2022 Bioenergy Industry Status Report

Kristi Moriarty, Tom McCarran, Arpit Bhatt, Jacob Kenny, Ling Tao, and Anelia Milbrandt

National Renewable Energy Laboratory

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Preface

This report provides a snapshot of the bioenergy industry status at the end of 2022. The report complements other annual market reports from the U.S. Department of Energy's (DOE's) Office of Energy Efficiency and Renewable Energy and is supported by DOE's Bioenergy Technologies Office (BETO). The *2022 Bioenergy Industry Status Report* focuses on data covering multiple dimensions of the bioenergy industry and does not attempt to make future market projections. The report provides a balanced and unbiased assessment of the industry and associated markets. It is openly available to the public and is intended to complement International Energy Agency and industry reports with a focus on DOE stakeholder needs.

The bioenergy economy engages multiple industrial sectors across the biomass-to-bioenergy supply chain—from agricultural- and forestry-based industries that produce biomass materials to manufacturers and distributors of biomass-based fuels, products, and power to the ultimate end-user markets. The breadth of this report focuses on activities that occur after the production of biomass. The report compiles and integrates information to provide the bioenergy industry status at the end of 2022 and includes 10 years of past data to show trends over time. It also highlights some of the key energy and regulatory drivers that have impacted the bioenergy industry as it develops. The information is intended for technology developers, policymakers, and other bioenergy stakeholders interested in bioenergy industry development.

The report begins with a discussion of the overall size and composition of the domestic bioenergy market and follows with sections on biofuels, biopower, and bioproducts. The biofuels section is broken out by fuel type with detailed sections on sustainable aviation fuel, renewable diesel, ethanol, biodiesel, and renewable natural gas. The report also offers an overview on biochemicals and biopower.

The information contained in this report is intended to communicate an understanding of the U.S. bioenergy industry status. On behalf of DOE and BETO, I hope that you explore and find value in this report.

Sincerely,
Valerie Reed
Director, Bioenergy Technologies Office
U.S. Department of Energy Office of Energy Efficiency and Renewable Energy

Acknowledgments

Funding for this report came from the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy's Bioenergy Technologies Office. This report is an update to the previous *2013 Bioenergy Market Report*, *2015 Bioenergy Market Report*, *2016 Bioenergy Industry Status Report*, and the *2017 Bioenergy Industry Status Report*. The authors would like to thank the contributions of Amy Schwab and John Lewis to previous versions of the report.

List of Acronyms

AFDC	Alternative Fuels Data Center
ASTM	ASTM International
B5	5% biodiesel, 95% petroleum diesel blend
B20	20% biodiesel, 80% petroleum diesel blend
B100	pure biodiesel
Btu	British thermal unit
CARB	California Air Resources Board
CI	carbon intensity
DOE	U.S. Department of Energy
E10	10% ethanol, 90% gasoline blend
E15	10.5%–15% ethanol and gasoline blend (approved for use in model year 2001 and newer vehicles)
E85	high ethanol blend between 51% and 83% ethanol, depending on season and geography
EIA	U.S. Energy Information Administration
EPA	U.S. Environmental Protection Agency
FFV	flexible-fuel vehicle
FT	Fischer-Tropsch
GHG	greenhouse gas
HBIIP	Higher Blends Infrastructure Incentive Program
HC	hydrocarbon
HEFA	hydroprocessed esters and fatty acids
IRA	Inflation Reduction Act
LCFS	Low Carbon Fuel Standard
MMBtu	million British thermal units
MY	model year
NREL	National Renewable Energy Laboratory
RFA	Renewable Fuels Association
RFS	Renewable Fuel Standard
RIN	Renewable Identification Number
RNG	renewable natural gas
SAF	sustainable aviation fuel
SIP	synthetic isoparaffin
SK	synthesized kerosene
SKA	synthetic kerosene with aromatics
SPK	synthetic paraffinic kerosene
TBtu	trillion British thermal units
USDA	U.S. Department of Agriculture

Executive Summary

The *2022 Bioenergy Industry Status Report* compiles and integrates information to provide a snapshot of the current state and historical trends influencing the development of domestic bioenergy markets as of the end of 2022. The information is intended for technology developers, policymakers, and other bioenergy stakeholders interested in bioenergy industry development. The bioenergy economy engages multiple industrial sectors across the biomass-to-bioenergy supply chain—from agricultural- and forestry-based industries that produce biomass materials to manufacturers and distributors of biomass-based fuels, products, and power to the ultimate end-user markets. It also highlights some of the key energy and regulatory drivers that have impacted the bioenergy industry as it develops. The breadth of this report focuses on activities that occur after the production of biomass.

At the end of 2022, U.S. bioenergy consumption (shown in Figure ES-1) was led by ethanol, which accounts for 64% of total U.S. bioenergy production. The other leading contributors were renewable diesel (12%), biodiesel (11%), and biopower (10%). Other advanced biofuels contributed a small but increasing amount (more than 3%). Compared with 2013, the relative market share for ethanol declined while biodiesel, renewable diesel, and other advanced biofuels increased.

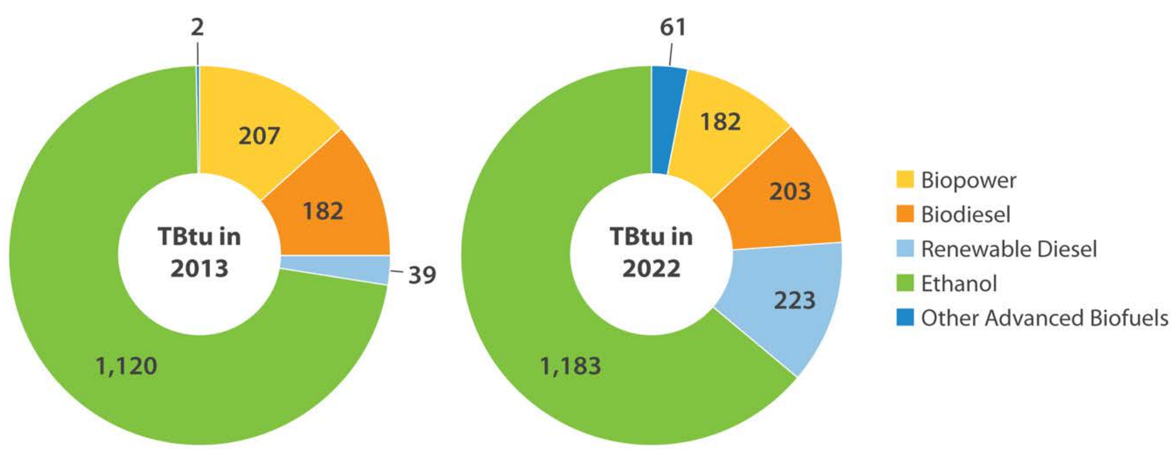

Figure ES-1. U.S. bioenergy market (1,551 trillion British thermal units [TBtu][1] total in 2013 and 1,852 TBtu total in 2022).

Source: ethanol, biodiesel, and renewable diesel: U.S. Energy Information Administration (EIA) (2023a; 2023b; 2023c); biopower: EIA (2023d); other advanced biofuels: U.S. Environmental Protection Agency (EPA) (2023a). Advanced biofuels include biobutanol, cellulosic fuels, heating oil, jet fuel, naphtha, renewable natural gas, and renewable propane.[2] This figure only includes the volume and electricity produced, not the associated coproducts.

Figure ES-2 shows the development of the biofuels industry from 2013 through 2022. Renewable diesel, a drop-in fuel, experienced tremendous growth in capacity and consumption in recent years due to major petroleum companies converting refineries. Biodiesel's contribution has largely remained at a similar level, with a slight decrease in recent years that is likely a result

[1] One trillion British thermal units is equivalent to 0.001 quads.

[2] Detailed fuel volume data are available in Appendix A.

of the growing renewable diesel market. Ethanol remains the top contributor to the bioeconomy. Other advanced biofuels continue to increase market share, with renewable natural gas (RNG) dominating this category. The pandemic impacted all fuel markets in 2020, but markets largely returned to prepandemic levels by 2022.

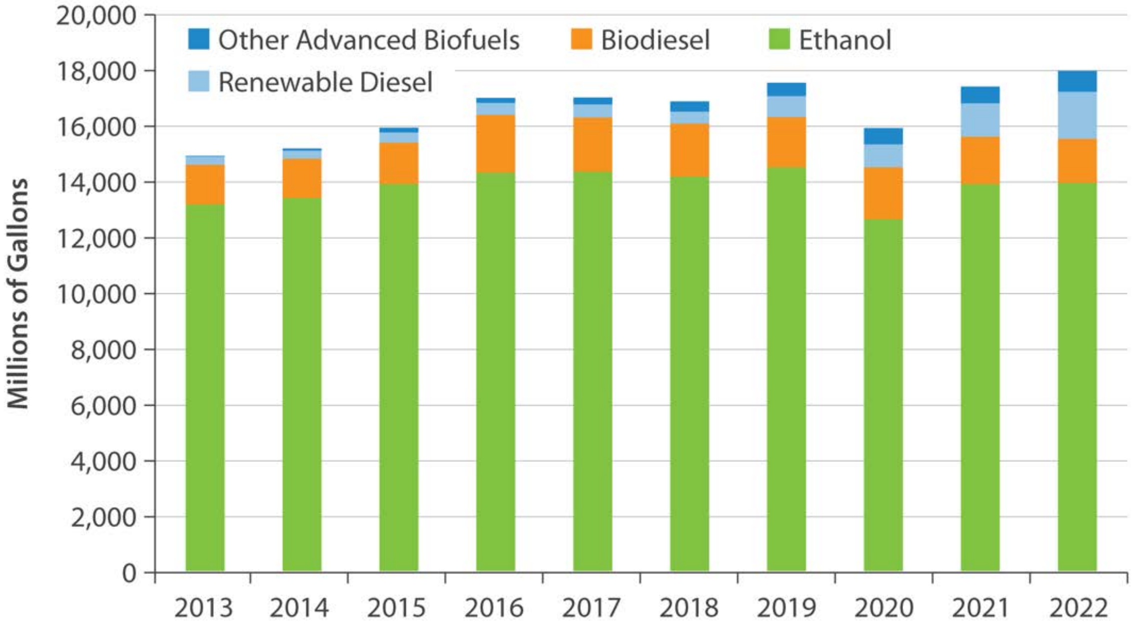

Figure ES-2. U.S. biofuel consumption.

Source: ethanol, biodiesel, renewable diesel: EIA (2023a; 2023b; 2023c); other advanced biofuels: EPA (2023a)[3]

Economic and job impacts from the bioeconomy are considerable. Industry organizations fund studies use an economic input-output model to estimate economic and job impacts. The Renewable Fuels Association (RFA) funds an annual study of ethanol's impact on the economy. The study found the 2022 impact to gross domestic product, household income, and taxes was $57 billion, $35 billion, and $12 billion, respectively (Urbanchuk 2023). Ethanol's direct and induced jobs were more than 78,000 and 342,000, respectively. A study funded by the Clean Fuels Alliance of America assessed impacts based on a 2021 biodiesel and renewable diesel market of 2.5 billion gallons of domestic production and 600 million gallons of imports (LMC International 2022). The study found an economic impact of $23 billion and support of more than 75,000 direct and indirect jobs. The implied average wage in the biodiesel/renewable diesel market was $47,900. RNG's contribution includes an estimated 38,000 jobs and $4.8 billion to gross domestic product (RNG Coalition 2022). For every 1 million British thermal units (MMBtu) of RNG generated, 22 jobs were created (RNG Coalition 2022).

Sustainable aviation fuel (SAF), made from nonpetroleum feedstocks, is drop-in fuel that reduces emissions from air transportation. SAF can be blended at different levels with limits of 10% to

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[3] Data for advanced biofuels were obtained from the EPA's Public Renewable Fuel Standard data and were based on volume. Other advanced biofuels include biogas, butanol cellulosic diesel, cellulosic gasoline, cellulosic heating oil, naphtha, renewable heating oil, renewable natural gas, and sustainable aviation fuel. This dataset includes small volumes of imported advanced biofuels.

50%, depending on the feedstock and how the fuel is produced. SAF provides a near-term solution to decarbonizing aviation, which was responsible for 8% of U.S. transportation greenhouse gas emissions in 2021 (EPA 2023b). The Sustainable Aviation Fuel Grand Challenge is a joint effort from the U.S. Department of Energy (DOE), U.S. Department of Transportation, U.S. Department of Agriculture, and other government agencies working to expand SAF production, reduce costs, and enhance sustainability.[4] The Grand Challenge seeks to increase production to 3 billion gallons by 2030 and 35 billion gallons by 2050. At the time this report was prepared, there were three commercial domestic producers and one international producer supplying the U.S. market. These plants also produce renewable diesel, and specific SAF capacities were not reported. Estimated 2022 volumes were 15.7 million gallons, a substantial increase from 1.8 million gallons in 2018 (EPA 2023a). This represents a small fraction of domestic 2022 jet fuel consumption of 23.9 billion gallons (EIA 2023e).

Renewable diesel meets the same ASTM D975 fuel quality specification as petroleum diesel. It is a drop-in fully fungible replacement for diesel and can be used in existing infrastructure and engines. Consumption grew from 295 million gallons in 2013 to nearly 1.7 billion gallons in 2022 (EIA 2023c). For years, the market was served by two large U.S. plants in Louisiana and imports. In the past 3 years, domestic production has grown significantly, largely driven by petroleum companies converting existing refineries. As of January 2023, there are 17 plants with 3 billion gallons of capacity (EIA 2023f). More plants are expected in the near term.

Biodiesel production and consumption have been stable over the past decade, peaking in 2018 with slight declines from 2018 through 2022. In 2022, production and consumption were both about 1.6 billion gallons (EIA 2023b). The number of plants has been declining since 2018, and there are currently 59 plants with just over 2 billion gallons of capacity (EIA 2023g). Blends up to B5 (5% biodiesel, 95% petroleum diesel) are considered diesel fuel per ASTM D975. B20 (6% to 20% biodiesel) that meets ASTM D7467 is approved for use in various vehicles and engines. Biodiesel is also used for off-road applications such as home heating oil.

Renewable diesel combined with biodiesel represented 5.3% of the 62 billion gallon-per-year diesel market (EIA 2023b; 2023c; 2023e). The impact is particularly pronounced on the West Coast where diesel consumption was at its lowest level since 2002—the use of biofuels is the key driver (EIA 2023h). California accounts for 99% of consumption due to the state's Low Carbon Fuel Standard, which enables a higher price compared to other fuel markets (EIA 2023i). In 2022, consumption of renewable diesel exceeded biodiesel for the first time (EIA 2023b; 2023c).

Currently, biodiesel, renewable diesel, and SAF use the hydroprocessed esters and fatty acids pathway and same feedstocks, which include waste fats, oils, and greases and vegetable oils. There is considerable competition for these feedstocks as new plants come online, particularly the large renewable diesel plants. There is also competition from other industries who use these feedstocks. SAF research is focused on commercializing technology pathways that use other feedstocks. There is near-term potential to use ethanol as a feedstock for SAF via the alcohol-to-jet pathway—including a plant starting operations in early 2023 (Kann 2024).

[4] https://www.energy.gov/eere/bioenergy/sustainable-aviation-fuel-grand-challenge

Ethanol serves as a substitute for gasoline and as an octane enhancer. Nearly all commercial ethanol biofuel production was from conventional cornstarch-based feedstock. Production and consumption in 2022 were nearly 15.4 and 14 billion gallons, respectively (EIA 2023a). As of January 2023, there were 192 plants with 17.4 billion gallons of capacity (EIA 2023j). Half of the capacity is in Iowa, Nebraska, and Illinois (RFA 2023a). For years, the United States has effectively been at a blend wall—where the entire gasoline market is blended with E10. As of September 2022, the blend rate of ethanol into gasoline was 10.4% (RFA 2023b). The growth comes from E15 blends, which can be used in model year 2001 and newer vehicles, and E85, which can be used in flexible-fuel vehicles.[5] The export market is strong, with net exports for the 13th straight year, now valued at $4.1 billion (RFA 2023b).

RNG is a pipeline-quality gas made from biomass waste feedstocks that is interchangeable with conventional natural gas. It can be used in natural gas vehicles in compressed or liquefied form. RNG qualifies as a cellulosic biofuel under the Renewable Fuel Standard and is currently the main contributor to this fuel category (EPA 2023a). In 2022, EPA reports consumption of 667 million ethanol gallon equivalents, or roughly 51.4 trillion British thermal units (TBtu) of compressed and liquefied RNG (EPA 2023a). Costs to produce RNG vary and depend on the feedstock used and if the technology pathway is anaerobic digestion or thermal gasification. Modeled production costs estimated a range between $6.50 and $32.60/MMBtu (American Gas Foundation 2019). There is still significant opportunity for growth, as current production represents 3.9% of the potential market (American Gas Foundation 2019).

Biomass electricity generation (biopower) accounts for nearly 6% of all utility-scale renewable energy generated in the United States and about 1.2% of total U.S. electricity generation (EIA 2023d; 2023k). Both installed biopower capacity and generation have been declining since 2017. In 2022, the top five states with the largest biopower generation were Georgia, California, Florida, Virginia, and South Carolina (EIA 2023l). Most of the biopower is generated from woody biomass, including byproducts (e.g., black liquor), solids (e.g., railroad ties and utility poles), and residues, such as those from pulp and paper mills or sawmills (EIA 2023l).

Biochemicals and bioproducts are two broad categories used to classify products produced from biomass feedstocks. Conventional bioproducts, including building material, pulp and paper, and forest products, have long been available, whereas emerging bioproducts with a focus on research and development include biochemicals, bioplastics, and bioadhesives. Bioproducts derived from bioresources can replace (either directly or indirectly) some of the fuels, chemicals, plastics, etc., that are currently derived from petroleum. Many biochemical and bioproduct manufacturers currently treat their production and pricing information as confidential because they pursue competitive advantages within this emerging market sector. However, wood pellets are a well-established competitive market, and EIA reports plant, pricing, and export data (EIA 2023s). This report considers four types of bioproducts: (1) wood pellets; (2) platform and intermediate chemicals (emerging bioproducts), as well as the conventional bioproducts; (3) lignin; and (4) biochar.

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[5] E15 is a blend of 10.5%–15% ethanol and gasoline; E85 is an ethanol-gasoline blend containing 51% to 83% ethanol, depending on geography and season.

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1 Biomass to Bioenergy Overview

Bioenergy—fuel, heat, and power derived from biomass sources—is an evolving market that produces and supplies renewable alternatives to fossil fuel sources. This report covers the following:

- Biodiesel: an alternative to diesel that is typically produced from lipids (vegetable oils and fats, oils, and greases)
- Ethanol: typically produced from corn starch and less often from cellulosic feedstocks
- Renewable diesel: a drop-in replacement for diesel currently produced from lipids
- Renewable natural gas (RNG): pipeline-quality gas, derived from renewable organic sources, which is interchangeable with conventional natural gas
- Sustainable aviation fuel (SAF): a drop-in replacement for jet fuel currently produced from lipids; alcohols expected as a feedstock soon
- Marine biofuels: both drop-in and other replacement fuels produced from various renewable sources
- Biopower: generation of electricity from biomass sources such as wood wastes, municipal solid waste, landfill gas, and other biomass
- Biochemicals and bioproducts: production of platform and intermediate biochemicals, lignin, biochar, and wood pellets.

The production, distribution, and use of bioenergy involve activities across a broad supply chain. These activities include the production of raw biomass in fields or forests; harvest, collection, storage, and transportation of these materials; and preprocessing of the raw biomass materials—sizing, drying, or other mechanical, thermal, or chemical treatment—to produce a feedstock that can be fed into biorefinery conversion processes or into biopower-generating facilities. Distribution and use include delivering the bioenergy to market as well as the technical capability for the end use of these products. While the bioenergy market is global and well established in other parts of the world, only the U.S. market was investigated and documented for this report.

In 2022, U.S. bioenergy production surpassed 1.8 trillion British thermal units (TBtu)[6] from ethanol, biodiesel, renewable diesel, advanced biofuels—including SAF and RNG—and biopower (U.S. Energy Information Administration [EIA] 2023a; 2023b; 2023c; 2023d; U.S. Environmental Protection Agency [EPA] 2023a). U.S. bioenergy consumption (Figure 1) was led by ethanol, which accounts for 64% of total U.S. bioenergy production. The other leading contributors were renewable diesel (12%), biodiesel (11%), and biopower (10%). Other advanced biofuels contributed a small but increasing amount (more than 3%). Compared with 2013, the relative market share for ethanol declined while biodiesel, renewable diesel, and other advanced biofuels increased.

[6] One TBtu is equivalent to 0.001 quads.

