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BIOENERGY TECHNOLOGIES OFFICE

2015 Bioenergy Market Report

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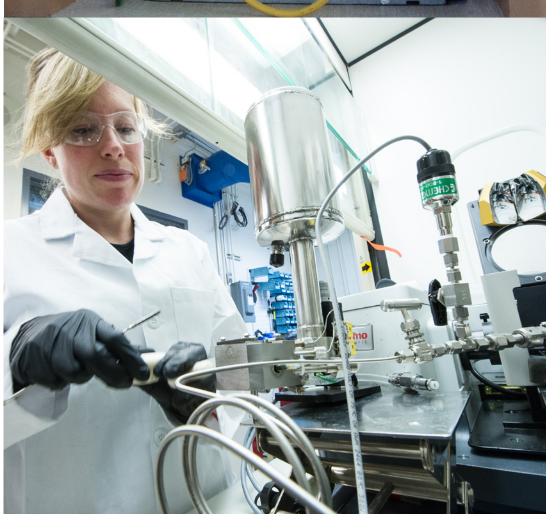

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Preface

This report provides a status of the markets and technology development involved in growing a domestic bioenergy economy. It compiles and integrates information to provide a snapshot of the current state and historical trends influencing the development of bioenergy markets. This information is intended for policy-makers as well as technology developers and investors tracking bioenergy developments. It also highlights some of the key energy and regulatory drivers of bioenergy markets. This report is supported by the U.S. Department of Energy's (DOE's) Bioenergy Technologies Office (BETO), and, in accordance with its mission, pays special attention to the progress and development of advanced liquid transportation fuels from cellulosic and algal biomass.

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.

After opening with a discussion of the overall size and composition of the bioenergy market, this report features two major areas: one detailing the two major bioenergy markets—biofuels and biopower—and another giving an overview of bioproducts that have the potential to enable bioenergy production.

The biofuels section is broken out by fuel type with sections on ethanol, biodiesel, and hydrocarbon fuels (gasoline, diesel, and jet fuel). Ethanol includes both conventional starch ethanol and cellulosic ethanol. This report covers the development of the conventional ethanol industry as a backdrop for emerging cellulosic ethanol production, and discusses challenges with absorbing new production into the market. Hydrocarbon fuels include the developing renewable hydrocarbon biofuels market. Finally, the report offers an overview of the renewable natural gas, biopower, and bioproducts markets.

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

Sincerely,
Jonathan L. Male
Director, Bioenergy Technologies Office
Office of Energy Efficiency and Renewable Energy
U.S. Department of Energy

Acronyms and Abbreviations

AD	anaerobic digestion
ADM	Archer Daniels Midland
AEO	Annual Energy Outlook
AFDC	Alternative Fuels Data Center
ASTM	ASTM International
ATJ	alcohol-to-jet
B5	5% biodiesel, 95% petroleum diesel blend
B20	20% biodiesel, 80% petroleum diesel blend
B100	pure biodiesel
BETO	Bioenergy Technologies Office
Btu	British thermal unit
CAFE	Corporate Average Fuel Economy
CFR	Code of Federal Regulations
CHP	combined heat and power
DOE	U.S. Department of Energy
E10	10% ethanol, 90% gasoline blend
E15	10.5%–15% ethanol and gasoline blend (approved for use in MY2001 and newer vehicles)
E85	high ethanol blend between 51% and 83% ethanol, depending on season and geography
E100	neat ethanol
ege	ethanol gallon equivalent
EIA	U.S. Energy Information Administration
EISA	Energy Independence and Security Act of 2007
EPA	U.S. Environmental Protection Agency
EtOH	ethanol
FFV	flexible-fuel vehicle
FT	Fischer-Tropsch
gge	gasoline gallon equivalent
GHG	greenhouse gas
GWh	gigawatt-hour
HEFA	hydrogenated esters and fatty acids
kWh	kilowatt-hour
LCOE	levelized cost of electricity
LFG	landfill gas
MSW	municipal solid waste
MTBE	methyl tertiary-butyl ether
MW	megawatt
MY	model year
NORA	National Oilheat Research Alliance
NREL	National Renewable Energy Laboratory
RFS	Renewable Fuel Standard
RIN	Renewable Identification Number
RNG	renewable natural gas
RVO	renewable volume obligation
SIP	synthetic iso-paraffin
SKA	synthetic kerosene with aromatics
SPK	synthetic paraffinic kerosene
syngas	synthesis gas
TBtu	trillion Btu
ton	short ton
UL	Underwriters Laboratories
USDA	U.S. Department of Agriculture
VEETC	volumetric ethanol excise tax credit

Executive Summary

This report provides a status of the markets and technology development involved in growing a domestic bioenergy economy. The report compiles and integrates information to provide a snapshot of the current state and historical trends influencing the development of bioenergy markets. This information is intended for policy-makers as well as technology developers and investors tracking bioenergy developments. It also highlights some of the key energy and regulatory drivers of bioenergy markets. 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.

