and for reviewing this report. Finally, we thank the reviewers of this report for their valuable comments. Stakeholders and reviewers are listed below by company/organization names. Note that "stakeholders" and "reviewers" do not imply endorsement of the presented analysis by either individuals or companies/organizations.

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List of Acronyms

BGPY	billion gallons per year
CFR	*Code of Federal Regulations*
CCS	carbon capture, and storage
CI	carbon intensity
CO	carbon monoxide
CO_2	carbon dioxide
DCO	distillers corn oil
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
FAA	Federal Aviation Administration
FCC	fluid catalytic cracking
FOG	fats, oils, and greases
FT	Fischer–Tropsch
GGE	gasoline gallon equivalent
GHG	greenhouse gas
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies
HC-HEFA	hydroprocessed hydrocarbons, esters, and fatty acids
HEFA	hydroprocessed esters and fatty acids
IRA	Inflation Reduction Act
LCFS	low carbon fuel standard
MAC	marginal abatement cost
MFSP	minimum fuel selling price
MGPY	million gallons per year
MV	market value
MV ROIC	return on invested capital without consideration of incentives
NREL	National Renewable Energy Laboratory
PGM	platinum group metal
PM	particulate matter
RD	renewable diesel
RIN	EPA renewable identification numbers
ROIC	return on invested capital
SAF	sustainable aviation fuel
SPK	synthetic paraffinic kerosene
UCO	used cooking oil
USDA	U.S. Department of Agriculture

Purpose of the State-of-Industry Reports

This series of sustainable aviation fuel (SAF) state-of-industry reports aims to provide a thorough evaluation of the emerging SAF production industry, and foster communication among the stakeholders (both public and private) involved in the SAF supply chain. While the report is primarily concerned with the production of SAF, the nature of producing hydrocarbon fuels means that some of the information included will be relevant to the production of other liquid transportation fuels.

In addition to this report on the hydroprocessed esters and fatty acids (HEFA) pathway, the project team plans to release a series of reports covering the overall SAF framework, the alcohol-to-jet (ATJ) pathway, the Fischer–Tropsch (FT) pathway, and possibly the pyrolysis-to-jet (PTJ) pathway.

These reports center on identifying any weak links in the supply chain that have the potential to hinder the production of SAF, particularly in reaching the production goals set by U.S. Department of Energy, the U.S. Department of Transportation, the U.S. Department of Agriculture, and other federal government agencies as part of the SAF Grand Challenge. The reports focus primarily on hurdles for the 2030 goal of 3 billion gallons per year (BGPY) but also identify some of the challenges to achieving the 2050 goal of 35 BGY. To identify these obstacles, the project team interviewed key stakeholders such as SAF and renewable diesel producers, crude oil refining companies, environmental organizations, airlines, biomass producers, pipeline owners, and other experts in relevant fields.

HEFA Pathway State-of-Industry Report

Currently, the HEFA pathway is the only method commercially deployed to produce significant amounts of SAF. As a result, SAF produced via the HEFA pathway is expected to make the largest contribution to achieving the 2030 production target. This report presents a comprehensive analysis and evaluation of the supply chain, including identification of potential obstacles that could hinder commercial production and use of SAF produced through the HEFA pathway. We held extensive discussions, consultations, and collaborative sessions with stakeholders in the HEFA SAF supply chain, discussing critical topics such as feedstock generation, potential production volume of SAF, comparison of economic and sustainability metrics to those of petroleum, and assessment of the HEFA SAF industry's ability to grow and contribute to achieving SAF Grand Challenge goals.

Executive Summary

Climate change is a pressing issue that requires immediate and decisive action to ensure a sustainable future. To reduce carbon dioxide (CO_2) emissions and speed up the transition to net-zero aviation, the Biden Administration has launched the Sustainable Aviation Fuel (SAF) Grand Challenge to scale up production of SAF.[1] The Grand Challenge aims to support production of 3 billion gallons per year (BGPY) of SAF by 2030, and 35 BGPY of SAF by 2050.

In this report, we provide an overview of the current state of the hydroprocessed esters and fatty acids (HEFA) SAF industry, guided by the perspectives of interviewed industry stakeholders.

Currently, the HEFA pathway is the only commercially deployed method to produce significant amounts of SAF and renewable diesel (RD). As a result, SAF produced by HEFA pathway may make the largest contribution in achieving the 2030 production target, depending on constraints on production of RD. Announced domestic total SAF production capacity is expected to reach 2.0 BGPY[2] by 2030 [3], with most of this expected to come from HEFA. Based on this study's analysis, total announced domestic HEFA capacity (RD and SAF), including construction and planned projects, is expected to reach about 9.6 BGPY by 2030.[2]

A notable trend is emerging: Future facilities are increasingly being designed to produce either or both SAF and RD. Therefore, this report analyzes both the HEFA to SAF and the HEFA to RD pathways. Establishing HEFA capability to produce RD will accelerate production capability for SAF. **The production ratio of SAF and RD will depend on market conditions, incentives, facility capabilities, and feedstock availability**.

While some stakeholders believe that the 2030 goal may be achieved solely via HEFA, others believe that overreliance on HEFA may be detrimental to the development of other pathways necessary to meet the 2050 goal. **Industry feedback and our analysis indicate that the HEFA pathway alone will not be sufficient to reach the 2030 goal due to competition for constrained feedstock supply and announced new HEFA capacity. Development of additional pathways to produce SAF will be crucial to meet the 2030 and 2050 goals.**

HEFA Feedstock Supply and Logistics

This report conducts a comprehensive analysis and evaluation of the HEFA SAF supply chain. Our aim is to assess the current status of the industry and identify potential challenges that could hinder the commercial production and use of SAF produced through the HEFA pathway. We have had extensive discussions, consultations, and collaborative sessions with industry stakeholders in the HEFA SAF supply chain. These discussions include HEFA feedstock availability, potential production capacity of HEFA SAF, comparison of economic and

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[1] While the term "SAF" can have multiple meanings, this report uses the Commercial Aviation Alternative Fuels Initiative definition, with the additional constraint of a GHG emissions reduction of 50% relative to Jet A. Thus, only the biogenic jet fuel fraction coprocessed qualifies as SAF. Refer to the *Sustainable Aviation Fuel (SAF) State-of-Industry Report: State of SAF Production Process* [1] for a discussion on SAF definitions and considerations for this series of reports.

[2] The publicly available facility capacities refer to total capacity, including SAF and other renewable fuels such as RD or renewable naphtha. The individual SAF capacity of HEFA facilities is not always disclosed. Thus, the total domestic SAF capacity may vary influenced by the potential SAF production considered for each facility and the introduction of newly announced projects (as of December 2023, 17 facilities were announced) [2].

sustainability metrics to those of petroleum, and assessment of the HEFA SAF industry's ability to grow and contribute to achieving SAF Grand Challenge goals.

All industrial stakeholders identified feedstock supply as a major barrier to scale up production of SAF via the HEFA pathway. These stakeholders mentioned that securing feedstock supply is challenging for plants in operation and for those under construction.

Multiple industries (including biofuels) in the U.S. utilize the entire 23 million tons of domestic HEFA feedstock produced annually. **Due to land use, trade, and infrastructure constraints, it is *not* anticipated that the U.S. production of HEFA feedstock will increase significantly.** Soybean oil, the most abundant HEFA feedstock in the country, accounts for 57% of total domestic feedstock production, followed by fats, oils, and greases (FOG) comprising about 28%, and corn oil making up roughly 9%. The remaining portion of HEFA feedstock is from canola and other vegetable oils. **The HEFA SAF industry is severely feedstock constrained and may have to depend on imported feedstock in the near term and work toward developing technologies for alternative feedstocks like algae and oilseed cover crops in the long term**.

It is important to account for the environmental impact of feedstock production, which can impact availability for fuel producers and end users. Many producers prefer the use of inedible animal fats, sustainably produced resources, or waste materials as part of a circular economy. FOG may be preferred from this perspective, but its generation is linked to human and livestock/poultry population growth. As a result, expected growth is not significant in the future (~33% increase by 2050). Cover crops (such as camelina and pennycress) and algae are considered attractive alternatives, as they do not require additional land that would otherwise be used for food and feed production.

From 2012 to 2020, the prices of HEFA feedstocks were relatively flat. **However, due to increased renewable fuels production (mainly RD) and limited supply, the prices of HEFA feedstocks have recently increased significantly (Figure ES-1).** It has been projected that soybean oil and FOG prices may moderate depending on market conditions.

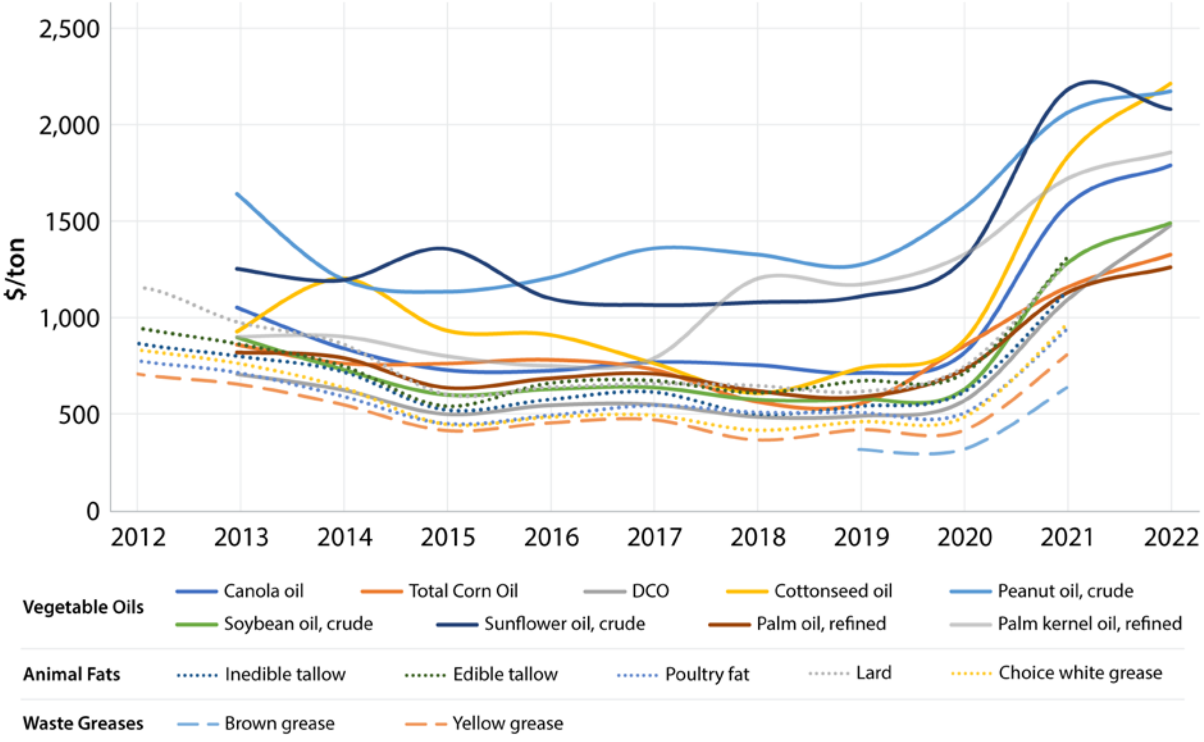

Figure ES-1. HEFA feedstocks prices over time

In the U.S., the top five states for producing animal fats are Nebraska, Texas, Kansas, Iowa, and North Carolina, while waste greases are processed at various locations across the country. Vegetable oil production facilities are mostly located in Iowa, Illinois, and the North and East regions (including Indiana, Kentucky, Maryland, Ohio, Pennsylvania, and Virginia). Transportation of these materials across long distances to fuel facilities in the West, particularly in states such as California that have low-carbon fuel standards, results in increased carbon intensity (CI) scores and additional logistic expenses for HEFA SAF production.

HEFA Process and Logistics

Industry stakeholders consider the HEFA process a mature technology that entails some technical challenges in scaling up SAF production, but technology is *not* considered a major barrier.

HEFA feedstocks require pretreatment to meet the quality standards for the HEFA process. Pretreatment makes it possible to use cheaper, lower-quality raw materials, reducing production costs and adding flexibility in processing a variety of oil-based feedstocks.

For repurposed petroleum refinery equipment, challenges include controlling the reactor temperature, reducing unit capacity (maintaining only 25%–50% of the original unit capacity), new catalysts for renewable feedstocks, additional separation infrastructure, space/footprint availability, and other investment requirements. Many of these challenges can be addressed *a priori* in greenfield units. **Repurposing fossil fuel petroleum refineries to oxygenated feedstocks will generally result in derating nameplate production capacity.**

Building new HEFA SAF facilities or repurposing petroleum refineries can take anywhere from 2 to 5 years. This could make it challenging to meet the 2030 SAF production objectives.

Although coprocessing renewable streams with fossil streams can speed up SAF production while minimizing capital expenditures, SAF production through HEFA coprocessing is limited to a maximum of 5% cofeed of HEFA feedstocks. ASTM is currently considering increasing the HEFA coprocessing limit to 30% to improve the cost efficiency of using refinery equipment, as well as other incentives. In 2023, an additional coprocessing option, termed here as fractionation coprocessing, was approved, which enables the blending of up to 24% previously hydroprocessed biomass intermediate streams with a petroleum stream in traditional refineries to generate a jet fuel blend containing up to 10% renewable hydrocarbons (ASTM D1655-23. Annex A1.2.2.3).

Some industry stakeholders believe coprocessing is a quick and cost-effective approach making it an efficient solution. Others argue that building stand-alone facilities can create more job opportunities and offer more fuel options relative to coprocessing in existing refineries. Coprocessing may displace the need for standalone new SAF refineries to some extent. Fuel produced through HEFA SAF coprocessing at petroleum refineries will, after blending with fossil Jet - A, be ASTM D1655 approved and thus can be transported primarily through existing pipelines in a business-as-usual manner.

While the pathways for SAF and RD are similar, conditioning an RD facility for producing HEFA SAF might not be immediate and could require additional processing steps and investment. Specifically, more severe isomerization and hydrocracking are necessary to achieve jet fuel's cold-flow specifications. In addition, SAF yields are typically lower than RD yields, necessitating adjustments to the fractionation units, the adoption of alternative methods to maximize production, and an increased demand for hydrogen. RD systems may not have sufficient fractionation capabilities, but this is required for SAF production.

Additional Inputs Required for the HEFA Pathway

Sourcing hydrogen is a major challenge for HEFA SAF facilities. Hydrogen needs are significantly higher than for fossil jet production, between 2 and 19 times more per gallon of fuel produced. Concerns have been raised by industry stakeholders regarding the potential difficulties for refineries to obtain sufficient hydrogen. Some feedstocks such as palm oil will require renewable hydrogen to meet the GHG emissions reductions targets under the SAF Grand Challenge. If a refinery does not have sufficient hydrogen capacity, the use of HEFA processing may be limited.

The source of hydrogen has a significant impact on its CI score, which in turn affects the eligibility of the fuel for incentives. Some industry stakeholders are concerned about the availability and costs of hydrogen produced through electrolysis using renewable electricity. Though it has a lower CI score, this is a relatively new commercial-scale technology that requires a significant capital investment and renewable electricity.

Policies, Permitting, and Approvals Impacting the HEFA SAF Supply Chain

Industry stakeholders have identified durable policies as key barriers to reaching SAF production targets. Current policy slightly favors RD. Industry stakeholders propose that the balance between RD and SAF production be shaped by government policies and incentives. They expressed concern that competition for feedstock could have a negative impact on the SAF sector.

The Inflation Reduction Act (IRA) allows two complementary schemes for generation of SAF and RD fuel credits in the 2023–2024 time-frame, and from 2025–2027 they merge into the Clean Fuel Production Credit.

Although the ASTM-approved blending level for HEFA SAF is capped at 50%, Jet A/A-1 standards allow only 25%–26.5 vol % aromatics, and HEFA synthetic paraffinic kerosene (SPK) limits it to 0.5 wt. % before blending. Industry stakeholders suggest conducting research to clarify standards associated with higher blending ratios and alternative feedstocks or pathways.

HEFA SAF facilities may emit air pollutants such as volatile organic compounds, nitrogen oxides, sulfur oxides, carbon monoxide, and particulate matter (PM_{10} and $PM_{2.5}$), which are governed by federal and local air regulations. Specific emissions controls may need to be implemented to comply with the clean air regulations.

Industry stakeholders have identified permitting as a crucial factor for constructing RD and HEFA SAF facilities. Thus, the permitting process needs to be streamlined and community engagement needs to be enhanced.

Economics and Sustainability of the HEFA Pathway

Industry stakeholders raised concerns about the elevated selling prices of SAF in the market. They see the slow development of the SAF industry as an indication of the price difference between the high production cost (which results in high selling price) of SAF and the market price for Jet A.

Techno-economic and life cycle analyses were conducted to evaluate the economics of producing SAF and RD via the HEFA pathway. The analysis considers key variables such as plant configuration, capital costs, plant capacity, hydrogen sourcing, and feedstock type, price, and CI score.[3]

The minimum fuel selling prices (MFSPs)[4] of HEFA SAF estimated in this report range from \$1.84 per gasoline gallon equivalent (GGE) to \$9.40/GGE (Figure ES-2) for all scenarios considered (Table 3). **The MFSPs of RD are slightly lower than those of SAF.** As a reference point, the prices (sales to end users, exclusive of taxes) of fossil-based jet fuel and diesel in

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[3] The present analysis considers the nth-plant assumption that similar plants have been built and operated before, and the cost estimates are based on the collective experience and knowledge gained from constructing and operating previous plants of the same type. Nonetheless, the first SAF facilities are more likely to encounter elevated costs, primarily stemming from the inherent risks associated with pioneering the establishment of a new industry.

[4] The MFSP is defined as a gallon of reference fuel-equivalent product that yields a net present value of zero for the project. The default reference fuel is gasoline. The MFSP represents the lowest price at which a fuel product can be sold to cover all the associated capital and operating costs, including financing and profit.

California in 2021 were $1.85/GGE and $2.36/GGE, respectively [4]. The retail prices (including taxes, distribution, and marketing) for jet and diesel fuel in California were $3.14/GGE (March 2022) [6] and $5.76 (September 2023) [5], respectively.

Feedstock costs are the most significant component of the MFSP for both HEFA RD and SAF. Therefore, the volatility of feedstock prices can significantly impact the financial risk of the HEFA process.

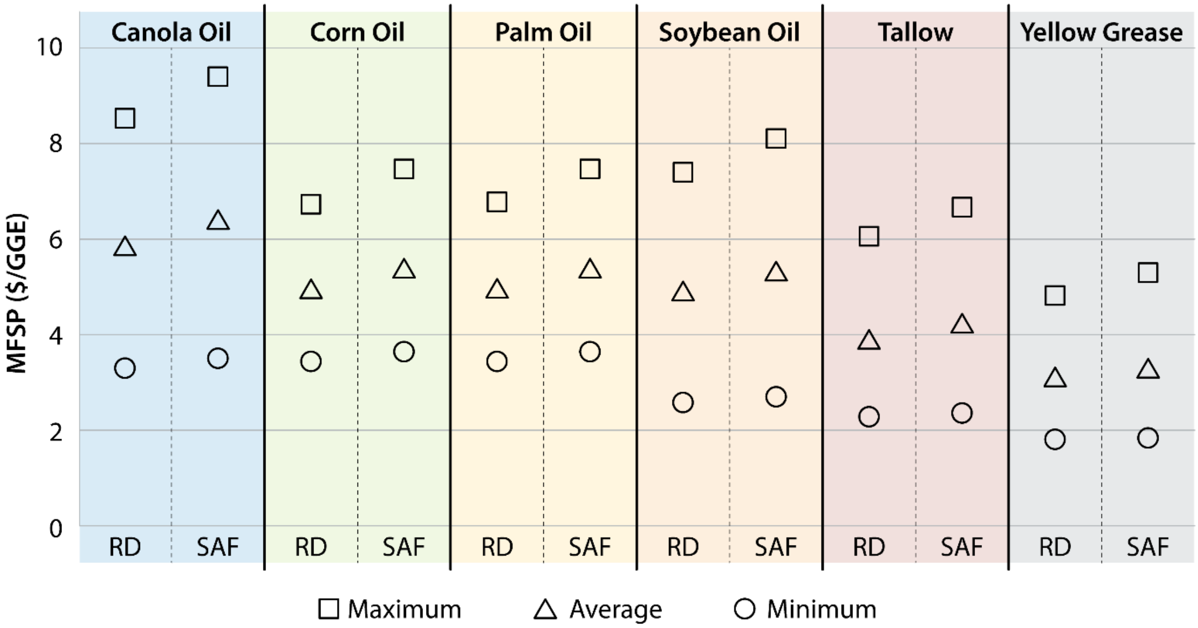

Figure ES-2. Range of MFSPs for HEFA SAF and RD for all input value ranges.

Note: Corn oil pathway is based on distillers corn oil, not edible corn oil.

In contrast, capital costs do not impact MFSP significantly (for the feedstocks and scenarios reflected here), so capital cost reductions through improvements on conversion or HEFA coprocessing have minimal cost impact. Though not major economic drivers, access to capital, risk with higher capital expenditures, and justification for capital expenses are still seen by stakeholders as barriers to project acceptance, especially for new facilities. Additionally, industry stakeholders are concerned about the adverse impact of downturns in economic conditions which may increase risk.

By factoring in GHG emissions reductions and the incentive amount for which a given fuel qualifies, the return on invested capital (ROIC) is calculated based on market value (MV) only (not including incentives) and MV plus revenue from federal and state incentives. Total revenues, including incentives, for several cases were greater than production costs,[3] showing **profitability potential** assuming the jet fuel market price is at $2.50/gal (wholesale, spot price, equivalent to $80/bbl West Texas Intermediate).[5]

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[5] From 2017 to 2022, the spot price of jet fuel on the U.S. Gulf Coast varied between $1.56 and $3.37 per gallon [7].

MV ROIC (based only on MV revenue) is negative[6] **for RD and SAF production for all feedstocks except yellow grease, which has a slightly positive MV ROIC.** By factoring in the GHG emissions reductions and the amount of incentive that the fuel qualifies for, the ROICs after federal and state incentives (using California as an example) can be significantly increased. **ROICs after incentives are positive for both RD and SAF, except for palm oil-derived SAF and HEFA coprocessing-produced canola oil-derived SAF.**

The ROICs after incentives suggest that producing RD is preferable to producing HEFA SAF.[7] Today, RD is being priced as a commodity fuel blendstock and SAF remains a niche product at current production volumes.

Policy incentives increase significantly when CI is reduced. Although sourcing hydrogen from water electrolysis with renewable electricity instead of natural gas reduces CI by at least 10%, some industry stakeholders view electrolytic hydrogen technologies as too expensive and not yet widely available enough to prove viable. **Results suggest that incentives partially offset additional costs for sourcing hydrogen via electrolysis, but no incentives entirely cover additional costs.**

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[6] Analysis assumes that incentives are valid for the 30 years of plant life.

[7] Details on the applicable federal and state incentives considered for this study are discussed in the *Sustainable Aviation Fuel (SAF) State-of-Industry Report: State of SAF Production Process* [1].

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1 Introduction

Key Takeaways

- The HEFA pathway is a well-established and cost-effective option among the SAF pathways.
- The HEFA pathway may play a key role in advancing the SAF industry and progress toward the 2030 production goals of the SAF Grand Challenge.
- Renewable HEFA fuel (RD and SAF) operational and announced capacity in the U.S. is about 9.6 BGPY by 2030.
- Most of the operating facilities and facilities under construction are currently focused on the production of RD and are not optimized for making SAF.
- By 2030, the production capacity for HEFA SAF is expected to reach 2.0 BGPY.

The global aviation industry is one of the major contributors of carbon emissions, responsible for about 2% of global greenhouse gas (GHG) emissions [8, 9] and 3% of total U.S. GHG emissions prior to the COVID-19 pandemic [10]. A drop-in renewable fuel provides a unique opportunity to decarbonize the aviation sector. The Biden Administration issued the Sustainable Aviation Fuel (SAF) Grand Challenge, an executive action to coordinate leadership between industry, government, and other stakeholders to ramp up domestic production of this drop-in renewable fuel [11–13]. The SAF Grand Challenge aims to reach a production of 3 BGPY of SAF by 2030, and 35 BGPY of SAF by 2050.

U.S. jet fuel consumption was nearly 25.3 BGPY in 2023 [14]. The U.S. Environmental Protection Agency's (EPA's) renewable identification numbers **approximate domestic consumption of SAF at around 23 million gallons per year (MGPY) in 2023 [15], accounting for less than 0.1% of U.S. jet fuel demand**. The plant production capacity of RD as of January 1, 2023, amounted to 3.0 BGPY [16]. Thus, a major effort is needed to ramp up production of SAF in order to reach the 2030 production goal.

The HEFA pathway is the most mature and among the least expensive of the ASTM-approved SAF pathways, so it is anticipated to play a central role in achieving the 2030 production target of 3 BGPY. While some industry stakeholders believe that the 2030 goals may be achieved solely via HEFA, others believe that overreliance on HEFA because it is a proven and commercially available technology may be detrimental to the development of other pathways, which are needed to achieve the 2050 goals.

1.1 HEFA SAF Process Overview

The HEFA pathway uses feedstocks made up of esters and fatty acids, including vegetable oils, animal fats, algal oils, and waste greases, which are used for both food applications and industrial uses [17]. The process for the conversion of HEFA feedstock (vegetable oils, animal fats, waste greases, and algal oil) to SAF includes three major steps: pretreatment, hydroprocessing, and product fractionation.

Pretreatment, typically begins as soon as the HEFA feedstock is received in the processing facility. Whether pretreatment is needed and what steps it entails depends on the quality of the HEFA feedstock and the input requirements of the HEFA conversion technology. The pretreatment stage eliminates or lowers contaminants before the conversion stage, helping maintain the conversion catalyst's life span and ensuring consistent conversion input quality for better process control.

Several **hydroprocessing technologies** are offered commercially: Neste Oil's NexBTL [18], UOP's Ecofining [19, 20], Axens' Vegan [21], Topsoe's HydroFlex [22], Chevron Lummus Global's (CLG) ISOTERRA [23], and Sulzer's BioFlux [24]. A **product fractionation** unit is used to recover multiple fuel products from reactor effluent. The HEFA process is discussed in section 3,while a more detailed description of the HEFA process is in Appendix D.

Stand-alone HEFA processes typically involve two catalytic steps: hydrodeoxygenation and isomerization/hydrocracking (see details in Appendix D.1) [25]. Companies such as Diamond Green Diesel and Chevron have constructed greenfield stand-alone RD/SAF facilities in Louisiana and Texas (see Figure 1 and Table B-1).

HEFA feedstocks can also be coprocessed with petroleum intermediates in petroleum refineries. Both hydroprocessing (hydrotreating and hydrocracking) and fluid catalytic cracking (FCC) unit operations can be used for HEFA coprocessing low-carbon feedstocks. For example, Chevron's El Segundo Refinery was one of the first in the U.S. to produce SAF (a batch) through HEFA coprocessing [26]. Outside of the U.S., companies like TotalEnergies in France [27], BP in Germany [28], and ENI in Italy [29, 30] are producing SAF via HEFA coprocessing. A detailed process design can be found in ASTM D1655 Annex A1 [31] and is described in Appendix D.2.

Repurposing or retrofitting an existing unit, (such as a hydrotreating unit) in a refinery, biodiesel facility, or corn ethanol plant is another option to produce HEFA fuels. PBF Energy (colocated with a refinery in Louisiana) and East Kansas Agri-Energy (colocated with an ethanol distillery in Kansas) are opting for colocating a renewable fuel process inside existing facilities [32–34].

1.2 HEFA Production Capacities

The total operational capacity of renewable fuel facilities in the U.S. is currently 4.7 BGPY. Currently, only a small number of facilities are producing SAF via the HEFA pathway (Table B-1), with 6 of the 20 facilities ready to produce SAF: Neste (Porvoo, Finland, and Singapore), ENI (Livorno, Italy), TotalEnergies (La Mede, France), World Energy (Paramount, California), and Montana Renewables (Great Falls, Montana). However, several RD facilities now in operation have the potential to be upgraded to produce SAF (Table B-1). Neste's MY SAF is already available at key global airports, including San Francisco International Airport (SFO) and Los

Angeles International Airport (LAX) [35]. The EPA renewable identification numbers (RIN) provide an approximated 2022 domestic SAF consumption of 15.8 MGPY [36, 37]. In 2022, approximately 8.0 million gallons of SAF were imported into the U.S., while 1.0 million gallons were exported [38, 39]. Hence, **imports constitute a significant portion (about 44% in 2022) of SAF consumed in the U.S.** As of 2023, estimated domestic SAF consumption (based on RINs generated transactions) is approximately 25.8 million gallons per year, with 12.3 million gallons imported [15].

Four facilities and expansions being built, with startup dates between 2024 and 2027, will add a total renewable fuel capacity of 0.9 BGPY (see Figure 1), bringing total capacity to about 5.6 BGPY. Among these four facilities, only one will have the capability to produce SAF and RD.

The announced facilities with operations planned to start from 2023 to 2028 (updates on some of these projects have not been provided), will add additional renewable fuel capacity of 4.0 BGPY, bringing total capacity to about 9.6 BGPY. Around 11 of the 13 planned facilities and expansions will be equipped for SAF production. **While current SAF production volumes represent only a fraction of those for RD, a notable trend is emerging: Future facilities are increasingly being designed with the versatility to produce both SAF and RD**. Establishing this infrastructure will be crucial in meeting the growing demand for SAF. The locations of the operating, under construction, and planned facilities are illustrated in Figure 1.

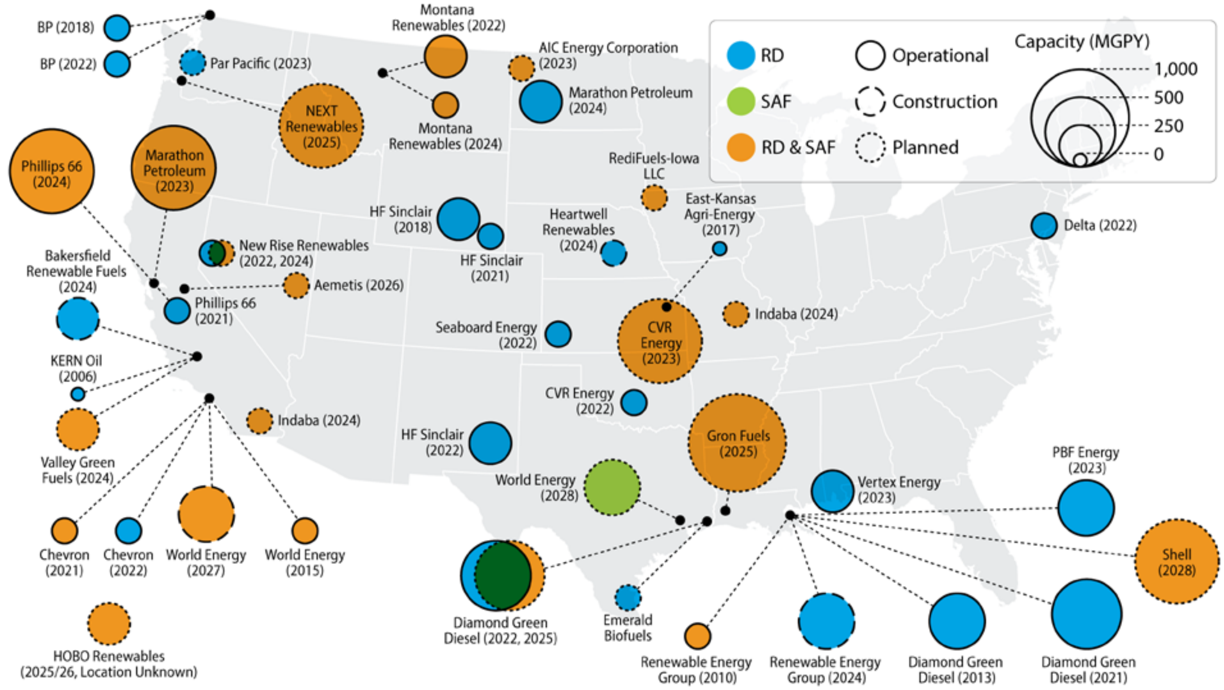


Figure 1. Location and capacity of HEFA SAF and RD facilities, including expansions, in operation, under construction, and planned in the U.S.

Announced total capacity for SAF production, including announced alcohol-to-jet, FT, and power-to-liquid facilities, is expected to reach 2.0 BGPY[2] by 2030, with the majority announced from HEFA [3]. An additional 1.0 BGPY would be needed to meet the 3-BGPY

2030 SAF production goal. If covering this gap with five HEFA SAF grassroots facilities, each with a capacity of 200 MGPY, the required investment would range from $1.2 to $2.5 billion.

It is crucial to develop additional pathways to produce SAF and to meet the 2030 production goal. Diversifying production pathways can also reduce reliance on a single type of feedstock and mitigate uncontrollable factors that affect production, such as crop disease, pests, extreme weather, droughts, and trade issues.

For this report, comprehensive analyses and evaluations of the HEFA SAF supply chain were performed, identifying potential obstacles to the commercial production and use of SAF produced through the HEFA pathway. We held extensive discussions, consultations, and collaborative sessions with HEFA SAF supply chain stakeholders about topics including HEFA feedstocks, potential HEFA SAF volume, comparison of economic and sustainability metrics to those of petroleum, and assessment of the HEFA SAF industry's ability to grow and contribute to achieving the SAF Grand Challenge goal.

The goal of this report is to provide a thorough evaluation of the emerging SAF production industry and to foster communication among stakeholders (both public and private) involved in the HEFA SAF supply chain. Section 2 discusses the commercial feedstocks used to produce renewable fuels, specifically SAF. The section examines their generation, preprocessing, logistics, availability, geographic distribution, and production projections. Section 3 details the configurations of processes involved in upgrading feedstocks to SAF and addresses related technical challenges, including those related to upgrading RD facilities to manufacture SAF. Section 4 discusses additional inputs the SAF supply chain requires and associated risks that can disrupt the entire chain. The approvals, permits, and policies governing SAF production and utilization are examined in Section 5. Section 6 discusses the results of techno-economic, life cycle, and air quality analyses.

2 Feedstock Supply and Logistics

Key Takeaways

- HEFA SAF alone may not be sufficient to meet the 2030 SAF production targets due to current feedstock limitations and competition from other biofuels production (e.g., RD, biodiesel, and marine fuel).
- The availability of domestic feedstock, with the supply expected to remain flat in the near future, is a major obstacle to expanding HEFA SAF production.
- The HEFA SAF industry may have to rely on imported feedstock and concentrate on long-term feedstock development, such as algae and oilseed cover crops.
- Fats, oils, and greases (FOG), such as used cooking oil/greases, are preferred to vegetable oils as feedstock due to low impact on food supply and the environment as well as lower CI.

The HEFA pathway uses oils and fats (or lipids) as feedstock. These **HEFA feedstocks include vegetable oils, byproducts from corn ethanol and pulp paper mills, animal fats, waste greases, and algae oils.** These resources are described in more detail in the following sections, including information on their current and projected supply, consumption, geographic distribution, collection logistics, and other considerations.

2.1 Vegetable Oils and Byproducts

Vegetable oils produced in the U.S. include soybean, corn, canola, sunflower, cottonseed, and others used primarily in food applications (e.g., peanut and olive oils).

Soybean oil accounts for 74% of vegetable oils produced in the U.S. [40]. The U.S. is the second largest soybean oil producer (after China) and exporter (after Argentina).

- **Production** has increased in the past 10 years to about 13 million tons (in 2022) and is projected to increase slightly (~13%) to about 15 million tons by 2032 (Table 1).
- **Consumption** of soybean oil for biofuels production (primarily biodiesel and RD) has also increased in the past 10 years but is projected to remain almost flat between now and 2032.
- **Prices** for soybean oil have fluctuated (Figure ES-1 and Table G-5), reaching an all-time high in the past 2 years, but projections from the U.S. Department of Agriculture anticipate prices to decline in the next 3–4 years, and then remain flat until 2032 [40, 41].
- **Geographic distribution** of production is concentrated in three areas, with Iowa alone accounting for 21% of U.S. soybean oil, and six other states (including Indiana, Kentucky, Maryland, Ohio, Pennsylvania, and Virginia) producing 22% (Table 2).