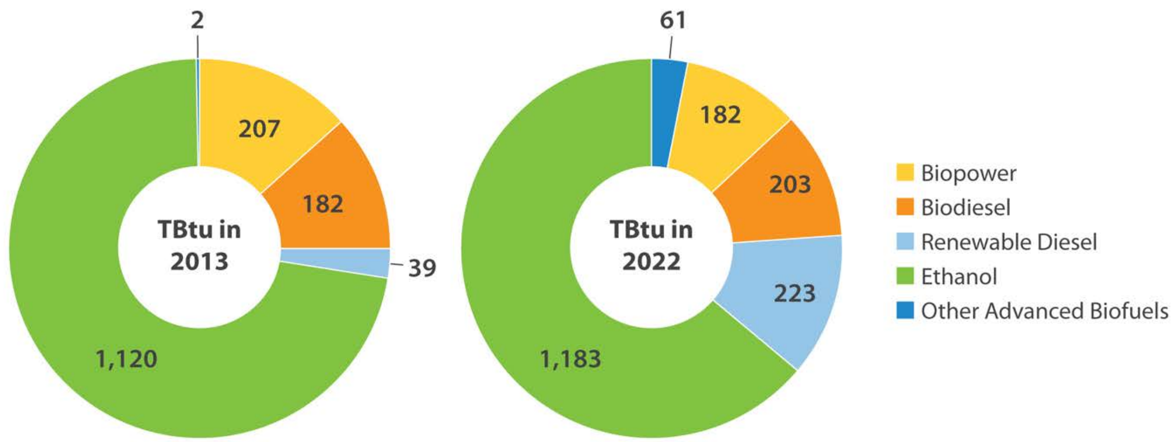

Figure 1. U.S. bioenergy market (1,551 TBtu total in 2013 and 1,852 TBtu total in 2022).

Source: ethanol, biodiesel, and renewable diesel: EIA (2023a; 2023b; 2023c); biopower: EIA (2023d); other advanced biofuels: EPA (2023a).

Advanced biofuels include biobutanol, cellulosic fuels, heating oil, renewable jet, naphtha, and renewable natural gas, and renewable propane.[7] This figure only includes the volume and electricity produced, not the associated coproducts.

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[7] Detailed fuel volumes are available in Appendix A.

2 Biofuels

Figure 2 shows the development of the biofuels industry from 2013 through 2022. Renewable diesel, a drop-in fuel, experienced tremendous growth in capacity and consumption in recent years due to major petroleum companies converting refineries. Biodiesel's contribution has largely remained at a similar level, with a slight decrease in recent years that is likely a result of the growing renewable diesel market. Ethanol remains the top contributor to the bioeconomy. Other advanced biofuels continue to increase market share, with RNG dominating this category. The pandemic impacted biodiesel, ethanol, and conventional petroleum fuels in 2020, but markets largely returned to prepandemic levels by 2022. Both renewable diesel and SAF grew in all years, including 2020.

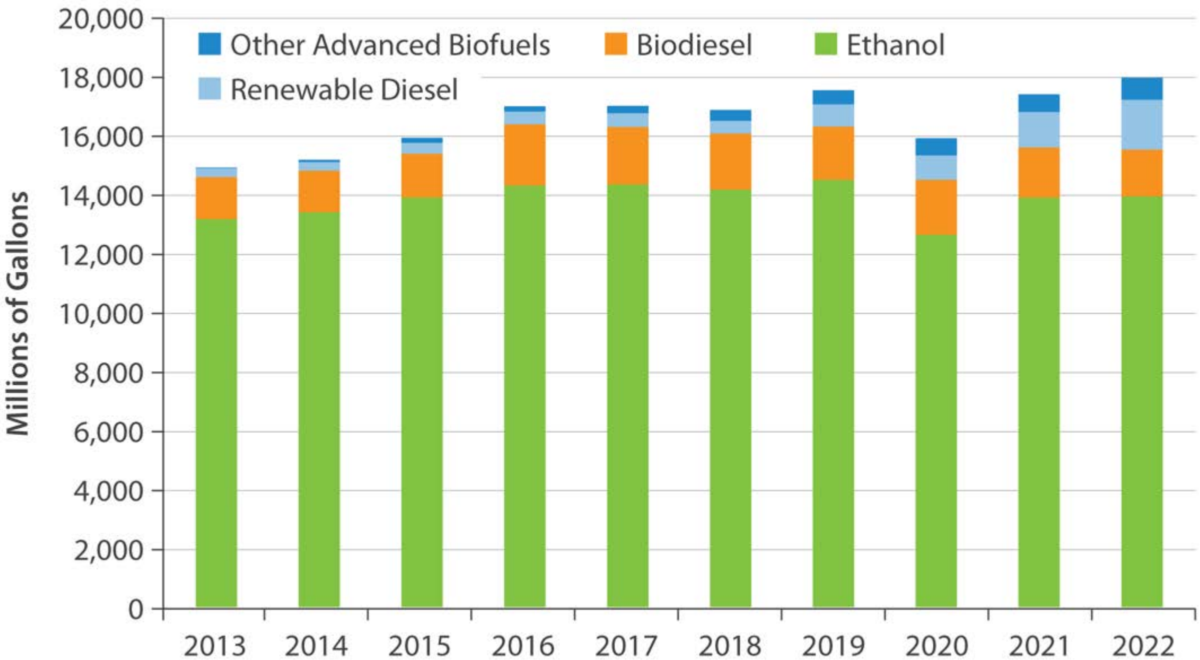

Figure 2. U.S. biofuel consumption.

Source: ethanol, biodiesel, renewable diesel: EIA (2023a, Tables 10.3a, 10.4a, and 10.4b); other advanced biofuels: EPA (2023a)[8]

The following section covers multiple biofuels topics, including policies that impact the market, feedstocks, and detailed sections on SAF, renewable diesel, biodiesel, ethanol, and RNG.

2.1 Biofuels Policies and Incentives

The following is a summary of the most significant policies impacting biofuels markets. The emphasis is on federal policies and incentives. A short section on low-carbon fuels standards is included due to the significant impact California's Low Carbon Fuel Standard (LCFS) has on

[8] Data for advanced biofuels were obtained from the EPA's Public Renewable Fuel Standard data and were based on volume. Other advanced biofuels include biogas, butanol cellulosic diesel, cellulosic gasoline, cellulosic heating oil, naphtha, renewable heating oil, renewable natural gas, and sustainable aviation fuel. This dataset includes small volumes of imported advanced biofuels.

biofuels markets. The Alternative Fuels Data Center (AFDC) website provides details on all federal and state laws and incentives for biofuels.[9]

The emphasis is on federal policies; however, low-carbon fuel standards are also discussed due to California's impact on biofuels markets. Incentives and potential credit schemes are also discussed.

2.1.1 Renewable Fuel Standard

A primary market driver for U.S. biofuels production and consumption is the Renewable Fuel Standard (RFS). The purpose was to reduce oil imports, grow the domestic bioeconomy, and reduce greenhouse gas (GHG) emissions. The RFS originated with the Energy Policy Act of 2005 and expanded under the Energy Independence and Security Act (EISA) of 2007 (U.S. Congress 2007). The RFS established biofuels volumes increasing annually and provided the EPA with the authority to adjust required volumes based on availability. While the legislated volumes were through 2022, EPA is responsible for establishing volume standards for each year.

To meet the fuel blend requirements, the RFS program assigns obligated parties (fuel refiners and importers) a renewable volume obligation, which is the volume of renewable fuels the party is required to blend based on a percentage of the company's total fuel sales. Figure 3 compares the volumes legislated by the Energy Independence and Security Act to EPA's annual renewable volume obligations and Renewable Identification Numbers (RINs) generated. Energy Independence and Security Act volumes were reduced annually due to the lack of available cellulosic biofuels. Fuel producers and importers have largely met EPA's volumes.

EPA manages and tracks RFS compliance through RINs. There are four overall RFS categories: (1) renewable fuel, which is largely satisfied by conventional corn grain ethanol, (2) advanced biofuel, (3) biomass-based diesel, and (4) cellulosic biofuel (EPA 2023d).[10] Figure 4 illustrates how these RIN designations are nested in a way that allows fuels to meet more than one RFS category. RFS GHG emissions reduction requirements are 20% for renewable fuel, 50% for advanced biofuel and biomass-based diesel, and 60% for cellulosic biofuels.[11]

RINs are generated when designated biofuels are imported or are produced and conveyed with the volumetric sale of those biofuels until blended with petroleum products or sold to an obligated party. Once the fuel is blended, the RIN is used to demonstrate a company's renewable volume obligation compliance; then, the RIN is retired. RINs may also be sold or saved for meeting renewable volume obligation requirements in the next compliance year. Table A-1 in Appendix A details 2022 RIN generation (EPA 2023a).

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[9] https://afdc.energy.gov/laws

[10] Details of approved pathways and associated RINs are available from the EPA. https://www.epa.gov/renewable-fuel-standard-program/approved-pathways-renewable-fuel

[11] Facilities that existed or commenced construction prior to Dec. 19, 2007, are exempt from the 20% life cycle GHG emissions reduction threshold requirement; ethanol plants that began construction prior to Jan. 1, 2010, and use natural gas or biomass for thermal energy are also exempt.

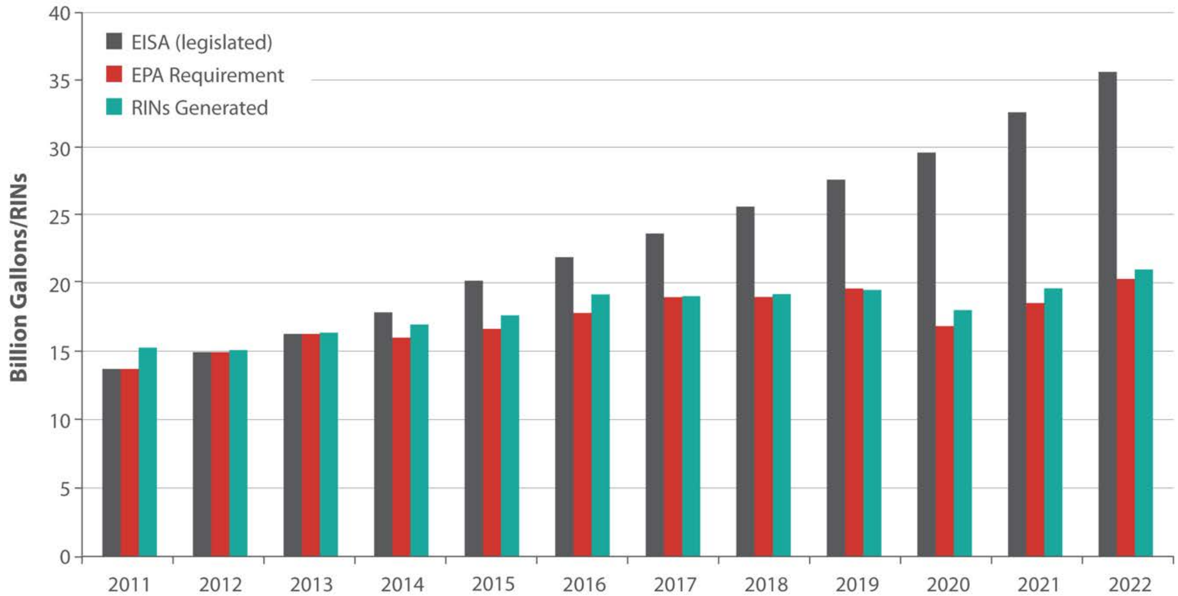

Figure 3. RFS comparison of Energy Independence and Security Act (EISA), renewable volume obligation, and RIN volumes.

Source: EPA (2023a; 2023d)

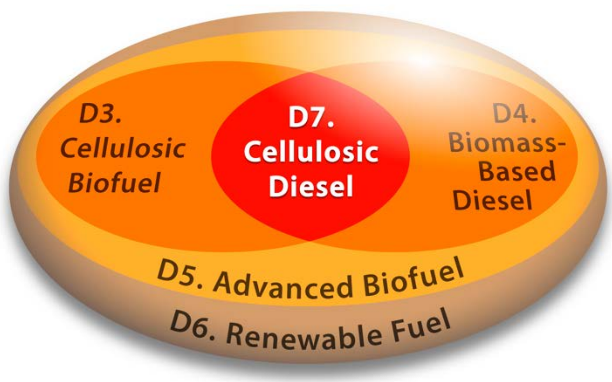

Figure 4. Nesting of biofuel categories under the RFS.

Cellulosic biofuel (D3) and biomass-based diesel (D4) are both nested within advanced biofuel (D5), which is nested within renewable fuel (D6).Diagram not to scale.

2.1.2 Low-Carbon Fuel Standards

The California Air Resources Board oversees California's LCFS.[12] The purpose of the LCFS is to decrease the carbon intensity (CI) of transportation fuels with both low-carbon and renewable fuels. The California Air Resources Board conducts life cycle analysis of GHG emissions for every fuel used in California and assigns them a CI, which is compared to a benchmark. Those below the benchmark CI generate a credit; credits enable renewable fuel suppliers to obtain a

[12] https://ww2.arb.ca.gov/our-work/programs/low-carbon-fuel-standard

higher price for their fuel and significantly impact markets. California accounts for 99% of domestic renewable diesel consumption and nearly all SAF (EIA 2023i).

Oregon's Clean Fuels Program assigns a CI to each fuel, and there is a credit system for fuels with CI below the threshold. The allowable CI for fuels statewide is lowered each year to achieve a 20% reduction by 2030 and 37% reduction by 2035 compared to 2015 levels (Oregon 2023). Washington's Clean Fuel Standard requires fuel suppliers to reduce their CI by 20% in 2034 compared to 2017 levels (Washington 2023). To achieve the targets, fuel producers can improve the efficiency of their fuel production process, produce or blend low-CI fuels, or purchase credits generated by low-CI fuel producers. Multiple other states are considering implementing LCFS.

2.1.3 Incentives

Many federal incentives have been made available for biofuels to extend their availability in the market. This section summarizes current and near-term programs and does not cover expired incentives.[13] The Inflation Reduction Act (IRA) of 2022 extended and amended several biofuels incentives (Internal Revenue Service [IRS] 2023).

The IRA extended the existing Biodiesel and Renewable Diesel Mixture Excise Tax Credit until Dec. 31, 2024. It provides a $1.00-per-gallon (gal) incentive for biodiesel and renewable diesel. The IRA provided a $1.25/gal SAF incentive for fuel achieving a 50% reduction in GHG emissions compared to conventional jet fuel and an additional $0.01/gal for each percentage over 50%, for a maximum incentive of $1.75/gal for fuel produced between Jan. 1, 2023, and Dec. 31, 2024 (IRS 2023). Beginning in 2025, the existing biofuels credits will be replaced with the technology-neutral Clean Fuel Production Credit. The base amount of the incentive is $0.20/gal and $0.35/gal for non-aviation fuels and SAF, respectively (IRS 2023). The incentive increases to $1.00/gal and $1.75/gal for non-aviation and SAF, respectively, for plants meeting prevailing wage, apprenticeship, and GHG emissions reduction requirements (IRS 2023).

There are several biofuels infrastructure tax credits and grant programs. The Alternative Fuel Infrastructure Tax Credit provides a tax credit of 30% of infrastructure costs or 6% of property subject to deprecation up to $100,000 (IRS 2023). This is subject to the IRA provisions of census tract not in an urban area, population census tract where the poverty rate is at least 20, or metropolitan or nonmetropolitan area where median family income is less than 80% of state median family income. This incentive expires Dec. 31, 2032. The U.S. Department of Agriculture's (USDA's) Higher Blends Infrastructure Incentive Program (HBIIP) provides grants to extend the availability of ethanol blends above E10 and biodiesel blends above B5. HBIIP provides a grant for 75% of project costs for gas station owners with 10 or fewer stations and for distributors with 80% of volume as home heating oil. HBIIP grants of 50% are available for larger station owners and terminals. HBIIP has $500 million in funds available through 2024 (Federal Register 2023).

[13] The AFDC Laws & Incentives tool provides information on all federal and state alternative fuels and vehicles laws and incentives. www.afdc.energy.gov/laws

Both DOE and USDA provide loan programs. USDA's Biorefinery, Renewable Chemical, and Biobased Production Manufacturing Assistance Program provides a loan guarantee up to $250 million for advanced demonstration-scale biorefineries.[14] Similarly, DOE's Loan Programs Offices provides loans to advanced biorefineries.

2.2 Feedstocks

In 2022, 94% of domestic ethanol production was from corn grain, 4% from cellulosic biomass, 2% from sorghum and wheat, and less than 1% from waste sugars (RFA 2023a). The 4% cellulosic biomass is derived entirely from bolt-on technology at existing conventional ethanol plants that extracts the nonedible corn kernel fiber, which is designated as a cellulosic feedstock under the RFS. In 2022, 35% of U.S. corn production was used to produce ethanol (AFDC 2023a).

Currently, biodiesel, renewable diesel, and SAF (via the hydroprocessed esters and fatty acids [HEFA] pathway) utilize the same feedstocks, which include waste fats, oils, and greases and vegetable oils. There is considerable competition for these feedstocks as new plants come online, particularly the large renewable diesel plants. There is also competition from other industries who use these feedstocks. SAF research is focused on commercializing technology pathways that use other feedstocks. There is near-term potential to use ethanol as a feedstock for SAF via the alcohol-to-jet pathway.

Figure 5 and Figure 6 show the inputs to domestic biodiesel, renewable diesel, and SAF production in 2022. The breakout for soybean oil use shows that biodiesel uses nearly twice as much as renewable diesel (Figure 7). Therefore, it is assumed that renewable diesel uses a higher proportion of fats, oils, and greases.

RNG is produced from landfilled organic matter (~72%), livestock/agricultural waste (~20%), food wastes (5%), and wastewater sludge (3%) (EPA 2023c). There is considerable opportunity for increased use of available feedstocks. For example, only 10% of collected landfill biogas is used for RNG production while 53% is flared to reduce methane emissions, 28% is used for electricity generation, and 8% is used in direct heating applications (EPA 2023c). It is estimated that biogas recovery systems are technically feasible for more than 8,000 large dairy and hog operations, but only 342 systems were operational during 2022 in the United States (EPA 2024).

Biomass electricity is produced from various resources. These include cellulosic material (e.g., woody and crop materials, such as crop residues), and biogas produced from landfills, wastewater, manure, and other organic wastes. Today, most U.S. biopower is generated from woody biomass—including byproducts (e.g., black liquor) and solids, such as low-quality wood (e.g., railroad ties and utility poles) and residues—in dedicated or cogeneration plants, such as pulp and paper mills or sawmills (EIA 2023l). Biogas is used to generate electricity for on-site use or sale to the grid and as a pipeline-quality gas. In 2022, solid wood and wood waste

[14] https://www.rd.usda.gov/programs-services/energy-programs/biorefinery-renewable-chemical-and-biobased-product-manufacturing-assistance-program

accounted for 36% of total biomass power generation while black liquor was 31%, landfill gas was 16%, and the organic portion of municipal solid waste was 11% (Figure 8) (EIA 2023l).

DOE's Bioenergy Technologies Office funds the *Billion-Ton Report*—a comprehensive feedstock analysis report of potential biomass feedstock resources in the United States inclusive of price, quantity, geographic location and distribution, and market maturity. The updated 2023 version was released in March 2024 (DOE 2024).

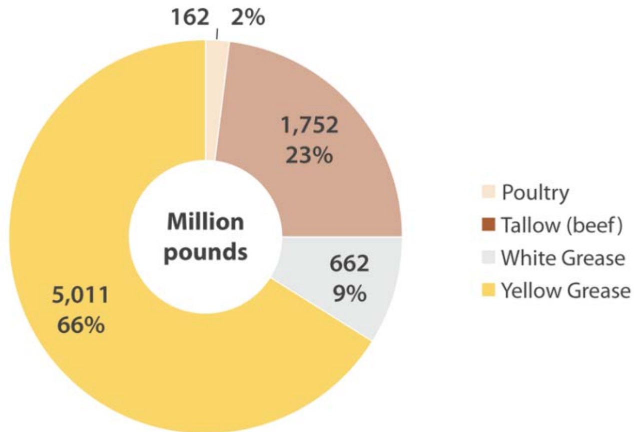

Figure 5. U.S. biofuel use of waste fats, oils, and greases.

Source: EIA (2023m)

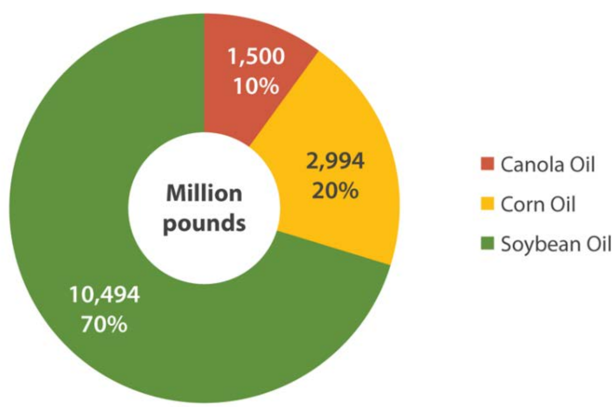

Figure 6. U.S. biofuel use of vegetable oil feedstocks.