At the end of 2015, the U.S. bioenergy market (shown in Figure ES-1) was dominated by conventional starch ethanol production, which accounts for three-quarters of total U.S. bioenergy production. Biodiesel and biopower make up nearly all the remaining production, while other advanced biofuels contribute a relatively small amount.[1] Biofuels make up the largest portion (approximately 87%) of the current bioenergy market, and this bioenergy market report focuses on documenting the biofuels market in the United States as it existed at the end of 2015.

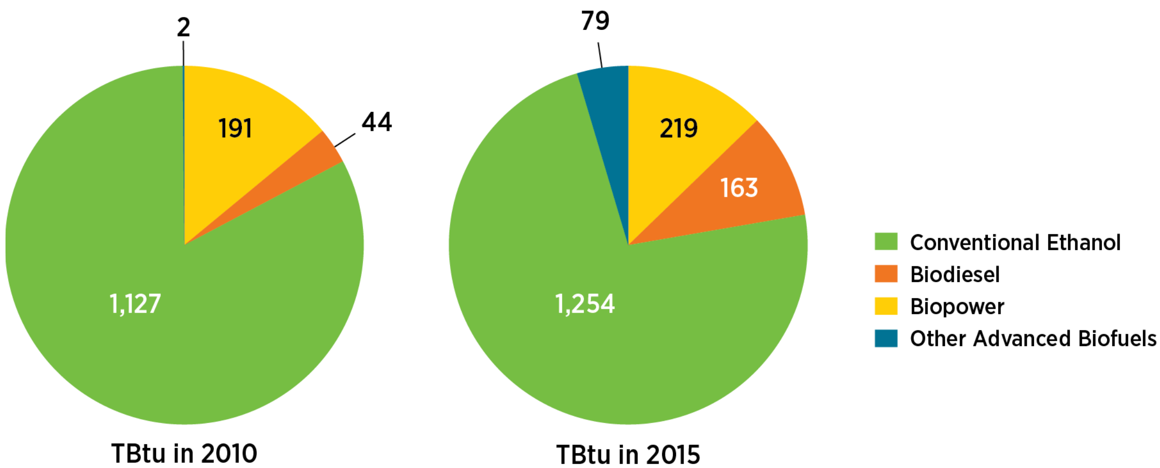

Figure ES-1. U.S. bioenergy market (1,400 trillion British thermal units [TBtu][2] total in 2010 and 1,700 TBtu total in 2015)

Sources: Conventional Ethanol and Biodiesel: EIA 2016a, Tables 10.3 and 10.4; Biopower: EIA 2016b; Other Advanced Biofuels: EPA 2016a. Advanced biofuels include renewable diesel, heating oil, and naphtha, as well as small volumes of imports used to meet federal requirements for advanced biofuels. Note: This figure only includes the energy content of the product fuels and power, and not the associated co-products.

Figure ES-2 shows the development of the biofuels industry from 2006 through 2015. Policy combined with favorable market conditions during this time led to growth in the number and capacity of biofuels plants as well as production. The build-out of starch-based ethanol plants and production was significant between 2006 and 2011 and since then production has not grown as much, reflecting the E10 blend wall. Driven by advanced

[1] Data for other advanced biofuels were obtained from the U.S. Environmental Protection Agency's (EPA's) Renewable Fuel Standard (RFS) data and based on volume generation. Other advanced biofuels include biogas, cellulosic ethanol, ethanol from other advanced feedstocks (including imported sugarcane ethanol), naphtha, renewable diesel, renewable gasoline, renewable heating oil, and renewable natural and liquefied gas. This data set includes small volumes of imported biofuels.

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

biofuels requirements under the Renewable Fuel Standard (RFS) (EPA 2016b), biodiesel production grew between 2011 and 2015. Advanced biofuels, which encompass a wide variety of fuels meeting RFS requirements for feedstocks, conversion pathways, and at least a 50% reduction in greenhouse gas (GHG) emissions, continue to make increases in market penetration.