Table 1. Past, Current, and Projected Soybean Oil Supply and Consumption [40, 41]

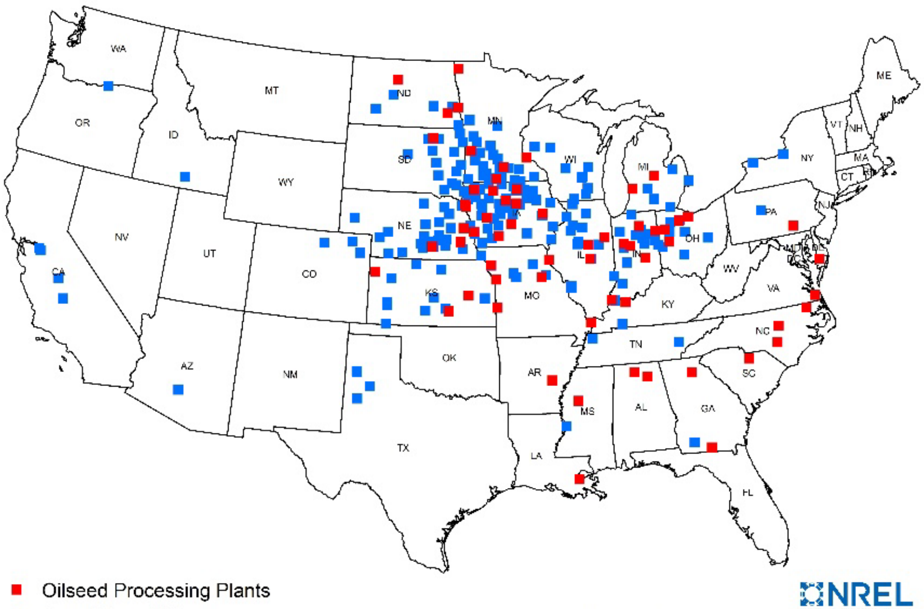
Soybean oil (million tons)	2012/2013	2022/2023	2032/2033
Beginning stocks, Oct. 1	1.3	1.0	1.2
Production	10	13	14.7
Imports	0.1	0.2	0.1
Total supply	*11.3*	*14.2*	*16.1*
Domestic disappearance	9.4	13.0	13.5
Biofuels	2.3	5.8	6.1
Food, feed, and other industrial	7	7.2	7.5
Exports	1.1	0.3	1.3
Total use	10.5	13.3	14.9
Ending stocks, Sept. 30	0.8	1.0	1.2
Soybean oil price ($/ton)	942	1,320	880

Soybean oil processing facility locations are shown in Figure 2. The description of typical crushing and refining processes are detailed in Appendix C.1.

Table 2. U.S. Soybean Oil Production in 2022 by Region[a] [42]

Region	Soybean Oil Production (tons)
Illinois	1,480,989
Iowa	5,683,388
North and East	2,874,104
North Central	2,192,736
South, West, and Pacific	1,494,150
West Central	2,265,357
Total	**12,990,723**

[a] North and East includes Indiana, Kentucky, Maryland, Ohio, Pennsylvania, and Virginia. North Central includes Michigan, Minnesota, North Dakota, and South Dakota. South, West, and Pacific include Alabama, Arkansas, California, Georgia, Louisiana, North Carolina, and South Carolina. West Central includes Kansas, Missouri, and Nebraska.



Source: NOPA, RFA

Figure 2. Oilseed processing plants and corn ethanol plants in the U.S.

Other vegetable oils produced in smaller quantities include canola, sunflower, and cottonseed:

- North Dakota is responsible for about 85% of **canola** produced in the U.S., but states in the Pacific Northwest, southern Great Plains, and mid-South are increasing acreage [43, 44]. Canola is used primarily in food applications, and the country imports 75% of its supply to meet domestic consumption needs [40].
- **Sunflower** is another predominantly edible oil, with U.S. production based primarily in North Dakota, but also in South Dakota and Minnesota [42].

- **Cottonseed** is grown in the South, with Texas, Georgia, and Arkansas supplying more than 50% of total U.S. production [42].

The **byproducts category** includes distillers corn oil (DCO), a byproduct of ethanol production, and crude tall oil, a byproduct of the pulp and paper industry.

- **DCO production in 2022 was about 2.1 million tons**, which is roughly 70% of total corn oil production in the country [45]. Figure 2 illustrates the location of corn ethanol plants, as an indicator for where DCO is produced. DCO is used as an animal feed ingredient or as biodiesel feedstock. Biodiesel, RD, SAF, and renewable heating oil produced from DCO are approved pathways for biomass-based diesel (D4) or advanced biofuel (D5) under the Renewable Fuel Standard program [46, 47]. Biodiesel production consumed 71% of total DCO (1.5 million tons) in 2022 [45, 48]. Historically and as shown in Figure ES-1, DCO prices were below those for soybean oil, but **high feedstock demand from the biodiesel and RD industries led to doubled DCO prices, which reached $1,360/ton during the 2022/2023 growing season** [40]. Its lower CI score compared to soybean oil under the LCFS (33 vs. 56 gCO_2e/MJ) makes DCO an attractive biofuel feedstock option [46].
- **Crude tall oil** is a byproduct of the kraft process used to make wood pulp, mainly from coniferous trees (e.g., pine). It is a source of raw materials such as fatty acids, rosin, turpentine, and pine pitch. Crude tall oil is used in asphalt, paint, lubricants, soap, tires, and other products including biofuels (primarily in Europe). Crude tall oil production in the U.S. is between 550,000 and 771,000 tons annually [49]. Prices have fluctuated but increased overall during the past few years and are currently at about $1,700/ton (Figure ES-1) [50].

Oilseed cover crops that have received attention as biofuels feedstock in recent years include camelina and pennycress:

- **Camelina** is an annual crop **currently produced on limited acres** in Montana, Colorado, Wyoming, eastern Washington and Oregon, and a few Southern states [51]. Camelina oil is edible and thus suitable for various applications.
- **Pennycress** is an annual cover crop suitable for crop rotation systems. Although it can be grown anywhere in the U.S., **commercial production is still under development**. The seed meal left over from oil extraction can be used as an animal feed with proper processing [52].

2.2 Fats, Oils, and Greases

FOG, which includes animal byproducts and waste grease unsuitable for human consumption, is generated by food handling operations. These materials consist of animal fats obtained from slaughterhouse and livestock farm waste, used cooking oil (UCO) from commercial and industrial cooking operations, and grease recovered from traps installed in the sewage lines of restaurants/food processing plants and wastewater treatment plants [53]. These materials are not used in their raw form and require processing or rendering. Rendering plants convert raw material into valuable products (commodities) such as edible and inedible animal fats (tallow from cattle, lard and white grease from hogs, and poultry fat from poultry), yellow grease (rendered UCO), and brown grease (rendered trap grease) used by various industries (e.g., animal feed, pharmaceuticals, cosmetics, lubricants, plastics, and biofuels).

- **Production** of FOG in the U.S. has been relatively flat in the past 10 years, at about 6.0–6.6 million tons annually [42, 54]. Of the tracked tonnage, inedible tallow represents 30% of total production, followed by UCO at 23%, and poultry fat at 15% [42, 54]. **The projected annual FOG resource is estimated to reach 8 million tons by 2050** based on forecasted human and livestock/poultry population growth [59]. Brown grease production is not tracked as regularly as the other materials, but an estimate from the National Renewable Energy Laboratory (NREL) indicates that **about 2.2 million tons may have been generated in 2019 [59]**.
- **Imports** of rendered fats increased sharply in the U.S. from 2021 to 2022, doubling to reach a record 1.1 million tons, with demand spurred by continued growth of the market for biomass-based diesel, especially RD [54]. This spike in demand is particularly evident in trends for imports of tallow (which increased more than 450% since 2017) and UCO (which increased more than 200% in just a year from 2021 to 2022).
- **Consumption** of FOG in 2022 was about 7 million tons, about 50% of which was used in feed, food, fatty acids, and other products, with the remaining 50% used by the biofuels industry [54]. Biofuels consumption of FOG tripled between 2019 and 2022, from 1.2 million tons to 3.8 million tons. UCO consumption in biofuels applications doubled from 2021 to 2022, while the use of other FOG remained relatively flat.
- **Prices** for FOG doubled between 2020 and 2021 due to increased demand for RD feedstock [54]. Prices continued to rise in 2022 and ranged from $1,400/ton for UCO to $1,800/ton for inedible tallow. It is expected that FOG prices will continue to rise slightly in the next few years, likely peak at that point, and begin a downward trend (as markets adjust to new supply, potentially from alcohol-to-jet or FT pathways)[8] at a rate depending on market conditions [59].
- **Geographic distribution** of waste grease generation mirrors population size—highly populated areas are also locations of large grease production (Figure 3). The top five states for animal fats production are Nebraska, Texas, Kansas, Iowa, and North Carolina. These states have the highest concentration of cattle, hog, and poultry production, slaughter, and rendering facilities in the country.

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[8] As the alcohol-to-jet and FT pathways become more widely available for commercial use, the renewable fuels market is likely to adapt to changes in feedstocks, technologies, and demand. This is expected to lead to more stable prices, or even a decline if the supply increases.

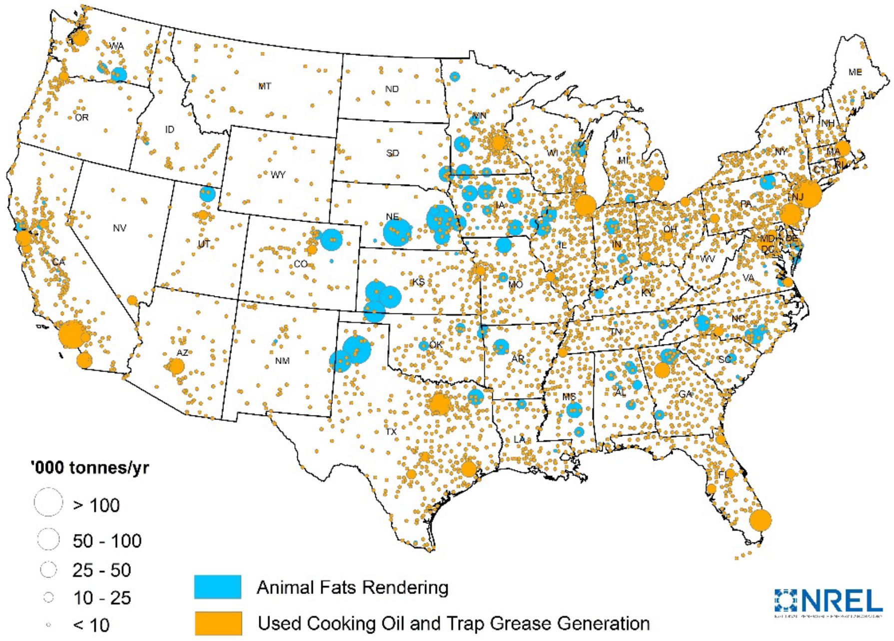

Figure 3. FOG production in the U.S. (2017).

A brief description of the logistics and processing associated with FOG is detailed in Appendix C.2, and a graphical overview of this process is shown in Appendix A.

2.3 Feedstock Supply Summary and Outlook

Figure 4 summarizes the current supply and demand of feedstock that can technically be used for HEFA processing (vegetable oils, animal fats, and waste greases) in the U.S. **Domestic HEFA feedstock production totaled about 22.9 million tons in 2022, while consumption reached 26.6 million tons. The biofuels industry consumed 11.7 million tons, and the remaining 14.9 million tons were mainly consumed by the food industry**, with a small amount used for other products (e.g., lubricants, soap, paint). In comparison, the operating capacity for biodiesel and RD as of December 2022 was about **4.7 BGPY** (2.1 BGPY for biodiesel and 2.6 BGPY for RD) [33]. To operate these facilities at full capacity, **roughly 18 million tons of lipid feedstock are required**.

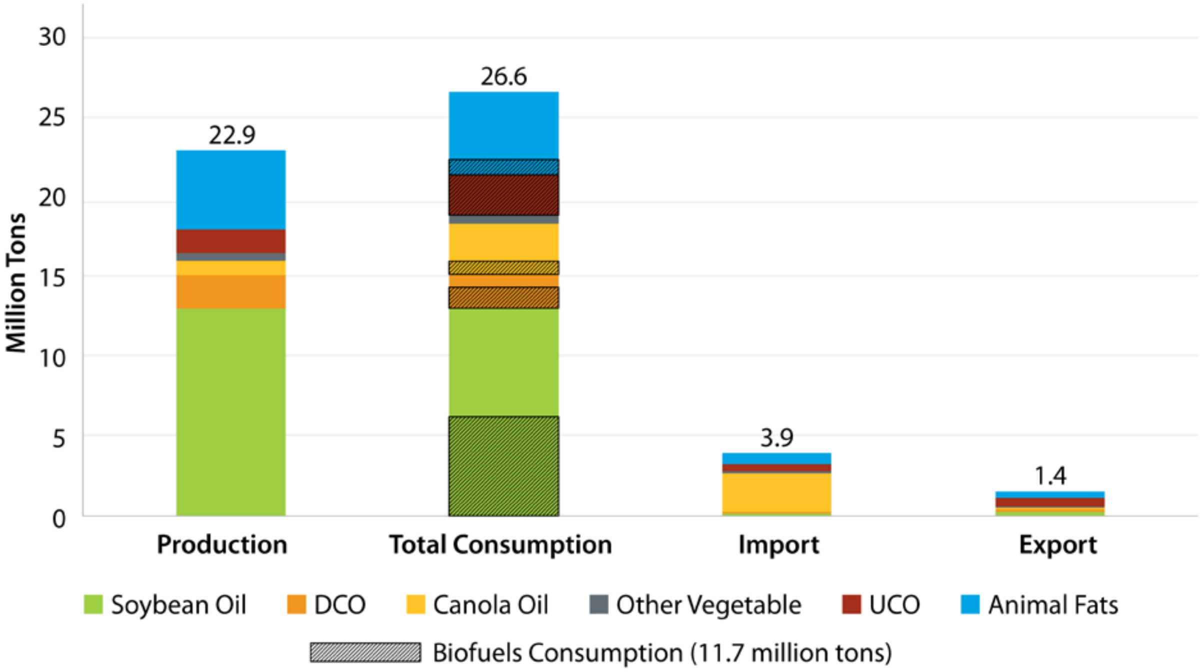

Figure 4. HEFA feedstock supply and demand in the U.S. (2022)

Note: Feedstock supply (production and imports) does not add up to feedstock disappearance (consumption and exports) due to beginning stocks not captured in the figure.

As the data indicate, there is certainly a concern about current feedstock availability to support SAF production, especially considering the numerous RD projects announced in recent years. Consistently, **industry stakeholders identified the availability of feedstocks as one of the top constraints for scaling up SAF production.** Most of these resources are projected to increase in coming years (Figure 5), but that supply may not be sufficient to support growing demand of the biofuels industry. The HEFA feedstock supply (production plus imports) is projected to increase by 14% (4.1 million tons), largely due to an increase in soybean production and FOG production and imports. The production of other feedstocks is projected to remain flat.

Due to increased domestic demand and international market changes, U.S. soybean oil exports declined by 70% in the past 10 years (Table 1). Domestic crushing capacity is increasing with at least 14 new oilseed processing plants in various stages of construction, expansion, or development [55]. Meanwhile, U.S. imports of FOG and vegetable oils also are on the rise, and that trend is likely to continue in the near future.

Demand for HEFA feedstock has an impact not only on its availability, but also on prices, as illustrated in Figure ES-1. **Increased demand for specific resources has resulted in price hikes.** This is certainly reflected in trends for several feedstocks such as UCO and DCO.

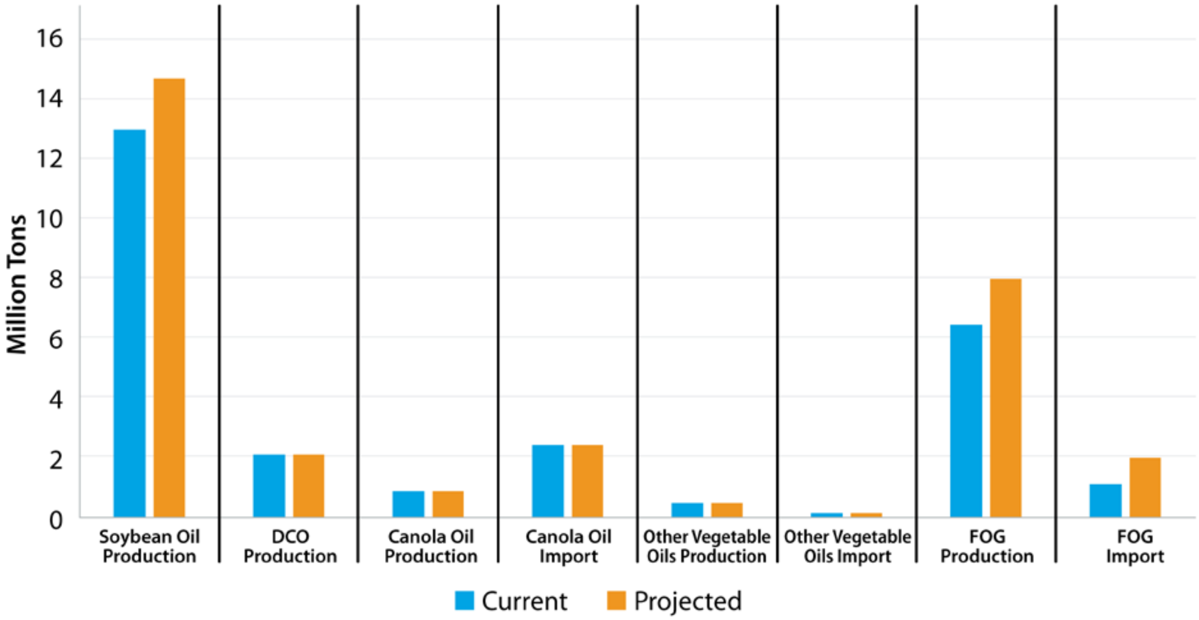

Figure 5. Current and Projected HEFA feedstock supply (2030–2032).

Note: This figure does not include feedstocks that are not currently produced in significant quantities, such as oilseed cover crops, which are still in the development stage for commercial production.

2.4 Emerging Biomass Resources for HEFA Feedstock Generation

The lipid content of algae **(algae oil)** is of particular interest for its potential as feedstock for HEFA SAF [56]. However, utilization of algae to produce biofuels or renewable fuels has not yet reached large-scale deployment.

- **Production**. For point-source carbon dioxide (CO_2) delivery, the potential production could be up to 235 million tons/year of algal biomass (ash-free dry weight) [57].[9] In the absence of higher-value byproducts, algal oil production would be 59 million tons/year.[10]
- **Price**. Biomass could be produced at an average of $655/ton (ash-free dry weight) [57]. The considerations for these values are discussed in Appendix C.3. Extracted algal oil (lipid) would have an overall average cost of roughly **$7–$8/gal of algae oil** ($1.0–$1.1/lb), though this cost could be considerably reduced with the inclusion of higher-value co-product.[11]
- **Geographic distribution**. Figure 6 depicts algae farm site locations across the U.S. that would support biomass production of 235 million tons/year. The U.S. Department of Energy's (DOE's) Bioenergy Technologies Office envisions reaching deployment at this scale as a **longer-term outlook—i.e., by a 2040–2050 time-frame** [58].

Algae farming and extraction of algae oil are described in Appendix C.3.

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[9] This potential was based on saline groundwater sourcing, with a lower achievable biomass potential of 104 million tons per year if relying on freshwater resources instead for algae cultivation.

[10] Accounting for a 95% lipid extraction yield.

[11] In more optimal locations for biomass production, algae oil may be produced at lower costs of ~$5–$6/gal ($0.7–$0.8/lb).

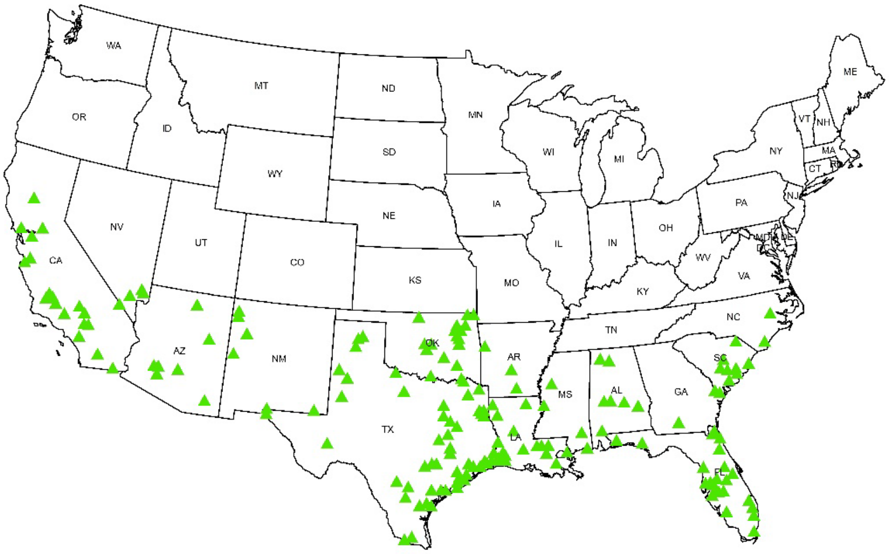

Figure 6. Suitable algae farm locations identified at the national scale, as could support the production of up to 235 million tons/year of microalgal biomass (saline cultivation) [57].

Camelina and pennycress, considered rotational **cover crops**, are not currently produced at significant amounts and their commercial productions are still under development. The analysis of the oilseed cover crops is presented in the Billion Ton 2023 report [59].

2.5 HEFA Feedstock Logistics

HEFA feedstock logistics are more streamlined in comparison to other SAF pathway feedstocks, such as cellulosic biomass, given that refineries and other fuel producers are experienced in handling liquid materials. Demand for these resources may impact the development of technologies related to their logistics. For example, increased demand for certain underutilized feedstocks (such as brown grease) may lead to advances in collection and processing technologies in order to increase utilization rate.

- HEFA feedstock is currently transported from production facilities (crushing plants for vegetable oils and rendering plants for FOG) to renewable fuel facilities or petroleum refineries via tanker trucks, freight trains, and cargo ships. There are no pipelines in place to transport biogenic oils.
- As shown in Figure 1, Figure 2, and Figure 3, animal fats are rendered primarily in central states, while waste greases are processed at various locations across the country. Vegetable oil production facilities are mostly located in the Midwest. Transporting these materials across long distances by truck to fuel facilities in the West, particularly in states that follow low-carbon fuel standards (e.g., California), results in increased CI scores and additional logistic expenses for HEFA SAF production.
- Some communities near fuel facilities are concerned about a potential increase in local pollution due to the higher traffic levels caused by the delivery of HEFA feedstocks [60]. These concerns can result in delays for the deployment of new facilities [61].

2.6 Other Considerations for HEFA Feedstocks

Food vs. fuel concerns and environmental considerations may limit feedstock availability. There are concerns about the use of soybean oil by the biofuels industry. The American Soybean Association states that their "processors are gearing up to process more soy and assure adequate soy oil is available for food, feed and fuel" [62]. However, some food industry groups, such as the American Bakers Association, believe that there is a shortage of soybean oil supply due to the growing production of biofuels, particularly booming RD production [62]. Many biofuel producers and end users prefer to use inedible feedstocks, sustainably produced resources, or wastes. For instance, inedible FOG (e.g., UCO, trap grease, inedible animal fats) do not compete with human consumption and have lower CI, and those treated as waste can contribute to a circular economy. Purposely grown crops such as camelina and pennycress are considered rotational cover crops and are thus not expected to encroach on land that would otherwise be used for food and feed production.

SAF vs. other biofuels production. HEFA SAF alone may not be sufficient to meet production targets due to current feedstock limitations and competition from other biofuels production. Without technological advancements, investments, and policy support related to algae and other purposely grown feedstocks, the feedstock outlook for this pathway would remain unchanged. HEFA SAF production faces feedstock competition not only from other industries, but also within the biofuels industry itself, for biodiesel, RD, and marine fuel production. Based on feedback from industry stakeholders, there is a level of uncertainty regarding diesel market coverage in the scenario of a manufacturers' shift from RD to SAF production. If most ground transportation (including freight) becomes electrified,[12] there may be a notable decrease in the need for liquid fuels in that sector, creating an opportunity to repurpose feedstock for harder-to-electrify markets such as aviation and marine fuels. In such instances, existing facilities may choose to switch production from RD to SAF.

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[12] Electrification of ground transportation is projected to take decades. Electric vehicles will only make up less than one-third of car and truck sales by 2050, even in a high oil price scenario [63, 64].

3 HEFA Pretreatment, Conversion, Blending, and Logistics

Key Takeaways

- Industrial stakeholders consider the HEFA technology to be mature, and therefore technology is not seen as a major barrier to scale up of SAF production.
- Pretreatment is needed to utilize low-quality and low-cost feedstocks, which will enable flexibility and diversity in feedstock selection.
- Design, construction, and shakedown/startup of a new HEFA SAF stand-alone facility may take 2–5 years.
- Coprocessing with fossil fuels may enable production and distribution of SAF using conventional refinery infrastructure and help reduce capital and operating costs.
- SAF produced via coprocessing currently limits HEFA feedstocks to a maximum of 5 vol %.
- Compared to RD, HEFA SAF production not only has lower yields, but also requires additional hydrogen and processing equipment.
- Repurposing fossil fuel petroleum refineries to oxygenated feedstocks will generally result in derating production capacity.

Production of SAF and RD via the HEFA pathway can be carried out in stand-alone processes or via coprocessing. ASTM D1655 Annex A1 approves coprocessing of up to 5 vol % of HEFA feedstock with fossil oil intermediates to generate SAF, in a process referred to here as **HEFA coprocessing**. The most recent revision of ASTM D1655 (2023) allows hydrocarbons derived from hydroprocessed monoglycerides, diglycerides, triglycerides, free fatty acids, and fatty acids (biomass) to undergo coprocessing via fractionation (referred in this work as **fractionation coprocessing**).[13] This section discusses the process of upgrading feedstocks to SAF and addresses related technical challenges and logistics considerations, including difficulties associated with retrofitting RD production facilities to manufacture SAF.

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[13] The stream used for coprocessing via fractionation shall not exceed 24% vol. of hydroprocessed mono-, di-, and triglycerides, free fatty acids, and fatty acids esters with the balance being conventionally sourced hydrocarbons. The final product is limited to 10 vol. % of synthetic hydrocarbons in the jet fuel product.

3.1 Stand-Alone Process Configuration

The stand-alone HEFA process converts100% bio-based feed into naphtha, SAF, and RD. The major steps in the stand-alone process are described in the following sections. A simplified and generic block flow diagram for the HEFA conversion is shown in Figure A-1, and a more technical discussion of the HEFA process is presented in Appendix D.

3.1.1 HEFA Feedstock Handling

The HEFA feedstock is transported to the fuel facility by tanker trucks, freight trains, or cargo ships. The oils are then stored for later processing. The characteristics of various HEFA feedstocks can differ significantly based on the biomass type. **The properties of the HEFA feedstock will determine how the receiving and storage systems are designed**. Due to different freezing points, certain oils can be pumped and stored at room temperature, while others must be heated. Some HEFA feedstocks have the tendency to solidify under low temperatures or polymerize under high temperatures. Additionally, HEFA feedstocks are susceptible to oxidative degradation, which can reduce storage time and necessitate the use of antioxidants (refer to Appendix D for more information) and/or nitrogen blanketing.

3.1.2 Pretreatment of HEFA Feedstocks

Whether pretreatment is necessary depends on the quality and type of biogenic feedstock. Due to high cost and market competition for food-grade vegetable oils, renewable fuel producers are opting for relatively low-value oils, such as yellow grease, animal fats, and unprocessed crude vegetable oils (non-degummed oils). Nonetheless, these oils may jeopardize the HEFA process with impurities that may increase corrosion, fouling, and gum formation; generate excessive pressure drops; and, importantly, reduce catalyst life span and conversion performance.

A range of impurities in HEFA feedstocks before pretreatment and the acceptable contaminant concentration for the hydroprocessing step are shown in Table D-1. The impact of these impurities on the HEFA process are discussed in Appendix D. For instance, industry stakeholders identified **phosphorous** as the main contaminant that needs to be removed in order to avoid catalyst poisoning, which results in partial or total deactivation and reactor fouling [65].

According to industry stakeholders, the HEFA feedstock quality is suitable for original consumer markets, but in most cases, feedstocks do not meet the quality required for RD or HEFA SAF production. Stakeholders' insights are backed up by the level of contaminants found in feedstocks (shown in Table D-1), with only refined vegetable oil of food-grade quality capable of meeting hydroprocessing quality requirements. These results indicate that capital expenses for pretreatment may be justified by making larger volumes of low-quality and low-cost resources into viable feedstock options.

Consulted industry stakeholders identified the pretreatment process as the primary technical challenge in renewable fuel production via HEFA. Pretreatment costs can impact the economic feasibility of new facilities and play a crucial role in determining the viability of future RD and SAF production investments. Increasing investments in pretreatment in the past several years provides evidence that industry recognizes the value of these processes. Impacts and challenges related to the pretreatment of HEFA feedstocks are discussed in Appendix D.

The renewable fuel industry currently uses pretreatment systems that are similar to those used by vegetable oil suppliers. A **typical pretreatment** involves degumming, adsorption, and neutralization:

- **Filtration** is used to remove insoluble impurities.
- The **degumming** step removes gums (rich solids/sludge) or gum-like materials, as well as the bulk of metals. Acid degumming, preferably utilizing edible acids such as acetic or citric acid, is one of the most popular degumming technologies used. This process generates waste streams of gums and wastewater. Phosphorus content is reduced by an order of magnitude.
- In the **adsorption or bleaching step**, activated clays (also known as bleaching earth) are used to adsorb polar compounds including phospholipids and soaps. This achieves low levels of phosphorous (<3 ppm) and total metals (<10 ppm) contents [66]. Spent adsorption material contains approximately 25%–30% residual oil [67, 68]. The bleaching earth or adsorbent cannot be reused; its disposal is discussed in Section 4.2 and Appendix E.
- Optional steps may be needed to **remove high polyethylene** in low-quality animal fats and **mitigate the chloride** content in UCO.

Alternative pretreatment technologies that are commercially available include:

- The Hydrothermal Cleanup technology patented by Applied Research Associates. The first commercial unit (10,000 barrels/day) started operations at Montana Renewables' RD and SAF facility in Great Falls, Montana [69, 70].
- The BioFlux Pretreatment technology, developed by Duke Technologies and licensed by Sulzer to pretreat FOG [71].

When handling multiple HEFA feedstocks of different types, a blending system may be used to create an optimized blend that falls within the pretreatment technology's capability ranges. For example, high concentration of heavy metals (which can poison catalysts) mean brown grease needs extensive cleaning and is only viable if diluted with other feedstocks.

Stand-alone vs. co-located. Pretreatment units can either operate independently (stand-alone), supplying treated HEFA feedstock to various facilities, or be situated within a larger fuel processing facility (co-located). Standalone units might appear to offer economies of scale that make them the cost-effective choice. However, transporting pretreated feedstocks can negatively impact the fuel's cost and CI. Conversely, co-located units eliminate the need for transporting pretreated feedstock, though they are limited by the scale of the HEFA process. The optimal location for the pretreatment process may differ based on a range of factors specific to individual operations. Most of the renewable fuel facilities currently in operation and under construction have co-located pretreatment units.

Waste management, while not a technical limitation, can pose logistic and economic challenges. Spent adsorbent disposal, which can contain 25%–30% of residual oil[14], presents opportunities to increase yields and production by reducing losses [67, 68]. See Section 4.2 for further discussion of waste streams.

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[14] With pressure leaf filters. When using plate and frame filters, losses are typically 35%–40% [69].

Companies involved in the design of pretreatment processes include Alfa Laval [72], Crown Iron Works [73], Desmet (Alfa Laval completed the acquisition of Desmet in 2022) [74, 75], Applied Research Associates Inc. [76], and Alden Group Renewable Energy [77].

3.1.3 Conversion and Separation

The core conversion steps that follow pretreatment involve hydroprocessing systems that incorporate both heteroatom removal or deoxygenation, and then isomerization and hydrocracking in subsequent reactors (see Figure 7). However, there are slightly different production strategies for targeting diesel or jet fuel. **Jet fuel production requires a more severe hydrocracking step** to achieve molecular weight reduction compared to the relatively mild operating conditions in hydroisomerization used for diesel production. The increased process severity for jet production needs to consider the combinations of reactor design, catalysts, and operating conditions.

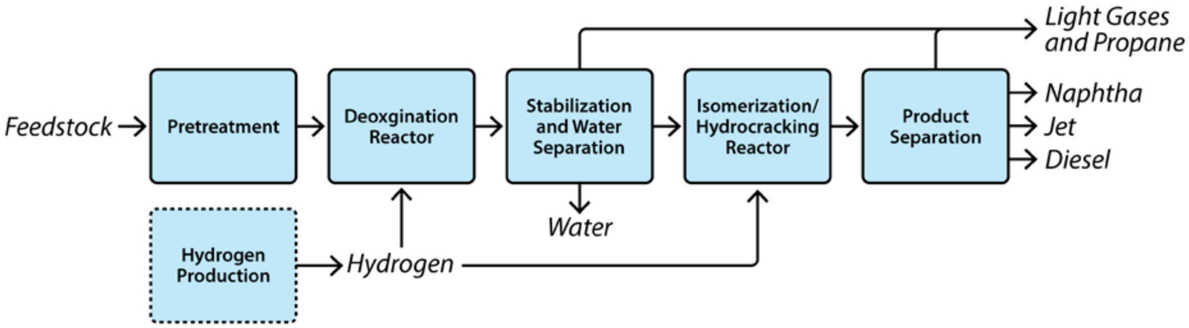

Figure 7. Simplified flow diagram for RD and biomass-based jet production process

Although the basic operations for hydroprocessing of biogenic feedstocks are the same for grassroots, converted/repurposed, or coprocessing units, there are some specific considerations for dedicated facilities that process 100% biogenic inputs. Whether the unit is newly constructed or a repurposed refinery facility, special consideration should be given to the following important needs:

- **Increased need for pretreatment.** Processing 100% biogenic feedstocks increases the importance of mitigating catalyst poisons.
- **Reactor design and control for high-oxygen feedstocks.** FOG feedstocks’ oxygen content ranges from 10 wt. % to 12 wt. %, with concentrations of total heteroatoms (sulfur and nitrogen) substantially higher than those found in fossil feedstocks. Heteroatom rejection reactions by hydroprocessing are highly exothermic. In order to control reactor temperatures safely below metallurgical limits, recycled gas and liquid are utilized as heat sinks to absorb the chemical energy released in exothermic reactions. Recycling liquid is an effective means to control temperature, but the recycled liquid displaces fresh liquid feed, thus reducing the overall capacity of the unit. This is an important consideration for repurposing or converting existing fossil hydroprocessing facilities to renewable feedstocks. This control temperature strategy also raises grassroots plants' capital and operating costs compared to similar capacity fossil plants. High ratios of gas and liquid recycles also increase the energy consumption, which potentially increases production cost and CI of the products.