Source: EIA (2023m)

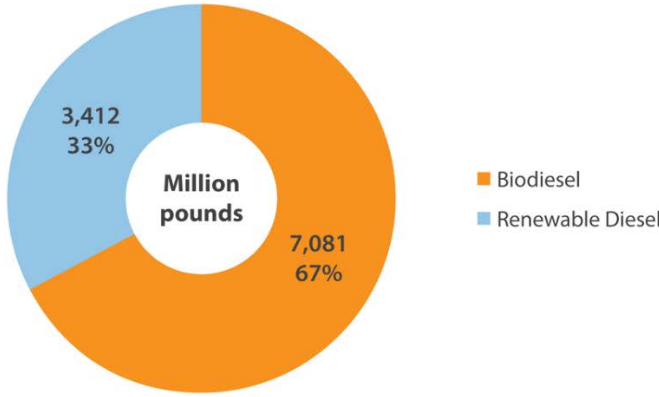

Figure 7. U.S. comparison of soybean use by renewable diesel and biodiesel.

Source: EIA 2023m

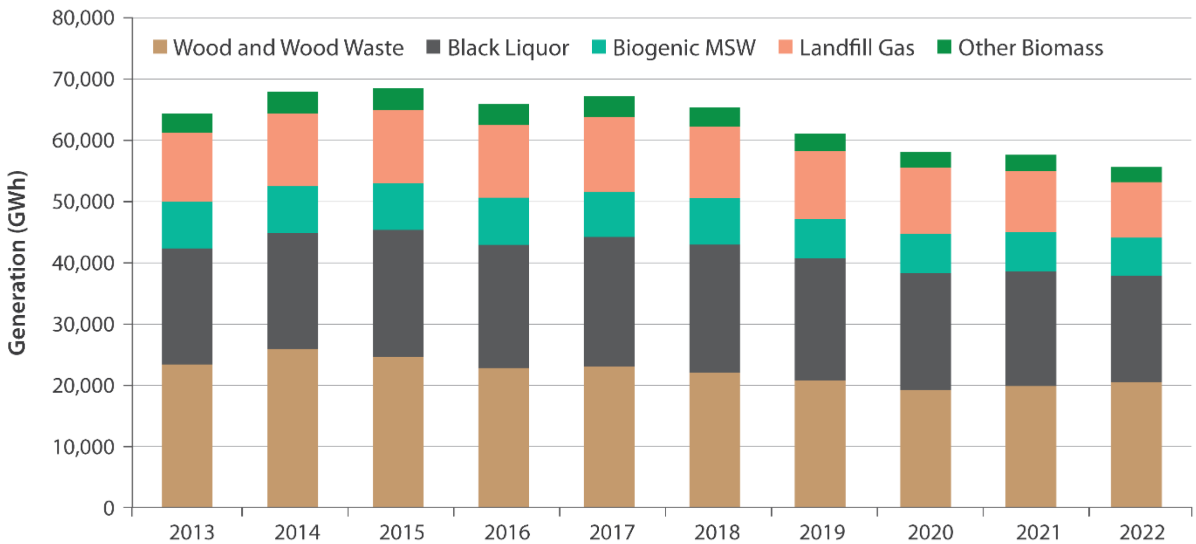

Figure 8. U.S. biopower generation sources

GWh = gigawatt-hour

Source: EIA (2023l)[15]

2.3 Economic Impacts and Jobs

The economic impacts for ethanol, biodiesel, renewable diesel, and renewable natural gas are available from their respective industry organizations. With limited SAF production, economic impacts and jobs data are not available.

[15] Other biomass includes other biomass solids, other biomass gases, agricultural crop residues, sludge waste, wood-waste liquids, and other biomass liquids.

The ethanol industry funds annual studies to determine the impacts of ethanol production on the economy (Urbanchuk 2023). These studies use IMPLAN—an economic input-output model to estimate gross value added (total value of the goods and services produced by businesses), income, and employment resulting from the corn grain ethanol industry each year. The study found the 2022 impact to gross domestic product, household income, and taxes was $57 billion, $35 billion, and $12 billion, respectively. Direct and induced jobs surpassed 78,000 and 342,000, respectively.

A study funded by the Clean Fuels Alliance of America assessed impacts based on a 2021 biodiesel and renewable diesel market of 2.5 billion gallons of domestic production and 600 million gallons of imports (LMC International 2022). The study found an economic impact of $23 billion and support of more than 75,000 direct and indirect jobs. The implied average wage in the biodiesel/renewable diesel was $47,900.

RNG's contribution includes an estimated 38,000 jobs and $4.8 billion to gross domestic product (RNG Coalition 2022). For every 1 MMBtu of RNG generated, 22 jobs were created (RNG Coalition 2022).

DOE's *United States Energy & Employment Report 2023* provides some statistical data on the diversity of employment in biofuels (DOE 2023a). Table 1 shows the differences between corn ethanol, other biofuels, the overall energy workforce, and national workforce.[16]

[16] The report defines other biofuels as fuels made from non-woody biomass, biodiesel, renewable diesel, waste fuels, and ethanol not produced from corn.

Table 1. Biofuels Job Demographics Comparison

Demographic	Corn Ethanol	Other Biofuels	Energy Workforce	National Workforce
Male	68%	65%	73%	53%
Female	31%	33%	26%	47%
Gender Nonbinary	<1%	1%	<1%	Insufficient data
Hispanic or Latino	11%	12%	18%	19%
Not Hispanic or Latino	89%	88%	82%	82%
American Indian or Alaska Native	1%	2%	2%	<1%
Asian	6%	7%	7%	7%
Black or African American	7%	10%	9%	13%
Native Hawaiian or Other Pacific Islander	2%	2%	1%	<1%
White	80%	75%	75%	77%
Two or More Races	3%	3%	5%	3%
Veterans	15%	8%	9%	5%
18 to 29	28%	31%	30%	22%
30 to 54	49%	55%	53%	54%
55 and Over	23%	13%	17%	24%
Disability	4%	4%	2%	4%
Formerly Incarcerated	<1%	1%	1%	2%

Data source: DOE (2023a)

2.4 Sustainable Aviation Fuel

SAF is a drop-in replacement fuel produced from renewable and waste feedstocks that can be used in existing aircraft, engines, and associated infrastructure. SAF provides a near-term solution to decarbonizing aviation, which was responsible for 8% of U.S. transportation GHG emissions in 2021 (EPA 2023d). SAF is a commercial fuel that has been in use since 2016.

The SAF Grand Challenge is a joint initiative of DOE, U.S. Department of Transportation, and USDA that seeks to reduce production costs, enhance sustainability, and expand the production of SAF. The near-term goal is to increase SAF production to 3 billion gallons by 2030, and the long-term goal is 100% SAF at 35 billion gallons by 2050.[17] All SAF will meet or exceed a minimum 50% reduction in life cycle GHG emissions compared to conventional jet fuel. An emphasis on feedstock innovation and conversion technologies is essential to reducing costs and is a key focus of the SAF Grand Challenge.

Research and development are heavily focused on finding technology pathways that can reduce costs and increase production. SAF must be blended with conventional jet fuel prior to use in

[17] https://www.energy.gov/eere/bioenergy/sustainable-aviation-fuel-grand-challenge

aircraft. Research is focused on enabling pathways that allow 100% SAF. There are currently eight synthetic paraffinic kerosene (SPK), synthetic kerosene with aromatics (SKA), and other approved pathways.

- Hydroprocessed esters and fatty acids (HEFA) fuels derived from used cooking oil, animal fats, vegetable oils, and algae (HEFA-SPK); 50% limit. SAF is currently produced via this pathway. Co-processing with petroleum feedstock is allowed at a 5% limit.
- Fischer-Tropsch (FT) fuels using solid biomass resources (e.g., wood residues) (FT-SPK); 50% limit. Co-processing with petroleum feedstock is allowed at a 5% limit.
- FT fuels with aromatics using solid biomass resources (e.g., wood residues) (FT-SKA); 50% limit.
- Hydroprocessed fermented sugars to synthetic isoparaffins (HFS-SIP); 10% limit.
- Alcohol-to-jet (ATJ-SPK) fuels produced from isobutanol or ethanol; 50% limit.
- Catalytic hydrothermolysis synthesized kerosene (CH-SK or CHJ); 50% limit.
- Hydrocarbon-hydroprocessed esters and fatty acids (HC-HEFA-SPK) from biomass resources (e.g., algae); 10% limit.
- Alcohol-to-jet synthetic paraffinic kerosene with aromatics (ATJ-SKA) from C2-C5 alcohols; 50% limit; approved but not yet published by ASTM.

Airlines are committed to purchasing SAF and have entered into numerous offtake agreements with existing and future producers. The International Civil Aviation Organization (2023) maintains a list of current offtake agreements that highlights the potential size of the market and committed airlines.

2.4.1 Consumption, Plants, and Capacity

EIA does not publish SAF data; therefore, the best approximation of SAF volumes are derived from EPA's RIN data. As evidenced in Figure 9, SAF production increases each year. This trend is expected to continue with two new commercial plants starting operations in 2023 and 2024 and a foreign producer expanding production. Figure 10 shows the high variability of monthly SAF RIN generation, which may represent market dynamics of plants producing both SAF and renewable diesel and potentially competition for foreign SAF or imported biointermediates processed into SAF in the United States (Neste 2022).

Despite increased production, SAF represents a tiny fraction of overall U.S jet fuel market of 23.9 billion gallons in 2022 (EIA 2023e). In 2022, the United States accounted for 28% of the world's overall jet fuel use—an increase over 2019, which was 24% (EIA 2023n), largely due to a rebound of domestic travel compared with international and business travel.

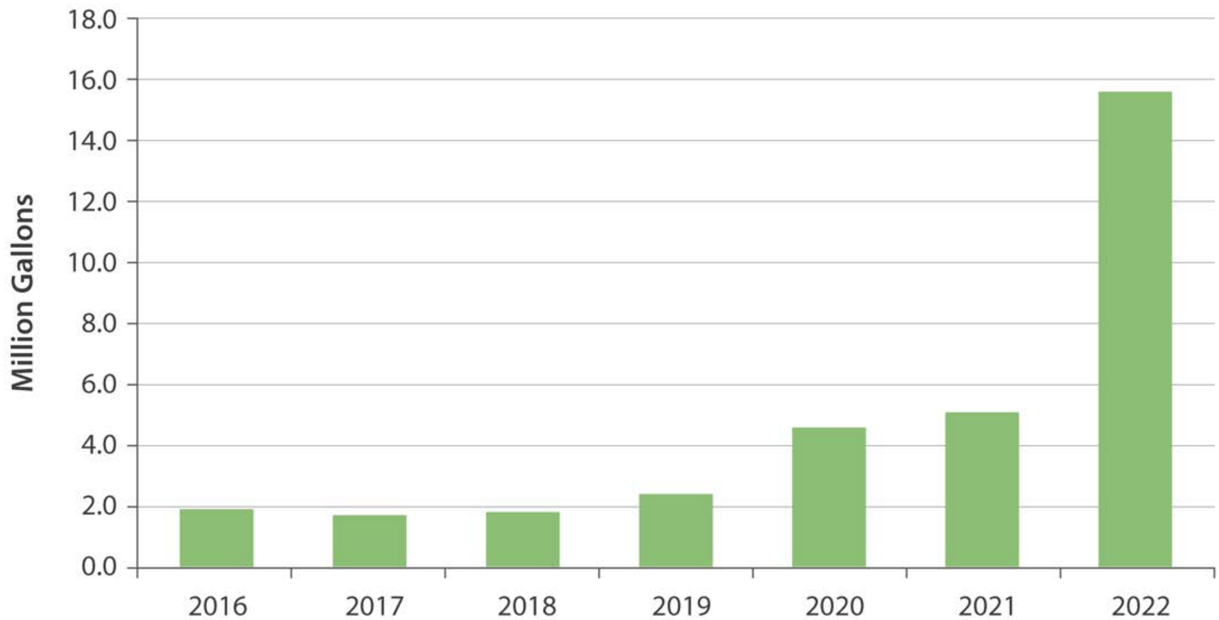

Figure 9. U.S. estimated annual SAF volumes.

Source: EPA (2023a)

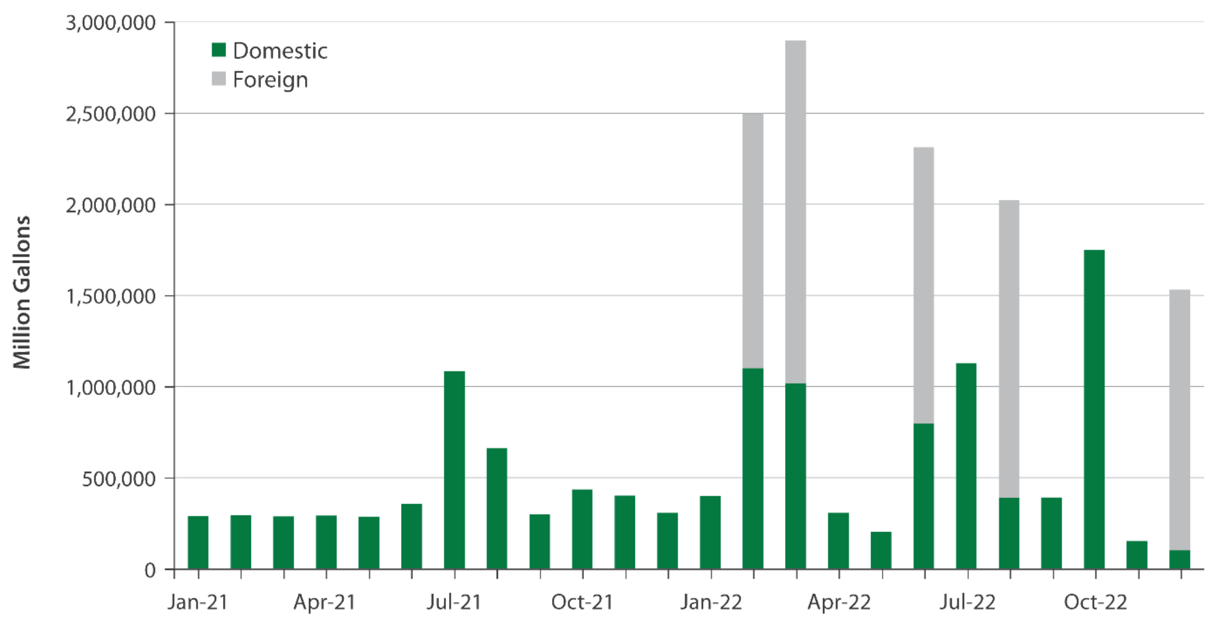

Figure 10. U.S. estimated monthly SAF volumes.

Domestic RINs were SAF-produced in the United States; foreign RINs represent imported SAF.

Source: EPA (2023a)

There are three commercial SAF plants serving the U.S. market as of 2023. Each of these plants also produces renewable diesel. World Energy's Paramount, California, facility began producing

SAF in 2016 and delivered it to Los Angeles International Airport. They have near-term plans to expand SAF capacity. Montana Renewables, located in Great Falls, Montana, entered the SAF market in the second quarter of 2023 (Voegele 2023a). Neste, a foreign producer, entered the U.S. market in late 2020, supplying multiple California airports. Neste in the process of expanding SAF capacity at both their Rotterdam and Singapore facilities (Neste 2023a). The International Energy Agency (IEA) reports five Neste plants under construction in Australia, Japan, Spain, Sweden, and the United Kingdom (IEA Bioenergy 2023).

Two near-term domestic plants are expected. LanzaJet's alcohol-to-jet facility is anticipated to start operations in early 2024 in Soperton, Georgia, with a reported combined capacity of 10 million gallons for both SAF and renewable diesel (LanzaJet 2023). Phillips 66's conversion of its Rodeo, California, refinery is nearly complete; it is capable of producing SAF, renewable diesel, and renewable gasoline with total capacity of 800 million gallons per year (Voegele 2024). Section 2.5.1 of this report details renewable producers. While most of those plants do not produce SAF today, they have the potential to do so if market conditions are favorable. IEA maintains a list of biomass conversion facilities that currently produce or intend to produce SAF. A list of these plants is available in Appendix A, including demonstration and pilot-scale plants.

2.4.2 Sustainable Aviation Fuel Trade

EIA does not report SAF trade data. EPA's RIN data from past years show both imports and exports (Figure 11). SAF imports come from Neste facilities (Neste 2023b).

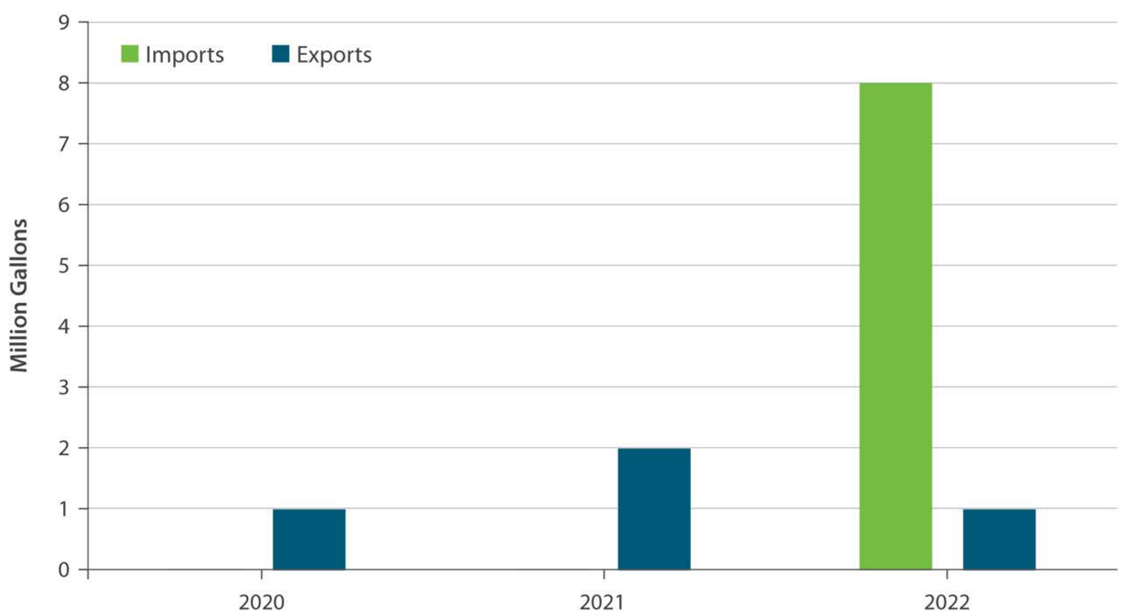

Figure 11. U.S. estimated SAF trade (based on RIN data).

Source: EPA (2023a; 2023e)

2.4.3 Blending and Logistics

SAF must be blended with conventional jet fuel, tested, and certified per ASTM D1655 prior to use in aircraft. Conventional jet fuel from refineries and imports are moved primarily by pipeline to terminals and onward to airports by pipeline or truck (Figure 12). SAF co-processed at an existing petroleum refinery or blended into refinery storage is certified per ATM D1655 and flows through the supply chain in a business-as-usual scenario.

SAF produced at a stand-alone facility must be blended somewhere in the supply chain with conventional jet fuel—previous reports examined options (Moriarty and Kvien 2021a; Moriarty, Milbrandt, and Tao 2021b). Fuel quality requirements and establishing SAF as ASTM D1655 certified prior to the airport was the key reason for identifying existing terminals as the best option for blending. Terminals have existing blending equipment, technology, permits, insurance, and staff knowledge because it is a part of their on-high transportation fuel activities. Terminals, including those owned and operated by petroleum companies, lease tanks and associated blending equipment to customers. Blending can occur at the terminal directly linked to an airport or anywhere upstream. A demonstration project brought SAF blended in Houston up the Colonial Pipeline and onward on Buckeye's pipeline to LaGuardia International Airport in New York (Neste 2022). While blending could occur at an airport, it would result in increased truck traffic, the need to add staff and blending infrastructure and technology, and a change to insurance (Moriarty 2023b).