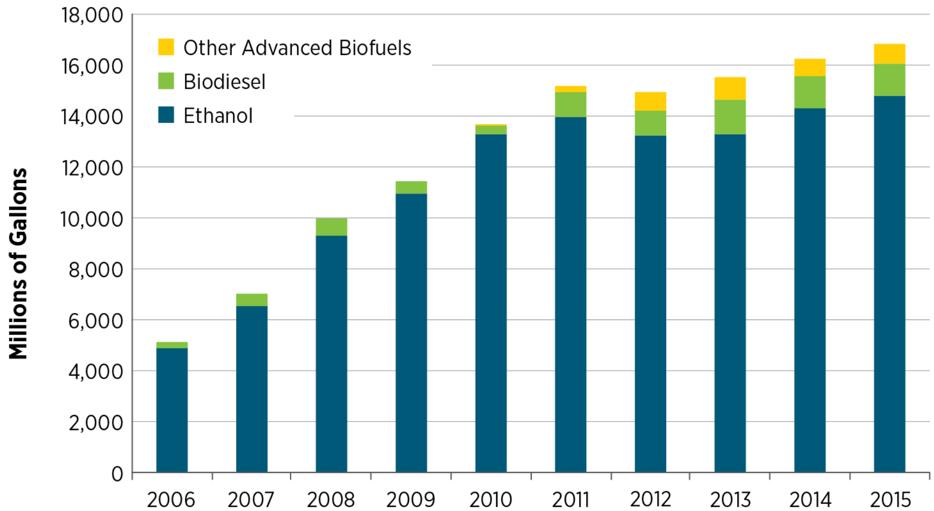

Figure ES-2. U.S. renewable liquid fuels markets

Sources: Ethanol and Biodiesel: EIA 2016a, Tables 10.3 and 10.4; Other Advanced Biofuels: EPA 2016a.[3] Other advanced biofuels include biogas, cellulosic ethanol, imported sugarcane ethanol, naphtha, renewable diesel, renewable gasoline, renewable heating oil, renewable compressed natural gas, and renewable liquefied natural gas.

Ethanol serves as a substitute for gasoline and as an octane enhancer. At the end of 2015, nearly all commercial ethanol biofuel production was from conventional corn starch–based feedstock. The cost of conventional ethanol is driven by the price of corn grain, production costs, and the sale of co-products such as distillers grains, and it is influenced by gasoline prices. At current levels of use, the nation is essentially at a blend wall—where the entire market for E10 (a blend of 10 volume percent ethanol into a gallon of gasoline) is met with conventional ethanol. While there are nearly 20 million flexible-fuel vehicles (FFVs) on the road today that can use higher ethanol blends up to E85, a majority of those vehicles are refueling with E10 gasoline.

Demand for ethanol could increase in future years due to U.S. Environmental Protection Agency (EPA) approval in 2011 of the use of E15 (a blend of 10.5% to 15% ethanol with gasoline) in existing vehicles with model years 2001 and newer. In 2015, less than 1% of stations offered E15 fuel, although more stations are expected to offer E15 fuel in future years due to a U.S. Department of Agriculture (USDA) funding program and industry funding of station infrastructure that can handle higher-level blends.

Conventional ethanol is commercially successful using starch-based feedstock. In 2015, the largest research and development push in the biofuels arena is for biofuels made from cellulosic biomass and algae. To accommodate increased production from cellulosic ethanol biorefineries, the domestic ethanol market would need to grow or exports would need to increase. The RFS requirement for cellulosic biofuels alone may not be enough to encourage investors given current market conditions, such as reduced oil prices and more fuel-

[3] Data for advanced biofuels were obtained from the U.S. Environmental Protection Agency's (EPA's) RFS data and were based on volume generation. Other advanced biofuels include biogas, cellulosic ethanol, ethanol from other advanced feedstocks (including imported sugarcane ethanol), naphtha, renewable diesel, renewable gasoline, renewable heating oil, and renewable natural and liquefied gas. This data set includes small volumes of imported advanced biofuels.

efficient vehicles. In 2015, cellulosic ethanol production increased to about 2.2 million gallons from about 0.73 million gallons in 2014 (EPA 2016a).

Economic impact analysis by industry (Urbanchuk 2016) estimates that ethanol contribution to U.S. gross domestic product increased from $17.7 billion annually in 2005 to $44 billion in 2015. The number of direct jobs has remained somewhat level, with 87,883 during the rapid build-out of plants in 2005 and 85,967 in 2015. The contribution of federal tax revenue from corn ethanol grew from $1.9 billion in 2005 to $4.8 billion in 2015.

Biodiesel production has generally increased during the past 10 years, primarily driven by two policies—the RFS and the biodiesel production tax credit. 2013 was the first year that biodiesel production and consumption exceeded the RFS requirement for biomass-based diesel due to favorable market conditions and a production tax credit. Economic impact analysis by industry (NBB 2016) estimates biodiesel industry economic impact increased from $1.4 billion annually in 2006 to $8.4 billion in 2015. The number of direct jobs biodiesel supported increased from just fewer than 7,000 in 2006 to more than 47,400 in 2015. Wage impacts increased from $260 million in 2005 to $1.9 billion in 2015, implying that the average job supported by the biodiesel sector paid a wage of approximately $39,300/year in 2015.