- **Derate unit capacity**. Feedback from industry suggests that a repurposed HEFA unit will have only 25%–50% of the available feed processing capacity compared to the original fossil feedstock design. The need to derate the unit capacity is driven largely by the renewable feedstocks' high heteroatom content, which results in greater hydrogen demand and reactor exotherm. The exact derate percentage is highly dependent on the original fossil feedstocks for the unit. For example, straight-run diesel consumes substantially less hydrogen than cracked distillate streams like light cycle oil from the catalytic cracking unit. Therefore, a repurposed straight-run diesel unit will require a more substantial derate (lower percentage of original unit design) compared to a unit originally designed for hydroprocessing of light cycle oil to finished products.
- **Catalysts designed for biogenic feedstocks**. Stand-alone units enable applications of specific catalysts designed for biogenic feedstocks and targeting desired product selectivity. In addition, catalyst loading strategies can be applied to mitigate problematic feedstock quality issues.
- **Performance guarantees.** The major technology licensors of HEFA provide performance guarantees for units that incorporate their processes. The primary licensed technologies include UOP Ecofining, Haldor Topsoe HydroFlex, Neste NEXBTL, and Axens Vegan. The performance agreements generally guarantee the product yield, product qualities, intervals between catalyst changes (catalyst lifetime), and process reliability or on-stream factor provide that the design criteria for the unit is met. The performance guarantees can apply to repurposed or converted fossil units and grassroots projects.
- **Optimization for variable SAF vs. RD yields.** Some technologies can be designed for variable yields to optimize between maximum RD and SAF depending on market conditions and available incentives.
- **Investment in new developments.** Major players in RD have made it a common practice to invest in the construction of new grassroots units. (see Figure 1 and Appendix B).
- **Product separation for SAF recovery.** RD units are designed with simple product fractionation systems to strip gases and naphtha-range products to recover a stabilized diesel product. However, fractionating jet fuel cut requires a more complex system to split the distillate product into jet (or SAF) and diesel. Industry stakeholders considered adding a separation unit for SAF to be more of an economic issue than a technical one. Refineries face water removal and wastewater management challenges due to increased flow rates and contaminant levels. These challenges are addressed in Section 4.2.
- **Adequate space/footprint for development and expansion.** Finding room for development and expansion can be a challenge for both grassroots and converted/repurposed facilities that are co-located at existing refineries. Many of today's refineries have evolved over time to process a variety of crudes, maximize carbon efficiency, and minimize emissions. Therefore, many refineries are space constrained due to the additions of units needed to maximize profitability while maintaining environmental compliance. In these cases, it may be challenging to fit another conversion unit within the battery limits or footprint of the refinery.

3.1.4 Construction of Stand-Alone Facilities

A major topic of discussion with industry contacts in renewable fuel production is the design and construction of grassroots and repurposed facilities. Industry's primary concerns in these areas are:

- **Construction time.** Based on industry interviews, the time required to design, construct, and start up a new HEFA facility ranges from **2–5 years** following budget approval. This range applies to projects that have been approved for expenditure and does not include the preliminary analysis steps such as project scoping. The range of construction periods also applies to both grassroots and repurposed units. However, there may be certain instances/projects where construction times are shorter for repurposed units than grassroots facilities.
- **Permitting requirements.** The impact of permitting requirements on project completion times is highly dependent on the location of the project. Some states have a more standardized and expedited process for approving new commercial projects and approving permits. However, other states have far more stringent requirements for new projects review, and public comment to consider environmental, community, and energy justice impacts. In addition, states that are aggressively pursuing decarbonization of the petroleum industry have been reluctant to approve projects that do not completely eliminate fossil feeds. A number of HEFA projects have been delayed and even cancelled due to extended permitting periods. Section 5.2 provides a detailed discussion on permitting.

3.2 Coprocessing HEFA Feedstocks

The coprocessing of HEFA feedstock in existing petroleum refineries has increased in recent years (see Figure 1 and Appendix B). **HEFA coprocessing offers a cost-effective alternative to stand-alone SAF facilities, requiring lower investment and minor adjustments to refinery operations.** However, converting HEFA feedstocks for refinery processing still presents challenges related to the instability of FOG feedstock, equipment corrosion, and byproduct generation.

While most of the coprocessing in petroleum refineries is used to produce RD, ASTM D1655 Annex A1 approves coprocessing of up to 5 vol % of HEFA feedstock with fossil oil intermediates to generate SAF (**HEFA coprocessing**). The same ASTM standard also allows for up to 5 vol % coprocessing of hydrocarbons derived from synthesis gas via a Fischer-Tropsch process using an iron or cobalt catalyst. The most recent revision of ASTM D1655 (2023) allows hydrocarbons derived from hydroprocessed monoglycerides, diglycerides, triglycerides, free fatty acids, and fatty acids (biomass) to undergo coprocessing via fractionation (**fractionation coprocessing**) [78].

3.2.1 Coprocessing Feedstock Handling

According to industry stakeholders, **handling HEFA feedstocks in a refinery is difficult, but not as challenging as handling other SAF feedstocks such as agricultural and forest residues**. This is attributed to the experience of refineries in handling liquid feedstocks as along with the wealth of available information and the prior experience gained from coprocessing HEFA feedstocks.

Refineries need systems for receiving, offloading, and storing HEFA feedstock, similar to those found in the stand-alone SAF facilities. Refineries already have systems in place to unload trucks, rail cars, or ships. Whether new offloading stations are required depends on the existing system capacity. The high levels of free fatty acids in numerous HEFA feedstocks may require higher-grade metallurgy (such as stainless steel) for offloading and storage systems.

Some industry stakeholders expressed that refiners may be reluctant to co-process alternative feedstocks as a replacement for traditional crude oil. This is because crude oil is readily, predictably, cost-effectively, and logistically accessible.

The **maximum concentration of impurities** recommended for coprocessing in hydrotreating, hydrocracking, and FCC units are similar to those reported in Table D-1 for the stand-alone hydroprocessing. However, the maximum amount of HEFA feedstock that can be coprocessed with fossil intermediates is limited to no more than 5 vol % bio-feedstocks. The concentration of impurities from the HEFA feedstocks is diluted by at least 20 times, depending on the density of the fluids. Thus, **the impurities contribution from most HEFA feedstocks to HEFA coprocessing feed will be low enough (at maximum co-feed ratio of 5 vol %) to meet hydroprocessing requirements** (see discussion in Appendix D.2, Table D-2).

While some fuel producers mentioned that refined vegetable oils and animal fats can be coprocessed without pretreatment in most cases, other fuel producers claim coprocessing without pretreatment presents technical obstacles and that some level of pretreatment remains essential. Refineries that co-process refined vegetable oils are looking into implementing in-house pretreatment processes that allow feedstock flexibility. **The pretreatment needs will differ based on the HEFA feedstock type and quality, as well as the refinery unit chosen for coprocessing**. The companies providing biogenic feedstock pretreatment technologies for HEFA coprocessing are the same as those mentioned in Section 3.1.2.

3.2.2 HEFA Coprocessing Conversion

DOE, national laboratories, and industry see upgrading existing infrastructure to process renewable and circular feedstocks as an opportunity to reduce the capital burden for biofuels production. Refiners have begun utilizing both hydroprocessing (hydrotreating and hydrocracking) and FCC unit operations for HEFA coprocessing of low-carbon feedstocks. Figure 8 provides a block flow diagram for coprocessing pathways utilizing these unit operations to produce renewable liquid fuels and chemical precursors. The pathways to RD and SAF are as follows:

- Feed to diesel **hydrotreating** units to produce RD
- Feed to distillate **hydrocracking** units to produce RD and SAF
- Feed to **FCC** and send (1) heavy naphtha product to light distillate hydroprocessing to produce SAF, and (2) light cycle oil product to distillate hydrocracking to produce RD and SAF.

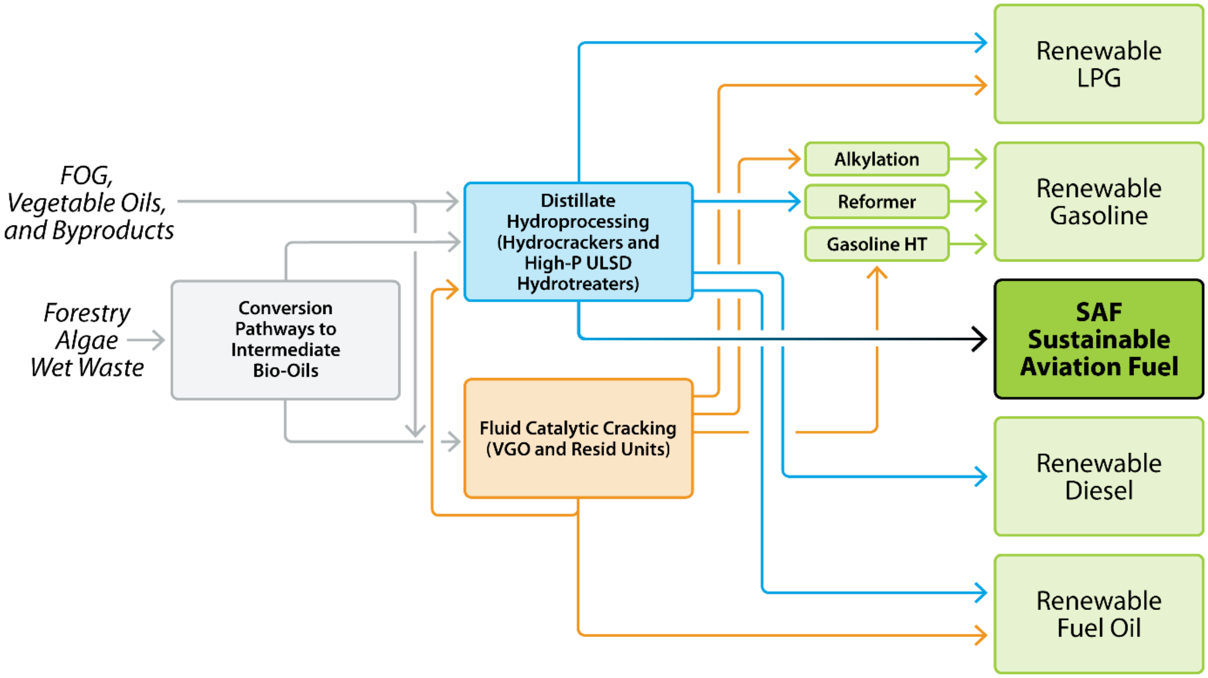

Figure 8. HEFA coprocessing pathways utilizing hydroprocessing and FCC.

Note: Output streams from hydrotreaters and hydrocrackers are blue, while output streams from FCC are red. Bold arrows indicate the SAF production pathways.

Benefits of HEFA Coprocessing

There are several potential benefits for refineries utilizing HEFA coprocessing of biogenic feedstocks as a means of diversifying facility inputs:

- **Minimization of capital investment.** HEFA coprocessing and repurposing offer the opportunity to minimize the capital burden associated with renewable fuel production. Many industry stakeholders point to capital investment as a significant barrier for entry in RD and SAF production. This is especially the case for small refining businesses with less balance sheet cash and access to debt funding than larger (major) refiners.
- **Dilution operational risk reduction.** Many of the operational risks associated with renewable feedstock processing are substantially reduced when these feedstocks are blended with traditional fossil feedstocks. With coprocessing, refiners can start small to minimize initial risk of their assets and continue to increase production as risks are mitigated and technology develops. This is analogous to the evolution of refineries in processing heavy, high-sulfur, high-total-acid-number crudes over time. A specific example of operational risk mitigation through HEFA coprocessing is related to reactor temperature runaways. The impact of reactor exotherm is smaller when coprocessing HEFA with fossil feedstocks compared to processing HEFA feedstocks alone. Furthermore, HEFA coprocessing with fossil feedstocks also reduces the need for pretreatment (Table D-2).
- **No disruption of crude distillation capacity.** Unlike crude oils, lipid-based renewable feedstocks do not require fractionation prior to upgrading via hydroprocessing or FCC.

Therefore, these feedstocks do not directly impact a refinery's capacity for total oil processing through the crude fractionation units.

- **Reductions in sulfur and nitrogen.** There are a few potential benefits to petroleum refiners related to reduced concentrations of sulfur- and nitrogen-containing compounds in renewable feedstocks. Through the refinery process, the sulfur and nitrogen in fossil crude oil are converted to hydrogen sulfide, sulfur dioxide, ammonia, and nitrogen oxides. All of these compounds require emissions control processes to minimize quantities and concentrations released to the atmosphere. Over time, petroleum refineries have become burdened with environmental control operations needed to meet increasing regulation of sulfur in fuels (e.g., low-sulfur gasoline, ultra-low-sulfur diesel). Refineries constrained by sulfur and nitrogen removal and recovery operations would benefit from feedstocks with lower contaminant concentrations. The following specific examples identify refinery constraints related to sulfur and nitrogen compounds:
    - **Acid gas scrubbing and sulfur plant capacity.** With increasingly strict requirements for desulfurization of gasoline and diesel fuels, refineries may be limited by their capacity to remove hydrogen sulfide and sulfur dioxide through acid gas scrubbing (or other solution-based scrubbing technologies) and to convert the recovered compounds to elemental sulfur in the sulfur plant. Biomass-derived intermediates are nearly sulfur-free and are therefore potentially attractive for refineries that are sulfur plant constrained.
    - **Water wash demand.** Several refinery unit operations, including heavy-oil hydrotreaters, hydrocrackers, and FCCs, require water wash to reduce corrosion risk in locations where salt deposition is anticipated. Water wash demands, largely dependent on the concentrations of hydrogen sulfide and ammonia in the streams, can be constrained by hydraulic capacity limitations and/or available water supplies (specifically in high-pressure operations). With lower amounts of sulfur and nitrogen in the feedstocks, refineries require less water wash to maintain constant concentrations of these elements.
    - **Product fractionator salt deposition**. Sulfur and nitrogen compounds contribute to the risk of corrosive salt deposition in various areas of a petroleum refinery, including the fractionators in hydroprocessing and FCC units. Salt deposition concerns can limit refinery operation and result in suboptimal product yields or unit rate cuts. Salt deposition, if not monitored and properly mitigated, can also cause significant corrosion issues and result in unplanned shutdowns of refinery equipment.

The analysis of hydroprocessing pathways shows that hydrogen consumption for both hydrodeoxygenation and isomerization/hydrocracking will be in the range of 2,400–2,800 standard cubic foot (scf) H_2/bbl (57–67 scf H_2/gal) [79–82]—depending on target yields. Based on these ranges, **the existing operations most suitable for conversions to produce RD and SAF from HEFA feedstock are cracked distillate hydrotreating and distillate to heavy feed hydrocracking units.**

The refinery unit capacity data (Table D-3) show that more than 150 BGPY of applicable hydroprocessing equipment exists in the U.S. refinery network (70-BGPY diesel hydrotreating, 51.2-BGPY gas oil and residue hydrotreating, and 37.2-BGPY hydrocracking feedstock capacity). In addition, refineries can increase renewable feedstock integration beyond coprocessing in hydroprocessing units by feeding other thermal and catalytic processes such as cokers and FCCs.

These conversion units utilize carbon rejection, as opposed to hydrogen addition, to increase hydrogen-to-carbon ratio in products. Therefore, **minimizing CI relies on optimization that factors in hydrogen availability and the capacities of different unit operations**.

Challenges of HEFA Coprocessing

Processing renewable feedstocks in a conventional petroleum refinery introduces several potential challenges and operational issues associated with the differences in physicochemical properties relative to petroleum crude oil. Refinery complexes are valuable and costly to maintain and repair. Therefore, refiners tend to be risk averse with introducing novel feedstocks into the plant. It is especially important to maintain the operational reliability of the refinery when introducing new feedstocks with different properties. Some of the challenges associated with refinery HEFA coprocessing are as follows:

- **Investments.** Additional modifications and investments may be required to implement coprocessing at different levels in a refinery. These may include modifications to stages including separation (to remove water content in the product stream), isomerization and/or hydrocracking (to meet SAF product quality requirements, mainly related to stability and cold-flow properties), and product fractionation (to recover multiple fuel products from the reactor effluent).
- **Tank farms.** Alternative feedstocks such as oils and fats may require new feeding systems and storage tanks. Refineries are reluctant to mix renewable feedstocks with fossil feedstocks due to different thermophysical properties and concerns about miscibility and thermal stability. The need for additional tanks, pumps, and feed piping also can exacerbate footprint constraints, as space is limited in many refinery facilities.
- **Contaminant metals.** Crude oils contain small amounts of inorganics, typically salts and porphyrins of vanadium and nickel that are removed by a desalting unit before fractionation. Refiners have developed strategies to mitigate and/or neutralize the impact of vanadium and nickel on catalysts over time [83]. New feedstocks in the refinery have the potential to introduce a new suite of potential catalyst poisons like potassium, calcium, and other alkali and alkaline earth metals [84]. These metals could act as severe/permanent poisons for hydrotreating and cracking catalysts (see Appendix D).
- **Acidity and corrosion**. Renewable and circular feedstocks can introduce new acidic and corrosive contaminants and properties to the refineries. Infrastructure needs to be compatible with new feedstock properties, but metallurgical upgrades can be costly (see Appendix D).
- **Carbon monoxide (CO) and CO_2.** CO and CO_2 will be produced in HEFA coprocessing operations and will likely enter the refinery fuel gas header with the light ends (ethane and lighter compounds). While amine systems may be able to remove a substantial portion of CO_2, they will not remove CO, which will reduce the overall heating value of the fuel gas. Because fuel gas is generally combusted to produce heat and power for the refinery, there are no other obvious concerns with the presence of CO and CO_2, but it is important to verify that there will be no negative impacts on refinery operations.
- **Oxygen.** HEFA feedstocks' relatively high oxygen content introduces several challenges and considerations during coprocessing. In the hydrodesulfurization reaction, oxygen-rich

feedstocks can inhibit sulfur removal, leading to an increase in sulfur content in the final product [85]. The inhibition of the hydrodenitrogenation reaction has been observed and is believed to be caused by the presence of CO and CO_2, which are formed during the hydrodeoxygenation reactions. In addition to the oxygen levels, the type of oxygen species is crucial, as certain species can trigger polymerization reactions, resulting in increased coking. The deposition of solids, such as coke or polymerization products, has been linked to pressure drops in hydrotreaters. The removal of oxygen in the FCC process leads to the production of more olefins and aromatics, which significantly impact fuel quality. This is particularly evident in the form of a lower cetane number in diesel fuel and a higher smoke point in jet fuel [86].

- **Water management.** The presence of oxygenated compounds will lead to increased process water yield from HEFA coprocessing units. While many of these unit operations yield water in the absence of renewable feedstocks, greater water yield is an important consideration for overall refinery water management. Wastewater management is discussed in Section 4.2.
- **Yield loss.** Hydroprocessing units used for coprocessing HEFA feedstock will experience reduced capacity compared to that of fossil streams. Jet fuel yield from coprocessing HEFA feedstocks are negatively impacted by their higher oxygen content, giving rise to carbon lost through the formation of CO and CO_2 due to decarbonylation/decarboxylation reactions [87]. Concerns about yield loss from displacing crude can be alleviated if coprocessing (hydroprocessing) units have additional capacity.

3.3 SAF vs. RD

Although the pathways for SAF and RD are similar and share a consistent process flow, it is important to understand the differences for comparative analysis. The project team has focused on understanding differences between SAF and RD in terms of operational severity, raw material and hydrogen demands, product yields, economics, and sustainability. The team developed models to determine the **yields for maximum RD and SAF fuel recovery** (see discussion in Appendix D.3).

Based on the summarized data sources, the NREL team derived a basis for hydrogen consumption that applies to both diesel and jet target product scenarios. Figure 9 shows the hydrogen consumption basis (operating line) with the operating points for diesel and jet fuel.

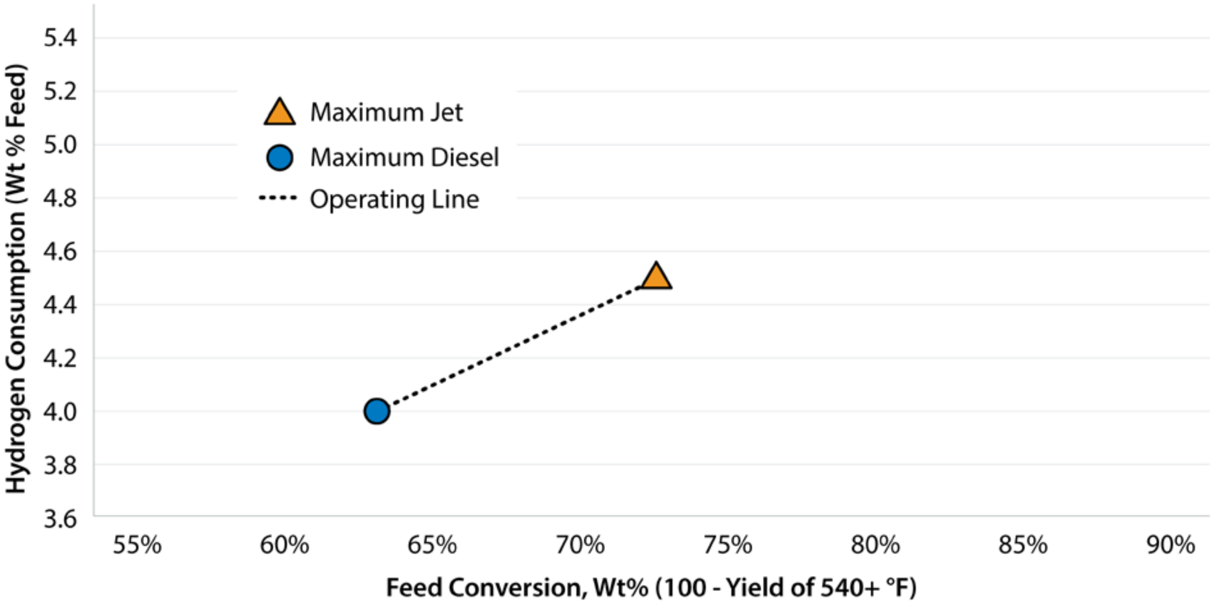

Figure 9. Hydrogen consumption basis derived from source data and process simulation results

Note: In x-axis,100% represents the total initial feedstock. The percentage yield of the distillate fraction with a boiling point above 282°C (540°F) (considered unconverted) is subtracted from 100% to determine the percentage of feedstock converted into the desired product and lighter fractions.

RD is a major competitor to HEFA SAF. Both RD and HEFA SAF are made from the same feedstocks, leading to concerns among stakeholders who fear that competition for feedstock could cause cannibalization of the RD and biodiesel sectors. This could, in turn, impede the use of renewable fuels in the marine industry. Moreover, producing HEFA SAF instead of RD reduces fuel yields while generating larger amounts of byproducts (Table G-1), and process reconfigurations may be required. Thus, production of HEFA SAF may not be as profitable as RD (see Section 6).

The pathways for SAF and RD are similar, however the production of SAF requires more severe isomerization and hydrocracking to achieve jet fuel's cold-flow specifications. In addition, SAF yields are typically lower than RD yields. These technical challenges may be one of the reasons why in 2021, only 8 million gallons of SAF were sold in California, making up just 0.3% of the total LCFS credits sold. In contrast, 941 million gallons of RD were produced in the same year, accounting for 36% of the total LCFS credits sold [88].

The production of SAF through HEFA coprocessing is limited by ASTM's maximum coprocessing ratio of 5 vol %, as well as its ineligibility for federal incentives. In comparison, the HEFA feedstock blending ratio of refineries producing RD through coprocessing is up to 30 vol %. The refining industry has gained expertise in coprocessing alternative feedstocks, such as crude tall oil, which are not approved for SAF production. In addition, due to the increasing demand for diesel and the incentives for renewable road fuels, the production of RD through coprocessing has become extremely appealing. **To encourage producers to produce SAF through HEFA coprocessing, they would require higher blending ratios, approval for alternative feedstocks, and more attractive incentives.**

4 Additional Inputs Required for the HEFA Pathway and Wastes

Key Takeaways

- Industry stakeholders agree that sourcing hydrogen presents a major challenge to achieving the production goals of the SAF Grand Challenge.
- The hydrogen source significantly affects SAF's CI score, as well as a fuel's eligibility for incentives.
- Some industry stakeholders are concerned about the energy source, location, and capital investment required for hydrogen produced via electrolysis.
- Ramping up production of HEFA feedstocks requires meticulous planning to reduce environmental risks linked to farming, including water consumption and fertilizer runoff.
- Phosphorus utilized in the refining of vegetable oil and the pretreatment of HEFA feedstocks, as well as metals used in hydroprocessing catalyst manufacturing, face supply chain risks due to increased competition and U.S. reliance on imports.
- Renewable fuel operations need more intensive wastewater treatment than modern petroleum refineries; at times this may require more extensive treatments or new facilities.
- Spent bleaching earth from vegetable oil refining and HEFA feedstocks pretreatment is not reused and can pose environmental hazards.

Meeting the SAF 2030 production goals will require the creation and development of a new industry. As a result, sectors that are linked to and provide supplementary inputs to the SAF supply chain, including chemical, utility, equipment, and waste management industries, must boost their capacity and operations. The key inputs to and waste streams from the HEFA SAF supply chain are discussed in this section. Additional details are presented in Appendix E.

4.1 Inputs for the HEFA SAF Supply Chain

4.1.1 Feedstock Generation

Generation of feedstocks for HEFA SAF production is complex, whether it involves livestock and oilseed crop farming or the development of UCO/yellow grease and algae oil industries. As part of HEFA SAF strategic deployment, it is recommended to assess agricultural risks including:

- **Water usage.** Crop production uses large amounts of freshwater in the U.S. food system, accounting for about 58% to 65% of the total freshwater consumption from 1997 to 2012 [89]. Thus, there are concerns about the water usage associated with the production of renewable fuels, particularly in the context of water scarcity and sustainable resource management. The water footprint of drop-in fuels produced via HEFA from soybean oil has been estimated at between 2 and 309 gallons of water per gallon of fuel, depending on the irrigation method used and location [90]. As worries continue to increase about a lack of water access for both farming and household needs, it is crucial to thoroughly evaluate available water sources and the amount needed to achieve the SAF production objectives.
- **Fertilizer runoff.** Overuse of fertilizers can lead to runoff contaminating both surface water bodies and groundwater. As the renewable fuel industry grows, so will the size and intensity of agricultural production, as well as the fertilizer runoff problem. **The EPA has identified phosphorus and nitrogen discharge from farm fertilizers as the greatest challenge to U.S. water quality [91].** While **nitrogen** can be obtained from atmospheric nitrogen and used for manufacturing fertilizers, energy is required to separate and purify it, with emissions penalties.
- **Seed availability**. Seed sources and distribution systems can be disrupted by sudden events such as conflicts and disasters and ongoing issues with social inequality, inefficiency, poor industry coordination, and unsuitable policies and regulations.

4.1.2 Feedstock Preprocessing

During the crushing and refining of vegetable oils, the main inputs are:

- **Solvents.** Extraction of oil using hexane-based solvent is the most common process in oilseed facilities. Because commercial *n*-hexane is a neurotoxin, it is listed as a hazardous air pollutant, and its facility-wide emissions are highly restricted [92, 93]. Vegetable oil extraction is the primary application for solvents containing hexanes, accounting for the majority of hexane market growth.
- **Phosphoric or citric acids.** Used in the degumming step of vegetable oil refining process, phosphoric acid is produced from phosphate rock and used primarily in fertilizer products. With phosphate rock reserves estimated to last only another 50–100 years, the phosphoric acid supply chain is at risk from increased competition and reliance on imports of raw materials [94]. There is an anticipated increase in the demand for citric acid, which is used mainly in the food industry, because of the rising requirement for food preservatives [95]. The optional chloride removal step in the HEFA feedstock pretreatment, based on a water wash, requires water and pH adjustment, while the polyethylene removal step, a cold filtration process, uses filter aids [67].

- **Potassium hydroxide and sodium hydroxide.** The removal of free fatty acids, which are more prone to oxidation than triacylglycerides, is crucial for creating a stable biogenic oil. The formation of soaps is achieved by neutralizing free fatty acids with alkali, such as potassium hydroxide or sodium hydroxide [96]. Sodium chloride is used to manufacture sodium hydroxide, while non-fertilizer potassium chloride is converted primarily to potassium hydroxide. Both sodium chloride and potassium chloride have low risk of supply disruption ratings assigned by the EPA [97, 98].
- **Bleaching earth.** Acid-activated bleaching earth is the most used adsorbent in the production of edible oils and fats. Demand is expected to grow due to the growth in markets for edible oils, biodiesel, and renewable fuels (RD and SAF) [99].
- **Other chemicals.** Although rendering facilities do not consume large amounts of chemicals, they still use certain chemicals to improve efficiency. For instance, antifoams are utilized to aid in the cooking step, refining aids are employed to neutralize free fatty acids before centrifugation, and acids such as phosphoric acid are added to regulate pH levels.

4.1.3 Catalysts for HEFA Coprocessing

A variety of **catalysts** are commercially available for hydroprocessing bio-based feedstocks. Providers of catalysts for HEFA SAF and RD **stand-alone processes** include Neste Oil [18], UOP [19, 20], Axens, Topsoe [22], REG, and Sulzer [24]. Catalysts needed for HEFA coprocessing of biogenic and fossil oils in hydroprocessing (hydrotreating and hydrocracking) are available from companies including Advanced Research Technologies, Axens, Clariant, China National Petroleum Co., Catalysts & Chemicals Industries Co., Albemarle, Honeywell UOP, Haldor Topsøe, Sinopec, Criterion, and Johnson Matthey. Suppliers of FCC catalysts used in coprocessing include W.R. Grace, Albemarle, BASF, Sinopec, and Catalysts & Chemicals Industries Co.

Supply challenges for metals related to the manufacturing of these catalysts include:

- **Platinum group metals (PGMs).** PGMs including platinum, palladium, rhodium, ruthenium, iridium, and osmium, are used in manufacturing oxidation and hydrogenation catalysts. While the catalyst market currently consumes the most PGMs (specifically platinum, palladium, and rhodium) [100], PGMs are also critical materials for several decarbonizing energy technologies (i.e., proton exchange membrane electrolyzers for hydrogen production and fuel cells for transportation and stationary energy storage). Most PGM production and reserves are located in South Africa and Russia, with the two U.S. PGM mines operated in the U.S. (owned by a South African company) producing less than 7% of the world supply [100]. Potential PGM supply chain vulnerabilities include:
    - Insufficient data to accurately evaluate and describe the PGM catalyst supply chains.
    - Reliance on energy-, water-, carbon-, and capital-intensive processes.
    - Decline in PGM supply from recycled catalytic converters as internal combustion engine vehicles are replaced by electric vehicles.
    - Technologies for recovering and recycling PGMs from proton exchange membrane electrolyzers and fuel cells are still in early stages of development.
    - Lack of domestic refining operations.

- Water electrolysis technology currently relies on proton exchange membranes, which are manufactured using iridium. The U.S. depends entirely on imports for its supply.

Further discussion on the supply of other metals, such as molybdenum, nickel, and cobalt, can be found in Appendix E.

4.1.4 Hydrogen Demand and Sourcing

Industry stakeholders agreed that **sustainable and low-cost hydrogen for the hydroprocessing process is a major constraint for the SAF supply chain** and the most significant technical and operational constraint for upgrading HEFA feedstock into SAF.

In the U.S., the oil refining industry is responsible for most hydrogen production and consumption. The second major use of hydrogen is for ammonia production, used mainly in fertilizers [105]. Dedicated hydrogen production is primarily performed via the steam methane reforming (SMR) of natural gas, which represents 76% of global hydrogen production. The balance of the dedicated global hydrogen production relies on coal (23%), with a small fraction using renewable sources such as water electrolysis, which accounts for ~1-2% [105].

Hydrogen consumption for HEFA SAF is significantly higher—57-67 scf H_2/gal[15] of biogenic feedstock—than the hydrogen required for jet fossil fuel production (4-12 scf H_2/gal of fossil hydrocarbon feed)[16] [84]. The primary reason for the greater hydrogen needs in HEFA processing is the requirement for hydrodeoxygenation, as well as the need to reduce nitrogen and other contaminants, hydrocracking, and isomerization. Industry stakeholders expressed their concerns regarding hydrogen production capacity and the rise in hydrogen demand for renewable fuel production.

The addition of HEFA feedstocks in refineries increases hydrogen consumption substantially. The increase in hydrogen requirements will take a toll on process economics and can be a limiting factor for implementing HEFA coprocessing in refineries that do not have excess hydrogen capacity.

Because highly saturated fatty feedstock sources such as tallow require less hydrogen than more unsaturated feedstock options (e.g., rapeseed oil) [85, 106], hydrogen requirements can play a role when determining the feasibility of a certain feedstock.

Higher federal and state incentives are available for SAF production pathways that offer larger GHG emissions reductions. Thus, the source of hydrogen and its production emissions affect the CI of SAF. For example, CO_2 intensity of hydrogen produced from natural gas without carbon capture, use, and storage is about 8 kg CO_2/kg H_2, while most hydrogen produced via electrolysis

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[15] The determination of the hydrogen consumption rate involved identifying a conservative (high) estimate of renewable diesel-based hydrogen consumption across various feedstocks from the literature [79-82]. This identified value was subsequently employed in HYSYS models to project the additional hydrogen required for the optimization of jet fuel production.

[16] 4-12 scf H_2/gal of kerosene/jet fuel hydrotreating. The primary source of jet fuel from fossil refineries is the straight-run kerosene stream of the crude fractionation unit. Refinery intermediates that undergo hydrotreating and hydrocracking may also contribute to jet fuel production. Hydrogen consumption ranges from 17-41 scf H_2/gal for cracked distillate hydrotreating and from 12-48 scf H_2/gal for distillate hydrocracking [84].

using renewable or nuclear-generated electricity is assigned a CI of zero, depending on the renewable source [105]. Using electrolytic hydrogen with renewable power sources to produce renewable fuels can lower the fuel's CI score compared to that of hydrogen produced via steam methane reforming.

Industry stakeholders view electrolytic hydrogen technologies using renewable power sources as expensive and not yet widely available, which can create financing burdens for SAF production. Stakeholders are concerned about the reliability of the electric grid due to the potential rise in electrolytic hydrogen production (using renewable power sources) and the electrification of light-duty vehicle fleets. While the number of electrolytic hydrogen projects is increasing [107, 108], production using renewable power sources is pricier than typical methods. The cost of producing hydrogen from natural gas is \$0.8–\$1.6/kg, while from low-carbon electricity the cost is \$3.2–\$7.8/kg [109]. Apart from the production cost, there are also concerns about the high water and electricity consumption involved in producing significant quantities of electrolytic hydrogen (see Appendix E). The Energy Earthshots Initiative of the U.S. DOE has set a goal to accelerate the development of clean energy solutions within the next ten years. The first Energy Earthshot, known as Hydrogen Shot, aims to decrease the cost of clean hydrogen by 80% to \$1 per kilogram in a decade [110].

Hydrogen is primarily produced from natural gas and coal today. Producing at the existing scale and transitioning to clean energy requires capturing CO_2 from fossil fuel hydrogen production. Producing low-carbon hydrogen at a large scale is possible via SMR with carbon capture and storage (CCS). Hydrogen produced via SMR with CCS is often cheaper than electrolytic hydrogen, because natural gas is a cheaper feedstock than renewable electricity. However, hydrogen produced via SMR with CCS typically comes with a higher CI score and may require a larger production scale to make the CCS investment economically viable, while electrolyzers operate on a smaller scale using modular technology that allows for easy expansion [105, 111]. Moreover, hydrogen produced via SMR with CCS depends on natural gas.. The reliance on natural gas may unintentionally support the ongoing use of fossil fuels, hindering the transition to cleaner energy sources, which remains a debatable point.

As the bioeconomy advances, the supply of renewable gases that can be used via SMR instead of natural gas for hydrogen production may increase. This potential expansion may not only offer a means to reduce GHG emissions, but also might enable the utilization of gases generated through diverse bioconversion processes [112]. For example, Topsoe's H2Bridge allows the use of renewable naphtha (a by-product of HEFA SAF production) as feedstock for producing hydrogen [113]. The impact of hydrogen sourcing in SAF's CI and cost are discussed in Section 6.

4.2 Waste Streams

Major waste streams generated from the SAF supply chain are wastewater and spent bleaching earth. The vegetable oil refining industry is experienced in dealing with the wastewater and spent bleaching earth generated from their day-to-day operations. As the demand for vegetable oils increases, the oil crop industry will need to expand its waste management infrastructure and operations.

HEFA SAF stand-alone facilities have the advantage of custom-designed water treatment plants to deal with the type and level of contaminants in the wastewater generated from the HEFA process. However, co-located processes or HEFA coprocessing for HEFA SAF production in refineries pose a challenge, as these introduce new waste streams.

Wastewater from renewable fuel production contains about 10 to 100 times more organic contaminants than typical petroleum refinery wastewater [114]. Additionally, wastewater generated from processing oil feedstocks contains emulsified oils, has natively low pH (<5), and involves high temperatures ranging from 50°C to 60°C [115]. HEFA coprocessing also generates higher quantities of wastewater which can contain residual oil and grease as well as some spent bleaching earth from the HEFA feedstocks pretreatment. It has been reported that when converting a petroleum refinery to an RD process, the expense of wastewater treatment can make up to 15% of the overall project cost [117].