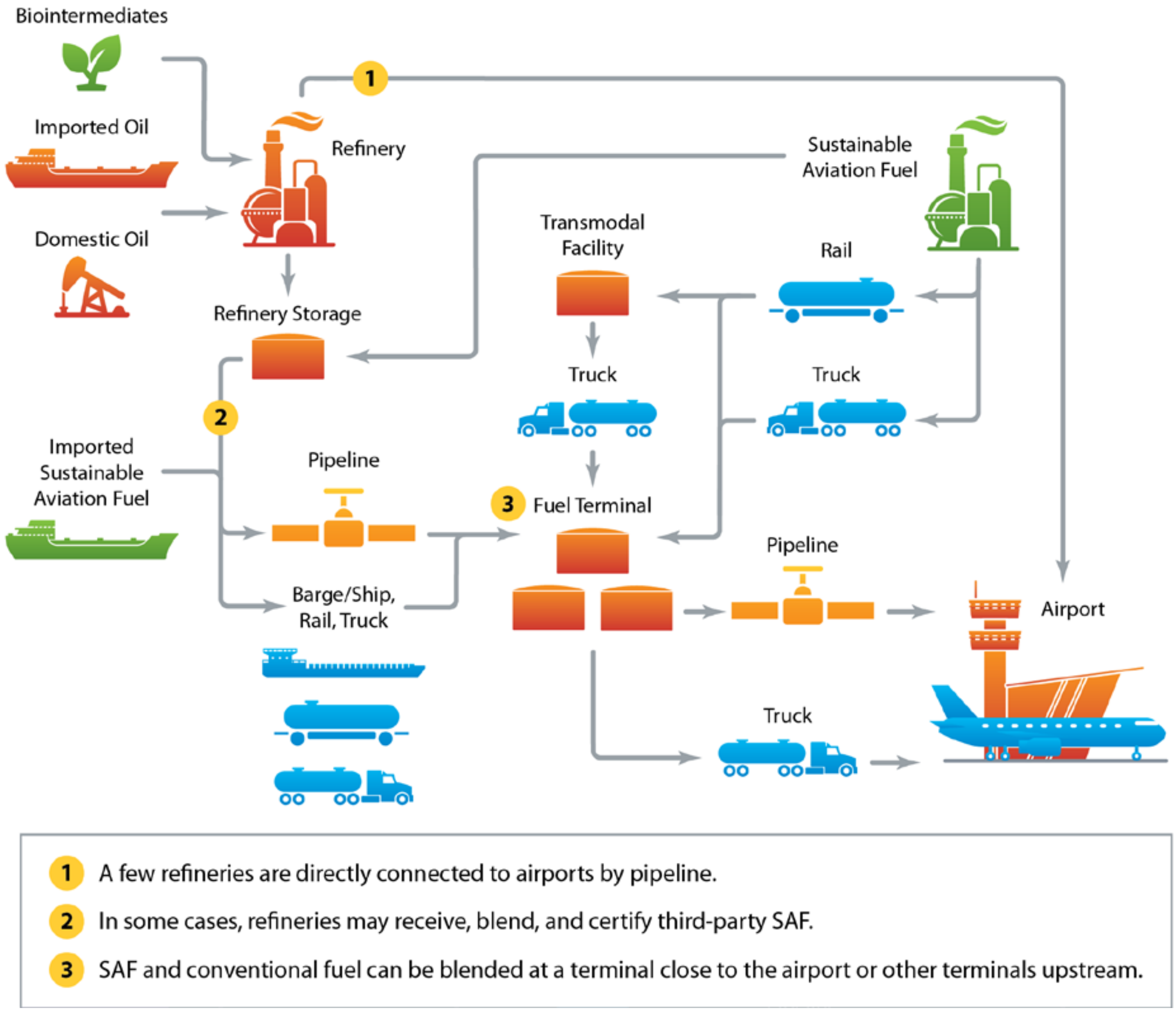

Figure 12. U.S. SAF and conventional jet fuel logistics

2.5 Renewable Diesel

Renewable diesel is a drop-in replacement for diesel typically produced from fats, oils, and greases. It is chemically the same as petroleum diesel and meets the ASTM D975 standard. As a drop-in fuel, it can be used in all existing infrastructure and engines intended for petroleum diesel. Renewable diesel meets the 50% GHG emissions reduction goal and qualifies as biomass-based diesel D4 RIN if it is not co-processed with petroleum feedstocks; it meets the advanced biofuel category D5 RIN if it is co-processed (EPA 2023c).

Renewable diesel and biodiesel are not the same fuels. They use different production technologies and meet different ASTM fuel quality specifications. Biodiesel details are available in Section 2.6 of this report.

Renewable diesel domestic production and consumption have grown significantly, largely due to conversion of petroleum refineries. Renewable diesel has good performance in cold weather and can therefore be blended in any amount up to 100%.

2.5.1 Production, Consumption, and Capacity

Renewable diesel is produced by traditional hydrotreating, which is how petroleum diesel is made. Hydrotreating involves reacting the feedstock with hydrogen under elevated temperatures and pressures in the presence of a catalyst. There are other production pathways that are not currently used for commercial production—they include biological sugar upgrading, catalytic conversion of sugars, gasification, pyrolysis, and hydrothermal processing.[18]

There has been tremendous growth in both production and consumption; consumption exceeded 1.7 billion gallons in 2022 (Figure 13, EIA 2023c). In January 2022, renewable diesel consumption exceeded biodiesel consumption, and this trend is expected to continue as capacity is expected to grow (Figure 14). EIA reports that West Coast petroleum diesel consumption is declining due to increased use of renewable diesel and biodiesel (EIA 2023h).

Due to favorable credits under their LCFS, California accounted for more than 99% of U.S. renewable diesel consumption in 2021 (EIA 2023i). Oregon, who also has an LCFS, accounted for less than 1% and was the only other state where renewable diesel was consumed in 2021 (EIA 2023i). It is expected that nearly all production and imports of renewable diesel will go to California until their market needs are met before it expands to other markets, likely in West Coast states with LCFS.

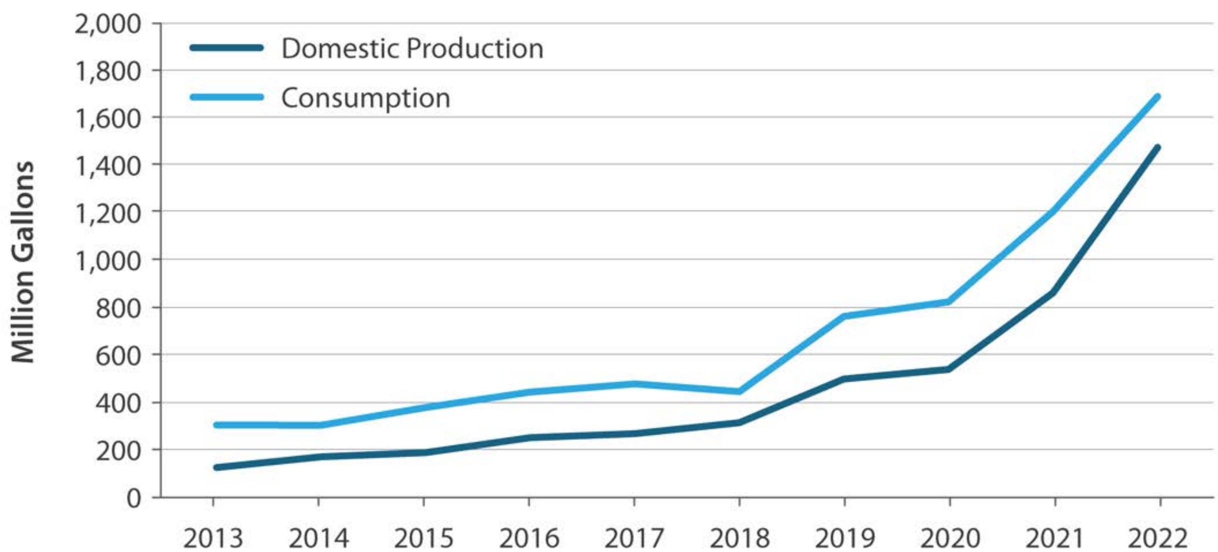

Figure 13. U.S. renewable diesel production and consumption.

Source: EIA (2023c)

[18] Details of other technology pathways are available on the AFDC: https://afdc.energy.gov/fuels/renewable_diesel.html.

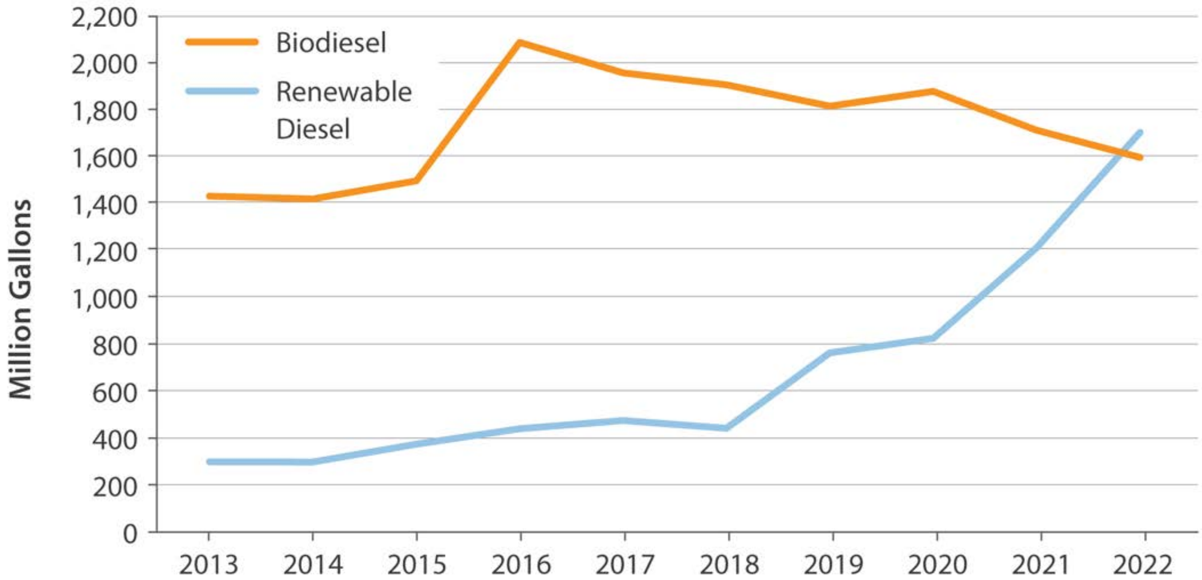

Figure 14. U.S. renewable diesel and biodiesel consumption.

Source: EIA (2023b; 2023c)

The number of plants and capacity have grown significantly in the past 2 years. For years, there were two large domestic producers and one significant foreign producer. Plant locations and capacities are shown in Table 2. Many of them started operations in 2022 and 2023. Most plants are conversions of existing petroleum refinery assets.

Most renewable diesel is made at dedicated plants; however, co-processing at existing petroleum refineries also occurs. Up to 10% renewable feedstock can be used at existing petroleum refineries with minimal or no capital expenditures (Shell 2023). Considerations include increased hydrogen consumption and heat release as well as potential challenges blending into the diesel pool due to cold flow properties. Two of these plants currently produce SAF, and a third is set up for SAF production. While the other plants do not produce SAF, their production processes could be updated to do so if market conditions were favorable.

Table 2. U.S. Renewable Diesel Plants and Capacity[19]

Plant	Location	Capacity (million gallons/year)
Altair Paramount LLC[a]	Paramount, CA	42
BP Products North America[b]	Blaine, WA	111
Chevron USA Inc[b]	El Segundo, CA	31
Cheyenne Renewable Diesel Co LLC	Cheyenne, WY	92
CVR Renewables Wynnewood LLC	Wynnewood, OK	121
Dakota Prairie Refining LLC	Dickinson, ND	192
Diamond Green Diesel LLC	Norco, LA	982
Diamond Green Diesel LLC	Port Arthur, TX	537
HF Sinclair Renewables Holding Co LLC	Artesia, NM	141
Jaxon Energy, LLC	Jackson, MS	25
Kern Oil & Refining[b]	Bakersfield, CA	6
Montana Renewables LLC[a]	Great Falls, MT	184
Phillips 66 Co[a]	Rodeo, CA	180
Renewable Energy Group	Geismar, LA	101
Seaboard Energy Kansas LLC	Garnett, KS	85
Shell Oil Products U.S.[b]	Norco, LA	54
Wyoming Renewable Diesel Co	Sinclair, WY	117
Total		**3,000**

Source: EIA (2023f) as of January 2023

[a] Altair and Montana Renewables facilities produce SAF; Phillips 66 is equipped to produce SAF but is not producing at the time this report was published.

[b] Refineries co-processing petroleum and renewable feedstocks.

2.5.2 Renewable Diesel Trade

All imports are from Neste's Singapore plant (EIA 2023o). The reduction in 2022 may be due to domestic production and foreign competition (Figure 15). EPA's public RIN data show a much higher number of imported and foreign generated RINs of 446 million in 2022 compared with EIA's import data of 263 million gallons in 2022 (EPA 2023a; EIA 2023o).

[19] EIA rounds capacity numbers.

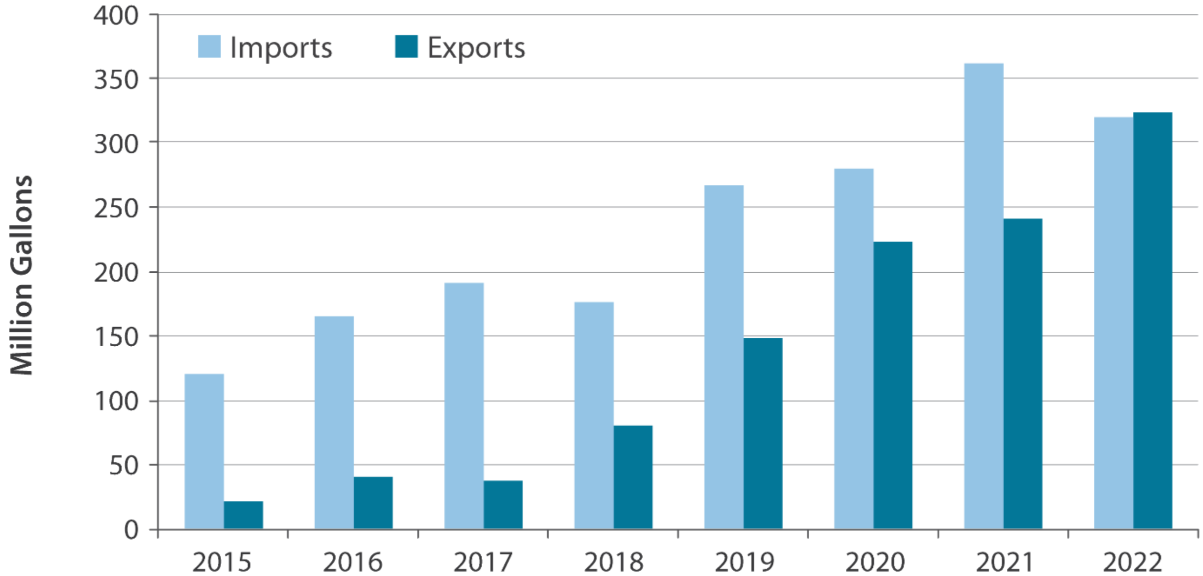

Figure 15. U.S. renewable diesel imports and exports.

Source: EPA (2023e)[20]

2.6 Biodiesel

Biodiesel is an alternative fuel manufactured for use in diesel engines. It is referred to as biomass-based diesel in the RFS, along with renewable diesel, which is a different alternative fuel described in Section 2.5 of this report. In 2022, biodiesel consumption accounted for 2.6% of the nearly 62-billion-gallon annual diesel market (EIA 2023b; 2023e).

Blends of biodiesel and conventional diesel fuel have physical properties similar to those of petroleum diesel. Blends of B5 (5% biodiesel, 95% petroleum diesel) or below meet ASTM fuel quality specification D975 for conventional diesel fuel and can be used in existing infrastructure and any compression-ignition engine intended for petroleum diesel. ASTM specification D7467 covers blends of B6 to B20 blends. B20 is the most common higher-level biodiesel blend, and engines operating on B20 have similar fuel consumption, horsepower, and torque to engines running on petroleum diesel. Some, but not all, engine and diesel vehicle manufacturer warranties cover the use of B20. B20 is approved for use in home heating oil, and there is an opportunity for growth in this market.

Pure biodiesel (B100, ASTM specification D6751) is typically used for blending with petroleum diesel and is rarely used in engines due to higher costs, cold weather performance issues, and lack of compatibility with existing vehicles and infrastructure. The biodiesel industry established a voluntary quality assurance program known as BQ9000 to support higher-quality fuels in the market.

[20] EIA reports renewable diesel export data, which vary slightly from EPA data (EIA 2023o). EPA data were used because they include both imports and exports.

Under the RFS, biodiesel generally meets the biomass-based diesel 50% GHG emissions reduction threshold. Biodiesel has historically been the main contributor to this fuel category, though renewable diesel overtook biodiesel in 2022 to become the most significant contributor to diesel RFS compliance (EPA 2023a).

2.6.1 Production, Consumption, and Capacity

Biodiesel is produced by transesterification—a process that converts fats and oils into biodiesel and glycerin (a coproduct) by reacting them with alcohol (typically methanol) and catalysts. Biodiesel production peaked at 1.8 billion gallons in 2018 and has declined in recent years to 1.6 billion gallons in 2022 (EIA 2023b). From 2013 through 2020, biodiesel consumption exceeded production due to biodiesel imports (Figure 16).

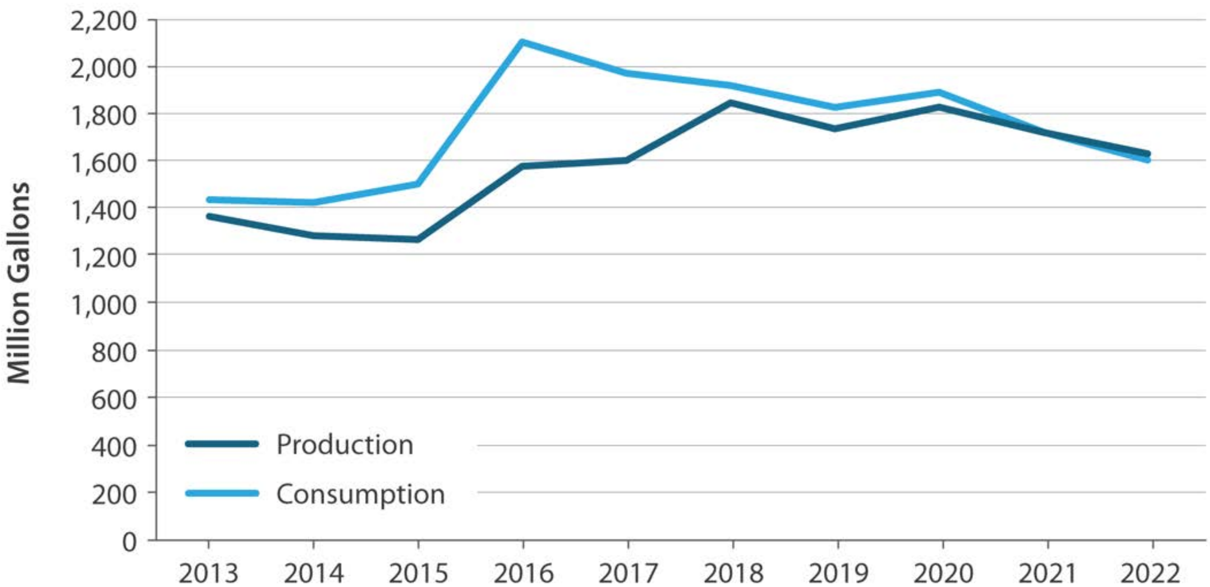

Figure 16. U.S. biodiesel production and consumption.

Source: EIA (2023b)

As of Jan. 1, 2023, there were 59 biodiesel plants with a total industry production capacity of more than 2 billion gallons in 29 states (Figure 17, Figure 18) (EIA 2023g). Biodiesel plant capacity ranges from less than 1 million gallons to up to 144 million gallons. The average biodiesel plant size is about 35 million gallons (EIA 2023g). About 70% of the production comes from the Midwest; the largest biodiesel producer is Chevron Renewable Energy Group, which operates 8 plants with a total production capacity of 432 million annual gallons (EIA 2023g). Both the number of plants and capacity have declined since 2018; however, utilization of capacity has increased. The decline in plants and capacity in the past years is likely due to economic impacts as well as increased renewable diesel production (Figure 14 in Section 2.5.1).

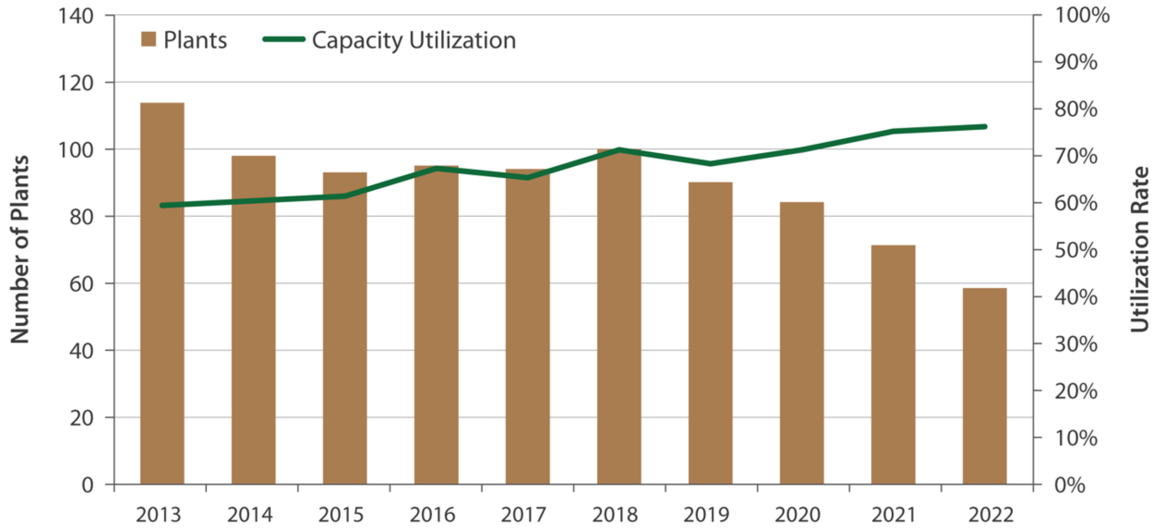

Figure 17. U.S. biodiesel plants capacity and utilization as of Jan. 1, 2023.