Thus, **greater volumes of wastewater from biofuel production require more intensive treatment than is typical for a modern petroleum refinery.** Existing regional wastewater facilities can become overwhelmed and may need extensive upgrades or new facilities [114, 116].

Because wastewater from biorefineries, such as renewable diesel facilities, is biodegradable, an opportunity exists to use anaerobic digestors to treat wastewater and produce renewable natural gas. Additionally, hydrogen can be produced from the renewable natural gas via steam methane reforming [114, 118] (see Section 4.1.4).

Spent bleaching earth can contain residual oil (25%–30%), water, and other impurities, and is about 0.5–2 wt. % of the oil feed [67]. For example, for soybean oil, bleaching earth dosage ranges from 0.3%–0.6% of oil feed [119]. The total amounts of spent bleaching earth (solid waste) will increase as the industry grows. When bleached earth becomes dry, it can self-ignite or smolder, and is treated as hazardous material for handling, storage, and transportation. Removal of spent adsorbent also can increase truck traffic to and from the facility.

High costs and environmental concerns make disposal of spent bleach clay in landfills impractical for most locations. Residual oil contained in spent clay can degrade to methane in the landfill, which can increase the CI of fuel [67, 68, 116]. Additionally, the residual oil may percolate into the soil and pollute water sources.

Alternatively, the spent bleaching earth can be sold to be used as solid fuel in boilers or as animal feed. Some companies recover residual oil from spent bleaching earth via solvent extraction. Other applications of used clays under development include use in wastewater treatment, biofertilizer, fuel briquettes, and non-fired wall tiles [120].

5 Approvals, Permits, and Policies

Key Takeaways

- Federal and state incentives are key to promoting SAF production and will influence choices between production of RD and SAF.
- Considering the limitation of HEFA feedstocks, it is important to carefully plan how to stimulate SAF production while meeting the demand for biodiesel and RD.
- It is crucial to streamline the financing process for HEF SAF facilities. Such facilities can take 2 to 5 years to construct after the final investment decision. This streamlining is necessary if these facilities need to be deployed by 2030.
- Implementation of HEFA coprocessing may be a fast and cost-effective (minimal capital investment) approach to contribute to the 2030 goals, but SAF produced via HEFA coprocessing is not eligible for the blender's tax credit.
- Industry stakeholders suggest conducting research to clarify ASTM standards associated with higher blending ratios and alternative feedstocks and pathways.
- Delays and difficulties in permitting, which is a precondition for constructing HEFA facilities, may lead to delays and impact project schedule and budget.
- Community buy-in and acceptance may significantly delay or prevent development of new, more sustainable SAF production facilities.
- Lack of more sustainable fuel production facilities may have a negative impact on the potential to increase energy justice for broader society.

This section covers the key elements of approved blending and fuel properties defined by ASTM, as well as the impact of permitting for HEFA SAF facilities and HEFA SAF-related federal and state incentive programs.

5.1 ASTM-Approved HEFA Pathways

There are two primary standards related to the approval of aviation fuels: ASTM D1655 and ASTM D7566. ASTM D7566 applies to aviation fuels that contain synthetic components from alternative sources, whereas conventional jet fuels are approved per ASTM D1655.

5.1.1 ASTM D7566: Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons

Synthetic paraffinic kerosene (SPK) is synthetic blending component that can serve as an alternative aviation fuel. Each batch of HEFA SPK and SPK derived from hydroprocessed hydrocarbons, esters, and fatty acids (HC-HEFA SPK), specifically from *Botryococcus braunii* algae, must meet the requirements outlined in ASTM D7566. In order to be referred to as SAF in this report, SPK must meet the SAF definition[1] stated in the *Sustainable Aviation Fuel (SAF) State-of-Industry Report: State of SAF Production Process* [1]. A summary of these requirements is shown in Table F-1, while ASTM D7566 is further discussed in Appendix F.

Industry stakeholders have expressed interest in the following topics related to these standards:

- **Blending ratios**. The amount of HEFA SAF that can be blended with conventional Jet A/A-1 is constrained up to 50% for HEFA SPK and 10% for HC-HEFA SPK by volume. However, **the capacity to blend SAF with jet fuel up to the blending limit is restricted by the characteristics of the conventional fuel**. This is because the blend must adhere to the Jet A/A-1 standards.
- **Aromatic content**. Jet A/A-1 specifications (defined in both D1655 and D7566) cap the maximum allowable content of aromatics at 25–26.5 vol % (depending on the test method). In contrast, the maximum concentration of aromatics in HEFA SPK batch before blending is limited to 0.5 wt. %. Therefore, HEFA SPK has a negative contribution (dilution) to the total aromatics content in HEFA SPK/Jet A/A-1 blend. Industry stakeholders expressed concern about the difficulties that arise from the low aromatics content requirements (<0.5 wt. %), which can affect the operation and design of HEFA SAF facilities in two ways:
    - Toward the end of the catalyst life, the hydroprocessing operating temperature is increased to compensate for the loss in activity [122]. Because the aromatics saturation conversion decreases at higher temperatures, the aromatics content in HEFA SPK will increase as the catalyst end of life approaches. Thus, more frequent turnarounds may be required to change the catalysts, resulting in considerable loss of revenue.
    - The single-stage hydroprocessing configuration produces fuels that contain a higher content of aromatics (above 0.5 wt. %) compared to the two-stage configuration. Facilities operating a single-stage configuration will not be able to produce HEFA SPK that complies with the aromatics content requirements.
- **Density.** The density specification for HEFA jet fuel is in the range of 0.730–0.772 g/cm³ (Table F-1) [25]. It is important to note that this density range is lower than the specification for Jet A/A-1, which ranges from 0.775–0.840 g/cm³ [31]. In fact, HEFA SPK does not even meet the lower boundary of the Jet A/A-1 range. Industry stakeholders noted that producers often need to develop highly selective processes or rely on specific, limited feedstocks to yield the desired density. This can potentially increase costs and decrease flexibility of

supply. Moreover, the lower density of HEFA SPK also results in lower energy density fuel that potentially can reduce aircraft range.[17]

- Industry stakeholders express concern about the limitations of blending and **recommend supporting research to reduce risks associated with higher blending ratios and explore additional pathways.** The Federal Aviation Administration (FAA) has provided funding for research to improve the approval process of ASTM specifications. It also provides funding to the Commercial Aviation Alternative Fuels Initiative, which assists producers in evaluating potential production of SPK [121].
- **Approved technologies**. ASTM D7566 does not specifically approve or disapprove any proprietary technologies. Instead, it sets out the criteria that must be met for a particular fuel or blend of fuels to be approved for use in aviation. Therefore, any proprietary technologies that meet the ASTM D7566 (Annexes 2 and 7) requirements can be used in the production of HEFA SAF [25].
- **Algae-based HEFA SPK**. The HC-HEFA SPK (Annex 7) process is the same as that described for HEFA SPK (Annex 2). However, Annex 7 only recognizes the *Botryococcus braunii* species of algae as a bio-source. The *Botryococcus braunii* species contains a high percentage of unsaturated hydrocarbons, known as botrycoccenes [123]. Thus, the Annex 7 pathway uses hydrocarbons in addition to free fatty acids and fatty acid esters. Please note that lipids derived from other, more conventional algae species would still qualify under Annex 2, in accordance with other lipid-based HEFA SPK feedstocks.

5.1.2 ASTM D1655: Standard Specification for Aviation Turbine Fuels

In 2018, ASTM approved the HEFA coprocessing of renewable feedstocks with crude-oil-derived middle distillates in petroleum refineries for jet fuel production. Requirements are shown in Table F-1.

Important topics for industry stakeholders include:

- **Renewable carbon content**. In practice, the HEFA feedstocks are being co-fed with petroleum intermediates in various units (Figure 8). While D1655 does not specify requirements for knowing the fossil versus present-day carbon content of the coprocessed product SAF/jet fuel blend, it establishes the importance of determining the renewable content in the product blend for regulatory purposes. This proportion can be determined based on radiocarbon (^{14}C) concentration via test methods in ASTM D6866 [31]. Industry stakeholders involved in HEFA coprocessing have stated that thorough ^{14}C testing can result in significant expenses for refineries, amounting to hundreds of thousands of dollars.
- **Blending ratios**. Multiple companies are currently coprocessing renewable feedstocks for producing RD at blending ratios above ASTM D1655's maximum allowed blending ratio for jet fuel production (5 vol %). Industry feedback suggests that maintaining a high co-feed ratio for RD production is more desirable than limiting it to 5% for SAF production. ASTM is evaluating the potential increase of the maximum blending for HEFA coprocessing from 5 to 30 vol % [124].

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[17] Holladay, Johnathan, Zia Abdullah, and Joshua Heyne. 2020. Sustainable Aviation Fuel: Review of Technical Pathways. Washington, D.C. U.S. Department of Energy. DOE/EE-2041. https://www.energy.gov/sites/default/files/2020/09/f78/beto-sust-aviation-fuel-sep-2020.pdf

- **Approved feedstocks.** In many cases, RD is commercially produced using feedstocks that ASTM has not approved for SAF (e.g., crude tall oil). Industry stakeholders recommend supporting the approval of new pathways and feedstocks for coprocessing in HEFA SAF production.

5.2 Other Permits and Certifications

Obtaining approvals and permits, a crucial stage in any major project, can potentially jeopardize the project's timeline and even lead to the project cancellation. **Industry stakeholders consider the permitting process to be a major constraint in the deployment of HEFA SAF facilities**, citing multiple examples of renewable fuel projects that have been cancelled or relocated due to lengthy, high-risk, and time-consuming permitting processes. Government support in making the permitting process easier could speed up the deployment of renewable fuels facilities, according to industry stakeholders. For example, HEFA facilities (typically considered chemical production facilities for air permitting purposes, as they produce hydrocarbon fuels[18]) are subject to environmental laws, including complex air quality regulations. While the expectation is that once SAF becomes less expensive (thanks to either technology advances or supporting regulations) new SAF facilities will be built quickly, the reality is that substantial permitting barriers will remain to building new facilities.

Other concerns expressed by industry stakeholders included:

- **Permits for coprocessing may also be constraints.** One of the interviewed fuel producer stakeholders mentioned that depending on the location, local governments may prefer complete conversions of refinery facilities from fossil to renewable sources, rather than approving permits for low levels of renewable feedstock integration.
- **Social resistance can be a major bottleneck in quick construction of new facilities.** Project delays and cancellations can happen for different reasons, especially when project developers or government entities do not acknowledge and address community concerns adequately, from the stakeholder mapping phase until project design and implementation. Studies reveal that opposition to renewable energy projects often stems from insufficient involvement and addressing of concerns of residents and environmental justice advocates. Furthermore, industry stakeholders have reported delays attributable to the intervention of certain stakeholder groups that were not included in initial phases of the project design [125–127].
- **Deployment of energy infrastructure and energy justice**. The construction of new energy related projects usually prompt questions related to the ability of the impacted communities to influence the deployment of energy infrastructure [128–130]. At the same time, industry advocates claim that such projects meet and sometimes even exceed permitting requirements and the communities willing to engage in the regulatory process have sufficient opportunity to participate. According to scholarly research, regulatory proceedings restrict participation to a specific group of individuals, typically those associated with the industry [128, 131]. Examining the debate over energy infrastructure reveals the challenges of providing reliable, affordable, and sustainable energy, as well as differing views on public involvement and energy justice [132, 133].

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[18] Facilities producing hydrocarbon fuels are considered chemical production facilities, one of the 28 listed source categories: https://www.pca.state.mn.us/sites/default/files/aq4-25.pdf.

- **Feedstock certification.** Industry stakeholders mentioned that standardized feedstock certification requires information on feedstock sourcing to avoid fraud (e.g., with UCO).

The analysis of two HEFA facilities in terms of their air emissions from the production of HEFA fuels is presented in Appendix F, serving as illustrative examples for future SAF production facilities to obtain permits.

5.3 Policies

Consulted industry stakeholders unanimously agreed that development and implementation of SAF-supporting policies and incentives are central to the successful development of a SAF industry. Another report in this series, *Sustainable Aviation Fuel (SAF) State-of-Industry Report: State of SAF Production Process* [1], discusses the legislation supporting the SAF industry in general.

Industry stakeholders have emphasized the following points regarding policies that affect the HEFA pathway:

- **IRA Section 40B** (Section 13203) provides a blender's tax credit to SAF producers, blenders or sellers. To be eligible for the tax credit, SAF must meet ASTM specifications defined in ASTM D7566 and certain FT provisions of ASTM D1655 A1 [134]. **HEFA SAF produced via HEFA coprocessing** (ASTM D1655, Section A1.2.2.1) **is not eligible for the blender's tax credit.** These tax credits are available for HEFA SAF stand-alone producers and can serve as an incentive for necessary capital investment. Because RD and SAF produced via HEFA coprocessing do not satisfy the definition of transportation fuel under IRA Section 45Z, they are ineligible for the Clean Fuel Production Credit.
- **Incentives support for stand-alone vs. coprocessing configurations**. Industry stakeholders noted that the HEFA SAF stand-alone process is favored by policies over HEFA coprocessing, as more capital is needed for the construction of new dedicated facilities that wouldn't be built otherwise. Some industry stakeholders believe that building stand-alone facilities can lead to more employment opportunities and provide a wider range of fuel options. Others believe that not including HEFA coprocessing in incentives is a major limitation to increasing SAF production. According to these stakeholders, implementing HEFA coprocessing is a fast and cost-effective approach to decarbonization, making it an efficient solution. As a result, providing tax incentives for HEFA coprocessing could significantly increase the chances of meeting the 2030 SAF Grand Challenge production goals. Nevertheless, this could divert government resources away from the investment in new infrastructure, while prolonging the lifespan of existing infrastructure and discouraging new investment.
- **According to industrial stakeholders, the ratio of SAF to RD production will be determined by policies.** Current policy incentives and higher SAF production costs favor RD production over SAF (see Economics and Sustainability Section) [1]. If HEFA feedstock usage shifts from RD to HEFA SAF production, there is a concern about how the diesel market would be supplied. The consulted industry stakeholders were uncertain about how the RD market would be covered in these circumstances. If ground transportation switches to electric power, there would be less demand for diesel. This could create an opportunity to use HEFA feedstocks in the production of SAF and marine fuel. It is important to carefully plan how to promote SAF production while meeting the demand for diesel via renewable fuels or

electrification to maintain the progress made toward decarbonizing the diesel sector. Additionally, the strong incentives for RD and SAF are leading to less favorable economics in the production of biodiesel. For instance, the New Leaf Biofuel plant in San Diego, California, has plans to cease biodiesel operations by the end of 2023. New Leaf Biofuel cites the challenging competitive landscape for community-sized plants like theirs, as major fuel refiners now own renewable fuel facilities, benefiting from broader access to feedstock and superior economies of scale. Additionally, community opposition to the plant's operations contributed to the decision to stop biodiesel production [135].

- **Policy Stability.** Industry stakeholders emphasized that investors require stability of policy for at least 10 years, as some new facilities depreciate over 10 to 15 years [84]. One major concern has been the frequent expiration and reinstatement of tax credits. The IRA Section 40B (2023-2024) and 45Z (2025-2027) only provides four years of incentives (from 2024) [136].[19] These risks can escalate the costs and impede the deployment of SAF facilities.
- **Farming incentives for HEFA feedstocks.** Industry stakeholders expressed opinions and concerns about support or incentives for farmers. Some stakeholders expressed concern over the lack of incentives or guarantees for farmers to shift toward producing crops for renewable fuel. While biomass producers do not receive renewable identification numbers or LCFS credits, they can still benefit through market responses and increases in commodity prices. Life cycle methodologies that recognize the benefits of regenerative agricultural practices and soil carbon accumulation may result in higher prices for crops with low CI.
- **Loans, loan guarantees, grants, and other federal assistance.** Access to financing to build or expand new facilities for HEFA SAF production is a concern expressed by industry stakeholders. The SAF Grand Challenge Roadmap considers the challenges around financing SAF facilities or expansions [12, 136]. Activities SC.4.1 and SC.4.2 of the SAF Grand Challenge Roadmap involve loans and loan guarantees and/or other federal assistance programs to finance SAF commercial-scale projects and feedstocks for SAF production. Additionally, Activity SC.4.6 aims to convene stakeholders to accelerate SAF supply chain investment. However, the beginning of these activities is planned for 2025–2030. The Fueling Aviation's Sustainable Transition (FAST) discretionary grant program from the FAA will make investments to accelerate production and use of SAF to support the U.S. aviation climate goal to achieve net zero GHG emissions by 2050. The SAF portion of the program, termed FAST-SAF, will provide $244.5 million in grants to support the build out of infrastructure projects related to SAF production, transportation, blending, and storage. The application period for the FAST-SAF Grants began toward the end of 2023 [137]. Fuel producer stakeholders estimate that getting a new HEFA SAF facility from design to operation takes 2–5 years from the financial investment decision, not including preliminary analysis. As a result, projects that can take advantage of these activities may not be able to begin operations until 2030 or after.
- Industry stakeholders expressed their desire for **clear, straightforward policies** that can reduce ambiguity, enabling businesses, individuals, and organizations to make well-informed decisions.

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[19] The 45Z credit applies to fuels produced after December 31, 2024, and sold before December 31, 2027.

6 Economics and Sustainability

Key Takeaways

- Estimated minimum fuel selling prices (MFSPs) of HEFA SAF range from $1.84 (yellow grease) to $9.40 (canola oil) per gallon of gasoline equivalent (GGE).
- Current incentives (for California) make it slightly more attractive to produce RD than SAF.[20,21]
- MFSPs of RD are lower than those of SAF for the same feedstock type due to higher yield to target product and lower hydrogen consumption for RD.[3,22] As a reference point, the prices (sales to end users, exclusive of taxes) of fossil-based jet fuel and diesel in California in 2021 were $1.85/GGE and $2.36/GGE, respectively [4].
- Feedstock cost volatility, the most significant component of the MFSP for HEFA RD and SAF, can significantly impact the financial risk of the HEFA process.
- Although capital expenses are not major drivers of overall HEFA SAF production costs, challenges in securing capital and justifying investments represent major constraints to small companies.
- The return on invested capital (ROIC), without incentives, for most of the analyzed scenarios are negative, underlining the inherent risk and financial challenges associated with renewable fuel projects in the absence of incentives. Therefore, incentives have a significant impact on a biorefinery's economic viability.[23]
- At current market price for hydrogen produced through water electrolysis, incentives only partially subsidize costs for associated CI reduction.
- Air quality permitting is a crucial step required prior to converting an underutilized or idled petroleum refinery to produce SAF.

This section discusses the results and key findings of techno-economic analysis and life cycle assessment.

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[20] Businesses that produce or import fossil fuels such as petroleum diesel are required to account for and mitigate their emissions under the California Cap-and-Trade Program. RD derives an advantage from an extra $0.39 allocated to RD based on CA State tax on petroleum diesel [1]. The California Cap-and-Trade program has a cap trajectory set through 2030.

[21] Details on how incentives are calculated can be found in the *Sustainable Aviation Fuel (SAF) State-of-Industry Report: State of SAF Production Process* [1].

[22] The retail prices (including taxes, distribution, and marketing) for jet and diesel fuel in California were $3.14/GGE (March 2022) [6] and $5.76 (September 2023) [5], respectively.

[23] For qualifying for incentives, reaching the GHG emissions reduction threshold of 50% reduction compared to the fossil baseline is critical.

6.1 Techno-Economic Analysis and Life Cycle Analysis

6.1.1 Base Cases and Scenarios Matrix

The analysis approach estimates three metrics for comparative analysis: MFSP, CO_2 marginal abatement cost (MAC)[24], and ROIC.[25] Variables considered for the economic and sustainability assessment are presented in Table 3. Economic assumptions and considerations taken for this analysis are detailed in Appendix G and the *Sustainable Aviation Fuel (SAF) State-of-Industry Report: State of SAF Production Process* [1]. Variables considered to define the scenarios in this report include fuel product, plant basis, type of feedstock, feedstock price and CI, facility capacity, capital cost expenditure, and hydrogen sourcing. The combination of these variables shown in Table 3 represents a comprehensive total of 5,832 distinct individual scenarios. The analysis inputs listed in italic text represent the base case scenarios. The input value ranges for the defined variables are defined in Appendix G.1.

The MFSPs before incentives for all HEFA SAF and RD scenarios (Appendix G.2) ranged from \$1.84–\$9.40 and \$1.80–\$8.53 per GGE, respectively (Figure G-4).[3] As a reference point, California 2021 fossil-based jet fuel and diesel sales prices for end users (exclusive of taxes) were \$1.85/GGE and \$2.36/GGE, respectively [4].

Table 3. Scenario Matrix

Range of variables considered for evaluating SAF and RD production scenarios for the economic and sustainability assessment. *Italic* text represents the base case scenario.

Scenario Variables	Scenario Matrix
Product Fuel	*Diesel* I *Jet*
Hydrogen source	*Natural gas H_2* I Electrolytic H_2 using renewable energy
Plant Basis	*Grassroots* I Conversion I Coprocessing
Feedstock type	Canola oil I Corn oil I *Soybean oil* I Palm oil I Tallow I Yellow Grease
Feedstock Price (Table G-4)	Low I *Average* I High
Feedstock CI (Table G-7)	Low I *Average* I High
Plant Capacity (Appendix G.1, CAPEX)	Low I *Average* I High
Total Capital Investment (Figure G-2 & Figure G-3)	Low I *Average* I High

A complete description of the analysis approach, including economic assumptions and considerations, are detailed in Appendix G and the *Sustainable Aviation Fuel (SAF) State-of-Industry Report: State of SAF Production Process* [1].

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[24] MAC refers to the cost associated with reducing one additional unit of pollution or GHG emissions. Additional information is given in Appendix G.1.

[25] ROIC measures how effectively a company or project is utilizing its invested capital to produce profits. Additional information is given in Appendix G.1.

6.1.2 Results and Discussion

The comparative results for the base case RD and SAF scenarios' MFSP and CO_2 MAC values are presented in Figure 10. The results show a gap in RD and SAF production cost ranging from \$0.20–\$0.30/GGE. The results also show a SAF CO_2 MAC \$40–\$50 more per ton of CO_2 compared to that for RD. Higher cost for SAF is mainly due to SAF's slightly lower hydrocarbon fuel yields and higher demand on hydrogen. These results support feedback from industry that additional economic incentives are required to spur greater interest in SAF production.

New RD/SAF facility development requires large capital investment. For example, investments of \$850 million (800 MGPY) [138] and \$1.48 billion (584 MGPY) [139] have been reported for planned repurposing of petroleum refineries for processing of renewable feedstocks, and \$1.45 billion (470 MGPY) [140] and \$1.25 billion (900 MGPY) [141, 142] for planned development of greenfield facilities. While access to financing presents challenges (see Section 5.3), **capital cost does not significantly impact MFSP and MAC when the plant scale is more than 200 MGPY** (Figure 10).

It should be emphasized that this analysis considers the assumption of the nth plant, and it is probable that the initial SAF facilities will face elevated costs, primarily stemming from the inherent risks associated with pioneering the establishment of a new industry. Average plant capacities of operational renewable fuel facilities for conversion, HEFA coprocessing, and grassroots basis are 125 MGPY, 34 MGPY, and 37 MGPY of renewable fuel (mainly RD), respectively. Approximately 20% of these facilities are capable of producing SAF.

Two large facilities came online in 2023: Marathon's Martinez Refinery (730 MGPY) and PBF Energy's facility (307 MGPY) in Louisiana [143, 144]. Seven major facilities with nameplates above 250 MGPY are planned for upcoming years. In 2024, these include Phillips 66's refinery (680 MGPY) in Rodeo, California and REG's facility (250 MGPY) in Geismar, Louisiana. Plans for 2025 include the expansion of World Energy's Paramount facility in California (295 MGPY), plus new facilities for World Energy in Texas (250 MGPY), Gron Fuels' (900 MGPY) in Louisiana, and NEXT Renewable Fuels (598 MGPY). Operation of Shell's Convent refinery (584 MGPY) in Louisiana is slated to begin in 2028.

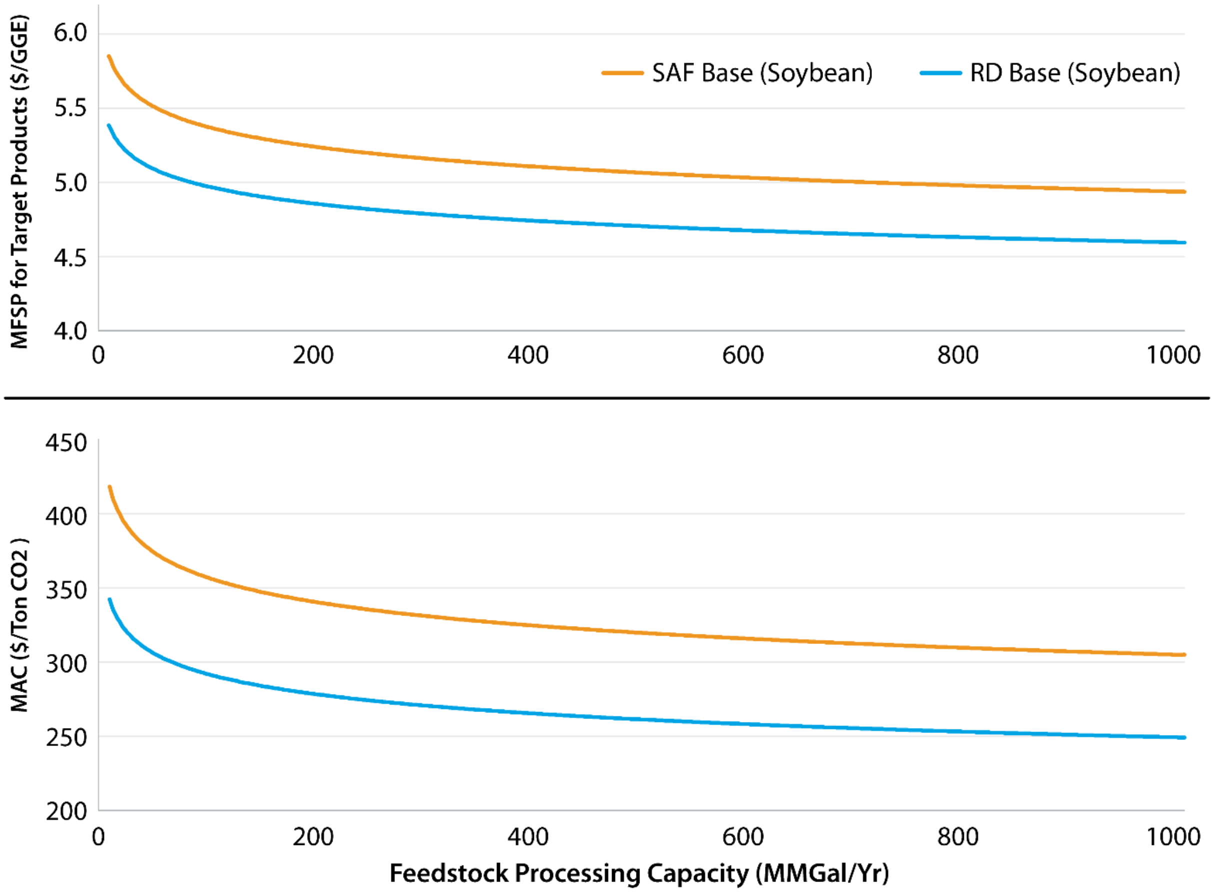

Figure 10. Base scenario (soybean oil) results for RD and SAF grassroots units. Top: MFSPs for both RD and SAF. Bottom: MACs for both RD and SAF.

As shown in the tornado chart (Figure 11), **the MFSP and MAC of HEFA RD and SAF are impacted mainly by federal and state incentives**[26] **and volatile feedstock costs**. For instance, soybean oil prices increased by $0.8/lb. from 2018 to 2022 (Table G-5). When comparing feedstock prices and capital investment (illustrated in Figure 12), the cost impacts from feedstock price variation are more significant than those from capital investment. This conclusion is consistent with studies from the literature [81, 145–148] and what we learned from industrial stakeholders.

Other factors that can affect the MFSP of SAF to a lesser extent include plant capacity, facility basis, capital cost, internal rate of return, and hydrogen cost. According to publicly available information, the expected internal rate of return for renewable projects is about 25%–30% [149]. Therefore, the range considered for the sensitivity analysis is 5%–30% (Figure 11).

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[26] The pricing of RIN, LCFS credits, and avoided deficits for petroleum diesel reflect 2023 prices and are subject to change over time, which can affect the value of the credits. Historical RIN value data and its impact on incentives is presented in the *Sustainable Aviation Fuel (SAF) State-of-Industry Report: State of SAF Production Process* [1].

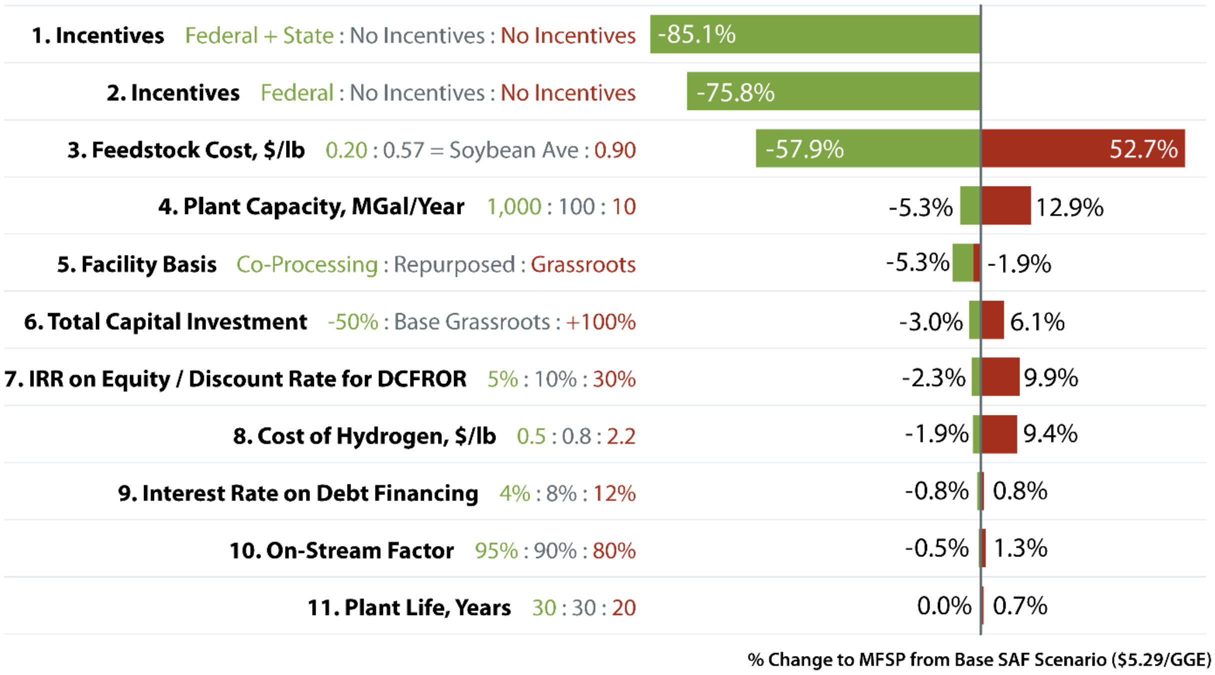

Figure 11. Sensitivity analysis on MFSP from the base SAF scenario.

Note: discounted cash flow rate of return (DCFROR), internal rate of return (IRR)

Capital cost reductions achieved through reduced cost conversions or HEFA coprocessing have minimal impact.[3] However, capital requirements, coupled with yield impact from jet production, increase costs for SAF relative to RD. **Capital cost hurdles will be more constraining for small companies compared to large industry players**. The conversion and HEFA coprocessing options offer advantages by utilizing existing equipment, reducing capital costs and improving the chances of project acceptance.

In addition to cost concerns, fuel producer stakeholders mentioned inflation as a factor that can significantly impact capital expenses, in some cases almost doubling costs. A capital cost multiplier was used to estimate how changes in capital expenditures affect the MFSP and MAC (Figure 12). Within a capital multiplier range of 0.5 to 4, the cost impact to the calculated MFSP is within $1/GGE. Furthermore, the escalation of capital and the rise in interest rates contribute considerably to an increase in risk, further complicating the task of obtaining capital.

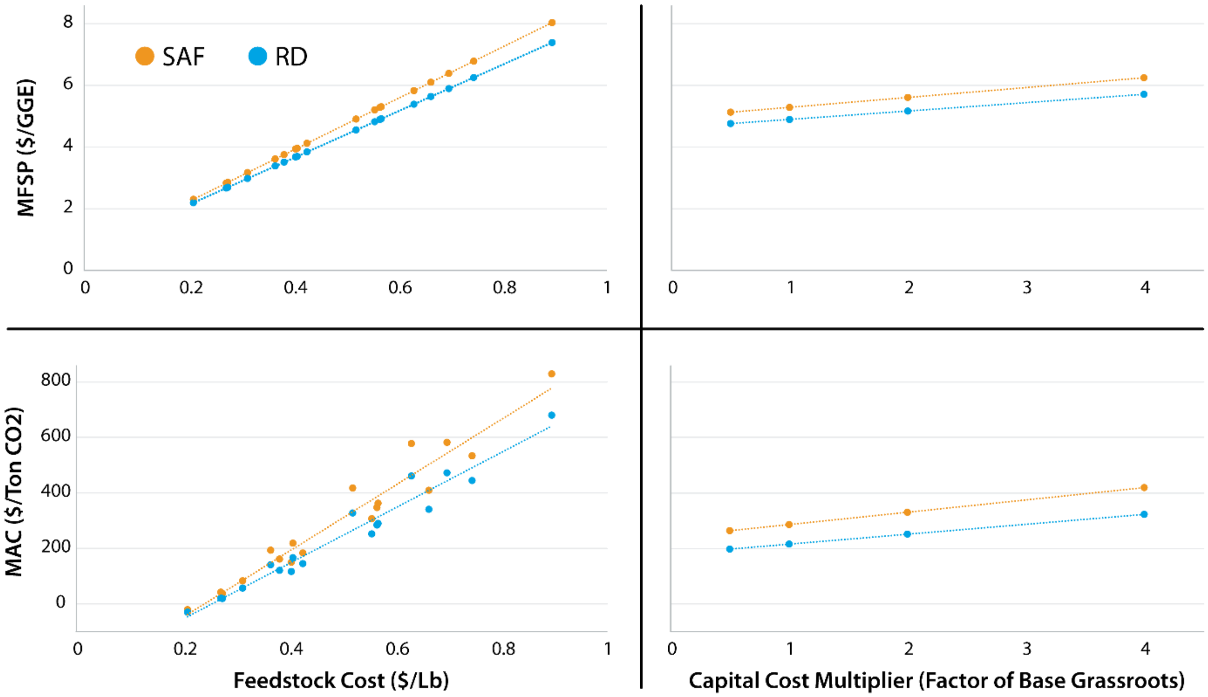

Figure 12. Impact of feedstock cost and capital cost on the MFSP and MAC of RD and SAF

Due to the significant impact of feedstock prices on production costs, low-cost and renewable feedstocks can substantially affect both MFSP and MAC. The incentives to encourage SAF production aim to increase revenue from renewable fuels. The extent of the incentives applied to renewable fuels is determined by reduction of life cycle GHG emissions compared with the fossil baseline. **To be eligible for the blender's tax credit, the fuel produced must achieve a minimum 50% reduction in GHG emissions threshold compared to petroleum-based fuel**.

The GHG emissions reduction level varies greatly depending on the source of the feedstock, as shown in Figure 13. CI scores enable a standardized comparison by utilizing a common denominator, facilitating an apples-to-apples assessment of emissions reductions across diverse industries or process configurations (such as coprocessing, grassroots, and conversion). Results show that in most cases, except for palm oil feedstocks, the renewable jet fuels meet the minimum threshold for HEFA SAF incentives, while RD meets this threshold in all cases. Depending on the life cycle analysis model used and land use change assumptions, fuel made from the same feedstock can have varying GHG emissions, as reported by multiple studies.

Land use change contributions to CI scores are complex, and thus their impact on product CI scores is not considered in this assessment. As one point of reference, CORSIA's default Indirect Land Use Change (ILUC) for soybean oil based HEFA jet fuel is 24.5 gCO_2e/MJ [150].

The CI scores presented in this report are calculated using Argonne National Laboratory's Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies (GREET) model. For more information on the sustainability methodology, please refer to Appendix G.1. Life cycle analysis methodologies and their impact on CI values are discussed in the *Sustainable Aviation Fuel (SAF) State-of-Industry Report: State of SAF Production Process* [1].

Because of higher yield loss and more hydrogen consumed for HEFA SAF than for RD, the resulting GHG emission reduction for HEFA SAF is slightly less than for RD (Figure 13).

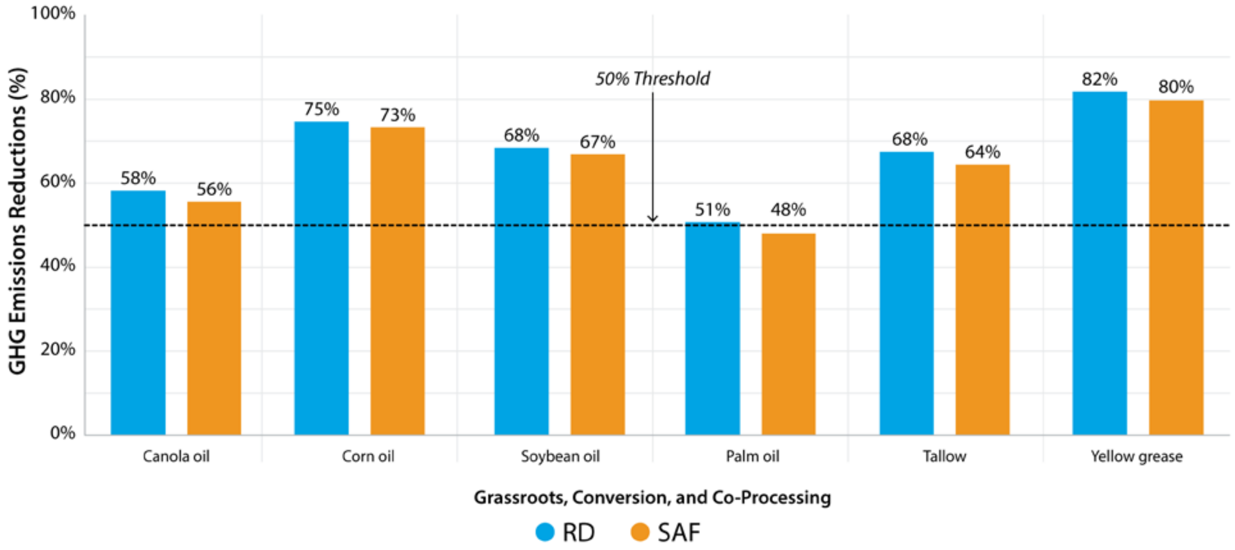

Figure 13. GHG emissions reductions related to RD and SAF produced in grassroots, conversion, and HEFA coprocessing facilities. The dashed line represents the 50% GHG emissions reductions threshold compared to petroleum-based fuel.

Note: In this plot, higher values represent greater reductions relative to petroleum benchmark. The corn oil pathway is based on DCO (non-edible corn oil).

The time frames under considerations in this report are from 2023–2024 (IRA Section 40B) and 2025–2027 (IRA Section 45Z).[7] To assess the financial feasibility of producing SAF and RD, an analysis of the ROIC[27] was undertaken. This approach applies California as a test case for state policies, while acknowledging the variation in policies across states.[28] Assumptions and considerations for the federal and state incentive estimates are described in Appendix G.3.This analysis determines the ROIC before incentives, denominated here as **market value (MV) ROIC, and the ROIC after incentives,** accounting for the impact of both California's state-level policies and federal level incentives.[28] The findings are illustrated in Figure 14.

The negative MV ROIC underscores the inherent risk associated with renewable fuel projects in the absence of incentives, emphasizing the financial challenges such enterprises face. Production of RD and SAF from yellow grease are the only scenarios that deliver positive ROICs without incentives, although these are significantly low (nearing zero). Consequently, the

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[27] ROIC measures how effectively a company or project is utilizing its invested capital to produce profits. ROIC definition is provided in Appendix G.1.

[28] The incentives applicable to the stand-alone (grassroots and conversion) production of RD and SAF are discussed in the *Sustainable Aviation Fuel (SAF) State-of-Industry Report: State of SAF Production Process* [1]. The details on the incentives for producing RD and SAF through HEFA coprocessing can be found in Appendix G.3.

HEFA SAF and RD production projects without incentives will not yield profitable returns under the assumptions used in the models.

Factoring in incentives related to GHG emissions reductions significantly increases ROICs.[3] ROICs after incentives are positive for all scenarios, except for the stand-alone production of SAF from palm oil and HEFA coprocessing from canola oil. Results indicate HEFA coprocessing is the most profitable production configuration, followed by the conversion strategy, with grassroots coming in last. This can be attributed to the use of existing assets for HEFA coprocessing, which results in a comparatively lower capital investment requirement compared to the conversion (repurposing) and grassroots strategies.

The utilization of limited HEFA feedstock for coprocessing in RD production, rather than SAF, has raised concerns among certain stakeholders, who believe that renewable electricity and hydrogen are more suitable for decarbonizing road transportation. However, these options are still seen as long-term solutions, especially for heavy-duty vehicles [151]. Industry stakeholders have concerns about cannibalization of RD production and its impact on the heavy-duty sector if SAF incentives are made competitive, especially before other low-carbon solutions for diesel markets are implemented.

Because policy incentives are targeting renewable fuel with a minimum 50% reduction of GHG emissions (compared to petroleum fuel), these **incentives help biorefineries increase production revenue**. This is particularly true for animal fats (tallow) and waste grease (yellow grease) feedstocks, which result in the highest ROIC after federal and state incentives for each process configuration (Figure 14). This implies—assuming renewable fuels can be sold at $2.50/gal (wholesale, spot price equivalent to $80/bbl. West Texas Intermediate)—a significant profit margin can be generated with credits from both federal and state incentives.[3] However, running a HEFA process entirely on tallow or yellow grease would be challenging due to constraint availability. Tallow and yellow grease/UCO account for 30% and 23% of total domestic FOG production (6.0–6.6 million tons), respectively, as stated in Section 2.2.

Moreover, **the level of credits offered by the 2025–2027 incentives that target decarbonization of the transportation sector are less than the current (2023–2024) incentive structures**. The benefits of the incentives to SAF will vary widely depending on factors such as process configuration, location, capacity, feedstock prices, CI, and hydrogen sourcing.

Industry stakeholders raised concerns about the elevated prices of SAF encountered in the market.[3] The reported average RD prices were $0.12/gallon higher than average diesel prices in California [152] between 2021 and 2022. During the same period, **the wholesale price premium of SAF was 2 to 4 times higher than that of conventional jet fuel.** However, the premium for SAF wholesale prices showed a decreasing trend in 2023 with a premium value of 2.3 times that of conventional jet [153].

The substantial difference between SAF and RD price premiums highlights that **RD is being priced as a commodity fuel blendstock and SAF remains a niche product at current production volumes.** In 2022, SAF production was only 1% of RD volumes [36, 37, 154]. The disparity can also be partially explained by the risks associated with the SAF industry's nascent stage of development.

Although aviation stakeholders mentioned that SAF is offered as an option to the public, currently most SAF is used by private companies. Thus, **stakeholders are concerned about the premium price of SAF, as well as how or by whom these costs will be covered, especially as the SAF industry consolidates**.

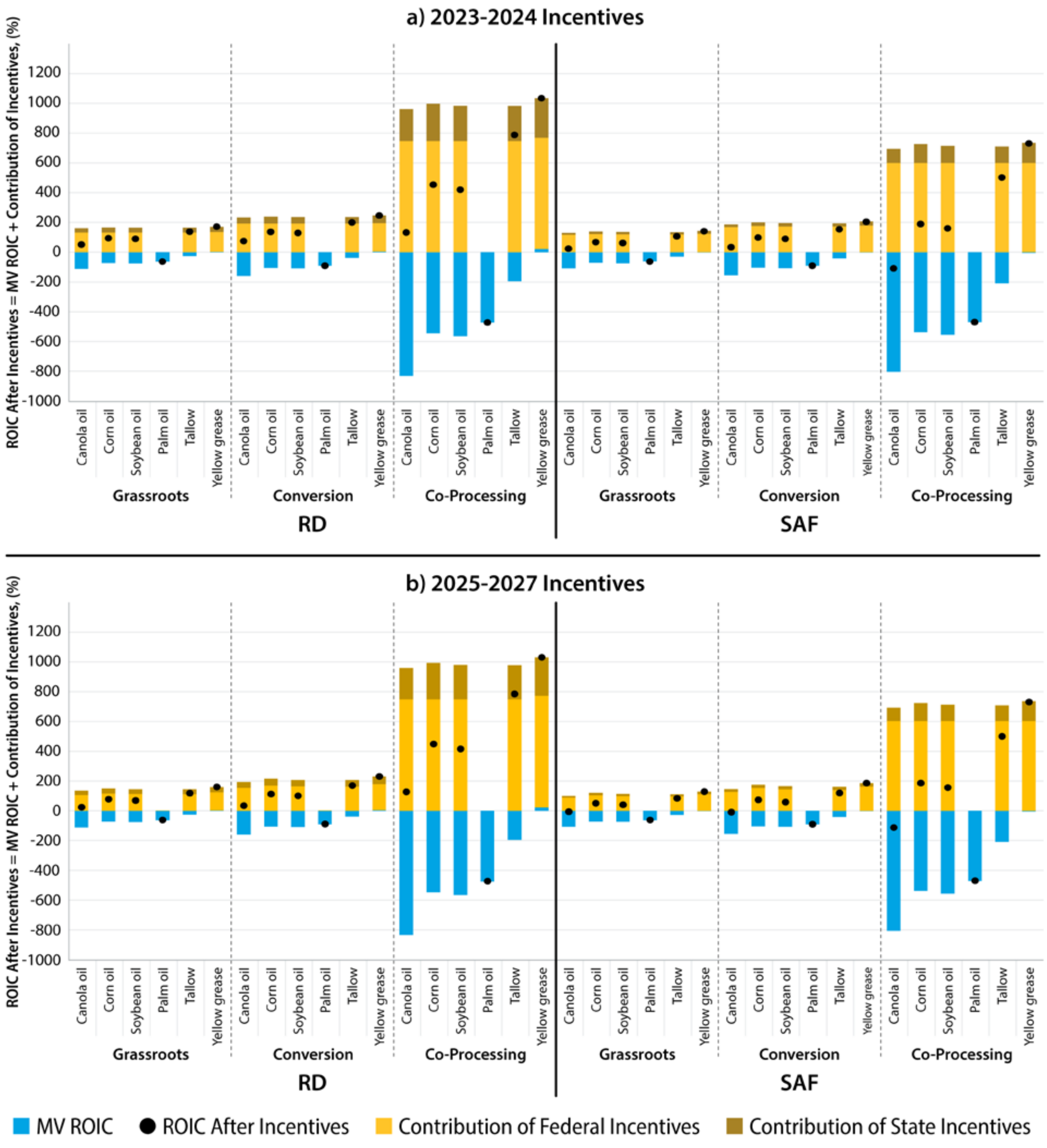

Figure 14. ROICs before and after federal and (California) state incentives for (a) 2023–2024 and (b) 2025–2027

Some industry stakeholders believe that the slow development of the SAF industry indicates a need for more substantial incentives. They suggest that once policies drive the market to meet goals, production ramp-up can happen quickly. Incentives help RD biorefineries improve profit margins, thus making it more economical to produce diesel, rather than SAF.

The MACs after incentives are shown in Figure 15. The present analysis considers the nth-plant assumption.[3] Results show that the 2023–2024 incentives are effective in reducing the MACs (for producers) below zero for the feedstocks and process configurations considered, except for palm-oil-based renewable fuels and canola-oil-based SAF produced via HEFA coprocessing. Because the 2025–2027 incentives offer fewer benefits, the MACs for SAF based on palm and canola oil for all process configurations remain positive.

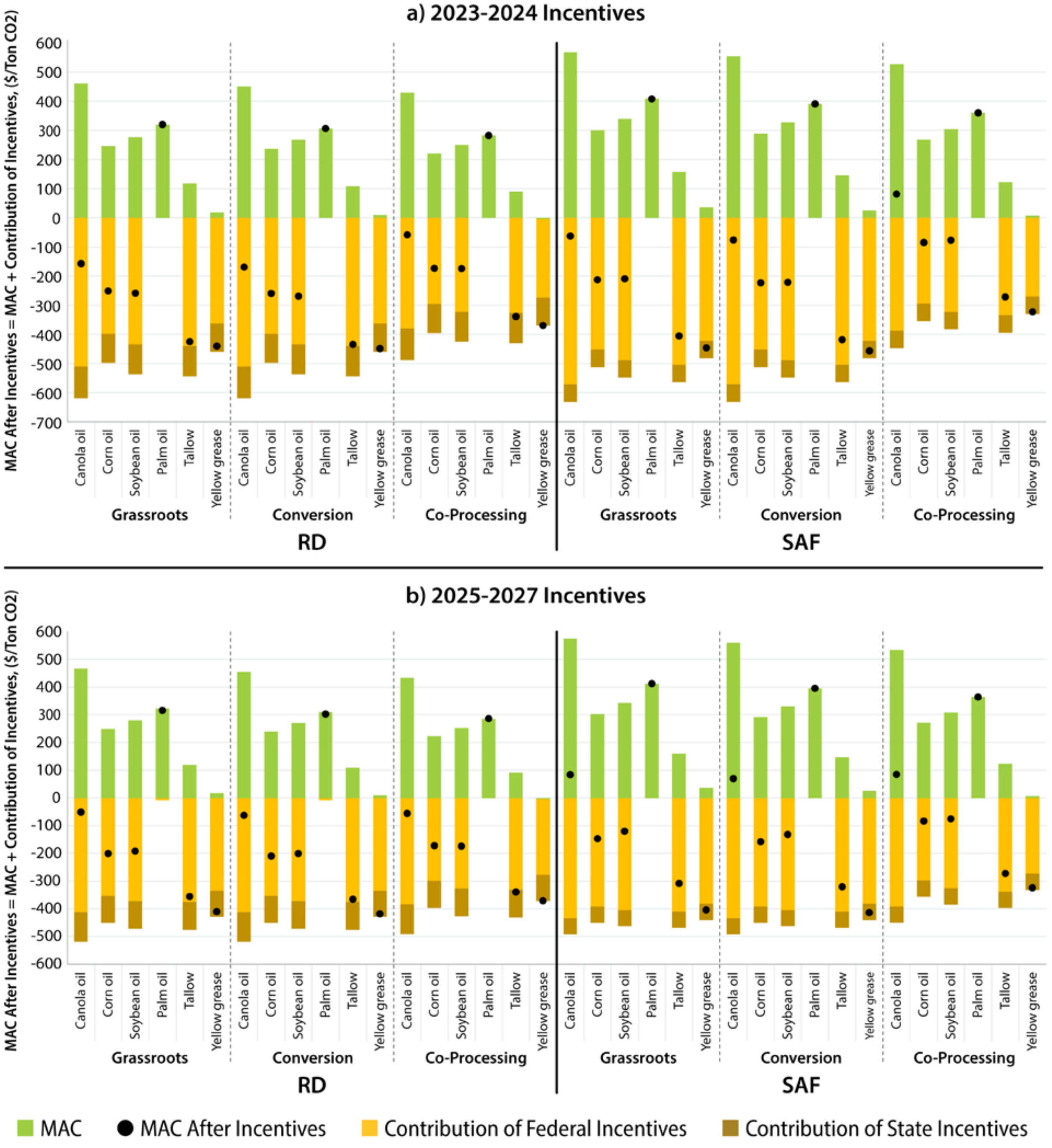

Figure 15. MACs after federal and state (California) incentives for (a) 2023–2024 and (b) 2025–2027

In addition to feedstock sourcing, hydrogen sourcing from clean energies or with CCS can further decrease CI scores. Figure 16 illustrates the difference in GHG emissions reduction of RD and HEFA SAF when sourcing hydrogen from either natural gas via SMR or via water electrolysis with renewable electricity. Sourcing hydrogen via electrolysis using renewable energy sources can result in GHG emissions reductions of as much as 10% and 13% for RD and SAF, respectively.

Sourcing electrolytic hydrogen using renewable energy sources is effective in lowering the CI of RD and HEFA SAF. Industry stakeholders expressed concern about sourcing low-CI hydrogen for SAF production, as some believe that **hydrogen electrolysis technologies are expensive and not yet widely available**.

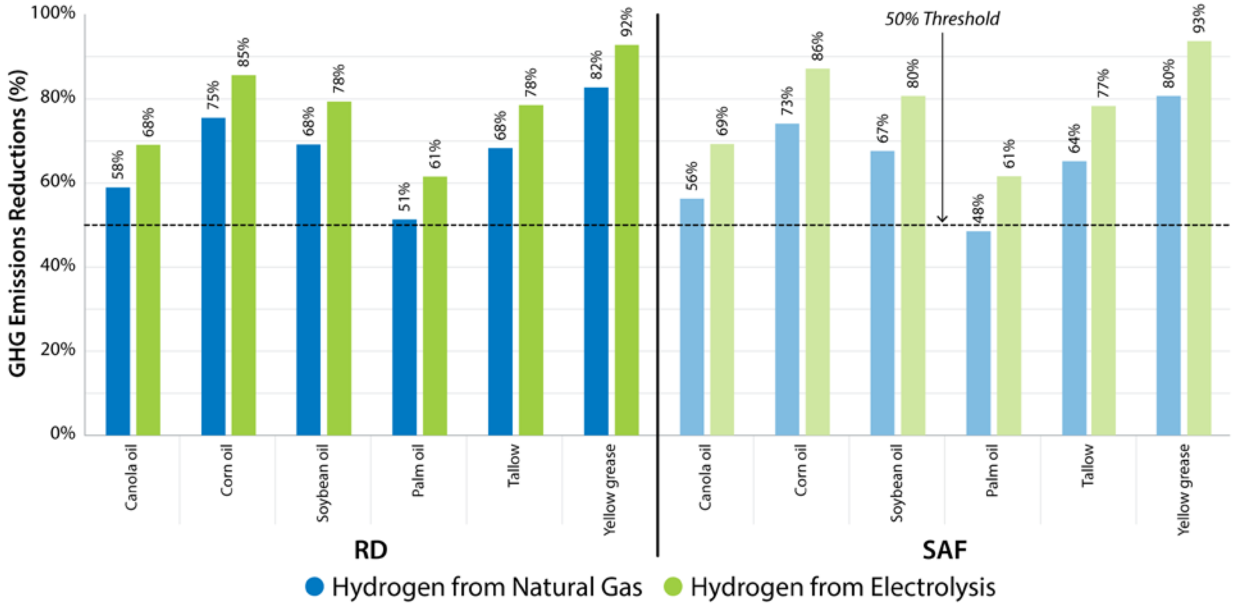

Figure 16. Impact of hydrogen source (grassroots facility) on GHG emissions reductions of RD and SAF.

Note: In this plot, higher values represent greater reductions relative to petroleum benchmark The dashed line denotes the minimum 50% reduction in GHG emissions from petroleum fuel necessary for incentive eligibility.

The MV ROIC and ROIC after incentives for RD and HEFA SAF that are produced with hydrogen from natural gas via SMR and water electrolysis using renewable energy sources and grassroots facilities, are displayed in Figure 17. The IRA Section 45V offers a credit for the generation of clean hydrogen, which is calculated as \$3 (adjusted for inflation) per kilogram of hydrogen produced, multiplied by the applicable rate determined by the life cycle GHG emissions rate of the hydrogen produced [136]. IRA Section 45Q provides a tax credit of \$85/tonne for every ton of CO_2 captured and permanently stored in geological formations [136, 155]. These policies aim to enhance the economic viability of CCS initiatives. Section 45Z deactivates both 45Q and 45V if the SAF is generated at the same facility eligible for those credits [156]. Because of the possibility of a single project qualifying for multiple credits, companies will need to evaluate various scenarios to optimize the value of their projects.

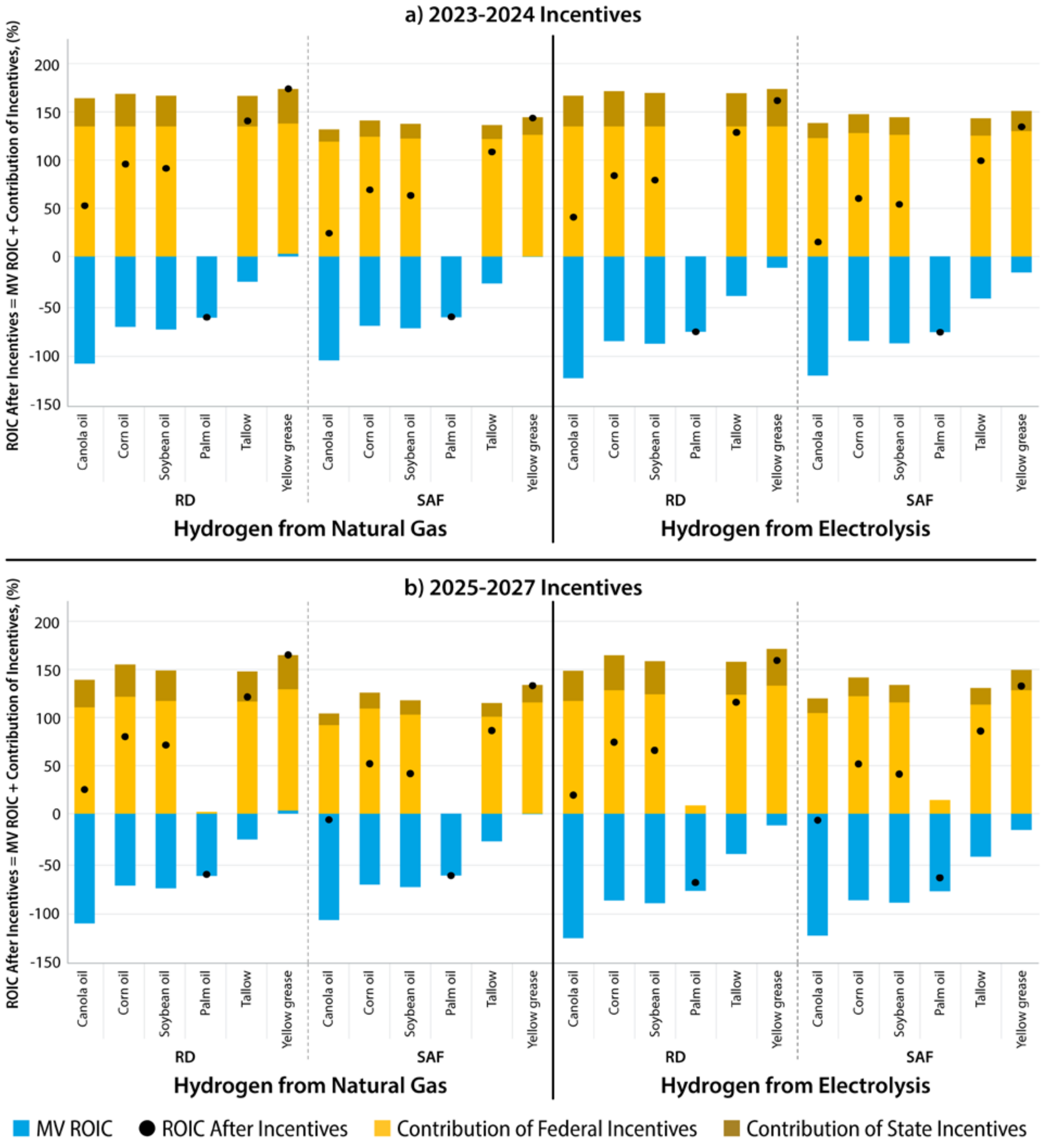

Figure 17. Impact of hydrogen source (grassroots facilities) for (a) 2023–2024 and (b) 2025–2027 incentives

Sourcing hydrogen via electrolysis with a higher price slightly decreased the ROIC after incentives, compared with the scenarios sourcing natural-gas-derived hydrogen. By sourcing hydrogen through water electrolysis, the GHG emission reductions of palm-oil-derived renewable jet fuel surpasses the GHG emissions reduction threshold required for incentives.[29]

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[29] Land use change impact on product CI scores is not considered in this assessment.

Exclusion of palm oil-derived jet fuel from the IRA's (Section 40B and 45Z) SAF definition means it does not qualify for incentives. In contrast, palm oil derived RD produced via stand-alone process is not excluded from IRA Section 45Z definition of “transportation fuel” [136]. Thus, palm oil derived RD can qualify for the Clean Fuel Production Credit (Table G-8) as long its emission rate is not greater than 47.4 gCO_2e/MJ (50 $kgCO_2e$/mmBTU) [136], equivalent to a GHG emissions reduction of 46.7%. **Additional costs for sourcing electrolytic hydrogen using renewable energy are partially subsidized by both incentive structures. However, neither current nor future incentives entirely cover additional costs.**[3]

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Appendix A. Block Flow Diagram of the HEFA SAF Supply Chain

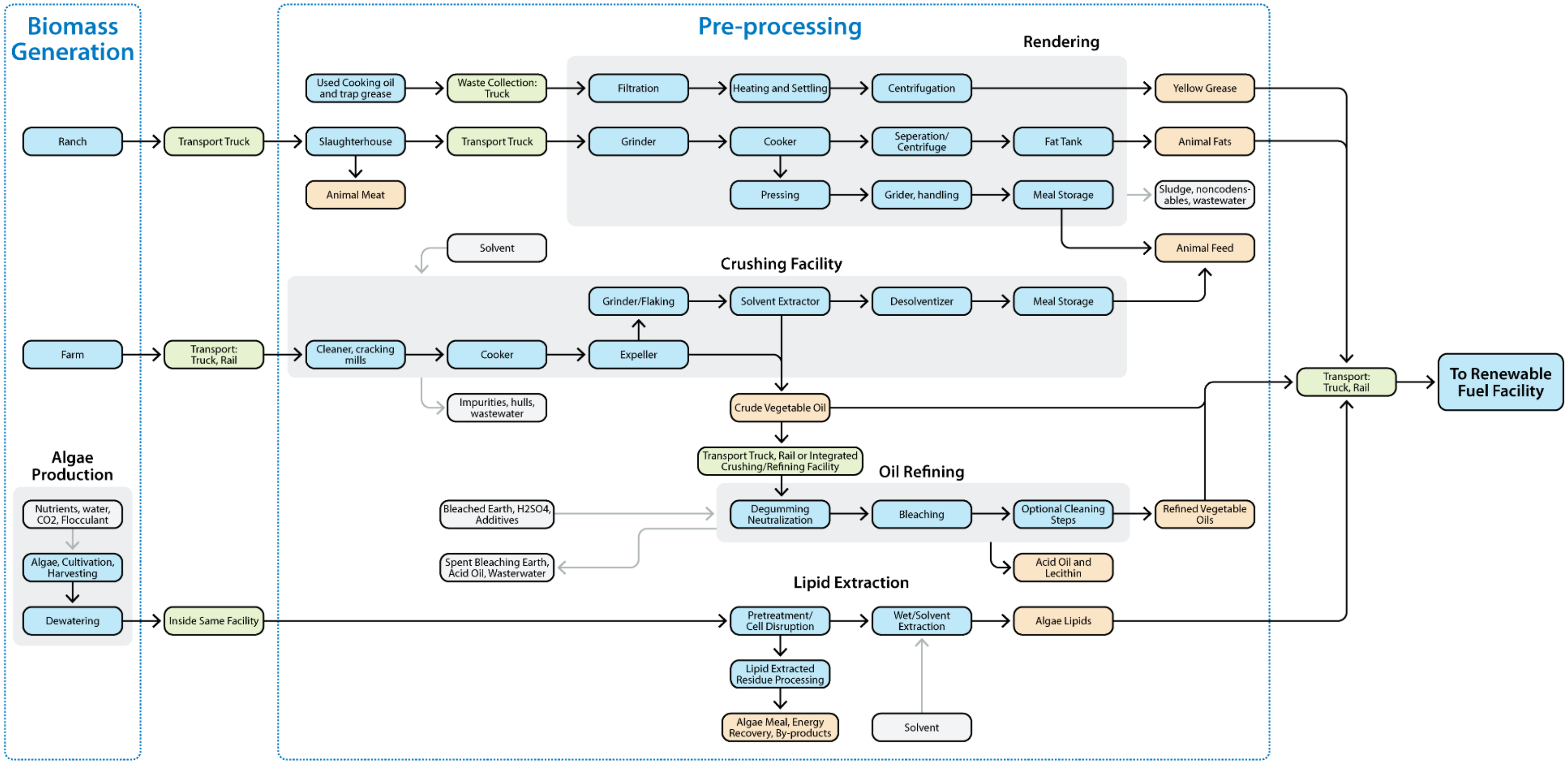

Figure A-1. Block flow diagram of HEFA SAF value chain part I: biomass generation, preprocessing, and logistics

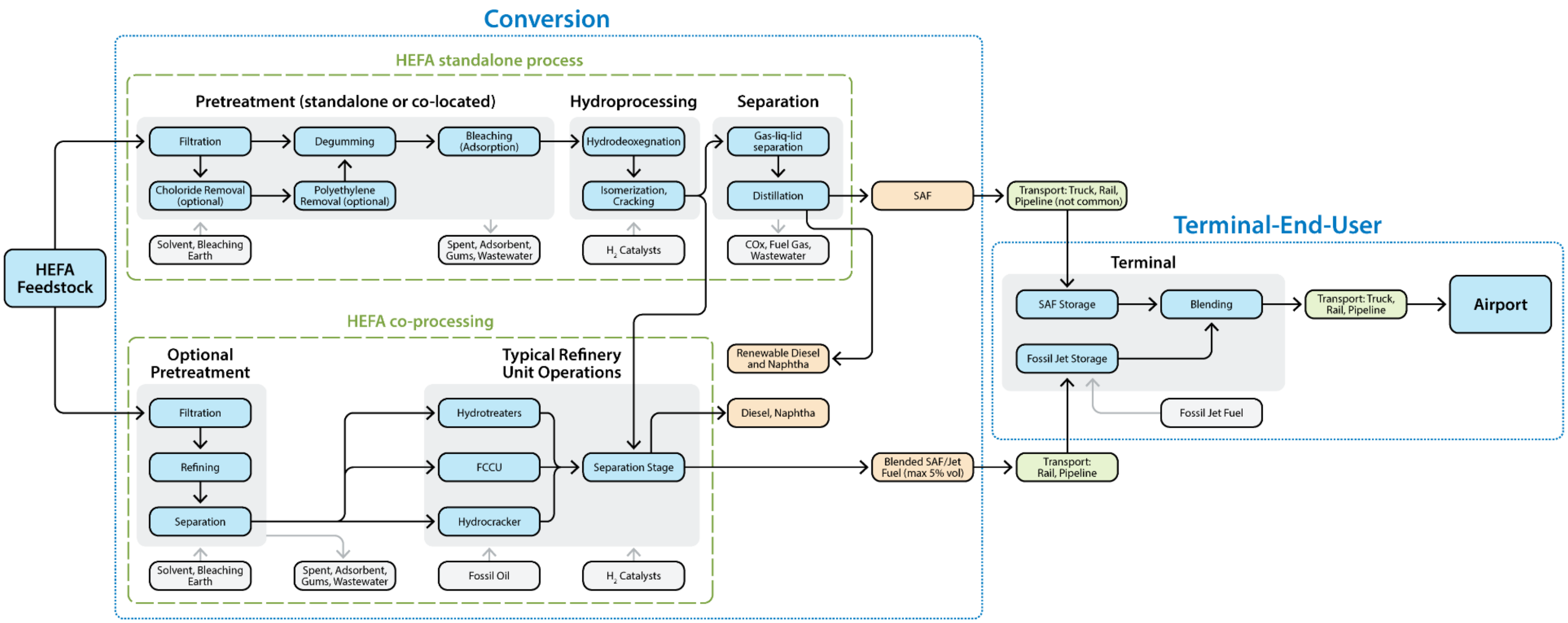

Figure A-2. Block flow diagram of HEFA SAF supply chain part II: fuel production and logistics.

Note: During coprocessing, renewable carbon becomes distributed throughout the refinery products. Therefore, it is crucial to determine the renewable carbon content of the SAF/jet fuel blend for regulatory compliance. Assessing the proportion of renewable carbon can be done using radiocarbon (^{14}C) concentration analysis as per ASTM D6866 [31].

Appendix B. HEFA Renewable Fuel Facilities

Table B-1. HEFA Pathway Projects for RD and SAF Production in the U.S.