Source: EIA (2023b; 2023g)

Capacity utilization calculated based on capacity and production.

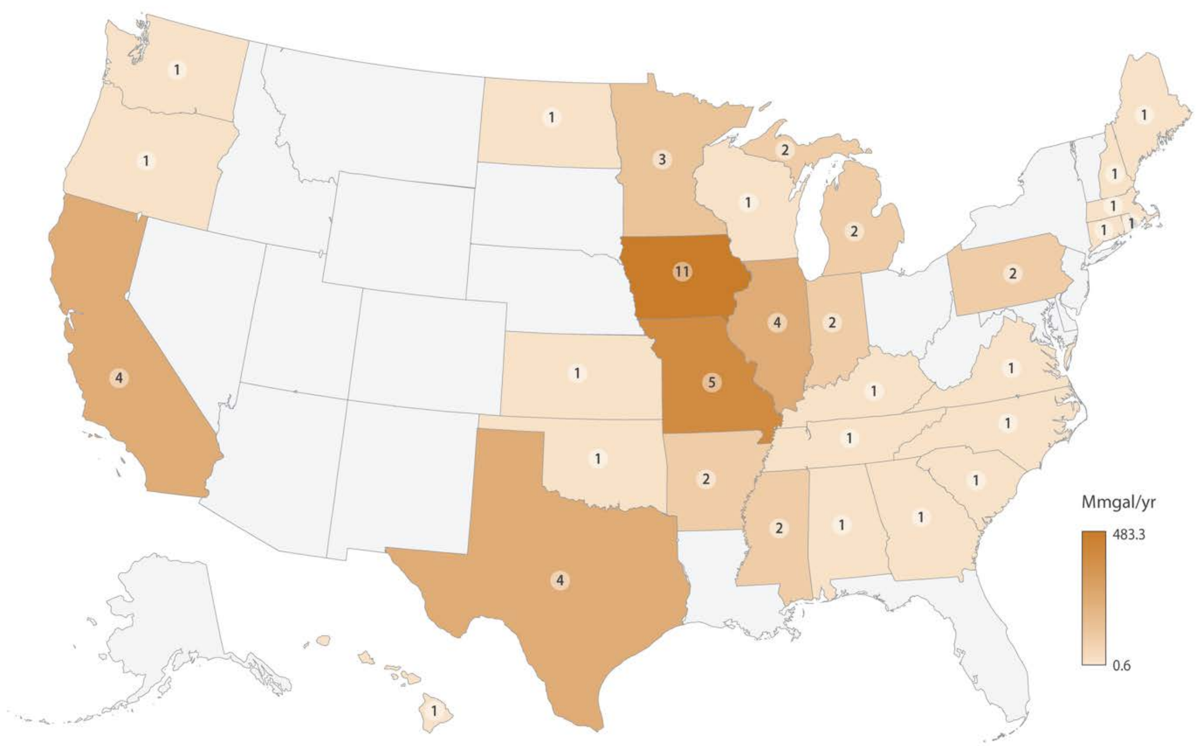

Figure 18. Biodiesel plants by state, January 2023.

Source: EIA (2023g)

2.6.2 Biodiesel Production Cost and Market Prices

Biodiesel prices are collected quarterly and are directly correlated with petroleum diesel prices (Figure 19, DOE 2023b). Biodiesel production costs vary based on the feedstock being used; plant size, type, and design; when the plant was built; and how the plant is managed. Iowa State University developed a model to track Iowa's biodiesel profit margins and production costs over time based on Iowa's biodiesel prices and costs for soybean oil and methanol, as well as other operating costs (Hofstrand 2023a). Historically, soybean oil has accounted for about 87% of operating costs at an average Iowa biodiesel plant, with lower costs for methanol and other operating costs. Increasing soybean oil prices since 2020 have increased soybean oil costs to 92% of operating costs. Production costs varied between \$2.28/gal and \$7.33/gal between January 2013 and December 2022 (Figure 20, Hofstrand 2023a). Biodiesel plants using other feedstocks, such as corn oil, canola oil, tallow, and waste grease, would experience different costs; however, feedstock costs typically comprise 70%–95% of overall operation costs (Tao and Aden 2009).

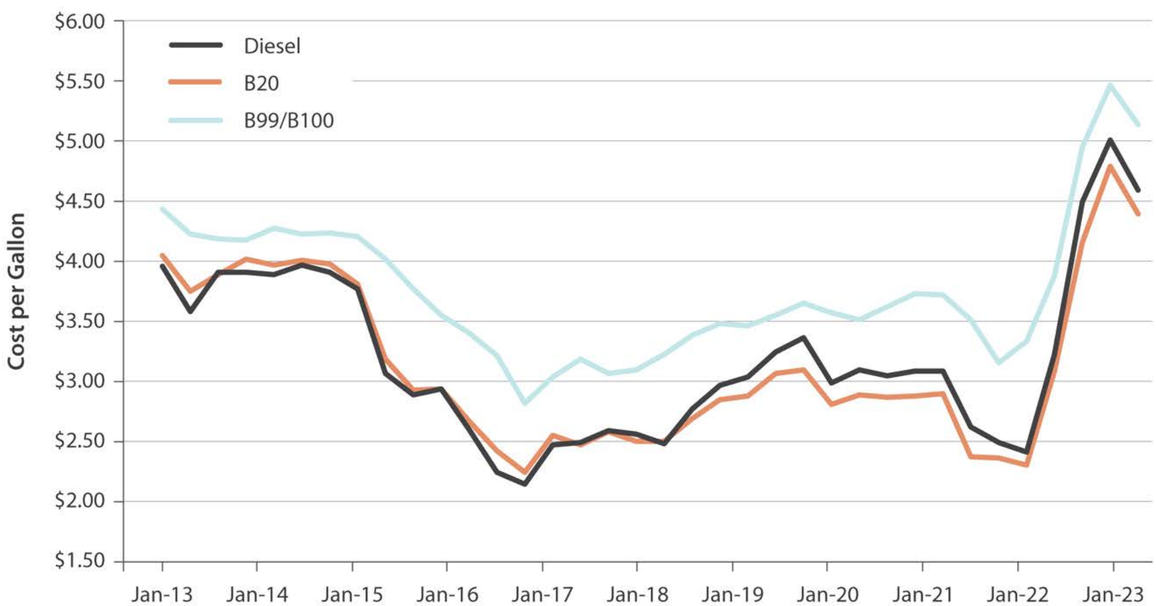

Figure 19. U.S. retail biodiesel prices.

Source: DOE (2023c)

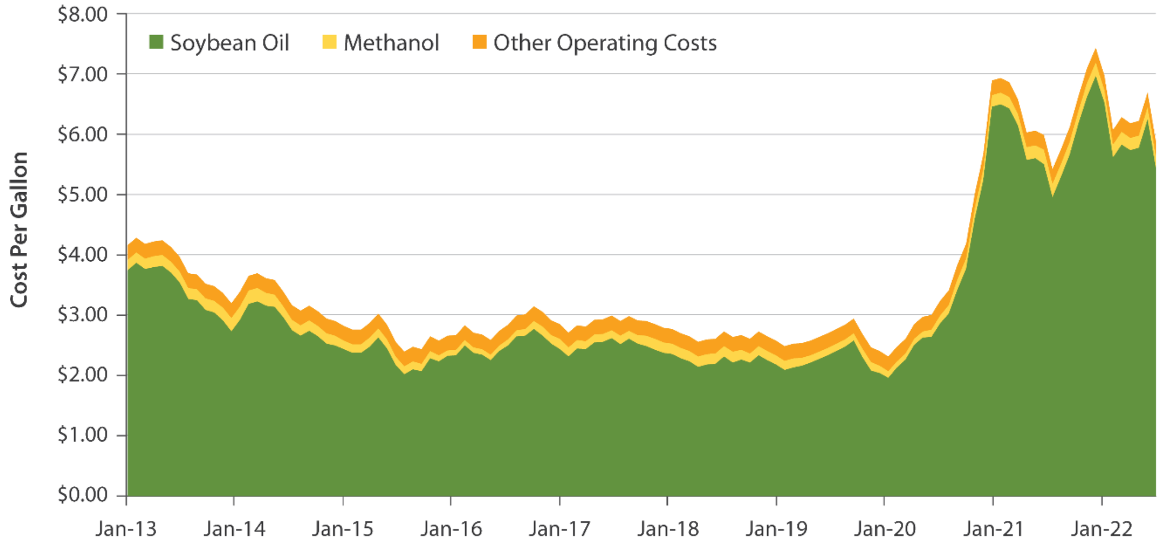

Figure 20. U.S. soybean-based biodiesel production cost trends.

Source: Hofstrand (2023a)

2.6.3 Coproducts Overview

The only coproduct of biodiesel production is glycerin, which is used in food, hygiene, and pharmaceutical products. Each gallon of biodiesel produced results in 1 pound of glycerin. Declining biodiesel production in recent years has contributed to higher prices for glycerin in U.S. markets. While glycerin had historically produced only pennies in revenue per gallon of biodiesel produced, glycerin prices increased steadily from 2020 through the end of 2022, reaching up to $600 per ton, or about $0.30 in revenue per gallon of biodiesel produced (Argus Media 2022).

2.6.4 Biodiesel Trade

U.S. biodiesel trade (Figure 21) dynamics are largely affected by policies. Imports grew significantly in 2016 and fell in 2017 because the United States imposed import duties on biodiesel from Argentina and Indonesia. Imports were from six nations; the majority came from Canada (49%) and Germany (31%) (EIA 2023o). The United States exported to nine nations in 2022, with Canada accounting for 80% and Peru accounting for 15% (EIA 2023p).

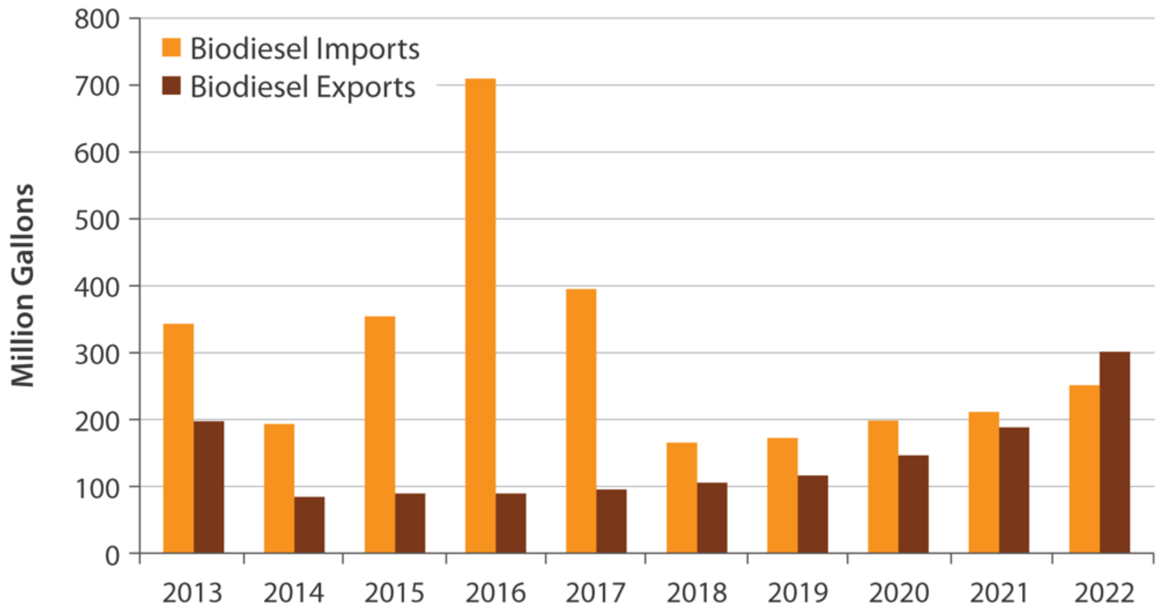

Figure 21. U.S. biodiesel imports and exports.

Source: EIA (2023o; 2023p)

2.6.5 Infrastructure

A patchwork of infrastructure regulations applies to the storage of biodiesel blends. Codes and standards for refueling agencies are developed and enforced by many organizations, including EPA's Office of Underground Storage Tanks (OUST), authorities having jurisdiction (typically fire marshals), UL (a third-party safety certification organization), the Occupational Safety and Health Administration, fire safety code organizations, and industry groups.

Blends of B5 and below are approved for use in all existing petroleum diesel infrastructure. For B20 blends, aboveground equipment at a gas station needs to be third-party certified for the fuel. Federal underground storage tank regulations require demonstration of compatibility for blends above B20, which can be demonstrated by using third-party certified equipment or by obtaining a compatibility letter from the manufacturer. All existing steel and fiberglass underground storage tank manufacturers have issued letters stating compatibility with B100; however, the decades-long usage of tanks means that there are tanks installed by manufacturers that are no longer in business, and these tanks cannot store blends above B20.[21]

As of the end of 2022, there were 1,193 stations offering B20 (Figure 22, AFDC 2023b). The reason for the significant increase in 2022 was due to a single large station reporting their station data. Biodiesel fueling stations are highly concentrated in the upper Midwest, with lesser concentrations in West Coast states. Minnesota mandates the sale of biodiesel,[22] Illinois provides

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[21] A list of biodiesel-compatible tanks, associated equipment, and UL-listed dispensers and hanging hardware is available on the AFDC website: www.afdc.energy.gov/fuels/biodiesel_infrastructure.html.
[22] Minnesota's blend requirement varies based on time of year. Details are available on Minnesota's legislature's website: www.house.mn.gov/hrd/pubs/ss/ssbiofuel.pdf.

a sales tax exemption, and Iowa provides a retailer tax credit. USDA's HBIIP resulted in more B20 stations and more terminals offering biodiesel in recent years. Moreover, an additional $450 million in funding is available from the program through 2024 (USDA 2023).

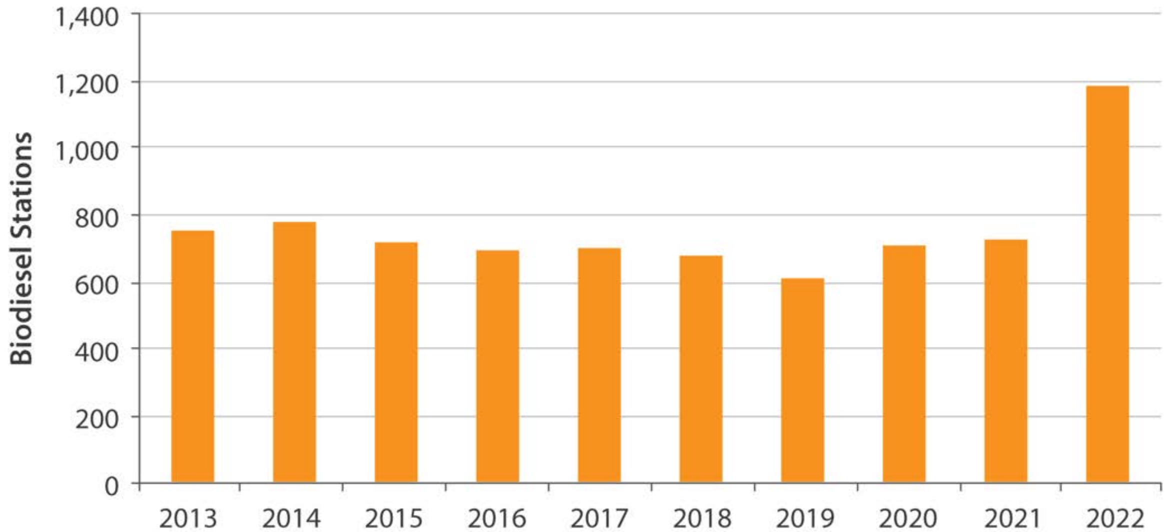

Figure 22. U.S. biodiesel refueling stations.

Source: AFDC (2023b)

2.6.6 End Use

Existing diesel vehicles can use B5 without any modifications to vehicles or infrastructure. As of 2022, 23 out of 32 major on-road vehicle manufacturers support the use of B20 in at least some of their vehicles.[23] Biodiesel is also used in off-road applications such as farm equipment and in backup generators.

There is an opportunity to increase biodiesel use in the home heating oil market, which is concentrated in the Northeast. Biodiesel blended with home heating oil is marketed as Bioheat fuel by the National Oilheat Research Alliance.[24] B20 can be used in standard home heating oil equipment.

2.7 Ethanol

Ethanol is a widely used biofuel made from corn grain and other plant materials. Ethanol has a long history of use in the United States, dating back to the introduction of motor vehicles. As a domestically produced biofuel, ethanol reduces reliance on imported petroleum products and provides jobs in rural areas. Under the RFS, corn grain ethanol, imported sugarcane ethanol, and

[23] Clean Fuels Alliance America original equipment manufacturer information: https://cleanfuels.org/wp-content/uploads/2023/07/oem-support-summary.pdf.

[24] The National Oilheat Research Alliance provides details on renewable fuels for home heating oil: https://noraweb.org.

cellulosic ethanol meet the 20%, 50%, and 60% GHG emissions reduction thresholds, respectively, of the RFS (EPA 2023c).

The ethanol market has expanded to be the largest (by joule) alternative fuel in the United States due to both regulation and market factors (Johnson 2021). Today, ethanol consumption is driven by both the RFS and octane requirements. Pipelines ship a variety of gasoline and gasoline blendstocks to meet demand, which varies regionally. Many of these products are sub-octane, meaning they have a lower octane than is required for sale to consumers at a station. Ethanol has a higher octane number than gasoline, and refiners provide a gasoline blendstock that, when blended with ethanol, will meet octane specifications necessary for vehicle performance needs. Ethanol is delivered to terminals or blenders by railcar, tanker truck, or barge, and it is then blended with gasoline and delivered by truck to stations.

Most gasoline sold in the United States contains ethanol, and nearly all ethanol is sold as E10 (EIA 2022). Another long-available blend is E85, which can be used in flexible-fuel vehicles (FFVs). E15 is approved for use in model year (MY) 2001 and newer vehicles. The blend rate of ethanol with gasoline reached 10.5% in summer 2022—this means that the market expanded beyond E10 with sales of E15 and E85 (EIA 2022). In states without a reformulated gasoline market, E15 typically cannot be sold in summer months due to a waiver needed for Reid vapor pressure. However, an ongoing EPA emergency fuel waiver has allowed sales of E15 nationwide year-round in 2022 and 2023 (EIA 2022). Nine midwestern states have approached EPA to address the Reid vapor pressure issue (RFA 2023b).

2.7.1 Production, Consumption, and Capacity

The majority of ethanol is produced using dry-mill technology (92%); a small number of larger plants use a wet-milling process (10%) (RFA 2023b). Dry milling is a process that grinds corn grain into flour and ferments only the starch component into ethanol with coproducts of distillers grains (an animal feed substitute) and carbon dioxide. Wet-mill plants primarily produce corn grain sweeteners, along with ethanol and several other coproducts (such as corn oil and starch).

Figure 23 highlights 2022 ethanol production and consumption of more than 15 billion gallons and nearly 14 billion gallons, respectively (EIA 2023a). Exports account for the difference in production and consumption. Figure 24 shows cellulosic ethanol production, which has declined in recent years. Since 2021, all cellulosic ethanol production is from bolt-on technology at existing conventional ethanol plants, which extracts the corn fiber byproduct for processing into ethanol. Adding cellulosic ethanol conversion technology to existing corn ethanol plants allows these facilities to diversify their portfolios.

As of January 2023, there were 187 fuel ethanol plants in 28 states, with an installed capacity of about 17.7 billion gallons (Figure 25, Figure 26, EIA 2023j). There are plants in 22 states with the majority in the Midwest (Figure 18, EIA 2023j). Plant ownership is not consolidated—there are approximately 109 ownership organizations. The four top producers account for 39% of installed capacity and 33% of plants: POET (33 plants, 2.9 billion gallons), Valero (12 plants, 1.6 billion gallons), Archer Daniels Midland (5 plants, 1 billion gallons), and Green Plains (11 plants, 962 million gallons) (EIA 2023j).