Company	Location	Operational Date	Capacity (MGPY)	Status	RD	SAF	Notes	References
Aemetis	Riverbank, California	2026	90	Planned	Y	Y	To use non-edible oils as feedstock: DCO, Tallow Camelina. Uses HydroFlex technology, renewable hydrogen.	[157–159]
AIC Energy Corporation (SAFuelsX)	Trenton, North Dakota	2023	100	Planned	Y	Y	Greenfield facility planned	[139, 160, 161]
Bakersfield Renewable Fuels (Global Clean Energy Holdings, GCEH)	Alon Bakersfield, California	2024	230	Construction	Y	-	Conversion of petroleum refinery to renewable fuel refinery	[139, 162–164]
BP	Cherry Point, Washington	2018	44	Operational	Y	-	HEFA coprocessing biofeedstock	[139, 165]
BP	Cherry Point, Washington	2022	67	Operational	Y	-	Expansion from 44 to 109 MGPY total capacity	[139, 165]
Montana Renewables (Calumet)	Great Falls, Montana	2022	175	Operational	Y	Y	Conversion hydrocracker to produce RD, then retrofitted additional winterization capability	[166, 167]
Montana Renewables (Calumet)	Great Falls, Montana	2024	55	Operational	Y	Y	Expansion from 175 to 230 MGPY capacity. Currently producing SAF and RD.	[166–171]
Chevron	El Segundo, California	2021	31	Operational	Y	Y	HEFA coprocessing biofeedstock	[26, 139]
Chevron	El Segundo, California	2022	123	Operational	Y	-	Conversion of hydrotreater to 100% renewable capability	[26, 139, 172]
CVR energy	Coffeyville, Kansas	2023	500	Planned	Y	Y	In Sept. 5, 2023, CVR Energy said the plant capacity would be up to 500 MGPY, of which up to 250 MGPY could be SAF	[139, 173–175]
CVR energy	Wynnewood, Oklahoma	2022	100	Operational	Y	-	Conversion of hydrocracking unit to process biofeedstock. Construction of a feedstock pretreatment, to be in service in the second half of 2023.	[139, 166, 176–178]
Delta	Trainer, Pennsylvania	2022	24	Operational	Y	-	HEFA coprocessing in a distillate hydrotreater	[139, 179, 180]
Diamond Green Diesel (Valero/Darling International)	Norco, Louisiana	2013	290	Operational	Y	-	Greenfield facility. Began construction Oct. 2011.	[139, 181–183]
Diamond Green Diesel (Valero/Darling International)	Norco, Louisiana	2021	430	Operational	Y	-	Expansion, additional 400 MGPY RD plus 30 MGPY renewable naphtha, for a total 690 MGPY facility capacity.	[139, 181–183]
Diamond Green Diesel (Valero/Darling International)	Port Arthur, Texas	2022	470	Operational	Y	-	Greenfield facility. 470 MGPY of RD and 20 MGPY renewable naphtha.	[139, 184]
Diamond Green Diesel (Valero/Darling International)	Port Arthur, Texas	2025	235 (added capacity to upgrade 50% to SAF)	Planned	Y	Y	Greenfield. Upgrade to convert 50% of its production to SAF. Schedule for completion in 2025.	[139, 184]
East Kansas Agri-Energy	Garnett, Kansas	2017	3	Operational	Y	-	Greenfield. Processing DCO.	[139, 185, 186]
Emerald Biofuels	Port Arthur, Texas	Unknown	110	Planned	Y	-	Greenfield. As of Jan. 2022, construction start pushed back to summer 2022. Construction phase has not been announced.	[139, 187, 188]
Gron Fuels	Port Charles, Louisiana	2025	900	Planned	Y	Y	Greenfield. Phase 1 of the complex schedule for 2025.	[141, 142, 189, 190]

Company	Location	Operational Date	Capacity (MGPY)	Status	RD	SAF	Notes	References
Heartwell Renewables	Hastings, Nebraska	2024	80	Construction	Y	-	Greenfield. To use UCO, tallow, other animal fats.	[139, 166, 191]
HOBO Renewable Diesel LLC	Unknown	2025/26	120	Planned	Y	Y	Conversion. RD production schedule by 2025 and SAF production schedule by 2026.	[139, 192]
HF Sinclair	Artesia, New Mexico	2022	138	Operational	Y	-	Conversion. On-stream Q2 2022. Pretreatment unit on-stream Q1 2022. Utilize Topsoe’s HydroFlex technology.	[139, 193, 194]
HF Sinclair	Cheyenne, Wyoming	2021	92	Operational	Y	-	Conversion. Utilize Topsoe’s HydroFlex technology.	[139, 194, 195]
HF Sinclair	Sinclair, Wyoming	2018	153	Operational	Y	-	Conversion. Utilize Topsoe’s HydroFlex technology.	[139, 194, 196]
Indaba	Imperial County, California	2024	100	Planned	Y	Y	Greenfield. Haldor Topsoe technology: HydroFlex and H2bridge	[139, 197–199]
Indaba	Missouri	2024	100	Planned	Y	Y	Greenfield. Haldor Topsoe technology: HydroFlex and H2bridge	[139, 197–199]
Kern Oil	Bakersfield, California	2009	6	Operational	Y	-	HEFA coprocessing tallow in hydrotreater	[139, 200–202]
Marathon Petroleum	Dickinson, North Dakota	2020	184	Operational	Y	-	Conversion. Utilize refined soybean oil and corn oil.	[139, 203, 204]
Marathon Petroleum	Martinez, California	2023	730	Operational	Y	Y	Conversion. Joint venture with Neste. Utilize animal fat, soybean oil, and corn oil, among others.	[166, 205–208]
New Rise Renewables (Camber Energy to purchase facility)	Reno, Nevada	2022	49	Operational	Y	-	Conversion. Use waste stream of vegetable oils and animal fats. New Rise Renewables, formerly known as Ryzen Renewables. Ryzen Renewables filed for bankruptcy. Camber Energy to acquire facility.	[139, 209–212]
New Rise Renewables	Reno, Nevada	2022, 2024	49 (RD capacity to be converted to SAF)	Operational (SAF production plan for summer 2024)	Y	Y	Started work to convert RD facility to SAF, production is expected to commence on summer 2024.	[213, 214]
NEXT Renewable Fuels	Port Westward, Oregon	2025	598	Planned	Y	Y	Greenfield. To use UCO, animal fats, and vegetable oils.	[139, 166, 215, 216]
Par Pacific	Tacoma, Washington	2023	34	Planned	Y	-	HEFA coprocessing. To use soybean oil.	[139, 217–219]
PBF Energy	Chalmette, Louisiana	2023	320	Operational	Y	-	Conversion. To use soybean oil, corn oil, and fats.	[139, 144, 220–222]
Phillips 66	Rodeo, California	2021	120	Operational	Y	-	Conversion. Use soybean oil.	[138, 139, 223]
Phillips 66	Rodeo, California	2024	680	Operational	Y	Y	Conversion. Project includes construction of new pretreatment units. Announced that facility now process only renewable feedstocks. Expected to star SAF production in FY24 Q2. To use UCO, fats, tallow, soybean oil.	[138, 139, 223–226]
RediFuels-Iowa LLC	Sioux Center, Iowa	Unknown	36	Planned	Y	Y	Plan to process yellow grease, brown grease, animal fats, non-food energy crop oils and algal oils in the future while employing the Biofuels ISOCONVERSION technology.	[227, 228]
Renewable Energy Group (Chevron)	Geismar, Louisiana	2024	250	Construction	Y	-	Expansion. To increase production to 340 MGPY. To use tallow, soybean, corn oil, UCO	[139, 166, 229]
Renewable Energy Group (Chevron)	Geismar, Louisiana	2010	90	Operational	Y	Y	Greenfield. Use tallow, soybean, corn oil, UCO.	[139, 229–232]
Seaboard Energy	Hugoton, Kansas	2022	85	Operational	Y	-	Conversion. Use animal fats and vegetable oils.	[139, 233–235]

Company	Location	Operational Date	Capacity (MGPY)	Status	RD	SAF	Notes	References
Shell	Convent refinery, New Orleans, Louisiana	2028	584	Planned	Y	Y	Conversion. Vegetable oils and animal fats.	[139, 236–239]
Valley Green Fuels	Kern County, California	2024	230	Planned	Y	Y	The plan was to be on-stream in the first half of 2023. Company requested increase in the dollar amount from $250,000,000 to an amount not to exceed $325,000,000 in tax-exempt bonds, and to change the project site location to Santiago Road in rural Kern County near Taft.	[130, 240–242]
Vertex Energy	Mobile, Alabama	2023	215	Operational	Y	-	Conversion. To use soybean oil, DCO, tallow, and UCO. Startup scheduled for Q2 2023.	[139, 243–247]
World Energy	Houston, Texas	2028	250	Planned	-	Y	Conversion	[166, 248]
World Energy	Paramount, California	2027	295	Construction	Y	Y	Expansion	[139, 249–251]
World Energy	Paramount, California	2015	45	Operational	Y	Y	Conversion. Uses technical-grade tallows and vegetable oil, including lower-grade fats, greases, and oils, such as UCO.	[139, 252, 253]

Appendix C. Feedstock Generation and Preprocessing

C.1 Vegetable Oils Processing

The vegetable oil process includes extraction to isolate crude oil from seeds in a crushing facility and refining of the crude oil to make it suitable for its end use [254]. In Europe and North America, the crushing and refining stages are being increasingly integrated [68]. An overview of the vegetable oil process is described below.

- **Seeds planting and harvesting.** Seeds are transported to a crushing facility via trucks, rail cars, or ships. Seeds are precleaned and stored (vertical silos or flat storage houses) before being processed [68].
- **Crushing**. As part of the crushing stage, the following operations are performed:
    - Seed preparation stage may include peeling, cracking, crushing, shelling, and/or dehulling to break the wall of the oil-containing cells and shape the material for further processing.
    - Seeds are conditioned by heating in the cooker. Vertical stack and horizontal rotary cookers are typically used.
    - After the cooking, the soft cracks are sent to expeller pressing, which generates two products [68, 96]:
        - Press cake: Flacking mills are often used to weaken the oil cells in the press cake, such that oil becomes accessible. To further recover fats from the press cake, two extracting approaches are taken:
            - Mechanical extraction (pressing). In the U.S., the continuous screw presses are used virtually exclusively for mechanical extraction [96].
            - The solvent extraction is more efficient than the pressing option, leaving an oil content of about 1–3 wt. % in the spent solids [68, 96]. The typical solvent used is hexane. The generated meal stream is then cleaned, dried, and stored for its use as feed for cattle.
        - Pressed raw oil: The raw oil from the solvent extraction steps, together with the pressed raw oil, is sent to the refining stage [68, 96, 254].
- **Refining.** There are two refining options: chemical and physical. The sequential process of degumming, neutralization, bleaching, and deodorization is called chemical refining, while the physical refining requires only bleaching and deodorization [254]. The crucial processing steps are described below:
    - **Degumming**: Phospholipids need to be removed, as they allow fast spoilage of the fat [96]. Degumming involves treatment with water or diluted acid, such as phosphoric or citric, which results in a gum containing phospholipids and trace metals that is then separated by centrifugation. In some cases, degumming, especially water degumming, is seen as part of the extraction stage rather than the

refining process. Gums removed are dried and converted to lecithin, which is used in the food, beverage, and pharmaceutical industries [254].

  - **Neutralization**: All fats contain free fatty acids, which are susceptible to oxidation and thus require removal. In this process, aqueous alkali (low concentration) like sodium hydroxide is used to remove free fatty acids in the form of soaps [254]. The soaps, called soapstock, are then separated using centrifuges, normally disc stack centrifuges. Some oil is lost with the soapstock, which needs to be properly disposed of. Splitting is the typical method used to treat soapstock, in which soapstock is split into acid oil, used as animal feed or chemical use, and water by acidification with strong acids (H_2SO_4) [255].
  - **Bleaching**: Most fats and oils are bleached to remove pigments. This process involves the use of an absorbent, such as Fuller's earth, which also removes residual soaps, chelated metals, and peroxides. The bleaching process is normally done under vacuum to avoid oxidation and related color fixation and as a continuous process [68]. **Bleaching is the most expensive refining step due to the bleaching earth and disposing costs, as well as oil losses.** Pressure leaf filters are used to separate the oil from the spent bleaching earth, after which residual content varies between **25% and 30%.**
  - **Deodorization**: The deodorization process removes volatile impurities and contaminants, off-flavors, and pigments. The deodorization design and operating conditions have been **optimized for producing edible oil** [68]. The deodorization process is basically a steam distillation under vacuum [254].

  The products from the refining stage are designed as refined, bleached, and deodorized (RBD) oils. Oil producers can apply additional processing steps to change the characteristics and functionality of the oil depending on its final use (e.g., dewaxing, hydrogenation, interesterification, winterization).

Vegetable oil specifications are defined in the U.S. by the National Institute of Oilseed Products, National Oilseed Processors Association, International Olive Oil Council, and American Soybean Association, among others. Note that these compositions vary with the biomass origin, type, seasonality, handling practice, and the way the biomass is processed.

C.2 Animal Fats Processing

Feedstock generation and collection:

- The **animal fats** supply chain starts in the ranches or farms where livestock are raised and grown. Livestock are then transported into slaughterhouses or poultry processing plants, where the animals are processed for human consumption. Slaughterhouses are subject to strict regulations and inspections to ensure food safety, animal welfare, and sanitation standards are maintained [256].
- The **yellow grease** supply chain starts at restaurants and other food processing establishments where UCO is discharged into holding tanks. The UCO in these containers is then collected by a rendering or hauling company. Haulers can take the grease to renderers, process it themselves, dispose of it at landfills or publicly owned treatment works, or sell it to a third party [257].

- **Brown grease** starts as trap grease, which is collected in grease traps installed in restaurant drainage systems with the objective of reducing the grease discharged into the sewer system. Once the traps are full, hauling companies pump out contents, transport it, and dispose of it similarly to UCO in various ways. Trap grease is often handled as a waste material with little value, and thus not all rendering facilities handle it [257].

Rendering process. Rendering plants process animal byproduct materials from animal slaughterhouses or poultry processing plants to produce fats, greases, high-protein meat, and bone meal. Rendering plants that work alongside animal slaughterhouses or poultry processing plants are called **integrated rendering plants**. Conversely, rendering plants that gather materials from different off-site sources are called **independent rendering plants**. Independent plants obtain raw material from multiple sources, including butcher shops, supermarkets, restaurants, wastewater treatment facilities, poultry processors, slaughterhouses, farms, ranches, feedlots, and animal shelters [258]. There are two types of rendering processes:

- **Edible rendering plants**. These plants are typically operated alongside meat packing plants and are subject to the standards set by the U.S. Department of Agriculture's Food Safety and Inspection Services. The U.S. Department of Agriculture regulations in the U.S. prohibit meat plants from processing different types of animals [259].
- **Inedible rendering plants** produce inedible tallow and grease and are operated by independent renderers or are part of integrated rendering operations. There are two processes for inedible rendering: (1) wet rendering process, in which the animal tissue is mixed with water and in an enclosed pressure vessel (cooker) [259], and (2) dry rendering process, which can be applied at a batch or continuous process. At present, only dry rendering is used in the U.S. [258, 260].
    - In the **batch** inedible rendering process, the raw material is fed via screw conveyer into a crusher. After sizing down the animal material, it is fed to a cooker. The vapor phase from the cooker is fed into an air cooler that generates a condensate and a non-condensable gas stream. The condensate is pumped into the wastewater management system, and the non-condensable gas is treated in the odor control system before being released into the atmosphere. The slurry coming out of the cooker is passed through a percolator drain pan that separates the protein-rich solid phase and the melted fat. The protein-rich solids are fed into a screw press that reduces the fat content. Resulting solids, named cracklings, are ground and screened to produce protein meal. Fats from the percolator drain pan and the screw press are then centrifuged or filtered and stored as animal fat.
    - The **continuous** inedible rendering process is like the batch process, but it uses a continuous cooker rather than multiple parallel batch cookers. Ground material is fed from a metering bin into the continuous cooker. The cooker's discharge is sent to the drainer conveyor, which serves the same function as the percolator drain pan in the batch system. The remaining operations are mostly similar to the operations performed in batch processing [258–260].

Processing of **UCO** in the rendering facility starts with the discharge of the fats into the grease processing system. UCO typically contains water and organic matter (food residues), and thus UCO is first screened normally via a vibratory screen to remove coarse solids. Next, UCO is heated to about 93°C in vertical processing tanks, evaporating some of the excess water. The oil is then stored in tanks for 36–48 hours to allow for gravity separation, generating a solid, water, emulsion layer, and grease product streams. The grease product (**yellow grease**) is skimmed off the top of the tank, while the solids settle to the bottom and are separated from the water layer above. To increase the recovery of yellow grease, the emulsion phase is fed to a centrifuge system that removes solids and water [257, 258].

Trap grease cannot be used as animal feed or pet food, nor can it be processed at facilities that produce ingredients for animal feed or pet food. Therefore, haulers collecting UCO or meat byproducts for use in animal feed may also collect trap grease but using different vehicles. Bringing trap grease to the facility that processes UCO or animal fats is not permitted [261]. Trap grease management is less transparent than for yellow grease, with haulers employing different methods to economically dispose of the grease [257]. Once trap grease is taken to a treatment plant, the grease is screened to remove large pieces of solids, and then the **brown grease** is separated from the aqueous layer, containing suspended solids, through processes like skimming, settling, or centrifugation. The separated grease can then be sent for recycling, fuel production, or other applications [262]. Consulted experts see brown grease as a challenging HEFA feedstock that **requires extensive cleaning and dilution due to its inconsistent makeup and high content of impurities**. Experts have differing opinions regarding brown grease's suitability as feedstock for renewable fuel production; some believe it is unsuitable, while others consider brown grease an option for producing renewable fuels. Industry experts mentioned concerns regarding the extra expenses associated with pretreating brown grease, controlling odors, process control, and establishing or improving collection systems.

Edible and inedible animal fats are certified and inspected by the U.S. Department of Agriculture. The quality of the animal fats must comply with the specifications set by the trade rules of the American Fats and Oils Association for animal fats and grease [259, 263]. Interviewed experts commented that although these **specifications provide a minimum standard, they are not intended to fulfill the feedstock quality requirements for RD or HEFA SAF**. Therefore, it may be necessary to conduct further analytical tests to identify any harmful compounds to the catalysts and take additional processing steps to eliminate them.

C.3 Algae Oils Processing

While multiple commercial strains are being cultivated for food and nutraceuticals**, there are no commercial biofuel production strains** (as there is no commercial algal biofuel industry). An overall block flow diagram of the algae lipid process for SAF production is shown in Figure A-1 and described here.

Cultivation. Microalgae are cultivated by different production methods and used in several commercial applications. Production systems include:

- **Closed photobioreactors** are constructed using clear materials and multiple configurations such as tubes or panels [264]. The photobioreactor may be a more favorable production method to produce high-value, low-volume products for nutraceuticals, cosmetics, and pharmaceuticals.
- **Open ponds** have the potential for lower investment, operational, and energy costs, thereby favoring the production of biomass for low-value applications like fuel [265–267]. Some disadvantages include greater contamination risk, low control of operating conditions, and

greater land and water requirements [268]. Open raceway ponds circulated with paddlewheels are the most widely used systems at the commercial scale, including at Viridios [269], Global Algae Innovations [270], iwi life (Qualitas) [271], BASF [272], Cyanotech [273], Earthrise Nutritionals [274], and AlgaEnergy [275], among others.

Harvesting and dewatering. Some of the strategies applied and under development to dewater algae solids include centrifugation, setting and sedimentation, screen filtration, membrane filtration, flocculation, filter presses, electrocoagulation, and ultrasonic separation [268, 276], though out of these, centrifugation is the most common operation applied commercially today. Ultimately, for processing the biomass through downstream conversion operations for RD or HEFA SAF fuel production, dewatering the algal solids up to 20 wt. % is often optimal [277, 278].

Lipid extraction. This generally involves a pretreatment or cell disruption step followed by solvent extraction. Cell disruption at large scale could entail expeller pressing or bead beating. Dilute acid pretreatment has also been shown to be effective [279]. These methods are usually used in combination with a solvent extraction step [280]. Hexane is typically used for large-scale extractions [280]. The high-purity lipid stream can then be sent to the HEFA fuel facility.

Price estimation. Key to the potential algae production rate shown in Section 2.4 are (1) the ability to achieve an annual average cultivation productivity of 25 $g/m^2/day$ (current state-of-technology benchmark is 18.5 $g/m^2/day$ [281]) while achieving lipid compositions of ~25 wt. %; (2) the assumption that full pond liners would be required; and (3) the achievement of technology maturity levels reflective of *n^th^*-plant economics. Roughly 7 million acres of total available cultivation area was identified to meet the screening criteria for algae cultivation, which could support 235 million tons per year of biomass production in the saline cultivation case.

More R&D is needed to develop algae technologies, and thus algal biofuels remain a longer-term option. Major barriers to commercial production of algal biofuels include high production costs tied to the need to further improve cultivation productivity while simultaneously improving compositional quality toward higher lipid levels; sourcing of concentrated and low-cost carbon dioxide; ongoing debates about the acceptability to utilize engineered strains in outdoor conditions; and culture reliability to withstand contamination. The economy-of-scale drivers dictate the need to operate very large farms thousands of acres in size to manage capital and labor expenses, greatly exceeding the scale in practice commercially today for higher-value niche applications (e.g., nutraceuticals).

Appendix D. HEFA Process Description

HEFA Feedstock Handling

The process starts with the arrival of HEFA feedstock via trucks, rail cars, or ships. Certain vegetable oils like soybean, canola, and sunflower oil are easier to manage because they have a low freezing point ranging from -17°C to -10°C. This means they can be pumped at ambient temperatures and stored at temperatures as low as 15°C [282]. Certain types of vegetable oils have a higher freezing point, such as cottonseed oil (48°C) and FOG feedstocks like beef tallow (32°C−38°C) and yellow grease (30°C–36°C). To ensure that animal fats and waste greases can be pumped and stored correctly, they must be heated to temperatures between 40°C and 45°C and stored at temperatures ranging from 25°C to 65°C [282]. This allows the oil to be pumped to a storage tank that keeps the oil at optimal storage temperature. The biogenic oil can solidify if the temperature drops or polymerize if it is too hot. Furthermore, biogenic oils are susceptible to oxidative degradation, a factor that can reduce their stability during storage. Consequently, the inclusion of antioxidants and/or nitrogen blanketing of storage tanks may be necessary to effectively prolong the shelf life of these oils. To ensure consistent quality and accurate analysis, it may be necessary to use a second tank when handling feedstock batches of different qualities. This will prevent any mixing and allow for proper quality assurance testing after the material has been offloaded.

D.1 Stand-Alone Process Configuration

Pretreatment of HEFA Feedstocks

The necessity for pretreatment. Initially, facilities such as Marathon’s Dickinson and Phillips 66’s Rodeo reportedly began producing RD without pretreatment using food-grade refined soybean oil [283]. Because the feedstock cost can make up to 88% of the total production cost, the use of food-grade refined oils as feedstock can lead to high production costs. In recent years, the cost of refined oils has risen significantly (Table G-5), putting economic strain on facilities that use refined oils as a feedstock. This has resulted in lower profit margins for these facilities [283]. This was due to a significant rise in feedstock prices, particularly for refined bleached and deodorized soybean oil. Starting operations under these high feedstock prices would not have been financially feasible. After the economics improved, CVR Energy began operating their plant and is now developing a pretreatment unit to process low-quality and low-cost feedstocks [283–285]. Similarly, other renewable fuel producers are designing facilities that allow them to use low-value oils such as yellow grease, animal fats, and unprocessed crude oils (non-degummed oils) to reduce production costs.

Impurities and contaminants. HEFA feedstocks contain impurities that are not present when handling traditional crude oils. These impurities may generate excessive pressure drops, gum formation, and importantly reduce the catalyst life span and conversion performance [286, 287]. A range of impurities content in HEFA feedstocks before pretreatment and the acceptable contaminant concentration for the hydroprocessing step are shown in Table D-1.

Table D-1. Published Feedstock Impurities Content Range Prior to Pretreatment and Hydroprocessing Quality Requirements

Color code: blue – max. limit of impurities for hydroprocessing, green – acceptable parameters, yellow – may meet requirements depending on feedstock quality, red – do not meet requirements.

Parameter	Units	Vegetable Oil (Crude) [a]	Vegetable Oil (Refined) [b]	Animal Fats [c]	UCO/ Yellow Grease [d]	Brown Grease [e]	Algae Oil [f]	Hydroprocessing Requirements [g]
Free fatty acids	wt. %	0.3–12.22	<0.05–0.07	0.61–20	2.72–7.38	>15	0.45–1.75	15–25
Moisture and volatile matter	wt. %	<0.3–0.5	0.1–0.41	0.02–1.5	0.16–1	-	-	0.05–0.07
Insoluble impurities	wt. %	0.02–0.25	0.006–0.01	0.1–0.5	0.04–0.5	-	0.128–0.474	0.01–0.05
Unsaponifiable	wt. %	0.85–1.7	0.3–0.99	0.02–1	0.05–1.5	0.5	0.44–0.6	<1
Phosphorus	ppm	17–642	1.0–3.7	43–643	5–132	23.5–301.2	287–340	<1–3
Total metals (Mg, B, Na, Fe, Zn, K, Ca, Si)	ppm	150	-	300	150	-	-	5–10
Nitrogen	ppm	50	-	700	60	-	-	200–350
Sulfur	ppm	2–15	<1	8–100	3–31	640	15-28	10–250
Chlorides (total)	ppm	10	<2	200	50	-	-	<5–50
Polyethylene	ppm	nil	-	200	50	-	-	20–50

[a] [67, 119, 288–292]
[b] [119, 289–294]
[c] [67, 288, 291, 292]
[d] [288, 291, 292]
[e] [288, 291, 292, 295–297]
[f] [292]
[g] [67, 87, 288, 298]

Contaminants to be removed can be categorized into two classes: oil-soluble and oil-insoluble. Insoluble impurities include seed fragments, meal fines, free water, resins, and waxes, while phospholipids, phosphatides, pigments, or trace metals are examples of oil-soluble impurities [299]. Main identified contaminants include:

- **Phosphorous** was identified by the interviewed experts as the main contaminant to be removed to avoid catalyst poisoning resulting in partial or total deactivation and reactor fouling [65]. Phosphorous can be present in the form of phosphorous or phospholipids. Phospholipids can be found in crude vegetable oils and animal fats in phosphorus concentrations of several hundred parts per million. **Phospholipids**, also called phosphatides, consist of fatty acid chains, glycerol, and a phosphate group and have the tendency to polymerize at high temperatures, leading to fouling in the equipment [287].
- **Metals** (magnesium, sodium, boron, calcium, iron, or potassium), pigments, sterols, fatty acids, and wax esters may also shorten the catalyst life span [300]. Metallic species (metal ions) attached with phosphatide complexes cause catalytic oxidation and polymerization

reactions in oil, resulting in pro-oxidant compounds such as aldehydes, ketones, acids, and alcohols. These alter the oil's oxidative stability and properties, leading to degradation [299].

- **Free fatty acids** tend to polymerize and contribute to the acidity of the oil; a high free fatty acid concentration increases the total acid number. High total acid numbers create the risk of corrosion and lead to carefully selecting the metallurgy of the front-end hydroprocessing section.
- **Water** contained (moisture) in HEFA feedstocks can promote hydrolysis reactions that generate free fatty acids. Mixing the biogenic feedstock with hydrogen and the hydrotreating catalyst causes the free fatty acids to be hydrotreated, eliminating these concerns [286].
- Other corrosion concerns are **chloride stress cracking** and **high-temperature hydrogen attack**, which are also important for traditional hydroprocessing units.
- Animal fats and UCO present unique challenges, as they may contain **polyethylene**, which can cause fouling and catalyst deactivation at high concentrations. Typical sources of polyethylene from animal fats may include items such as ears tags that pass into the rendering process to separate oil from the waste. Another source is the polyethylene packaging material from packaged meat that has passed its last use-by date. Because UCO is an undefined product, there may be residues in UCO from other waste oils [67, 287].

Strategic impact. Pretreatment can impact the economic feasibility of setting up new facilities and play a crucial role in justifying future investments in RD and SAF production. As evidence, increasing investments in pretreatment processes have been announced in the past years. For example, Marathon announced in 2022 that the company converted its Cincinnati biodiesel plant into a pretreatment facility (30.7 MGPY of feedstock) that, together with their Beatrice, Nebraska, pretreatment plant (58 MGPY), provides feedstock to their Dickinson RD facility [206, 300, 301]. An additional instance is Phillips 66's facility at Rodeo, San Francisco. Phillips 66 has taken the final investment decision to move forward with its Rodeo Renewed project to permanently cease processing of crude oil. This project includes the construction of new pretreatment units and is intended to handle tallow, UCO, fats, grease, and soybean oils [138, 223, 303, 304].

Typical pretreatment process. The steps and configuration of a typical pretreatment process will be dictated by the type and level of contaminants in the feedstock or blend of feedstocks and the downstream hydroprocessing technology requirements. A common configuration for pretreatment involves:

- The first step in a typical pretreatment is the removal of insoluble impurities via **filtration** and heating the oil to about 70°C [67, 305].
- Next, gums or gum-like material and the bulk of metals are removed in the **degumming step** [66]. The degumming process normally reduces the phosphorus content by an order of magnitude (e.g., from 528 to 11 ppm or 312 to 57 ppm for soybean oil) [306, 307]. For UCO, which should have a low metal and phosphorus content, the main objective of the degumming step is to reduce chlorides [67]. Most gums are hydratable and can be removed by water degumming, in which hydratable gums aggregate into oil-insoluble liquid crystals that can be separated by centrifugation. The non-hydratable phospholipids (salts of calcium, magnesium, and iron) can be separated via different techniques that involve the contact of phospholipids (gums) with a polar solvent, which prompt hydration of phospholipids and acidulation followed by neutralization to convert non-hydratable to hydratable phospholipids

[299]. In the acid degumming, metals are partially removed via conversion of organic metal salts to inorganic water-soluble salts, which are then removed via a water wash [67]. Edible acids such as acetic, citric, and tartaric acids are preferred, and toxic or corrosive acids are avoided. The acid that is most frequently used is citric acid. This process generates rich solids/sludge, also called gums, and wastewater as waste streams [67, 299].

- In the next step, named **adsorption or bleaching**, activated clays, also known as bleaching earth, are used to adsorb polar compounds, including phospholipids and soaps. This process removes the remaining gums and achieves low levels of phosphorous (<3 ppm) and total metals (<10 ppm) contents [66]. Powder clay is mixed with the degummed oil in an agitated tank. The bleaching can be achieved at atmosphere or vacuum via batch or continuous process at temperatures between 100°C and 120°C for 20 to 30 minutes [119]. After the contact time, the spent earth is removed via pressure leaf filters. Depending on the plant capacity, about 2–13 pressure leaf filters may be used, with one or two of them in standby. Oil leaves the process at about 90°C–95°C and can be cooled down for storage to about 50°C–60°C. The adsorption sections serve as a guard bed for the hydroprocessing catalyst. The bleaching earth or adsorbent cannot be reused, and its consumption can vary from 0.5 to 2 wt. % relative to the input oil flow.
- Optional pretreatment steps include **polyethylene removal** for removing high-polyethylene content in low-quality animal fats and **chloride mitigation** for UCO. Removal of chloride is challenging because only inorganic chloride can be removed. The removal of organic chlorides is limited; thus, if the content of organic chlorides exceeds recommended limits regarding corrosion, it can be dealt with by blending the feedstock or other mitigating measures [66, 67].

Flexible feedstock systems. When the pretreatment systems lack flexibility, pretreatment may need to be turned down to reconfigure and adjust the process when changing feedstocks, resulting in significant production and economic losses. Thus, a blending system may be required to blend different oils and create an optimized blend that falls within the pretreatment's capability ranges. This ensures the pretreatment process is fed with the best possible blend quality.

Stand-alone vs. colocated pretreatment. Pretreatment units have been built as stand-alone units or colocated in the fuel facility:

- Marathon operates two stand-alone pretreatment facilities in Cincinnati, Ohio (30.7 MGPY), and Beatrice, Nebraska (58 MGPY), which provide pretreated feedstock to their RD facility in Dickinson, North Dakota (184 MGPY) [207, 301, 302]. HF Sinclair operates a pretreatment unit at their Navajo refinery in Artesia, New Mexico, which provides pretreated feedstock to the RD unit in the same facility but also to their converted RD facility in Cheyenne, Wyoming [308, 309]. Internationally, Neste operates a stand-alone pretreatment facility located in Sluiskil, Netherlands, which provides pretreated feedstock to its refineries [310, 311].
- Marathon decided to colocate a pretreatment plant in their Martinez Renewable Fuel facility [312]. Similarly, Phillips 66’s project to convert its Rodeo refinery into a renewable fuel refinery involves colocated new pretreatment units and repurposing of existing hydrocracking units to enable conversion of waste oils, fats, greases, and vegetable oils [223].

Conversion and Separation

Process description. Specifically, the refined oils are mixed with hydrogen and sent to the deoxygenation reactor containing multiple fixed catalyst beds. Depending on the technology, deoxygenation reactors are operated in the temperature range of 300°C to 350°C (570°F to 660°F) and pressure range of 35 to 50 bar (500 to 700 psia). Triglycerides in the feed are converted into long-chain normal paraffins, which accompany the production of propane, CO_2, and water. Exothermic reactions produce heat and increase catalyst bed temperatures. Reactor temperatures are controlled by hydrogen recycle flows to interbed quenches. Liquid recycle ratios up to 1:1 may be required to control the exotherms resulting from 10 wt. % oxygen removal. Reactor effluent is cooled and flashed to have two product streams. One is the light gaseous stream, while the other one is the paraffinic liquid stream. The light product gases are flashed to recover and recycle unreacted hydrogen. The paraffinic liquid effluent is further separated/stabilized to remove water and light hydrocarbons in the fuel gas and liquified petroleum gas range. The liquified petroleum gas consists mainly of propane from the triglyceride reaction.

The paraffinic liquid is mixed with hydrogen and sent to another fixed catalyst bed reactor for hydroisomerization to improve cold-flow fuel properties and hydrocracking for molecular weight reduction to yield jet-range molecules. Depending on the target product slate (diesel or jet), the isomerization and hydrocracking reactors can be operated at mild (diesel) or higher-severity (jet) conditions to impact the product slate. Different catalysts can be applied to optimize the selectivity of desired products with operating conditions as well. The technologies investigated in this work have operating conditions ranging in temperatures from 570°F to 650°F and pressures from 500 to 1,100 psia. As expected, technologies that operate at higher pressure produce higher yields of renewable jet, with lower-pressure technologies yielding mainly RD. Effluent from the isomerization/hydrocracking reactor is cooled and fractionated into light gases, naphtha, jet/aviation fuel, and diesel products.

D.2 HEFA Coprocessing of HEFA Feedstocks

HEFA Coprocessing Pretreatment Requirements

Types of impurities and contaminants that impact the performance of the refinery units selected for HEFA coprocessing are the same as those discussed for the HEFA SAF stand-alone process:

- Alkali and alkaline earth **metals** and other inorganic species, such as phosphorus, can impact the longevity and efficacy of the catalysts. Metal deposition can damage the acid sites, metal sites, or both, and this deposition is not reversible even with catalyst regeneration [122]. To prevent a decrease in catalytic activity during HEFA coprocessing in an FCC unit, the rate of catalyst addition should be increased.
- **Phosphorus** species are rarely found in typical crudes but are present in HEFA feedstocks (Table D-1). However, several U.S. refiners reported issues with phosphorus deposits over the past year related to U.S. domestic production. Phosphorus has also been recently detected in both the crude feed and deposits from several Canadian refineries. Datasets containing approximately 2,200 total phosphorus results from Marathon’s operations in North America

over the past 5 years revealed that phosphorus content was significant for sources coming from both North American and international sources [313].

- High **carbon residue** values in the feedstock will translate into higher deposition of coke on a catalyst, thus causing catalyst fouling. In the FCC units, high-feed coke deposition will result in increasing regenerator temperatures and lower catalyst circulation. In the hydrotreater and hydrocracker, where catalysts are only regenerated after a number of years, any detrimental impact to catalysts can have critical consequences in the economic performance of a refinery. Moreover, polymerization/cracking of the HEFA feedstocks at elevated temperatures results in the formation of coke [314]. To limit polymerization and coking, it is often recommended to inject biofeedstock into the FCC reactor or hydrotreater separately from fossil feed. This helps to maintain a lower temperature for the biogenic feedstock [87].
- High **free fatty acid** contents result in low pH and high total acid number, which then increases corrosion in pipes and equipment [65]. Thus, corrosion concerns present a challenge, as many refineries use carbon steel pipes and equipment, and upgrading of metallurgy to higher-cost stainless steel, or higher grades like Hastelloy, may be necessary. When charged into the reactor, free fatty acids are quickly converted into products.
- **Chlorides** hydrolyze upon heating to HCl by hydrotreating and can create issues in hydrotreater effluents because of the formation of NH_4Cl salt deposits. Proper wash water practices can help manage chloride levels and prevent these problems [122].
- While crude oils typically contain <2% **oxygen**, biogenic feedstocks range from 10 to 12 wt. % oxygen content. During HEFA coprocessing, the hydrogen requirements are increased by the high oxygen content found in lipids, just as in the stand-alone hydroprocessing process. FCC catalysts are more tolerant than hydroprocessing catalysts to higher oxygen levels [87].
- In the hydrocracking operations, higher concentrations of **nitrogen** and **sulfur** result in an increase in the severity of the operations. While sulfur content in vacuum gas oil can be as high as 2.5–3.0 wt. %, higher sulfur levels will increase the H_2S content of the recycled gas and will have little or no effect on catalyst deactivation. The organic nitrogen compounds, which are converted to ammonia, compete with hydrocarbons for the active catalyst sites, resulting in a lower apparent activity of the catalyst. Thus, higher organic nitrogen concentrations require higher catalyst temperatures or volumes [122].

Impurity concentrations (Table D-2) show that after blending, the impurities content from most of the HEFA feedstocks is low enough to meet the hydroprocessing requirements.

Table D-2. Impurities Content in Vacuum Gas Oil and Estimated Contribution of Impurities From HEFA Feedstocks (Based on Table D-1), Considering a 5 vol % Blending Ratio

Color code: blue – maximum limit of impurities for hydroprocessing, green – acceptable parameters, yellow – may meet requirements depending on feedstock source, red – does not meet requirements.

Parameter	Units	Vacuum Gas Oil	Crude Vegetable Oil	Animal Fat	UCO/Yellow Grease	Algae Oil	Hydroprocessing Requirements
Phosphorus	ppm	0–2	0.04–1.6	2–32	0.3–7	15–17	<1–3
Total metal (Mg, B, Na, Fe, Zn, K, Ca, Si, V, Ni)	ppm	10.0–50.0	7.5	15	7.5	-	5–10
Nitrogen	ppm	29–1,900	2.5	35	3	-	200–350
Sulfur	ppm	1,900–20,200	<1	0.4–5	0.2–2	0.75–1.4	10–250
Chlorides (total)	ppm	-	<1	10	2.5	-	<5–50
Polyethylene	ppm	-	nil	10	2.5	-	20–50

The objective of the hydrotreating units in a refinery is to clean streams from impurities harmful to the catalysts used in downstream operations. For example, while the concentration of nitrogen and sulfur in vacuum gas oil is outside the recommended impurity contents for the HEFA stand-alone hydroprocessing (Table D-2), some hydrotreaters are design to remove sulfur, metals, polyaromatics, and Conradson carbon from vacuum gas oil to be used as FCC feed [315].