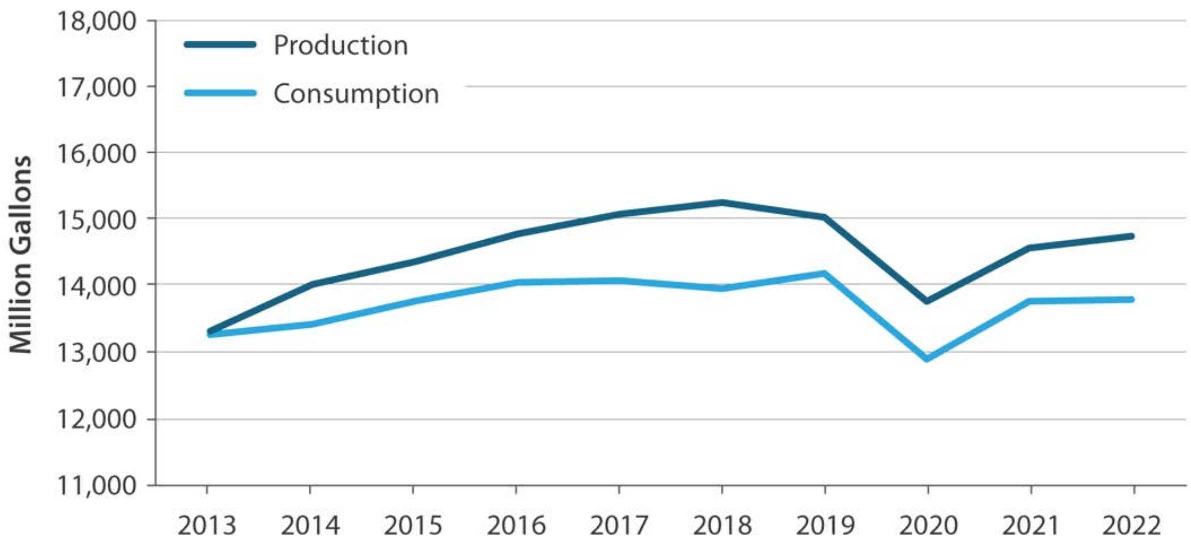

Figure 23. U.S. ethanol production and consumption.

Source: EIA (2023a)

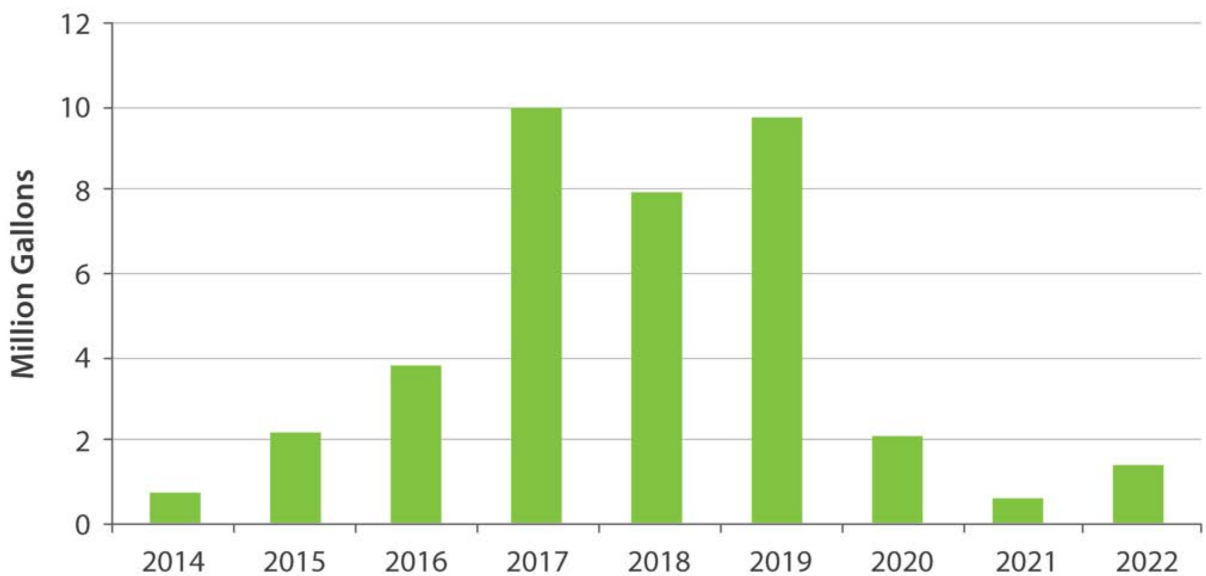

Figure 24. U.S. cellulosic ethanol production.

Source: EPA (2023a)

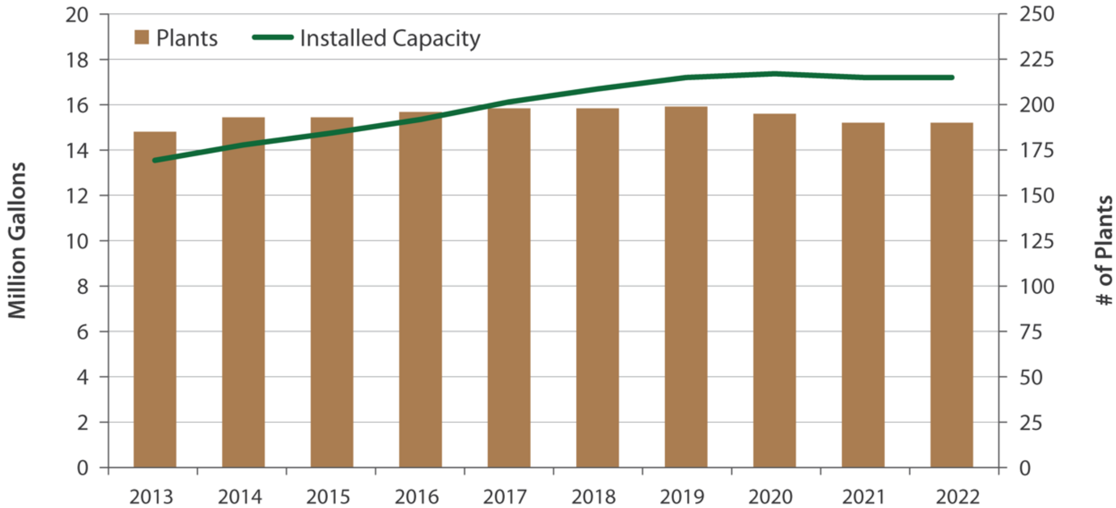

Figure 25. U.S. ethanol plants and capacity as of Jan. 1, 2023.

Source: EIA (2023j)

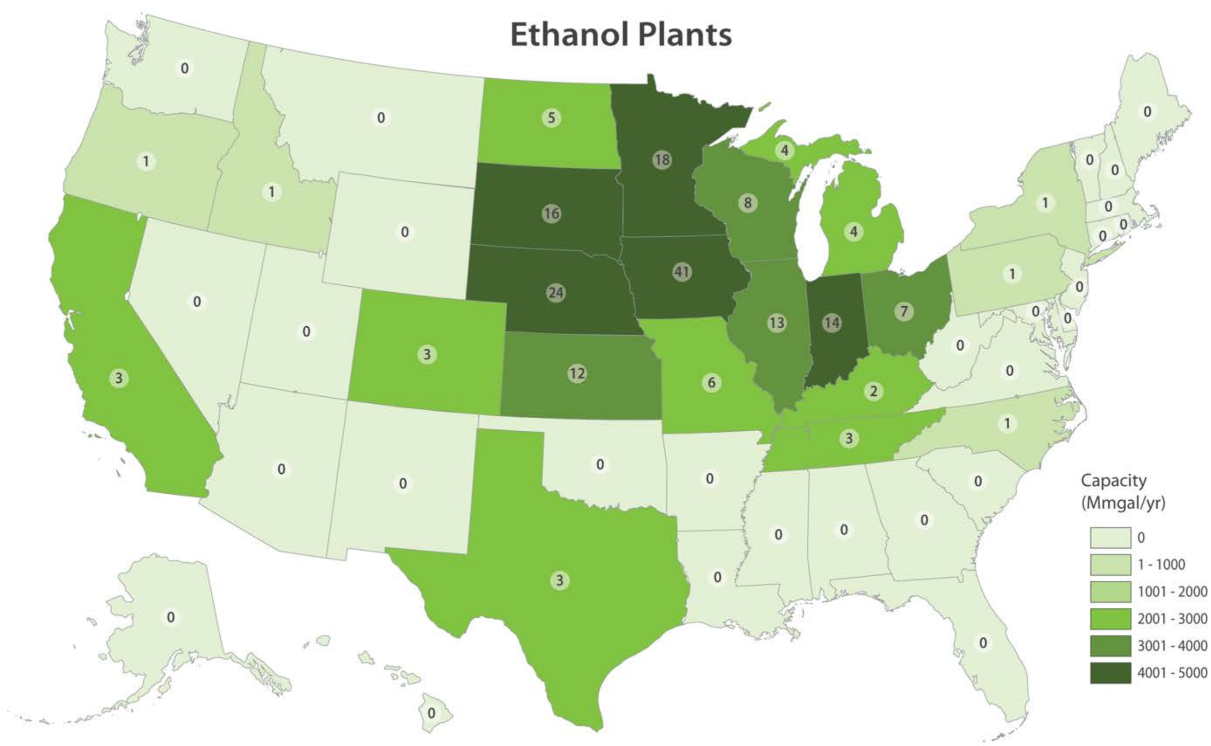

Figure 26. Ethanol plants by state, January 2023.

Source: EIA (2023j)

2.7.2 Prices and Production Cost

The primary drivers of ethanol prices are the cost of corn grain and the gasoline prices for which ethanol serves as a substitute product. Figure 27 compares ethanol and gasoline futures prices with corn grain prices.

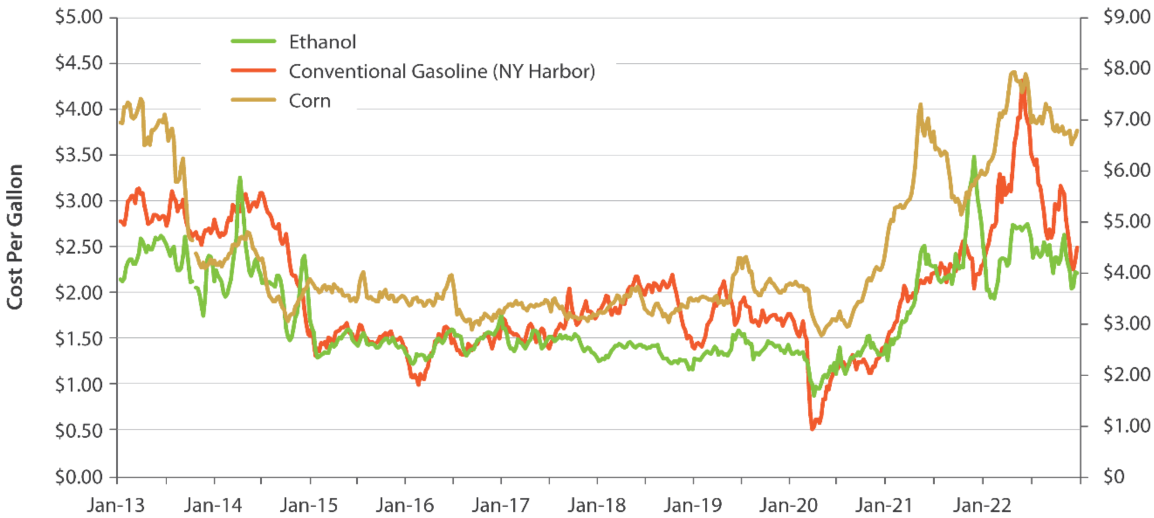

Figure 27. U.S. corn, ethanol, and gasoline prices.

Source: ethanol and corn grain: Ag Marketing Resource Center (2023a); gasoline: EIA (2023q). Ethanol and gasoline are price per gallon, not energy equivalent.

A model created by Iowa State University was used to estimate the production cost for a typical northern Iowa natural-gas-fired ethanol plant with an annual capacity of 100 million gallons (Hofstrand 2023b). The plant represents similar facilities built around 2007 in Iowa but may not be representative of plants in other regions (Hofstrand 2023b). The estimated production cost varied from $1.58/gal to $3.45/gal between 2013 and 2022, and corn accounted for 71% of production costs over the past 10 years (Figure 28, Hofstrand 2023a).

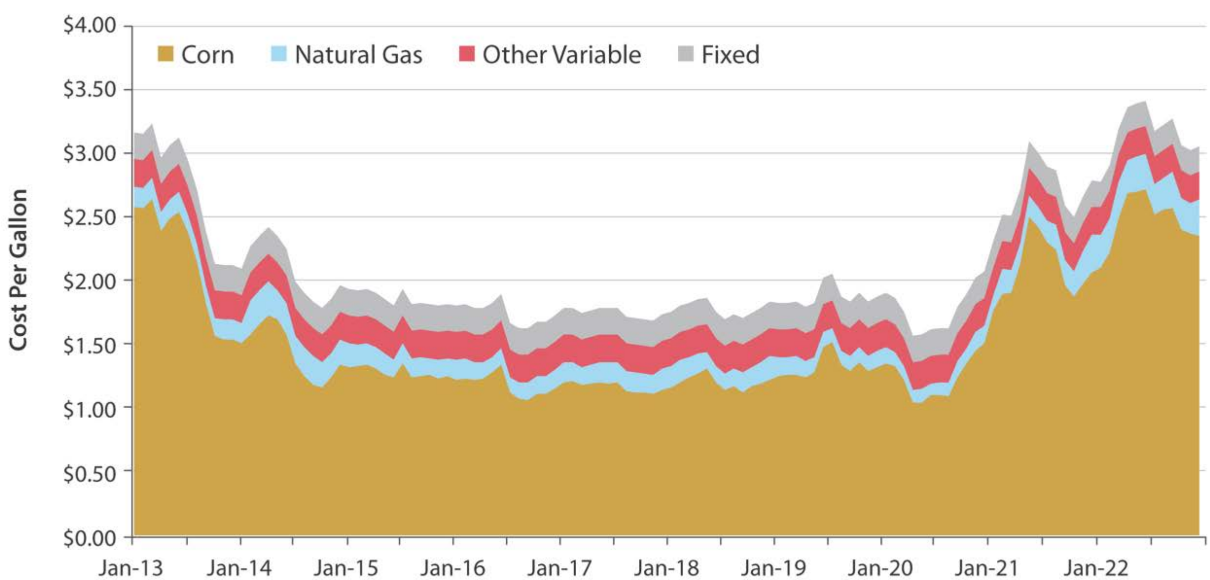

Figure 28. U.S. corn grain ethanol production cost trends.

Source: Hofstrand (2023b)

The largest ethanol markets are located on the east and west coasts of the United States, outside of the primary corn grain production region. Most ethanol produced in the United States is shipped on trains to those markets because ethanol is not shipped by pipeline due to fuel properties. Ethanol prices are typically lowest in the Midwest and increase as a function of transportation costs when shipped to other domestic markets.

2.7.3 Coproducts Overview

Fuel ethanol coproducts include distillers grains,[25] corn gluten meal/feed, corn oil, and carbon dioxide. The gross value of coproducts was $13.2 billion in 2022 (RFA 2023a). Corn grain is approximately two-thirds starch, which is converted into ethanol and carbon dioxide; the remaining are converted into distillers grains and corn oil. Distillers grains are the highest-volume coproduct and are sold as livestock feed, and about one-third is exported to 50 countries (Figure 29, RFA 2023b). The top three export markets in 2022 were Mexico, Vietnam, and South Korea (RFA 2023b).

About 90% of ethanol plants have added dry fractionation technology at the front end of their plant to extract nonedible corn oil at a rate of about 0.9 pounds per bushel, which is used as a feedstock for biodiesel/renewable diesel plants or in animal feed (RFA 2023a). Figure 30 shows corn oil production of 2.1 million tons in 2022 while 2.8 million tons of carbon dioxide were captured (RFA 2023c). Thirty percent of dry-mill ethanol plants capture carbon dioxide—those closer to cities sell carbon dioxide for use in pharmaceutical and food products (RFA 2023a). The ethanol industry is considering various carbon capture technologies, as they qualify for an IRA tax incentive of $85/metric ton.

[25] Distillers grains are sold in variations of two forms: wet distillers grains and dried distillers grains. Wet distillers grains have a short shelf life and are generally delivered to livestock operations within driving distance of ethanol plants. Dried distillers grains have a much longer shelf life and can be delivered to livestock operations throughout the country and exported.

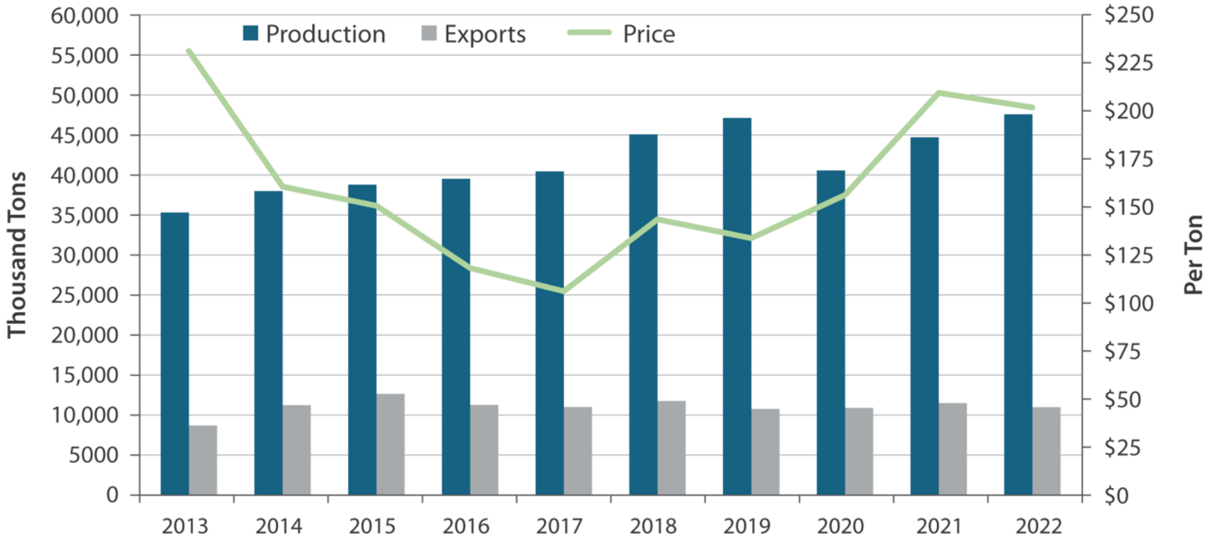

Figure 29. U.S. starch ethanol distillers grains production, trade, and price.

Source: production: RFA (2023c); exports: USDA-ERS (2023a); prices at production facilities (annual average of prices at production facilities in Iowa, Illinois, Nebraska, South Dakota, and Wisconsin): Ag Marketing Resource Center (2023)

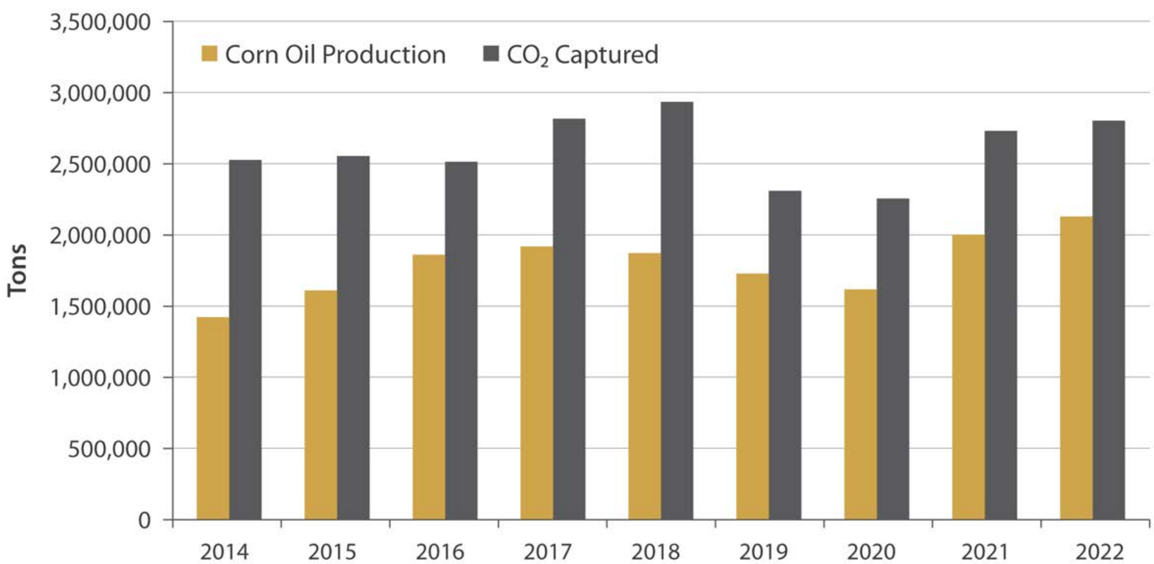

Figure 30. U.S. starch ethanol corn distillers oil and carbon dioxide captured.

Source: RFA (2023c)

2.7.4 Ethanol Trade

Ethanol is both imported and exported as a function of demand or biofuel use requirements in other nations (Figure 31). The United States is the world leader in ethanol production, accounting for 55% of 2022 world production (RFA 2023b). Nearly 100% of imports in 2022 were Brazilian sugarcane-based ethanol, which qualifies as an advanced biofuel under the RFS, and the remainder were from Canada (EIA 2023o). The United States exported 1.35 billion gallons valued at $4.1 billion in 2022, which was 8.8% of domestic production (EIA 2023p; RFA

2023b). Exports were to 50 nations, and the United States' three largest trading partners were Canada (37%), South Korea (12%), and the European Union (11%) (EIA 2023p).

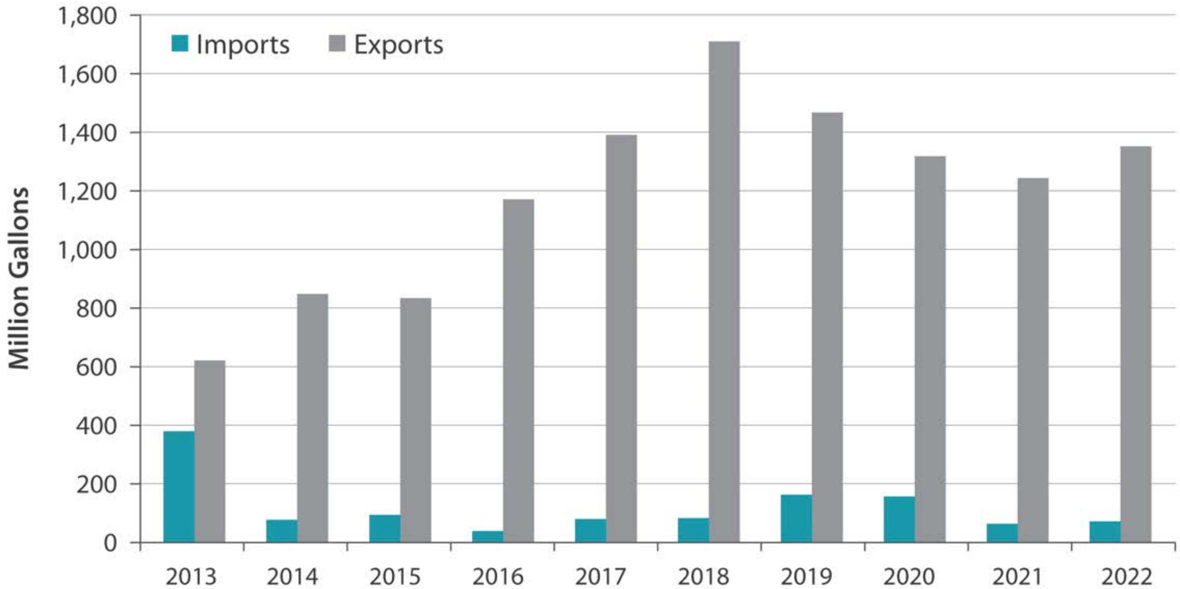

Figure 31. U.S. ethanol imports and exports.

Source: EIA (2023o; 2023p)

2.7.5 Infrastructure

Regulations have long accommodated the use of E10 in existing infrastructure. Blends above E10 require approvals and some specialized equipment to meet the patchwork of regulations that cover refueling infrastructure (summary in Section 2.6.5).

Stations interested in selling ethanol blends can refer to Clean Cities' *Handbook for Handling, Storing, and Dispensing E85 and Other Ethanol-Gasoline Blends*, which explains requirements for selling ethanol blends and provides lists of compatible and UL-listed equipment (DOE 2016).[26]

As of the end of 2022, E85 was available at 4,426 stations in 44 states (Figure 32, AFDC 2023b). As of the end of 2022, there were 2,900 stations in 30 states selling E15 (Growth Energy 2023). USDA's HBIIP resulted in more stations offering E15 and E85 in recent years, and an additional $450 million in funding is available from the program through 2024 (USDA 2023).

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[26] Clean Cities' *Handbook for Handling, Storing, and Dispensing E85 and Other Ethanol-Gasoline Blends* (DOE 2016) provides lists of compatible tanks, pipes, and associated underground storage tank equipment, as well as UL-listed dispensers and hanging hardware.

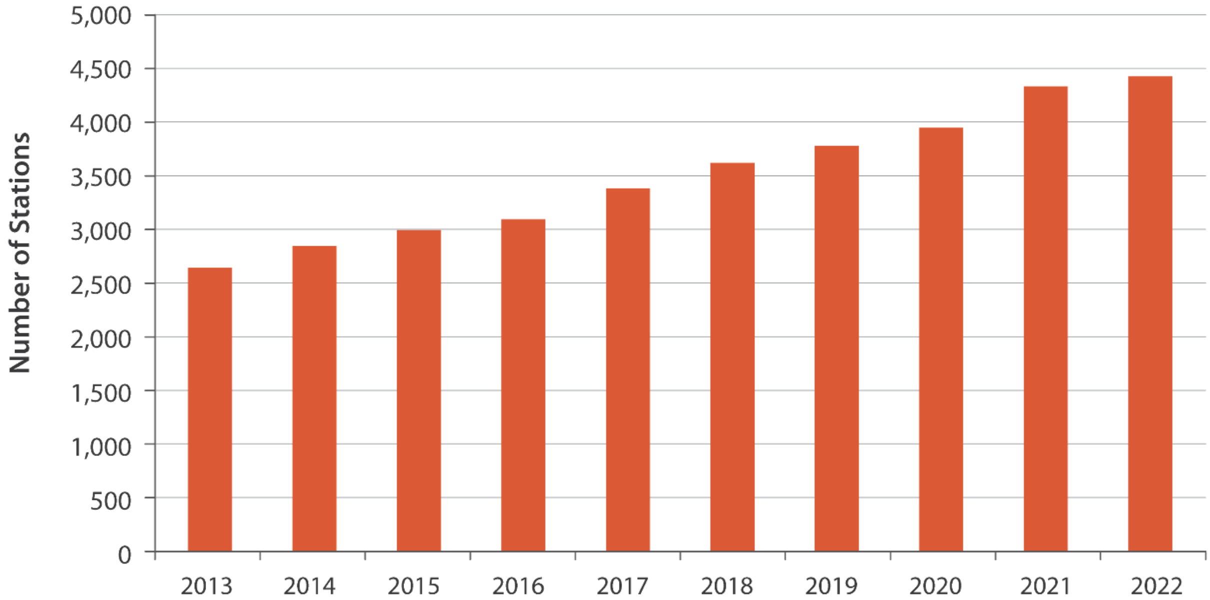

Figure 32. U.S. E85 stations.

Source: AFDC (2023b)

2.7.6 End Use

All 270 million U.S.-registered light-duty gasoline vehicles are able to operate on E10. MY 2001 and newer light-duty trucks and vehicles are approved by EPA to operate on E15 (EPA 2023f). At the end of 2022, 95% of the gasoline light-duty truck and vehicle population was MY 2001 and newer.[27]

FFVs can operate on any gasoline-ethanol blended fuel between E0 and E85, and there were nearly 21 million FFVs on U.S. roads at the end of 2022. There were 42 models from six manufacturers in MY 2017, but only four models offered from two manufacturers in MY 2023. The reason for the decline was a change to the National Highway Traffic Safety Administration's Corporate Average Fuel Economy standards, in which auto manufacturers receive a credit for FFVs sold. For MY 2020 and beyond, auto manufacturers must demonstrate that the vehicle is using E85 to obtain credits, which has led to a steep decline in the availability of FFVs.

2.8 Renewable Natural Gas

RNG, or biomethane, is a pipeline-quality gas that is interchangeable with conventional natural gas and thus can be used in natural gas vehicles. RNG is essentially biogas (the gaseous product of the decomposition of organic matter, composed primarily of methane, carbon dioxide, and other trace compounds) that has been processed to purity standards. Like conventional natural gas, RNG can be used as a transportation fuel in the form of compressed natural gas or liquefied

[27] Derived registration counts by the National Renewable Energy Laboratory, Experian Information Solutions.

natural gas. RNG meets the 60% GHG emissions reduction threshold to qualify as a cellulosic biofuel under the RFS and is currently the main contributor to this fuel category (EPA 2023a).

Biogas is produced from landfill biogas, agricultural wastes, food waste, and wastewater treatment plants through a biochemical process, such as anaerobic digestion, or through thermochemical means, such as gasification. With minor cleanup (e.g., siloxane removal), most biogas is used to generate electricity and heat. To fuel vehicles, biogas must be processed to a higher purity standard. This process is called conditioning or upgrading and involves the removal of water, carbon dioxide, hydrogen sulfide, and other trace elements. The resulting RNG has a higher content of methane than raw biogas, which makes it comparable to conventional natural gas and thus a suitable energy source in applications that require pipeline-quality gas.

RNG's contribution to the economy includes an estimated 38,000 jobs and $4.8 billion to gross domestic product (RNG Coalition 2022). For every 1 MMBtu of RNG generated, 22 jobs were created (RNG Coalition 2022). RNG systems offer socioeconomic benefits, including generating revenue streams and boosting the local economy. Along with generating revenues from wastes from the sale of renewable energy products, outputs from biogas systems can offer avoided costs of on-site electricity, heat, and transportation fuel.

2.8.1 Renewable Natural Gas Production and Potential

EPA reports nearly 578 million RINs or ethanol gallon equivalent of compressed RNG and about 91 million RINs or ethanol gallon equivalent of liquefied RNG were consumed in 2022 (EPA 2023a). Figure 33 shows the increase in RNG production over the past 10 years due to a combination of more production facilities coming online and increased production at existing plants. The combined 2022 volume corresponds to about 669 million gallons ethanol equivalent, or roughly 51.4 TBtu. RNG accounted for 69% of the fuel used in on-road natural gas vehicles in 2022 (Gage 2023).

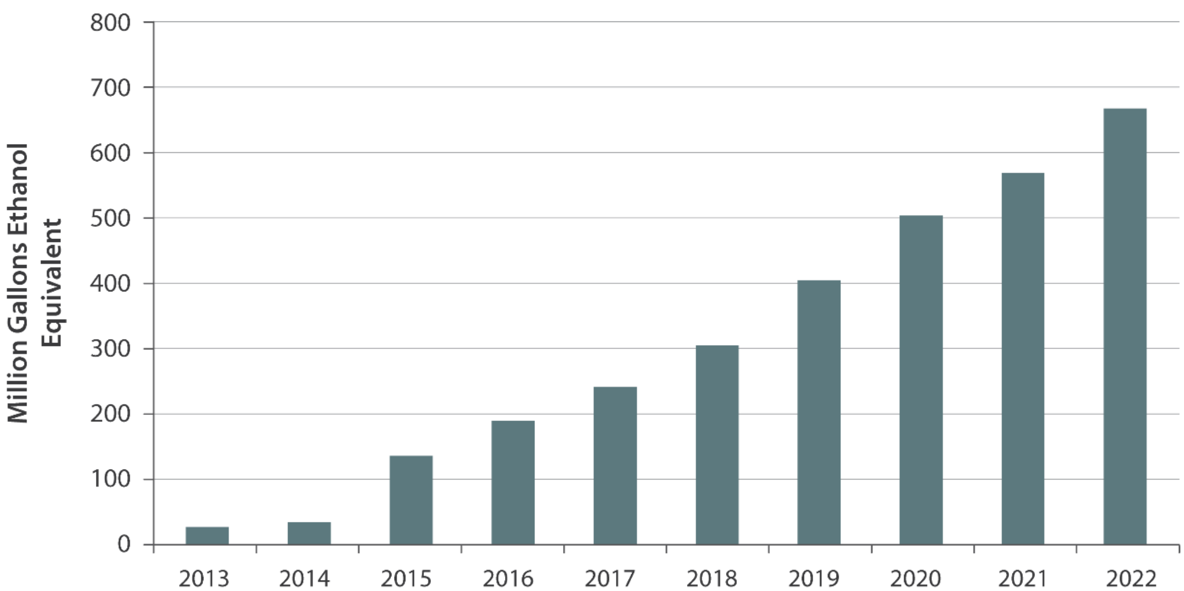

Figure 33. U.S. estimated renewable natural gas consumption.

Source: EPA (2023a)

A study funded by the American Gas Foundation evaluated low and high resource utilization scenarios for biogas to RNG through 2040. They estimate that anaerobic digestion potential is from 813 to 1,425 TBtu/y, and the potential from thermal gasification is between 487 and 1,714 TBtu/y (American Gas Foundation 2019).

Table 3. U.S. 2040 RNG Potential

Source	Low Resource Potential Scenario TBtu/y	High Resource Potential Scenario TBtu/y
Landfill Gas	528	866
Animal Manure	231	462
WRRF	24	34
Food Waste	29	64
Anaerobic Digestion Subtotal	**812**	**1,426**
Agricultural Residue	254	641
Forestry and Forest Residue	108	236
Energy Crops	123	838
Thermal Gasification Subtotal	**485**	**1,715**
Total	**1,297**	**3,141**

Source: American Gas Foundation (2019)

2.8.2 Other Uses for Renewable Natural Gas

Natural gas utilities are increasingly adding RNG to their pipeline mix to reduce carbon emissions. By the end of 2021, RNG projects produced an estimated 73 TBtu (ANL 2023). Approximately 43.9 TBtu, or 60% of total start-of-year capacity were used for transportation fuel to generate RINs in 2022 (Argonne National Laboratory 2023). Some portion of the remaining 29.3 TBtu or 40% of production capacity was probably sold to utilities or private entities as RNG for non-transportation pipeline use.

2.8.3 Renewable Natural Gas Production Costs

Production cost depends on many factors, including facility size, biomass availability and cost, conversion processes, conversion yield, capital costs, delivery costs, distribution infrastructure, and others. Table 4 shows estimated supply cost curves for each biogas source for RNG production. Landfill gas and water resource recovery facilities represent the most cost-effective sources of RNG. LCFS provide more carbon reduction credits for RNG produced from animal manure and food waste, allowing for economic development of projects with relatively high cost per million Btu.

Table 4. U.S. RNG Estimated Production Costs

Production Method	Source	Production Cost Range ($/MMBtu)
Anaerobic digestion	Landfill gas	$6.5 to $19 (est.)
	Animal manure	$18.4 to $32.6
	Water resource recovery facilities	$7.4 to $26.1
	Food waste	$19.4 to $28.3
Thermal gasification	Agricultural residue	$18.3 to $27.4

Source: American Gas Foundation (2019)

2.9 Marine and Rail Biofuels

International marine transport is responsible for transporting 90% of global goods and contributes about 3% of worldwide GHG emissions (DOE 2023c). Large ships are mostly fueled by heavy fuel oil. DOE is funding research projects to demonstrate the feasibility of sustainable marine fuels. Feedstocks under consideration include forestry and agricultural residues, energy crops, waste oils/fats/greases, manure, sewage sludge, landfill gas, algae, and municipal solid wastes. Biofuels accounted for less than 0.5% of global marine fuel use in 2022 (IEA 2023). During the pandemic, there were multiple successful trials of biofuels by large shipping companies (Kass et al. 2022).

Multiple sustainable marine fuels are under evaluation. Drop-in fuels would require minimal changes prior to use in existing engines and infrastructure. These include renewable diesel, biodiesel, hydrotreated vegetable oils, bio-oil, and bio-crude. Emerging, non-drop-in fuels include bio-methanol, lignin-alcohol mixes, and bio-based natural gas. These fuels may require new engine designs and other modifications. Ammonia from hydrogen is also being investigated.

DOE is working with the rail industry stakeholders to identify future propulsion technologies, research, and infrastructure needs to enable alternative fuels and engines to decarbonize rail transportation.

3 Biopower

Biomass power, or biopower, is the use of biomass resources to generate electricity. There are five major types of biopower-generation technologies: combustion, co-firing, gasification, anaerobic digestion, and pyrolysis. Combustion is used by most biopower plants today—bioenergy feedstock is burned directly to produce steam that turns an electricity-generating turbine (IRENA 2012). The steam could also be used for industrial processes or to heat buildings in combined heat and power facilities. Co-firing power plants substitute solid biomass for a portion of the other primary fuel in use. In gasification systems, solid biomass is heated in a restricted supply of air to produce an energy-rich gas that can fuel steam generators, combustion turbines, combined-cycle technologies, or fuel cells. Anaerobic digestion is a biological process in which microorganisms break down biodegradable material in the absence of oxygen. One of the end products of anaerobic digestion is biogas, composed primarily of methane, carbon dioxide, and other trace compounds. The methane is usually burned in a boiler to produce steam for electricity generation or for industrial processes, but it could also power microturbines and gas engines and feed fuel cells. Pyrolysis involves the chemical decomposition of organic materials at elevated temperatures in the absence of oxygen to produce liquid, gas, and char. The resulting pyrolysis oil can be used in traditional power generation and heating applications with minor modifications.

There are also modular bioenergy systems, which are biomass energy systems (e.g., combined heat and power, anaerobic digestion, and gasification) at small scale used in off-grid, distributed-generation applications. Combustion, combined heat and power, anaerobic digestion, and low-percentage co-firing are mature, commercially available technologies, whereas commercial gasification and pyrolysis are in earlier stages of development, demonstration, and deployment.

Biomass electricity generation accounts for nearly 6% of all utility-scale renewable energy generated in the United States and about 1.2% of total U.S. electricity generation (EIA 2023d; 2023k). Both installed biopower capacity and generation have been declining over the past 5 years, (Figure 34). In 2022, the top five states with the largest biopower generation were Georgia, California, Florida, Virginia, and South Carolina (EIA 2023l).

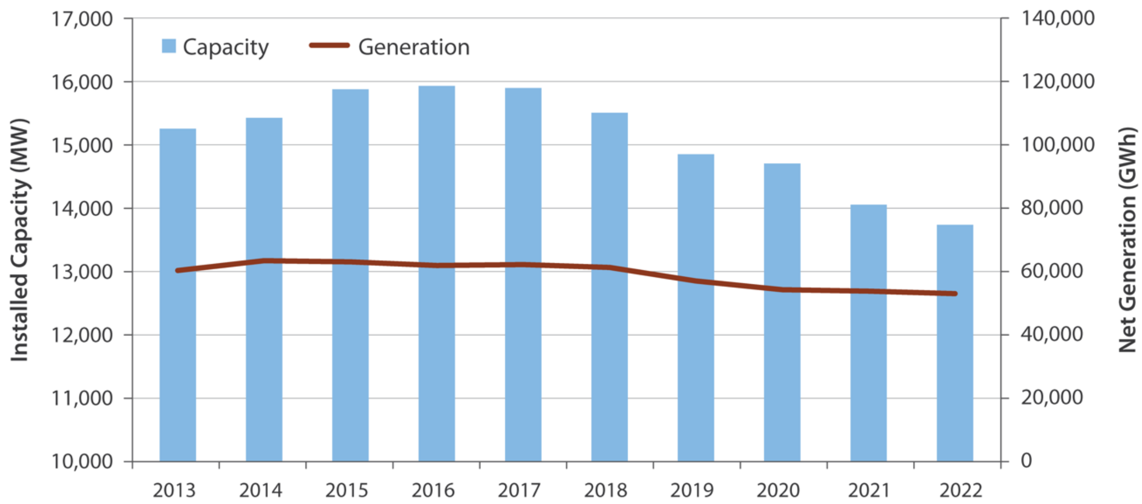

Figure 34. U.S. biopower capacity and generation.

GWh = gigawatt-hour; MW = megawatt

Source: EIA (2023l; 2023r)

4 Biochemicals and Bioproducts

Biochemicals and bioproducts are two broad categories used to classify products produced from biomass feedstocks. Conventional bioproducts, including building material, pulp and paper, and forest products, have long been available. Emerging bioproducts as a focus of research and development include biochemicals, bioplastics, and bioadhesives. Bioproducts derived from bioresources can replace (either directly or indirectly) some of the fuels, chemicals, plastics, etc., that are currently derived from petroleum. Many biochemical and bioproduct manufacturers currently treat their production and pricing information as confidential because they pursue competitive advantages within this emerging market sector.

The industrial sector is a key enabler for providing the energy and end-use products that use crude oil, natural gas, coal, and biomass to provide basic raw materials for producing the chemicals that are intermediates to most commercial and household products used worldwide. Although the petrochemical industry has been impacted by energy trends, increasing population, and global economic growth have led to supply chain imbalances that could potentially lead to increased uncertainty and future investment decisions. Regardless, the petrochemical industry in North America is expected to increase in the next 5 years driving the production of building block chemicals. With the increasing energy demand and use of end products, the chemical industry has become increasingly vigilant about using alternative nonfossil feedstocks to meet supply chain demand.