HEFA Coprocessing Conversion and Refinery Unit Capacities

Table D-3 summarizes the operating conditions of various types of existing refinery hydroprocessing units.

Table D-3. Operating Conditions for Refinery Units That Have Potential for Conversion to FOG [84]

Process Parameter	Kerosene/Jet Hydrotreating	Virgin Distillate Hydro-treating	Cracked Distillate Hydro-treating	Distillate Hydro-cracking	Gas Oil or FCC Feed Hydrotreating	Cracked Gas Oil Hydrocracking	Resid Hydro-cracking
Feed gravity (API)	40–50	30–45	15–30	15–30	15–25	0–20	(10) -15
Temperature (°C)	290–370	310–400	340–400	340–450	340–430	340–450	400–450
Pressure (psia)	700–1,000	700–1,500	1,000–2,500	1,000–2,500	800–1,200	1,500–3,000	2,400–3,000
H_2 partial pressure (psia)	500–900	500–1,200	800–1,800	800–2,300	600–1,000	1,200–2,700	1,900–2,700
Liquid hourly space velocity (h^{-1})	3–6	1–4	1–2	0.5–2	0.5–1	0.5–2	0.5–1
H_2 consumption (scf/bbl)	150–500	300–700	700–1,700	500–2,000	500–1,000	1,200–3,500	1,200–3,500
H_2-to-oil ratio (scf/bbl)	600–2,500	1,200–3,000	2,000–7,000	2,000–8,000	1,500–4,000	4,000–10,000	4,000–10,000

Refinery Capacity Summary (BGPY unless noted)								
U.S. total/PADD	**Totals**	**1A**	**1B**	**1C**	**2**	**3**	**4**	**5**
Atmospheric distillation	290.5	0	13	0.4	67.8	155.6	10.9	42.9
Vacuum distillation	131.6	0	5.8	0.1	28.4	71.5	3.8	22
Naphtha hydrotreating	70.6	0	4.1	0.1	20.4	34.2	2.3	9.6
Kerosene hydrotreating	24.0	0	1.1	0	5.1	13.3	0.6	3.8
Diesel hydrotreating	70.0	0	3.9	0.1	18.0	36.8	3.3	8.0
Gas oil and resid hydrotreating	51.2	0	0.3	0.1	11.3	26.9	1.7	10.9
Gasoline hydrotreating	44.8	0	1.1	0	9.2	28.9	0.6	4.9
Hydrocracking	37.2	0	0.7	0	5.8	21.2	0.9	7.5
Fluid catalytic cracking	85.1	0	4.8	0	21.0	44.2	3.2	11.9
Thermal cracking (coking and visbreaking)	44.9	0	0.8	0	9.4	25.2	1.1	8.4
Naphtha reforming	54.8	0	2.2	0.1	13.9	28.2	1.9	8.5
Alkylation	19.8	0	0.7	0	4.5	10.3	0.7	3.6
Isomerization	11.6	0	0.3	0	2.6	5.0	0.2	3.5
Aromatics	4.8	0	0.1	0	1.7	2.9	0.0	0.0
Asphalt and road oil	10.6	0	0.7	0	4.5	3.5	1.0	0.8
Fuels solvent deasphalting	6.1	0	0.3	0	0.4	4.1	0.1	1.2
Hydrogen (million cubic feet per year)	2,893	0	106	3	633	742	223	1,186
Lubricants	4.0	0	0.2	0.1	0.2	3	0	0.6
Petroleum coke	13.5	0	0.2	0	3.0	7.5	0.4	2.5
Sulfur (short tons per day)	40,453	0	1,073	1	8,732	24,140	911	5,596

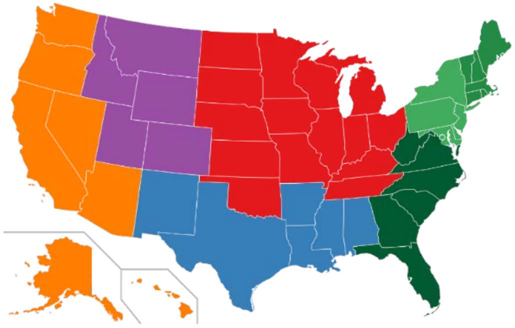

Figure D-1. Refinery capacity summary by Petroleum Administration for Defense District

Industry cases. Multiple refineries worldwide have introduced HEFA coprocessing of vegetable oils or FOG feedstocks. At their Lingen refinery in Germany, British Petroleum (BP) coprocesses UCO to produce SAF, while at their Cherry Point refinery in Washington in the U.S., BP converts vegetable oils and rendered animal fats into RD [28, 166]. At the El Segundo refinery, Chevron has reported the production of a batch of SAF [26, 139]. In Canada, Parkland coprocesses biofeedstocks (canola oil, tallow, and tall oil) at their FCC unit in Burnaby, British Columbia [139, 316, 317]. In 2010, Preem started coprocessing 30% of renewable feedstock in their Gothenburg refinery in Sweden. Preem and Topsoe have successfully achieved an 85% coprocessing rate of renewable feedstock [318, 319]. Similarly, UPM produces RD and renewable naphtha from tall oil in a stand-alone process at their Lappeenranta Biorefinery in Finland [320].

D.3 SAF vs. RD Discussion

Specific emphasis is placed on the process yield data where NREL has utilized published resources and also developed and applied an isomerization/hydrocracker model in Aspen HYSYS to assess predicted yield structures at different operating conditions on the SAF-RD spectrum. Conversion is impacted by catalyst, temperature, and (hydrogen partial) pressure.

The 280°C boiling point temperature represents the typical target cut point between jet and diesel fractions when a jet product is recovered. Figure D-2 shows the yield predictions from the model for maximum diesel recovery as a function of conversion. The dotted line represents the operating point for the RD scenario assessed in the project defined using source product yields. Similarly, Figure D-3 shows the yield predictions for maximum jet fuel recovery where the dotted line, now at higher conversion, represents the operating point for the renewable jet production.

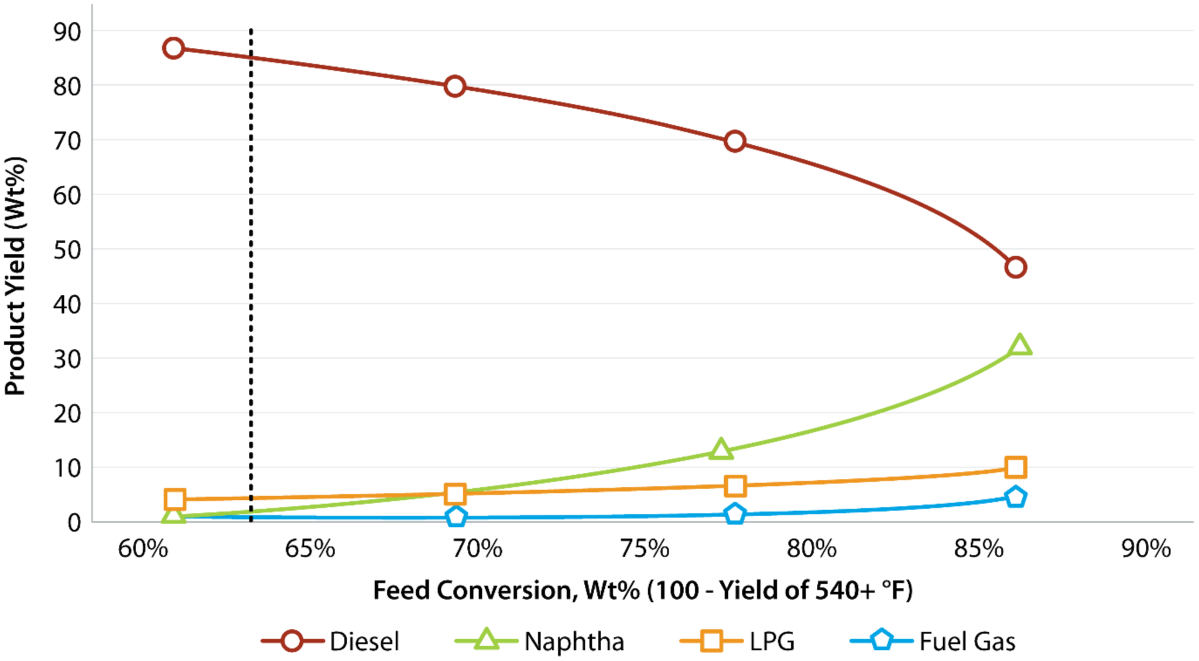

Figure D-2. Product yield model for RD production from Aspen HYSYS

Note: In x-axis, 100% represents the total initial feedstock. The percentage yield of the distillate fraction with a boiling point above 282°C (540°F) (considered unconverted) is subtracted from 100% to determine the percentage of feedstock converted into the desired product and lighter fractions.

The NREL team also utilized the isomerization/hydrocracking Aspen HYSYS model to assess estimates and trends for cold-flow fuel properties such as freeze point (<-40°C for Jet A) for meeting jet fuel specifications. The modeled results, in addition to published datasets, indicate that the jet fuel fraction will meet freeze point requirements at the specified operating point for the scenario.

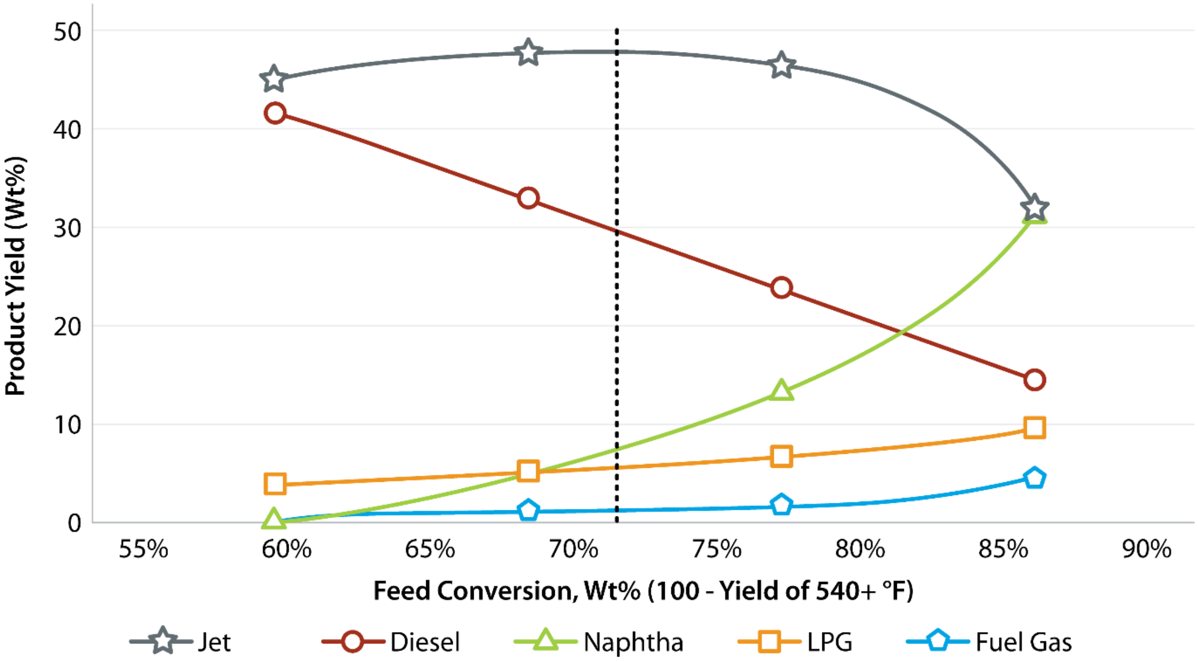

Figure D-3. Product yield model for renewable jet production from Aspen HYSYS

Appendix E. Additional Inputs and Waste Streams

Biomass Generation

Water usage. Water management and use issues stem from drought, flooding, population growth, and increased domestic, industrial, and agricultural demand. Climate change is exacerbating these problems [321]. Water usage for oilseed crops, livestock, and future algae farming are potential constraints in biomass generation for the HEFA SAF pathway. Options to lessen water usage have been proposed: enhancing the irrigation system by replacing sprinklers with a drip irrigation system that minimizes evaporation before the water reaches the plant's roots, relocating the production of water-intensive crops to regions with abundant water, and implementing genetic modifications that enhance drought tolerance [322].

Fertilizer runoff. Farmers supply nutrients, mainly nitrogen and phosphorus, to their fields via chemical fertilizers and animal manure. Overuse of fertilizers can lead to their runoff into water bodies, contaminating both surface and groundwater. This can result in a reduction of aquatic life, the formation of dead zones, and the emergence of harmful algal blooms that can disrupt the ecosystem and produce toxins that pose a risk to human health [323, 324]. There are farming techniques and practices recommended to reduce nutrient losses, including: adopting nutrient management techniques, conservation drainage practices, planting field buffers, and managing livestock access to streams [323, 325–327].

Seed availability can also pose a challenge if farming of oilseeds rapidly grows. Seed systems encompass the entities, actions, and organizations responsible for preserving crop variety, developing and selecting plants, and distributing and producing seeds. Seed security involves access to quality seeds with suitable genetic, physical, and physiological properties; farmers' stable access to seeds; and the resilience of the seed system to recover from shocks and stress [328].

Refining of Vegetable Oils and Pretreatment of HEFA Feedstocks

Solvents. The *n*-hexane found in commercial hexane, typically used as a solvent in vegetable oils pretreatment, is a neurotoxin. As a result, the EPA has classified *n*-hexane as a hazardous air pollutant, which prompted the creation of the National Emission Standards for Hazardous Air Pollutants [119]. Hexane usage in soybean crushing and oil extraction has been reported in 1.8-3.4 g/kg of oil [329]. Currently, these standards limit *n*-hexane emissions to 0.2 gallons/ton (0.56 g hexane/kg of oil) for facilities using conventional-style desolventizer to make soybean oil [92, 93]. Therefore, addressing *n*-hexane emissions is a crucial concern for soybean oil producers and could pose a difficulty for HEFA facilities that utilize hexane in their pretreatment process.

Virtually all *n*-hexane is obtained from petroleum, more specifically from naphtha via hydrodesulfurization, de-aromatization, and fractionation [330]. **Main impediments to hexane market growth are the concerns regarding its correct disposal due to its flammability and toxicity** [331]. Major hexane users include Exxon Mobil Corp., GFS Chemicals Inc., Merck, Phillips 66, and Royal Dutch Shell.

Degumming acids:

- **Phosphoric acid** is derived from phosphate rock through wet and thermal processes. The manufacturing of fertilizer products is the primary market for phosphate, making up 85% of total consumption. [332]. Phosphoric acid demand is primarily influenced by the demand for fertilizers, which is connected to population growth, consumer diets, and policies. Secondary applications for phosphate include livestock food, pH adjustment, cleaning agent formulation, sugar refining, and synthetic phosphate manufacturing. The availability of phosphate rock reserves determines the supply of phosphoric acid, with Morocco possessing the world's largest reserve [333]. The main phosphoric acid producers in the U.S. include Mosaic Company (3,900 million kilograms in 2019, about 58% of North America annual capacity), PCS phosphate, Itafos, and J.R. Simplot Co. Phosphoric acid is essential to the water treatment sector for pH adjustment and corrosion control. Phosphoric acid has **a moderate-high supply chain risk rating, considered an essential chemical for the water sector, which has experienced regional phosphoric acid supply disruptions in the past**. Supply chain risk concerns are due to increased competition and reliance on imports of raw materials [94].
- **Citric acid** is generally produced by fermentation of carbohydrates (dextrose, sucrose, or beet molasses) using *Aspergillus niger*. Archer Daniels Midland Company, Cargill Inc., and Tate & Lyle Inc. are the main producers of citric acid in the U.S. who use dextrose from corn as raw material. Citric acid finds its main application as a preservative in the food industry, with additional uses in the pharmaceutical and industrial sectors. The growing population will lead to a higher demand for citric acid due to increased needs for food preservatives [95].

Neutralization. Removing free fatty acids is essential to produce a stable biogenic oil product due to their higher susceptibility to oxidation compared to triacylglycerides. The formation of soaps is achieved by neutralizing free fatty acids with alkali, such as sodium hydroxide or potassium hydroxide [96]. Sodium chloride is used to manufacture sodium hydroxide. The U.S. is a top producer of sodium chloride and has plenty of rock salt and brines [98]. Thus, sodium chloride has a low-risk rating assigned by the EPA. Non-fertilizer potassium chloride is converted primarily to potassium hydroxide. While potassium chloride has a low-risk rating assigned by the EPA, the U.S. relies heavily on imports to meet domestic demand, which is in its majority used to produce fertilizer [97].

Acid-activated bleaching earths have traditionally been the most effective products in the bleaching of edible oils and fats. Furthermore, acid-activated calcium montmorillonite (bentonite) clay products have been dominant in this area. Acid-activated bleaching earth, the most-used adsorbent, is produced from high-purity calcium montmorillonite clays. Acid-activated clays provide a large surface area, ranging from 160 m^2/g to more than 300 m^2/g [334]. Typically, earth dosage ranges from 0.3%–0.6% for soybean oil [119]. The estimated global use of bleaching earth was between 1 and 2 million tons per year in 2019. Efforts to recycle or utilize spent bleaching earth are being developed, such as its use in wastewater treatment, biofertilizer, fuel briquettes, and fired wall tiles [120]. Alternative adsorbents are available, such as silica hydrogels or activated carbon [68, 335–337]. Filtration aids are used to increase flow rate during filtration, such as the diatomaceous earth (DE) or perlite filter aids [338].

HEFA SAF Process

Catalysts. Commercial catalysts are optimized for different feedstocks and process goals, for example feedstocks with high sulfur concentration, or feedstocks with high oxygen concentration [85]. The following describes two common hydrotreatment setups and the catalysts employed.

- The **single-stage hydrotreatment configuration** is a simpler line-up process without an interstage separation. This process is easier to construct, but full conversion is usually not achieved [339, 340]. A bifunctional catalyst allows for both hydrotreating and hydrocracking reactions in a single stage. These catalysts often include Ni-Mo, Co-Mo, Ni-W, or Co-W supported on alumina.
- The **two-stage hydrotreatm**ent setup involves separate stages for hydrotreating and cracking, with an interstage separation unit to remove H_2S and NH_3. The second reactor cracks the unconverted feedstock from the first reactor, leading to full conversion and a greater yield. For the initial stage, molybdenum and alumina catalysts have been employed, followed by the utilization of bimetallic catalysts like Ni-Mo, Co-Mo, and Ni-W in the subsequent stage [300].

For the **isomerization reaction**, some of the catalysts proposed include Pt, Pd, and Ni supported on amorphous or crystalline alumina, fluoride alumina, silica, ferrierite, ZSM-12, ZSM-21, SAPO-11, or SAPO-31 (e.g., Pt-Pd/Al_2O_3), or Pt, Pd, Ir, Ru, Rh, and Re supported on zeolites, sulphonated oxides, SAPOs, or micro-mesoporous silica-alumina [300].

The sourcing of metals for catalyst manufacturing might pose supply challenges, as explained below:

- The **molybdenum** supply chain is considered to have **high price volatility**. Molybdenum production is mainly concentrated in five countries—China, Chile, the U.S., Peru, and Mexico—accounting for 93% of the world's output [101].
- There are various concerns associated with **nickel** mining, including pollution, Indigenous rights, GHG emissions, and working conditions. The dominance of nickel production by a few countries may also present challenges, for example, the world's largest producer is Indonesia (45% of nickel mining in 2021). However, Indonesia only has 21% of global nickel reserves, slightly more than Australia (20%) and Brazil (16%) [102].
- **Cobalt** is also an essential metal used in the manufacture of batteries, whose market is expected to expand seven-folds by 2030. Cobalt production needs to grow 3 times by 2030 to meet the projected demand. The largest supplier of cobalt is the Democratic Republic of Congo, providing about 70% of world supplies. **Single-source risk, artisanal mining, human rights concerns, and labor practices are problems in cobalt production** [103].
- China is responsible for mining 80% of primary **tungsten**, with notable contributions from Vietnam, Russia, and Europe. Around one-third of the world's tungsten supply comes from tungsten-bearing scrap. Due to conflicts, international agreements limit sourcing raw materials from specific areas, which might also lead to supply disruptions.
- **Aluminum hydroxide**, used as catalyst support for hydroprocessing catalysts, is primarily produced from bauxite ($Al_2H_2O_4$). Historically, domestic bauxite production in the U.S. has been insignificant, making up less than 5% of the country's bauxite consumption, primarily for non-metallurgical purposes. Even though the U.S. relies solely on imported bauxite to

manufacture alumina and related chemicals, there have been no reported disruptions in the supply chain from 2000 to 2022 [341–343].

Hydrogen Sourcing

The U.S. produces about 10 million tonnes (Mt) per year of "on-purpose" hydrogen, about 12%–16% of the worldwide "on-purpose" production (70 Mt/y). Hydrogen production can be classified into three segments: merchant hydrogen, generated on-site or in a production facility and sold to a consumer; captive hydrogen, produced by the consumer for internal use; and byproduct hydrogen, recovered from byproduct process streams and consumed or sold to another company. Merchant and captive hydrogen production can be considered "on purpose." The major companies producing and selling liquid hydrogen are Linde, Air Products, and Air Liquide.

Demand. More than 80% of merchant hydrogen in the U.S. is sold to refineries for hydrocracking, ultra-low-sulfur diesel hydrotreating, FCC, and naphtha hydrotreating [344]. For hydrotreating and hydrocracking, a dedicated hydrogen production unit is normally required to produce a large volume of hydrogen with >99.5% purity [345]. Refinery hydrogen demand is expected to grow as fuel specifications globally further reduce acceptable sulfur content levels. **Under current trends, hydrogen demand in refineries is set to grow by 7% in 2030.** As there is already sufficient refining capacity globally to fulfill the expected need for oil products, 80%–90% of future hydrogen demand in the refinery sector would come from today's capacity [105]. According to projections, there will be a 1.7% annual increase in the demand of H_2 for ammonia from 2018 to 2030, with further growth expected in the future. Additionally, hydrogen demand for methanol is expected to grow at a 3.6% per year between 2018 and 2030. Alternative process technologies and feedstocks (carbon capture, electrolysis, and biomass to ammonia) could meet growing demand for hydrogen feedstock in the chemical sector for ammonia and methanol while reducing CO_2 emissions. However, these technologies would considerably increase demand for energy inputs and are more costly than using fossil fuels for hydrogen generation [105].

Generation:

- The hydrogen generated from natural gas or methane via steam methane reforming is often referred to as "gray hydrogen."
- When hydrogen produced via steam methane reforming, which produces CO_2 as byproduct, includes the use of carbon capture, utilization, and storage to trap and store this CO_2, it is called "blue hydrogen."
- Hydrogen produced via water electrolysis using renewable electricity is often called "green hydrogen." The GHG impact of electrolytic hydrogen depends on factors such as the type of renewable electricity used and whether additional renewable capacity is used for its production [346]. Apart from the production cost, there are also concerns about the high water and electricity consumption involved in producing significant quantities of electrolytic hydrogen. Stoichiometrically, around 9 liters of water are needed to produce 1 kg of hydrogen, while producing 8 kg of oxygen as a byproduct. Roughly twice the water volume required for hydrogen production via steam methane reforming. The efficiency of electrolysis ranges between 60% and 81%, depending on the technology type and load factor. Producing all of today's dedicated hydrogen output (69 Mt H_2) from electricity would result in an electricity demand of 3,600 TWh, more than the total annual electricity generation of the

European Union in 2022 (2,641 TWh), from which almost 40% came from renewable sources [105, 347]. In contrast, to cover all of the U.S. "on-purpose" hydrogen production (10 Mt H_2) from electricity would result in an electricity demand of ~522 TWh, about 12% of the electricity produced in the U.S. in 2022, 21.5% of which comes from renewable sources [348, 349].

- **Bio-based hydrogen production.** SAF and RD production also produces renewable methane, ethane, propane, and naphtha that can be used as feedstock for steam methane reformer (SMR) or autothermal reforming, facilitating the production of low-carbon hydrogen [350].

Appendix F. Certifications and Permits

ASTM D7566

Requirements for each batch of HEFA SPK (or HEFA jet fuel) and HC-HEFA SPK (HEFA SAF produced from *Botryococcus braunii* species of algae) are shown in Table F-1.

ASTM D7566 standard also defines "other detailed requirements" for all annexes (pathways) which are intended to verify the control of the SPK production processes during the scale-up stage. Tables A2.2 and A7.2 of ASTM D7566 display the requirements for HEFA SPK and HC-HEFA SPK, respectively. Compliance with these "other detailed requirements" is needed during the initial production scale-up stage. ASTM aims to shift these requirements to management of changes requirements once enough production experience is acquired. ASTM D7566 does not provide a specific timeframe or criteria to define sufficient production experience.

ASTM D1655

The coprocessing provision was added to Annex A1 of ASTM D1655, and it describes the extended requirements for aviation turbine fuels containing coprocessed renewable feedstocks via HEFA, FT, and fractionation.

While D1655 does not specify requirements for knowing the fossil versus present-day carbon content of the coprocessing produced SAF/jet fuel blend, it establishes the importance of determining the renewable content in the product blend for regulatory purposes. This proportion can be determined based on radiocarbon (^{14}C) concentration via Test Method D6866 [31].

Jet Fuel Quality

Table F-1. Conformity Test ASTM Specification and Test Methods for Coproduced Jet/HEFA Hydrocarbons Blend, and Jet/HEFA SPK and Jet/HC-HEFA SPK Blends

Sources: ASTM D1655 and ASTM D7566

Requirement	**Specification**			**ASTM Test Method**
ASTM Standard	D1655	D7566		
Fuel	Jet with co-hydroprocessed HEFA, FT hydrocarbons, or hydrocarbons from Esters and Fatty Acids	HEFA SPK	HC-HEFA SPK	
Table no. in ASTM standard	Table A1.1	Table A2.1	Table A7.1	
COMPOSITION				
Acidity, total mg KOH/g		Max 0.015	Max 0.015	D3242
Hydrocarbon composition				
Cycloparaffins, mass percent**		Max 15**	Max 50**	D2425
Aromatics, mass percent**		Max 0.5**	Max 0.5**	D2425
Paraffins, mass percent**		Report**	Report**	D2425
Carbon and hydrogen, mass percent**		Min 99.5**	Min 99.5**	D5291
Non-hydrocarbon composition				
Nitrogen, mg/kg**		Max 2**	Max 2**	D4659
Water, mg/kg**		Max 75**	Max 75**	D6304

Requirement	**Specification**			**ASTM Test Method**
ASTM Standard	D1655	D7566		
Fuel	Jet with co-hydroprocessed HEFA, FT hydrocarbons, or hydrocarbons from Esters and Fatty Acids	HEFA SPK	HC-HEFA SPK	
Sulfur, mg/kg**		Max 15**	Max 15**	D5453, D2622
Metals (Al, Ca, Co, Cr, Cu, Fe, K, Mg, Mn, Mo, Na, Ni, P, Pb, Pd, Pt, Sn, Sr, Ti, V, Zn), mg/kg**		Max 0.1 per metal**	Max 0.1 per metal**	D7111
Halogens, mg/kg**		Max 1**	Max 1**	D7359
VOLATILITY				
Distillation temp, °C				D86, D2887
T10 (10% recovered, temp)		Max 205	Max 205	
T50 (50% recovered, temp)		Report	Report	
T90 (90% recovered, temp)		Report	Report	
T50–T10				
T90–T10		Min 22	Min 22	
Final boiling point, °C		Max 300	Max 300	
Distillation residue, %		Max 1.5	Max 1.5	
Distillation loss, %		Max 1.5	Max 1.5	
Flash point, °C		Min 38	Min 38	D56 or D3828
DENSITY				D1298 or D4052
Density at 15°C, kg/m^3		730–772	730–800	D1298 or D4052
FLUIDITY				
Freezing point, °C max**	-40 Jet A	Max -40	Max -40	D5972, D7153, D7154, D2386*
	-47 Jet A-1			
Viscosity −40°C, mm^2/s	Max 12			D445
COMBUSTION				
One of the following requirements shall be met:				
(1) Smoke point, mm, or			Min 25.0	D1322
(2) Smoke point, mm, and				D1322
THERMAL STABILITY				
(2.5 h at control temperature of, °C min)	280	325	325	
Filter pressure drop, mm Hg	Max 25	Max 25	Max 25	D3241
Tube deposit rating				
(1) Annex A1 VTR, VTR Color code	Less than 3	Less than 3	Less than 3	
CONTAMINANTS				
Existent gum, mg/100 mL		Max 7	Max 7	D381*, IP 540
ADDITIVES				
Antioxidants, mg/L		Min 17, max 24	Min 17, max 24	

Requirement	Specification			ASTM Test Method
ASTM Standard	D1655	D7566		
Fuel	Jet with co-hydroprocessed HEFA, FT hydrocarbons, or hydrocarbons from Esters and Fatty Acids	HEFA SPK	HC-HEFA SPK	
Unconverted esters and fatty acids, mg/kg	Max 15			D7797
FAME, mg/kg		Max <5	Max <5	

* Extended requirements
** Other detailed requirements (D7566 Table A2.2 and Table A7.2)

Air Quality Analysis

Two HEFA facilities were explored in terms of their emissions from the production of HEFA fuels, as illustrative examples for future SAF production facilities to obtain permits.

World Energy Corp.

World Energy is a brownfield facility in Paramount, California, converted from an oil refinery previously owned by the Paramount Petroleum Corporation. The plant converts 45 MGPY of tallow and used cooking/corn oil into fuels, along with other byproducts. World Energy planned to increase its production capacity by repurposing the 575-MGPY petroleum refinery to a 295 MGPY renewable fuel facility [351]. New permits were approved in 2022 for the additional capacity, covering equipment, land acquisition, and emissions compliance. An overview of the prospective emissions impact and federally enforceable air quality regulations applicable to this facility is presented below:

- **Summary of emissions.** Figure F-1 shows the tons per year of the criteria pollutants that are estimated to be emitted from the 25,000-barrel/day feedstock facility [351]. The dotted line notates the major threshold for each pollutant, as set by the South Coast Air Quality Management District, which is the permitting authority for the World Energy SAF facility in Paramount. Within the district, major source thresholds are dependent on the attainment status of the facility location. Facilities that surpass these thresholds must obtain a Title V permit[30] for facility construction and operation permits. As indicated in the permit, nitrogen oxides surpass the applicable threshold after compliance with Regulations XIII and XX.[31]

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[30] With a Title V permit requirement, more stringent emissions controls are required to control facility waste to the environment.

[31] District regulations require emissions offsets or concurrent emissions reductions as part of the permitting process for stationary sources. Emissions offsets are required pursuant to Regulation XIII – New Source Review and Regulation XX – RECLAIM.

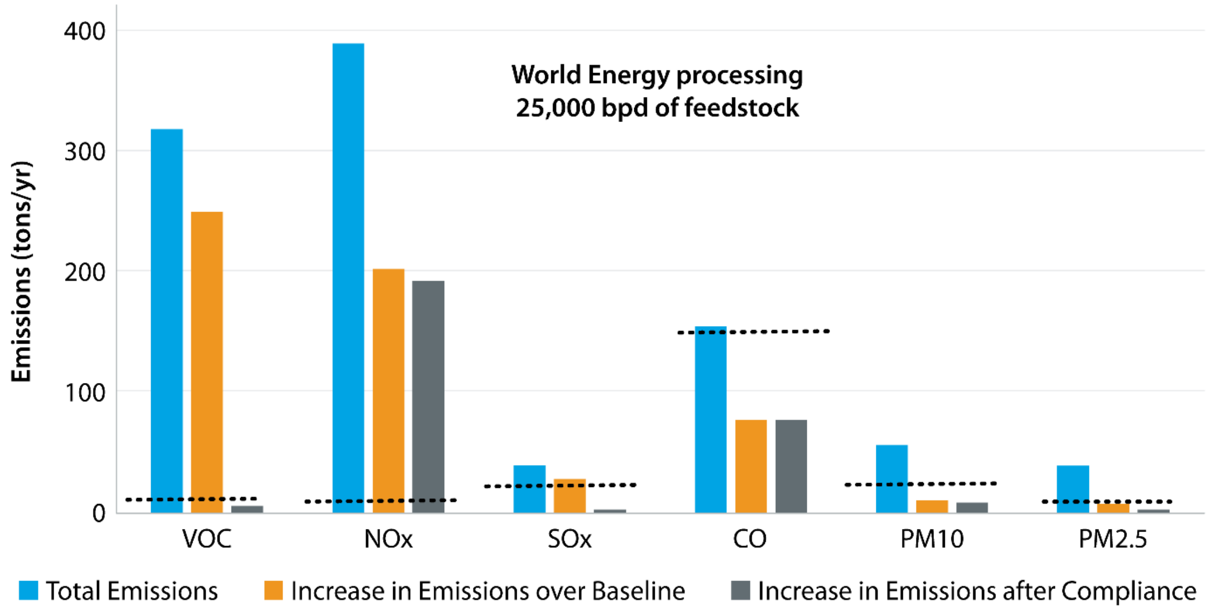

Figure F-1. Emissions related to the expansion of the World Energy Paramount facility

Note: (1) Total emissions are the sum of stationary and mobile sources from the World Energy SAF facility; (2) increase in emissions over baseline refers to the increase compared to the emissions from the 2011 refinery operations; (3) increase in emissions after compliance refers to the estimated emissions after compliance with Regulations XIII and XX; and (4) dotted line represents the major source threshold for each pollutant. Data source: Table 4.2.11 [351].

- **Applicability of federal regulations.** The facility is subject to New Source Performance Standards 40 *Code of Federal Regulations* (CFR) 60 and National Emission Standards for Hazardous Air Pollutants (c) 40 CFR 61, 40 CFR 63, 40 CFR 64, 40 CFR 68, 40 CFR 79, 40 CFR 80, and 40 CFR 82 with subsections of those regulations pertaining to specific unit operations. Federal regulations applicable to a specific unit operation or the whole World Energy facility are listed at the end of this section (Air Quality and Permitting).
- **Emissions control technologies.** To meet the regulatory requirements and emission limits specified in their air permit, the World Energy facility incorporated a number of control technologies to reduce the emissions of criteria emissions, including (but not limited to) the replacement of several older heaters with one new reformer heater equipped with a selective catalytic reduction (SCR) unit to control NOx, installation of a new flare and flare gas recovery system to reduce VOC, and modification of certain storage tanks by adding internal floating roofs. The fugitive emissions from the equipment (e.g., pump, valve, compressor) leaks are controlled and monitored pursuant to South Coast AQMD Rule 1173. VOC emissions from wastewater treatment are also monitored and controlled via Rule 1176. World Energy also adopted mitigation measures to reduce criteria air pollutant emissions from mobile sources (trucks, marine barge, trains)—for example, by requiring the use of newer trucks.

Montana Renewables LLC

Montana Renewables LLC is a brownfield facility converted from an oil refinery in Great Falls, Montana, previously owned by Montana Calumet Refinery. While built on the refinery's land, it is a separate entity from the parent organization, Calumet Specialty Products Partners L.P., utilizing the existing assets of the refinery for renewable fuel production [352]. The Montana facility at Great Falls has a permitted capacity of 230 MGPY (15,000 barrels per day) of renewable fuel from renewable feedstock (including canola oils and tallow) [353]. Montana Renewables is planning to scale up its operations to 276 MGPY in 2025 (Appendix B). Whether the incremental 3,000 b/d capacity will be utilized for SAF production is subject to a final investment decision [354].

Summary of emissions. At its current processing capacity of 173 MGPY of feedstock, Figure F-2 shows the estimated criteria pollutants from the entire facility. Because all pollutants are below the applicable Prevention of Significant Deterioration major source threshold of 100 tons per year of each pollutant, it is not classified as a "major stationary source" [355]. While at its current capacity it remains below the major source threshold, with the promise of further expansion on the horizon, additional permitting to adhere to these guidelines will be required.

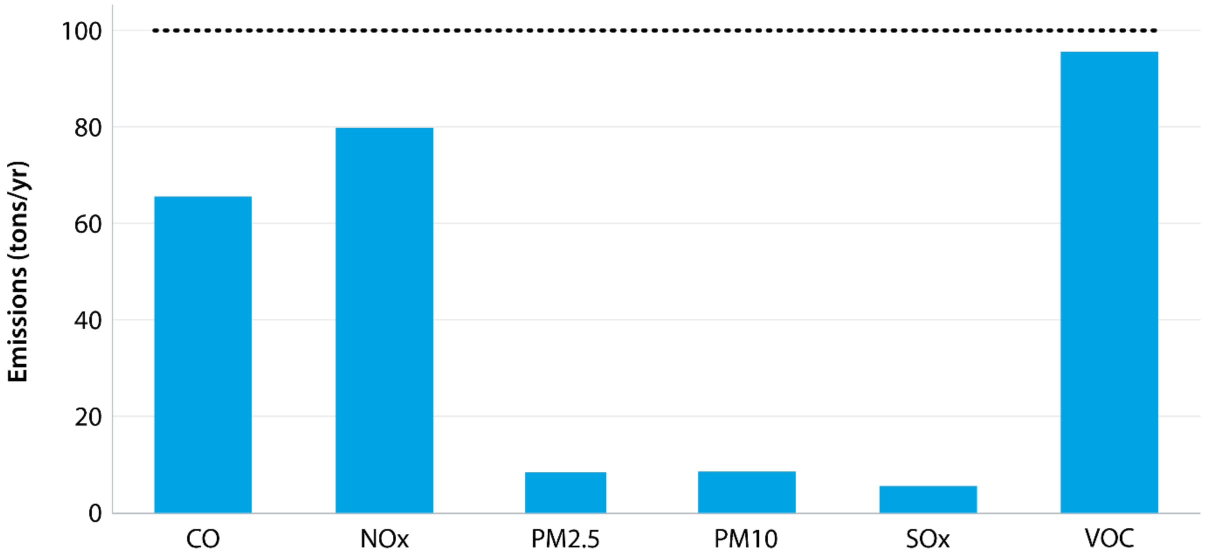

Figure F-2. Montana Renewables LLC criteria pollutants at about 173 MGPY barrels/day of feedstock capacity. Dotted line represents the major source thresholds applicable to Montana Renewables.

Source: [355]

Applicability of federal regulations. There are several federal regulations that limit the emissions of pollutants from certain units within the Montana Renewables process. The facility is subject to New Source Performance Standards 40 CFR 60 and National Emission Standards for Hazardous Air Pollutants 40 CFR 61 and 40 CFR 63, with subsections of those regulations pertaining to specific unit operations. Federal regulations applicable to a specific unit operation or the whole facility are listed at the end of this section (Air Quality and Permitting).

Emissions control technologies. The Montana Renewables LLC processing plant integrates several control technologies to reduce the emissions of criteria emissions. For process heat, Montana utilizes ultra-low-NO_x burners, fuels with lower sulfur content, and best practices for combustion. For their vessels and tanks, fixed roofs submerged with fill and carbon adsorption control have been applied to limit the volatile organic compound emissions. The fugitive emissions from the equipment leaks are controlled through emission monitoring using a leak detection and repair program, while carbon adsorption is used to reduce volatile organic compounds from blowdown drum and wastewater operations.

Air Quality and Permitting

Federal regulations applicable to a specific unit operation or the whole facility are listed in the following subsections.

World Energy Corp.

- 40 CFR 60 Subpart A: General Provisions applicable to the owner or operator of the stationary source for which New Source Performance Standards are prescribed under this part [363].
- 40 CFR 60 Subpart GG: Standards of Performance for Stationary Gas Turbines [364].
- 40 CFR 60 Subpart GGG: Standards of Performance for Equipment Leaks of VOC in Petroleum Refineries for which Construction, Reconstruction, or Modification Commenced After January 4, 1983, and on or Before November 7, 2006 [365].
- 40 CFR 60 Subpart GGGa: Standards of Performance for Equipment Leaks of VOC in Petroleum Refineries for Which Construction, Reconstruction, or Modification Commenced After November 7, 2006 [366].
- 40 CFR 60 Subpart IIII: Standards of Performance for Stationary Compression Ignition Internal Combustion Engines [367].
- 40 CFR 60 Subpart XX Standards of Performance for Bulk Gasoline Terminals [368].
- 40 CFR 60 Subpart J: Standards of Performance for Petroleum Refineries [369].
- 40 CFR 60 Subpart Ja: Standards of Performance for Petroleum Refineries for Which Construction, Reconstruction, or Modification Commenced After May 14, 2007 [370].
- 40 CFR 60 Subpart Kb: Standards of Performance for Volatile Organic Liquid Storage Vessels (Including Petroleum Liquid Storage Vessels) for Which Construction, Reconstruction, or Modification Commenced After July 23, 1984 [371].
- 40 CFR 60 Subpart QQQ: Standards of Performance for VOC Emissions From Petroleum Refinery Wastewater Systems [372].
- 40 CFR 60 Subpart UU: Standards of Performance for Asphalt Processing and Asphalt Roofing Manufacture [373].
- 40 CFR 61 Subpart FF National Emission Standard for Benzene Waste Operations [374].
- 40 CFR 63 Subpart AAAAAAA: National Emission Standards for Hazardous Air Pollutants for Area Sources: Asphalt Processing and Asphalt Roofing Manufacturing [375].
- 40 CFR 63 Subpart BBBBBB: National Emission Standards for Hazardous Air Pollutants for Source Category: Gasoline Distribution Bulk Terminals, Bulk Plants, and Pipeline Facilities [376].
- 40 CFR 63 Subpart ZZZZ: National Emissions Standards for Hazardous Air Pollutants for Stationary Reciprocating Internal Combustion Engines [377].
- 40 CFR 68 – Accidental Release Prevention [378].
- 40 CFR 79: REGISTRATION OF FUELS AND FUEL ADDITIVES [379].
- 40 CFR 80: REGULATION OF FUELS AND FUEL ADDITIVES- Clean Fuels [380].
- 40 CFR 82 Subpart B: Servicing of Motor Vehicle Air Conditioners [381].

- 40 CFR 82 Subpart F: Subpart F—Recycling and Emissions Reduction [382].
- 40 CFR Part 64: COMPLIANCE ASSURANCE MONITORING [383].

Montana Renewables LLC

- 40 CFR 60, Subpart A – General Provisions, applicable to the owner or operator of the stationary source for which New Source Performance Standards are prescribed under this part [384].
- 40 CFR 60, Subpart Dc – Standards of Performance for Small Industrial-Commercial Institutional Steam Generating Units, applicable to steam generating units [385].
- 40 CFR 60, Subpart Kb – Standards of Performance for Volatile Organic Liquid Storage Vessels (Including Petroleum Liquid Storage Vessels), applicable to storage tanks [371].
- 40 CFR 61, Subpart A – General Provision, applicable to the owner or operator of the facility for which National Emission Standards for Hazardous Air Pollutants are prescribed under this part [386].
- 40 CFR 61, Subpart M – National Emissions Standard for Asbestos, applicable to active waste disposal sites [387].
- 40 CFR 61, Subpart FF – National Emission Standard for Benzene Waste Operations, applicable to owners and operators of chemical manufacturing plants, coke byproduct recovery plants, and petroleum refineries [374].
- 40 CFR 63, Subpart A – General Provision, applicable to the owner or operator of the facility for which National Emission Standards for Hazardous Air Pollutants are prescribed under this part [388].
- 40 CFR 63, Subpart FFFF – National Emission Standards for Hazardous Air Pollutants: Miscellaneous Organic Chemical Manufacturing, applicable to the whole facility [389].
- 40 CFR 63, Subpart DDDDD – National Emission Standards for Hazardous Air Pollutants for Major Sources: Industrial, Commercial, and Institutional Boilers and Process Heaters, applicable to boilers and process heaters [390].

Appendix G. Economic and Sustainability Information

G.1 Economics and Sustainability Framework and Methodology

The general approach followed for the HEFA pathway economic and sustainability analysis is presented in the *Sustainable Aviation Fuel (SAF) State-of-Industry Report: State of SAF Production Process* [1].

Process Material Balances and Utility Demands

Process mass balances and basis for raw materials and utilities required are summarized in Table G-1 and Table G-2, respectively.

Table G-1. Process Mass Balance Basis for Techno-Economic Analysis Scenarios

Process Mass Balance (wt. %)	Renewable Diesel	Renewable Jet (SAF)
Vegetable oil feed	100.0%	100.0%
Hydrogen	4.0%	4.5%
Fuel gas	-1.0%	-1.5%
Liquefied petroleum gas	-4.5%	-6.0%
Naphtha/gasoline	-1.5%	-8.5%
Kerosene/jet fuel	0.0%	-46.1%
Diesel fuel	-85.0%	-30.4%
CO and CO_2	-4.0%	-4.0%
Aqueous phases and solids	-8.0%	-8.0%
Totals	0.0%	0.0%
Closure	100.0%	100.0%

Table G-2. Utility Demand Basis for Techno-Economic Analysis Scenarios

Process and Utility Demands (per gallon feedstock)		Renewable Diesel	Renewable Jet (SAF)
Bleaching chemicals	lb/Gal	0.015	0.015
Heterogeneous catalyst	$/Gal	0.014	0.014
Cooling water	kGal/Gal	0.033	0.043
Electricity	kWh/Gal	0.094	0.105
Natural gas	MBTU/Gal	0.006	0.006
Steam	klb/Gal	-0.003	-0.003

Fixed Operating Costs

Figure G-1 shows the default fixed operating cost curve for all assessed technologies plus the individual data points for both biodiesel and RD/SAF.

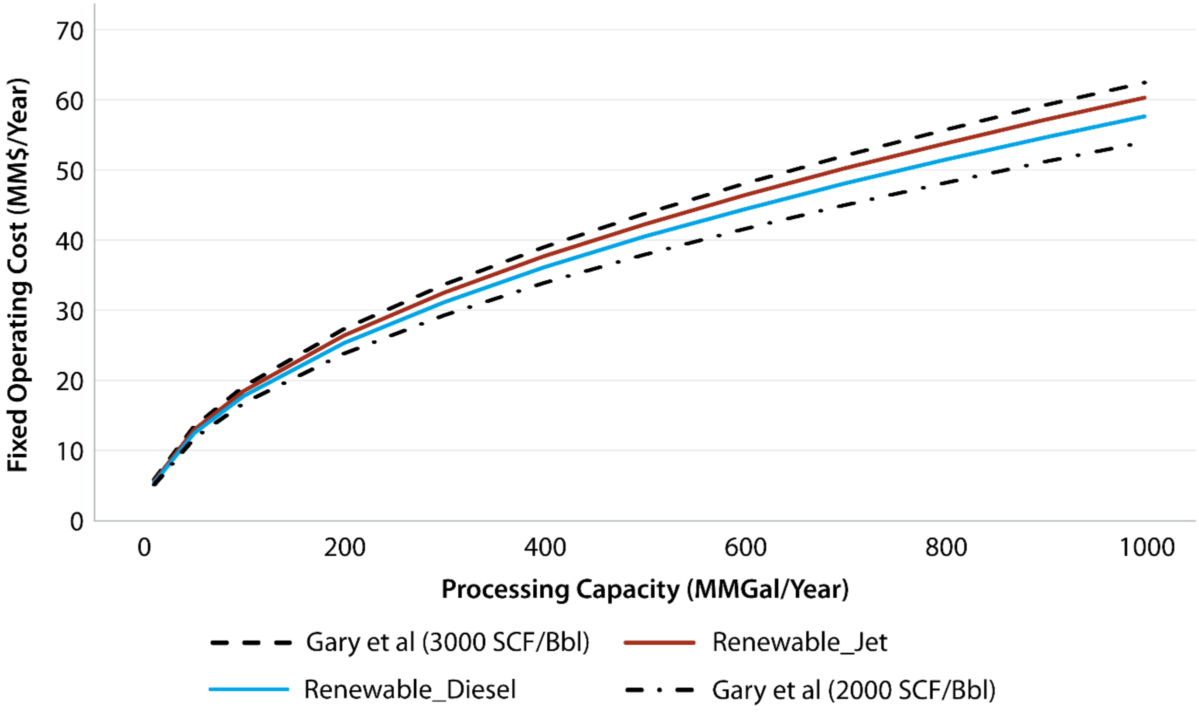

Figure G-1. Fixed operating cost basis for comparative analysis derived from data sources

Variable Operating Costs

Quantities of raw materials and utilities consumed are defined in Table G-3 and Table G-4. These consumption values are combined with pricing data, summarized in Table G-4 and on-stream factor to calculate annual variable operating costs. The default values for the process inputs represent the best estimates for raw material costs derived from both IHS reports [356] and published NREL techno-economic analysis [81, 357]. Note that hydrogen is considered an operational expense rather than an expenditure for constructing hydrogen generation facilities.

Table G-3. Default Values for Raw Materials and Utility Costs

Feed, Raw Material, and Utilities Costs		Default Values
Oil feedstock	$/lb	Variable
Natural gas hydrogen (via SMR)	$/lb	0.791
Electrolysis sourced hydrogen (using renewable energy sources)	$/lb	2.041
Bleaching chemicals	$/lb	0.8
Catalyst	$/$	1.0
Cooling water	$/kGal	0.16
Electricity	$/kWh	0.057
Natural gas	$/MBTU	4.3
Steam	$/klb	7.6

Oil feedstock values are assessed as variable ranges for different feedstocks studied in the project. The feedstock cost ranges evaluated are summarized in Table G-4, while historical feedstock data are shown in Table G-5.

Other than the oil feedstock costs, all default pricing values are corrected for the basis year using plant cost indices per NREL's techno-economic analysis approach [81, 357].

Table G-4. Feedstock Price Ranges Assessed in the Techno-Economic Analysis

$/lb	Canola Oil	DCO	Soybean Oil	Palm Oil	Tallow	Yellow Grease
Low	0.359	0.278	0.289	0.296	0.252	0.185
Average	0.490	0.419	0.403	0.400	0.347	0.265
High	0.896	0.664	0.746	0.631	0.569	0.405

Vegetable oils and FOG feedstocks prices have increased notably from the 2015–2019 levels, reaching record prices; see Table G-5. Biogenic oils prices are affected by multiple factors, making price predictions highly complex.

Table G-5. Historical Prices of Vegetable Oils and FOG Feedstocks

Wholesale ($/ton)	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Canola oil, Midwest					1,056	849	734	729	773	758	718	816	1,583	1,792
Corn oil, edible, crude, tank cars, wet/dry mill Chicago, IL					863	767	765	785	735	569	556	853	1,157	1,328
DCO, inedible, FOB Eastern Corn Belt					710	631	504	548	553	490	493	569	1,091	1,481
Cottonseed oil, PBSY, Greenwood, MS					932	1,207	940	916	771	614	740	879	1,830	2,215
Peanut oil, crude, tank cars FOB Southeastern mills					1,644	1,207	1,137	1,207	1,360	1,330	1,275	1,568	2,061	2,175
Soybean oil, crude, tank cars, FOB Decatur, IL					900	737	604	632	641	578	579	626	1,281	1,492
Sunflower oil, crude Minneapolis, MN					1,256	1,195	1,361	1,105	1,068	1,081	1,112	1,299	2,180	2,083
Palm oil, refined, CIF, bulk, U.S. ports					823	797	642	688	713	625	593	732	1,130	1,263
Palm kernel oil, refined, CIF, bulk, U.S. ports					904	906	806	754	788	1,202	1,175	1,327	1,721	1,859
Coconut oil, crude, tank cars, NY					885	1,204	1,045	1,383	1,608	1,003	707	952	1,569	1,749
Inedible tallow (Chicago)	502	669	993	874	805	727	527	579	619	504	544	615	1,138	-
Edible tallow (Chicago)	552	703	1,067	969	858	785	579	648	691	626	679	751	1,310	-
Edible tallow (Gulf)	550	714	1,070	938	876	728	511	677	663	601	671	670	n/a	-
Poultry fat (Mid-South)	463	570	900	784	719	599	455	495	549	513	512	506	942	-
Yellow grease (Missouri River)	406	523	845	715	660	555	419	458	475	370	423	418	810	-
Lard (Chicago)	572	770	992	1,160	981	870	608	642	661	651	620	744	1,282	-
Choice white grease (Missouri River)	464	596	925	840	767	645	452	487	498	420	464	484	967	-
Brown grease	-	-	-	-	-	-	-	-	-	-	320	320	640	-

Data sources: FOG: Render Magazine, Market Reports [54, 358]. Brown grease prices collected via NREL industry survey. Vegetable oil: [40]

Table G-6. GHG Emissions of Biogenic Feedstocks Generation and Pre-Processing

Source: [82]

Feedstock	CI (gCO_2e/MJ)
Soybean oil	12.3
DCO	1.7
Canola oil	22.2
Beef tallow	6.7
Yellow grease	6.1

Capital Costs

Capital costs are another consideration for the hydroprocessing pathways. Capital cost ranges for both RD and SAF pathways were derived based on various process technologies, including UOP Ecofining, Haldor Topsoe HydroFlex, Neste NEXBTL, Axens Vegan, published cost resource for refinery hydroprocessing units [359], and industry feedback for grassroots (newly constructed) units, conversion units that are converted or repurposed fossil refinery units, and HEFA coprocessing where FOG feedstocks are combined with fossil feedstocks in existing refinery units. **The present analysis considers the nth-plant assumption**. **Nonetheless, the first SAF facilities are more likely to encounter elevated costs, primarily stemming from the inherent risks associated with pioneering the establishment of a new industry.**

The capital cost bases for nine key comparative analysis scenarios are shown in Figure G-2 and Figure G-3 for RD and SAF, respectively. The term conversion in this context refers to the utilization or repurposing of existing petroleum refining infrastructure. **Feedstock processing capacities of 10, 100, and 1,000 MGPY are considered in the case matrix.**

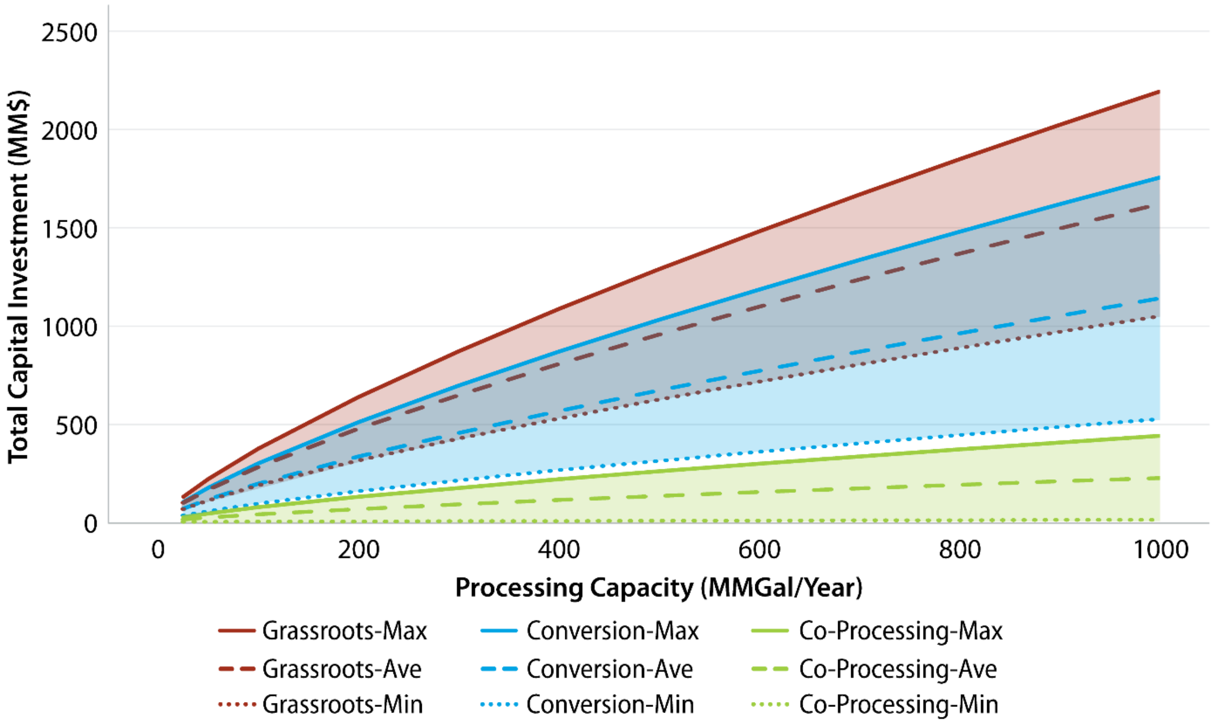

Figure G-2. Capital cost basis for RD

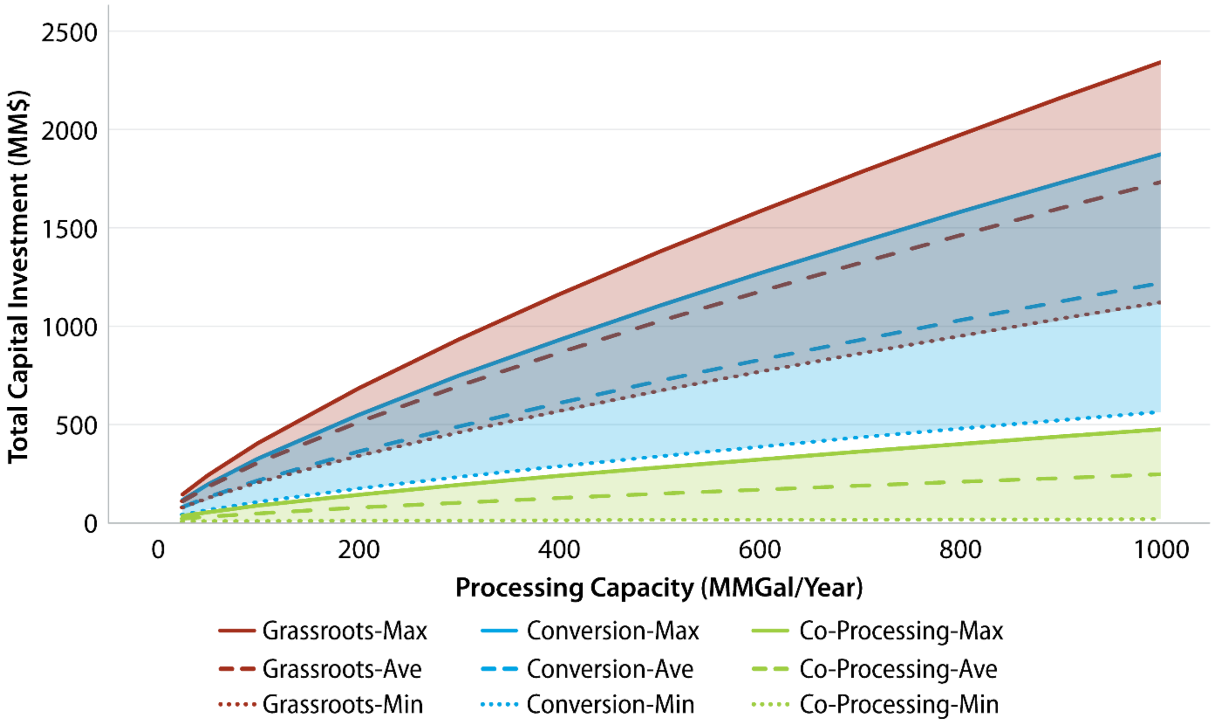

Figure G-3. Capital cost basis for SAF

Carbon Intensity and Marginal CO_2 Abatement Cost

Table G-7 summarizes the GHG emissions parameters, expressed as CI scores, applied from GREET, CORSIA and other published resources. Land use change contributions to CI scores are complex and specific to feedstock source and location. **Therefore, the impact of land use change on product CI scores is not considered in this assessment.**

Table G-7. Product GHG Ranges for RD and SAF Used in the Techno-Economic Analysis

Fuel	CI, gCO_2e/MJ	Canola Oil	DCO	Soybean Oil	Palm Oil	Tallow	UCO
RD	Low	33.150	12.350	20.060	33.834	17.650	8.630
	Average	38.193	23.194	28.864	45.025	29.683	16.655
	High	47.440	45.050	41.057	71.999	51.900	30.150
SAF	Low	33.981	12.416	20.841	34.700	19.800	8.966
	Average	39.527	23.784	29.534	46.319	31.654	18.014
	High	49.287	46.803	41.500	74.179	53.920	31.324

The total emissions from Table G-7 are used to quantify the GHG reduction relative to baseline values (defaults are 95.58 gCO_2/MJ for gasoline, 89 gCO_2/MJ for jet, and 91.4 gCO_2/MJ for diesel), and MAC is calculated by (Eq. 1):

$$MAC = f\ x\ \frac{MFSP - Market\ Price}{Energy\ Content\ x\ GHG\ Reduction} \qquad \text{(Eq. 1)}$$

where: MAC = marginal abatement cost (\$/ton CO_2); *f* = factor for mass conversion (g/ton) = 907,185; MFSP = minimum fuel selling price (\$/gal reference fuel) for target product; market price (\$/gal reference fuel); energy content (MJ/gal reference fuel); and GHG reduction (gCO_2/MJ) for target product.

The market price for MAC calculations is set at \$2.50/GGE, which corresponds to \$80/bbl West Texas Intermediate benchmark price.

Return on Invested Capital (ROIC)

ROIC is a financial measure that gauges how effectively a company or project is utilizing its invested capital to produce profits. The ROIC is defined by:

$$ROIC = \frac{Net\ operating\ profit\ after\ taxes\ (NOPAT)}{Invested\ Capital\ (IC)} \qquad \text{(Eq. 2)}$$

where NOPAT is the cash earnings a company or project can generate from its operations, while invested capital is the total capital needed to generate NOPAT, including equity and debt. An elevated ROIC denotes efficient capital utilization and profit generation, whereas a lower ROIC may imply inefficiency or suboptimal capital allocation.

G.2 Assessment of Variability in MFSP and MAC

Figure G-4 provides a complete assessment of variability in MFSP[3] and MAC that results from the ranges of results that correspond to the input ranges summarized in Table 3.

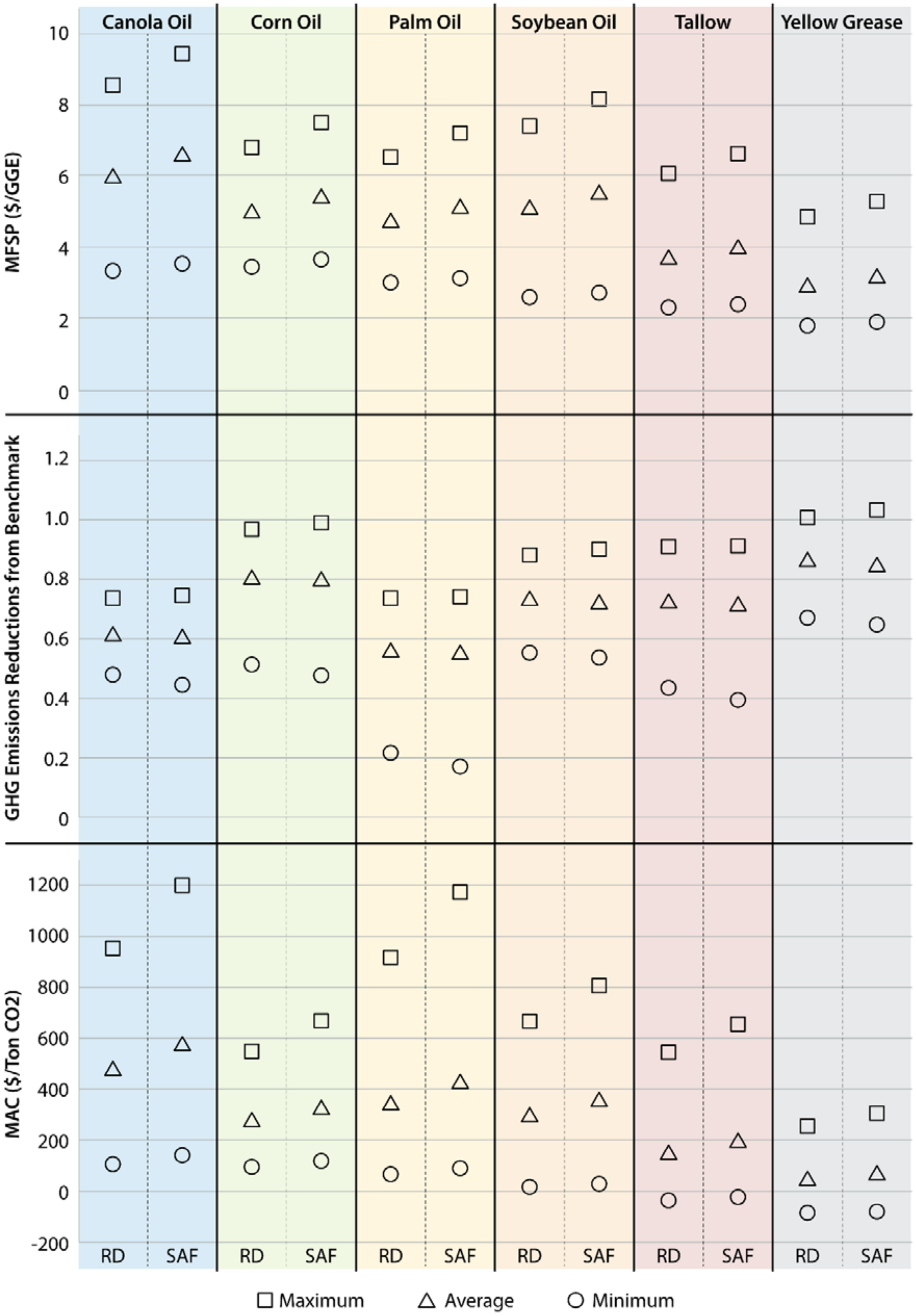

Figure G-4. MFSPs of SAF and RD (without incentives) for all input value ranges and scenarios

G.3 Applicable HEFA Coprocessing Incentives

Combined incentives provide different levels of support for RD and SAF when produced via HEFA coprocessing, including the Renewable Fuel Standard (RFS) and California state policies such as LCFS credits and avoided deficits for petroleum diesel through LCFS and Cap-and-Trade. (California policies are used as a representative state case). **The pricing of renewable identification numbers (RIN),[32] LCFS credits, and avoided deficits for petroleum diesel reflect pricing in 2023 and are subject to change over time, which can affect the value of the credits.** LCFS values reflect compliance in years 2023 and 2025. Incentives applicable to the stand-alone production of SAF and RD, via grassroots or conversion, are presented in the *Sustainable Aviation Fuel (SAF) State-of-Industry Report: State of SAF Production Process* [1]. Sample RD and SAF fuels were assessed over a range of CI values (and percentage of reduction in life cycle GHG emission reductions). A comparison based on RD and SAF with a CI of 18 are shown in Table G-8. RD and HEFA SAF produced via HEFA coprocessing are not eligible under the Clean Fuel Production Credit (CFPC, provided through the 2022 IRA).

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[32] The D5 RINs price for January to October 2023 ranged from $0.88 to $1.92 [360].

Table G-8. Comparison of Select Federal Incentives for RD and SAF Produced by HEFA Coprocessing, 2023–2024 and 2025–2027, for RD and SAF with CI of 18 gCO_2e/MJ (80% GHG emission reduction compared to petroleum fuel)

Incentives 2023–2024	RD (maximum credits USD per gal)	SAF (maximum credits USD per gal)
CI 18 (80% reduction in life cycle GHG emissions)		
Federal RFS RINs • D5, advanced biofuels • Equivalence values: 1.7 RD, 1.6 SAF • RIN price Jan. 9, 2023, $1.73.	$2.94	$2.77
State: California LCFS credit • LCFS credit pricing Jan. 3, 2023, $69.00/mt • 2023 compliance year.	$0.64	$0.62
State: Value added to RD based on avoided deficits for petroleum diesel (California LCFS) [a] • Pricing Jan. 3, 2023.	$0.10	NA
State: Value added to RD based on avoided deficits for petroleum diesel (California cap-and-trade) [a] • Pricing Jan. 3, 2023.	$0.29	NA
Total federal and state: if value added to RD by costs incurred included toward RD value.	$3.97	$3.39
Incentives 2025–2027	**RD (maximum credits USD per gallon)**	**SAF (maximum credits USD per gallon)**
CI 18 (80% reduction in life cycle GHG emissions)		
Federal RFS RINs • D5, biomass-based diesel • Equivalence values: 1.7 RD, 1.6 SAF • RIN price Jan. 9, 2023, $1.73.	$2.94	$2.77
State: California LCFS credit • LCFS credit pricing, Jan 3, 2023, $69.00/mt • 2025 compliance year.	$0.61	$0.60
State: Value added to RD based on avoided deficits for petroleum diesel (California LCFS) [a] • Pricing Jan. 3, 2023.	$0.10	NA
State: Value added to RD based on avoided deficits for petroleum diesel (California cap-and-trade) [a] • Pricing Jan. 3, 2023.	$0.29	NA
Total federal and state: If value added to RD by costs incurred included toward RD value.	$3.94	$3.37

[a] Additional California incentives added to RD reflect costs incurred by petroleum diesel from California's cap-and-trade and LCFS policies, based on pricing from Jan. 3, 2023 [361], similar to comparison by Boutwell [362].

For the time frame from 2023–2024 [362]**:**

- The Renewable Fuel Standard provides incentives at $2.94/gal for RD and $2.77/gal for SAF.
- The California LCFS values are based on CI. For RD with a CI of 18 gCO_2e/MJ (80% GHG emission reduction compared to petroleum fuel), the credit is $0.64/gal. For SAF with the same CI, the credit is $0.62.

- Value added to RD based on compliance costs incurred by petroleum diesel ($0.39), from the California cap-and-trade ($0.29) and LCFS ($0.10) policies, were based on Jan. 3, 2023 pricing [361], similar to data published by Boutwell [362].
- Combined federal and state incentives provide $3.97/gal for RD and $3.39/gal for SAF, for a CI of 18 gCO_2e/MJ (80% GHG emission reduction compared to petroleum fuel).
- Fuel (RD or SAF) derived from palm feedstocks are not eligible for federal incentives or California state incentives and avoided deficits, during 2023–2024.

For the time frame from 2025–2027:

- The RFS provides incentives at $2.94/gal for RD and $2.77/gal for SAF.
- The California LCFS values are based on CI. For RD with a CI of 18 gCO_2e/MJ (50% GHG emission reduction compared to petroleum fuel), the credit is $0.61/gal. For SAF with the same CI, the credit is $0.60.
- Value added to RD based on compliance costs incurred by petroleum diesel ($0.39), from the California cap-and-trade ($0.29) and LCFS ($0.10) policies, were based on Jan. 3, 2023 pricing [361], similar to data published by Boutwell [362].
- Combined federal and state incentives provide $4.56/gal for RD and $4.46/gal for SAF, for a CI of 18 gCO_2e/MJ (80% GHG emission reduction compared to petroleum fuel).
- Fuel (RD or SAF) derived from palm feedstocks is not eligible for federal incentives or CA state incentives and avoided deficits, during 2025-2027, except stand-alone RD from palm feedstocks are not excluded from the Clean Fuel Production Credit (45Z).

The eligibility of the HEFA renewable fuels for federal and state incentives is summarized in Table G-9.

Table G-9. Summary of the HEFA Renewable Fuels Eligibility for Federal and State Incentives

Incentives	Policies	RD				SAF			
		Coprocessing		Standalone		Coprocessing		Standalone	
		Feedstock type							
		Palm oil	Other	Palm oil	Other	Palm oil	Other	Palm oil	Other
Federal	RFS	✗	✓	✗	✓	✗	✓	✗	✓
	Biodiesel Tax Credit	✗	✗	✗	✓	✗	✗	✗	✗
	SAF credits (Section 40B)	✗	✗	✗	✗	✗	✗	✗	✓
	CFPC (Section 45Z)	✗	✗	✓	✓	✗	✗	✗	✓
State	LCFS credit	✗	✓	✗	✓	✗	✓	✗	✓
	CA avoided deficits for diesel	✗	✓	✗	✓	✗	✗	✗	✗

Note: ✓ indicates the HEFA fuel from a feedstock qualify for a policy incentive while ✗ indicates the fuel does not qualify for incentives