Production of bioproducts can (1) enable the production of bioenergy feedstocks as coproducts to improve the economics of the primary fuel product in an integrated biorefinery (Biddy, Scarlata, and Kinchin 2016) or (2) enable industrial learning to develop technologies and processes essential to the long-term production of biofuels and bioenergy. A broad range of chemicals and their production from alternative feedstock sources to increase the deployment and scale up the production of these chemicals were assessed. The future potential for 12 selected chemicals and provided details on key drivers and challenges associated with moving toward production of biomass-derived technologies. Furthermore, it evaluated the impacts of scaling up these technologies on accelerating the production of biofuels.

The 2019 report commissioned by the USDA BioPreferred Program (Daystar et al. 2020) provides an analysis of specific bio-based segments within the U.S. economy. The report evaluates agriculture and forestry, biorefining, bio-based chemicals, enzymes, bioplastic bottles and packaging, forest products, and textiles as the seven major bio-based product industries contributing to the U.S. economy. It specifically excludes contributions to the economy from energy, livestock, food, feed, and pharmaceuticals. The report stated that in 2017 U.S. biobased products accounted for 4.6 million jobs and a $470 billion contribution to the economy. Biobased products displaced 9.4 million barrels of oil and reduced GHG emissions by 12.7 million metric tons of carbon dioxide equivalents per year (Daystar et al. 2020).

Historically, federal incentives and policies have been focused on biofuels; however, recent investments under several federal programs are investing in biochemicals and bioproducts (The White House 2022). Iowa, Minnesota, and Nebraska offer bioproducts production tax credits.[28]

Within this context, this report considers four types of biochemicals and bioproducts: wood pellets, platform and intermediate biochemicals, lignin, and biochar.

4.1 Wood Pellets

Wood pellets are made from compacted sawdust or other residue streams of the wood harvesting and processing industries, including, for example, the milling of lumber or manufacture of wood products (World Forest Industries 2023). Chipping, shredding, and milling are typical first-process steps to create a uniform, doughlike material that is fed through a press containing holes of a uniform size. The pressure of the press causes the temperature of the wood to increase greatly, causing the wood's natural lignin to plasticize slightly, forming a natural binder that holds the pellet together as it cools (Walker 2010). The main advantages of pelletizing are the creation of consistent physical and chemical characteristics, including an improvement of the feedstock's homogeneity, quality, flowability, bulk, and energy density.

As of December 2022, there were 97 wood pellet plants in the United States with a total annual capacity of 13.4 million tons employing 2,6101 people (EIA 2023s). A number of different feedstocks are used to produce pellets. In 2022, 15.7 million tons of feedstock were used (Figure 35) to produce approximately 10.5 million tons of wood pellets (EIA 2023s). Woody feedstock prices ranged between $24 and $39 per ton, and feedstock types used to produce wood pellets include other residuals (41%), roundwood/pulpwood (24%), sawmill residuals (16%), and wood product manufacturing residuals (19%) (Figure 35, EIA 2023s). Production is concentrated in the South (~85%) due to the availability of feedstocks and proximity for export to European Union nations (EIA 2023s).

In 2022, 10.5 million tons of wood pellets were produced and 8.8 million (85%) were exported (Figure 36, EIA 2023s). The key market driver for exports is bioenergy policies across northwestern Europe. In 2022, the top exports markets were the United Kingdom (59%), the Netherlands (20%), and Japan (7%) (Voegele 2023b). The average domestic and export prices were $203.99 and $195.48 per ton, respectively (EIA 2023s).

[28] For more information on the Iowa Renewable Chemicals Production Tax Credit, visit https://www.iowaeconomicdevelopment.com/RenewableChem. For more information on the Minnesota Renewable Chemical Production Incentive Program, visit https://www.mda.state.mn.us/environment-sustainability/renewable-chemical-production-incentive-program.
For more information on Nebraska's Chemical Production Tax Credit Act, visit https://opportunity.nebraska.gov/programs/incentives/renewable-chemical-production/.

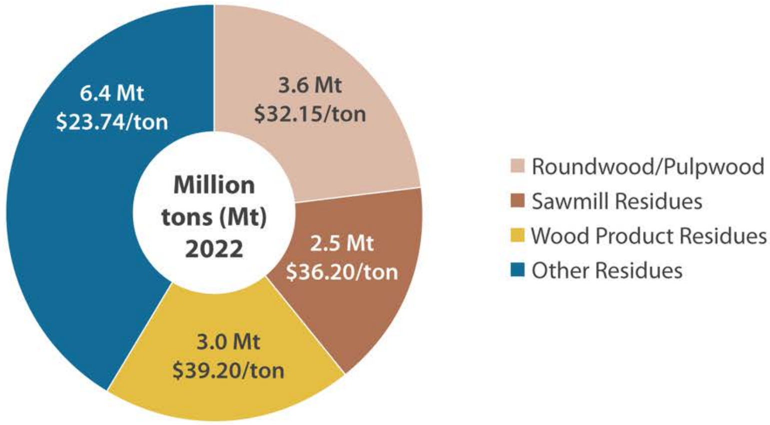

Figure 35. U.S. wood pellet feedstock usage and prices in 2022.

Source: EIA (2023s)

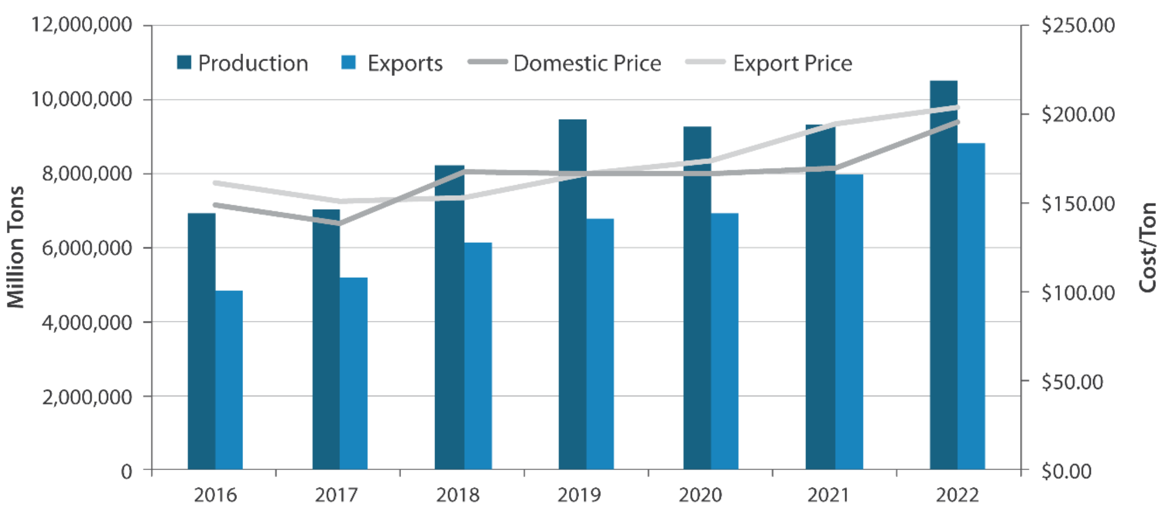

Figure 36. U.S. annual production, exports, and prices of wood pellets.

Source: EIA (2023s)

4.2 Platform and Intermediate Biochemicals

The biochemicals market is an emerging and immature market; thus, market production volumes and prices are unavailable. A nationally accepted system for certifying and tracking production volumes (similar to RINs for biofuels) and competitive market pricing for many biochemicals do not yet exist. Examples of manufacturers producing platform and intermediate chemicals include DuPont Tate and Lyle's 1,3-propanediol facility in Tennessee, AGAE Technologies biosurfactant facility in Oregon, and NatureWorks' polylactic acid facility in Nebraska (DOE 2015). Commercial production of biochemicals is developing to seek out cost advantages (relative to traditional petrochemical production routes), GHG emissions reductions, and U.S. independence from foreign oil. Additionally, these facilities are stimulating the biomass feedstock supply chain for future producers of biofuels and bioproducts.

Two important reports on chemical analysis include (1) *Chemical Bandwidth Study Exergy Analysis: A Powerful Tool for Identifying Process Inefficiencies in the U.S. Chemical Industry* (Ozokwelu, Porcelli, and Akinjiola 2006) and (2) *DOE Bandwidth Study: Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in U.S. Chemical Manufacturing* (Brueske et al. 2015). The 2006 study relied on extensive software simulations to identify the quality of energy consumed in manufacturing chemicals and the amount of energy that could be recovered. The 2015 study compared diverse industrial, academic, and governmental consumption data to analyses of reported plant energy consumption data in the Manufacturing Energy Consumption Survey conducted by the EIA for data year 2010. Additionally, the 2015 study expanded the number of chemical products studied from 44 to 74 and updated energy consumption and production values to 2010 (Brueske, Kramer, and Fisher 2015).

According to the recent DOE report, *Pathways to Commercial Liftoff: Decarbonizing Chemicals & Refining* (Brennan et al. 2023), chemical production and refining accounted for ~11% (~533 MT) of energy-related carbon dioxide emissions in 2021 and ~38% of all industrial carbon dioxide emissions. Bio-based materials provide sustainable alternatives for fossil-based chemicals, reducing the need for conventional virgin plastic and the combustion of nonrenewable fuels in two main ways:

- Bio-feedstocks for conventional chemicals and materials. Renewable biomass can produce bio-based chemicals feedstocks, such as bio-based ethylene or bio-naphtha, which can directly replace traditional chemicals with the same end-use specifications.
- Bio-based replacement materials. Bio-based feedstocks can also be made into new materials, such as biodegradable polyhydroxyalkanoates and polyhydroxybutyrates.

These bioproducts can replace fossil-based plastic and provide performance-advantaged properties (e.g., increased strength and tolerance for heat or moisture) (Brennan et al. 2023).

4.3 Lignin

Lignin is an aromatic heteropolymer that constitutes between 15% and 30% of the mass of plants, making it the second most abundant terrestrial biopolymer behind cellulose and the only large-volume renewable resource composed of aromatics (Ragauskas et al. 2014).

Lignin extraction from biomass is an essential process step prior to ethanol production in cellulosic biorefineries as well as in the pulp and paper industry. High extents of lignin extraction can be attained, leaving behind relatively pristine carbohydrate pulps suitable for downstream conversion (Humbird et al. 2011). Research progress in lignin valorization (conversion) into saleable products has comparably lagged carbohydrate conversion technologies due to the difficulty of further targeted upgrading of extracted lignin. The recalcitrance arises due to the generation of reactive intermediates via the cleavage of labile aryl ether bonds during extraction, which subsequently react to form new C-C bonds. These new linkages are difficult to cleave, making the resulting lignin resistant to further upgrading (Kim et al. 2011). Markets for condensed lignins include dispersants and adhesives, among others, but less than 2% of generated lignin is estimated to be sold as these coproducts, with the majority being burned for process heat in the pulp and paper industry (Bajwa et al. 2019).

Lignin valorization to fuels and chemicals has substantial potential to improve both the economic and environmental viability of biorefineries (Davis et al. 2018; Corona et al. 2018). Aside from fuels, lignin can be converted into high-value products such as polymers, pharmaceuticals, and other fine chemicals (Sun et al. 2018; Afanasenko et al. 2024; Wu, De bruyn, and Barta 2023).

4.4 Biochar

Biochar is a solid material obtained from the thermochemical conversion of biomass in an oxygen-limited environment. Biochar, in the form of a charcoal, can be used as a soil amendment and thus represents an avenue for GHG mitigation by contributing to carbon sequestration when applied to soils (Hofstrand 2010). Because pyrolysis is one of the conversion pathways used to produce biofuels, biochar can be produced as a coproduct with biofuels produced via pyrolysis.[29] While the process for producing biochar is similar to that used for producing fossil-based charcoal, the primary use of charcoal is as a fuel for the production of heat, thus differentiating charcoal as a product from biochar based on application (International Biochar Initiative 2018).

The pyrolysis process is the thermal decomposition of organic materials in an oxygen-free environment at about 300°C to 600°C. This process converts biomass into biochar, pyrolysis gas, and bio-oil products. During pyrolysis, the lignocellulosic components (cellulose, hemicellulose, and lignin) go through different stages, including depolymerization, fragmentation, and cross-linking, resulting in a variety of products. The solid and liquid products comprise the char and bio-oil, and gaseous products are pyrolysis gas (C1–C2 hydrocarbons), carbon dioxide, and carbon monoxide. The biochar yield depends on operational conditions, including temperature, residence time, heating rate, and pressure, among which temperature is the main parameter. Increasing temperature leads to a decrease in biochar yield and an increase in pyrolysis gas. However, higher temperature also leads to higher stable carbon in biochar, which is a desirable property if long-term carbon sequestration in biochar and soil is the driving factor for the production and application of biochar from biomass.

Pyrolysis can be classified as either fast or slow pyrolysis depending on the heating rate, temperature, residence time, and pressure. Fast pyrolysis has a high heating rate (>100°C/second and liquefies solid biomass into bio-oil, which can be converted to fuel products. In slow pyrolysis the rate of heating is low (e.g., around 1°C/second), which produces more biochar than other coproducts, such as pyrolysis gas. It should be noted that the small amount of bio-oil produced during slow pyrolysis is different from the energy-rich bio-oil from fast pyrolysis (Brown, Wright, and Brown 2011). In practice, condensable liquids or bio-oil from slow pyrolysis are not expected to be recovered as coproducts; these liquids are typically burned with pyrolysis gas for process energy.

Biochar production is assumed to be co-located with a corn starch ethanol plant and employs slow pyrolysis conversion using corn stover as feedstock. The bolt-on slow pyrolysis process is energy self-sufficient and generates extra pyrolysis gas. One of the options for using the extra pyrolysis gas could be the displacement of natural gas with pyrolysis gas to meet process heat

[29] Pyrolysis oil is sold in the northeastern United States as renewable heating oil, which could enable the production of biochar as a coproduct for sale as a bioproduct: http://www.energy.gov/sites/prod/files/2015/04/f22/demonstration_market_transformation_butcher_5301.pdf.

demand at the corn starch ethanol facility. This strategy could help reduce the CI of corn ethanol production in addition to the carbon sequestered in biochar when applied to cropland.

A recent study by Thengane et al. (2021) investigated the cost, market, and barriers of commercial-scale biochar production and application in California using locally available agricultural and forestry biomass. Given the large variations in feedstock cost as well as differences in technology and capacity, the study found that biochar production cost in California could range from $200 to $1,000 per U.S. ton, with an average of around $400 per U.S. ton for most producers. Detailed techno-economic analyses for commercial-scale biochar production via slow pyrolysis using corn stover are scarce.

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Appendix A. EPA RIN Data

Table A-1. 2022 Renewable Identification Number Generation

Source: EPA (2023a)

Fuel	Equivalence Value (EV)	Cellulosic Biofuel (D3)		Biomass-Based Diesel (D4)		Advanced Biofuel (D5)		Renewable Fuel (D6)		Cellulosic Diesel (D7)	
		RINs (ethanol eq.-gallons)	Volume (gallons)	RINs (ethanol eq.-gallons)	Volume (gallons)	RINs (ethanol eq.-gallons)	Volume (gallons)	RINs (ethanol eq.-gallons)	Volume (gallons)	RINs (ethanol eq.-gallons)	Volume (gallons)
Ethanol	1	1,396,503	1,396,503			109,468,380	109,468,380	14,418,411,081	14,418,411,081		
Liquid propane gas	1.1					4,792,374	4,356,702				
Biodiesel	1.5			2,790,490,929	1,860,308,147						
Naphtha	1.4, 1.5					94,980,691	63,421,803				
Heating oil	1.6			550,200	343,875	3,042,574	1,901,608				
Renewable jet fuel	1.6			25,311,805	15,819,877						
Non-ester renewable diesel	1.6, 1.7			2,970,432,552	1,750,829,725	129,144,016	75,967,064	127,436,021	74,962,365		
Cellulosic heating oil	EV application required									236,352	236,352
Renewable compressed natural gas	n/a	576,679,829	576,679,829			1,053,739	1,053,739				
Renewable liquefied natural gas	n/a	90,517,844	90,517,844								

Appendix B. Operational and Under Construction Sustainable Aviation Fuel Plants

Table B-1. Operational and Under Construction Sustainable Aviation Fuel Plants

Plant Name	Location	Technology	Feedstocks	Notes
Operational				
Biomaterial in Tokyo Co.	Kawasaki-shi, Japan	Fermentation	Lignocellulosics	Pilot
BP	Castellon, Spain	Hydrotreatment	Oil crops, oils, and fats	Co-processing with petroleum
CSIR-Indian Institute of Petroleum	Dehradun, India	Hydrotreatment	Jatropha, used cooking oil	Pilot; feedstock input 100 tonnes/year
Eni	Livorno, Italy	Hydrotreatment	Used cooking oil	Co-processing with petroleum; SAF output of 10,000 tonnes/year
Eni	Gela, Sicily	Hydrotreatment	Used cooking oil	RD 750,000 tonnes/year
Eni	Taranto, Italy	Hydrotreatment	Used cooking oil	Co-processing with petroleum
Euglena Co	Yokohama-shi, Japan	Hydrotreatment	Used cooking oil, microalgae	Pilot; 125 m^3/yr
Gevo	Sisbee, TX	Alcohol-to-jet	Isobutanol	Pilot; SAF output 265 m^3/yr
Montana Renewables LLC	Great Falls, MT	Hydrotreatment	Waste fat, oil, and grease	SAF output 2,000–15,000 barrels/day
Neste	Porvoo, Finland A	Hydrotreatment	Palm Oil, rapeseed oil, and animal fat	2 plants; SAF 100,000 tonnes/year, RD 280,000 tonnes/year
Neste	Rotterdam, Netherlands	Hydrotreatment	Oils and fats	RD 800,000 tonnes/year
Neste	Singapore	Hydrotreatment	Oils and fats	RD 800,000 tonnes/year
Pertmina	Cilacap, Indonesia	Hydrotreatment	Oil crops, oils, and fats	SAF 450,000 m^3/yr
Preem	Gothenburg, Sweden	Hydrotreatment	Oil crops, oils, and fats	RD 290,000 tonnes/year
Total	Dunkirk, France	Gasification	Straw, forest waste, dedicated energy crops	FT liquid 8,000 tonnes/year
Total	Dunkirk, France	Gasification	Forest waste, straw, green waste, dedicated crops	Pilot; FT liquid 60 tonnes/year
Total	La Mede, France	Hydrotreatment	Sustainable vegetable oils, treated wastes (animal fats, cooking oils, residues)	RD 500,000 tonnes/year
World Energy	Paramount, CA	Hydrotreatment	Oil crops, oils, and fats	RD output 130,000 m^3/yr

Under Construction				
AgBioEn	Katunga, Australia	Gasification	Organic residues and waste streams, cereal straw	
Consortium Toshiba	Japan	E-fuels biomass hybrid	Waste gases	
GreenflexJET Demo	Berkeley, United Kingdom	Hydrotreatment	Waste biomass, vegetable oils	1,200 tonnes/year (SAF output)
OMV	Schwechat, Austria	Hydrotreatment	Oil crops, oils, and fats	Diesel with biogenic content (160,000 tonnes/year)
Respol	Cartagena, Spain	Hydrotreatment	Organic residues and waste streams	RD output 250,000 tonnes/year
St1 Gothenburg	Gothenburg, Sweden	Hydrotreatment	Tall oil	RD output 200,000 tonnes/year

Source: IEA (2023)
FT = Fischer Tropsch; RD = renewable diesel

Appendix C. ASTM Sustainable Aviation Fuel Pathways

Table C-1. ASTM D7566 SAF Production Pathways

Pathway	Approved Name	Blending Limitation	Feedstocks
Fischer-Tropsch synthetic paraffinic kerosene	FT-SPK, ASTM D7566 Annex A1, 2009	50%	Municipal solid waste, agricultural and forest wastes, energy crops
Hydroprocessed esters and fatty acids	HEFA-SPK, ASTM D7566 Annex A2, 2011	50%	Oil-based feedstocks (e.g., jatropha, algae, camelina, and yellow grease)
Hydroprocessed fermented sugars to synthetic isoparaffins	HFS-SIP, ASTM D7566 Annex A3, 2014	10%	Sugars
FT-SPK with aromatics	FT-SPK/A, ASTM D7566 Annex A4, 2015	50%	Same as A1
Alcohol-to-jet synthetic paraffinic kerosene	ATJ-SPK, ASTM D7566 Annex A5, 2016	30%	Cellulosic biomass
Catalytic hydrothermolysis synthesized kerosene	CH-SK or CHJ, ASTM D7566 Annex A6, 2020	50%	Fatty acids or fatty acid esters or lipids from fat oil greases
Hydrocarbon-hydroprocessed esters and fatty acids	HC-HEFA-SPK, ASTM D7566 Annex A7, 2020	10%	Algal oil
Alcohol-to-jet synthetic paraffinic kerosene with aromatics	ATJ-SKA, ASTM D7566 Annex A8, 2023	50%	C2 to C5 alcohols
Fats, oils, and greases co-processing	FOG co-processing ASTM D1655 Annex A1	5%	Fats, oils, and greases
FT co-processing	FT co-processing ASTM D1655 Annex A1	5%	FT biocrude