Renewable hydrocarbon biofuels, sometimes referred to as "drop-in fuels," meet ASTM International fuel quality specifications for gasoline, diesel, and other petroleum fuels that allow them to be used in existing engines and infrastructure (AFDC 2016a). Renewable hydrocarbons are produced from biomass sources through a variety of biological, chemical, and thermal processes. At the end of 2015, there were two commercial facilities (the Diamond Green Diesel and AltAir Fuels facilities in Louisiana and California, respectively) producing renewable hydrocarbon biofuels. Two other facilities (the Renewable Energy Group Inc. [formerly Dynamic Fuels] and KiOR facilities in Louisiana and Mississippi, respectively) were fully constructed, but idled during 2015 due to market conditions or mechanical issues. Despite mixed commercial success during 2014 and 2015 for renewable hydrocarbon biofuels, development continues for biofuel products that can directly replace petroleum-based liquid transportation fuels.

In 2015, biopower accounted for 12% of all renewable energy produced in the United States and about 1.6% of total electricity generation. While the installed biopower capacity has been increasing over the past 10 years, biopower generation has remained almost flat during that period. In 2015, the top five states with the largest biopower generation were California, Florida, Georgia, Virginia, and Maine. Today, most of the 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 co-generation plants—such as pulp and paper mills or sawmills (EIA 2016c). Economic impact analysis estimates that a 50-megawatt (MW) dedicated biomass power plant utilizing direct combustion and using corn stover as feedstock could support about 25 direct onsite jobs during its operation (NREL 2014). A typical 3-MW landfill gas (LFG) electricity project can directly create 5 construction jobs and indirectly create another 20 to 26 direct jobs during the construction year (Pierson 2013). Over their life, LFG projects are expected to add more than $1.5 million in new project expenditures and increase the statewide economic output by $4.1 million (Pierson 2013).

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 in compressed or liquefied form. RNG qualifies as a cellulosic biofuel under the RFS and is currently the main contributor to this fuel category (cellulosic ethanol provides a minor input). EPA reports that about 93 million gasoline gallon equivalents (gge), or roughly 10.8 trillion British thermal units (TBtu) of compressed and liquefied RNG, were produced under the RFS2 program in 2015. This volume accounts for only 2.7 % of the estimated RNG potential in the United States (NREL 2013).

Conventional bioproducts and emerging bioproducts are two broad categories used to categorize products produced from biomass feedstocks. Examples of conventional bioproducts include building materials, pulp and paper, and forest products. Examples of emerging bioproducts include bioadhesives, biopolymers, and biochemicals. Emerging bioproducts are active subjects of research and development, and these development efforts have been driven by the price of traditionally petroleum-based products, the environmental impact of petroleum use, and an interest in becoming more independent from foreign oil. Bioproducts derived from bioresources can replace (either directly or indirectly) some of the fuels, chemicals, plastics, etc., that are currently derived from petroleum. Bioproducts can enable the production of bioenergy, either as co-products to improve the economics of the primary fuel product in an integrated biorefinery, or as enablers in developing technologies and processes essential to the long-term production of biofuels and bioenergy. This report considers four types of bioproducts: platform and intermediate chemicals (emerging bioproducts), along with lignin, biochar, and wood pellets (conventional bioproducts).

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1 Biomass-to-Bioenergy Overview

Bioenergy—fuels, heat, and power derived from biomass sources—is an evolving market that produces and supplies renewable alternatives to fossil fuel sources. This report considers the following bioenergy markets due to their market relevance at the end of 2015:

- Conventional ethanol—ethanol produced from starch (typically corn grain)
- Cellulosic ethanol—ethanol produced from cellulosic biomass, such as agricultural residues and woody resources
- Biobutanol—an alcohol that can be used as a fuel or fuel additive currently produced from starch sources
- Biodiesel—an alternative to diesel that is typically produced from lipids.
- Renewable hydrocarbon biofuels—diesel, jet fuel, and gasoline replacements compatible with existing engines and infrastructure, produced from various sources, such as vegetable and waste oils as well as cellulosic or algal biomass
- Renewable natural gas (RNG)— pipeline-quality gas, derived from renewable organic sources, that is interchangeable with conventional natural gas
- Biopower—generation of electricity from biomass sources
- Bioproducts and co-products—including bioproducts and co-products that are produced in conjunction with biofuels, or that enable bioenergy production.

Production, distribution, and use of bioenergy involve activities across a broad supply chain. These activities include the production of the raw biomass in field or forest; harvest, collection, storage, and transportation of these materials; and preprocessing 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 are inclusive of distribution of and the technical capability to use biofuels, bioproducts, or biopower in end-use markets. 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 2015 market report.

In 2015, U.S. bioenergy production surpassed 1,700 trillion British thermal units (Btu) from ethanol, biodiesel, renewable hydrocarbons, and biopower (EIA 2016a; EPA 2016a). A comparison of the contributions of biofuels and biopower to bioenergy production in 2015 is shown in Figure 1. Conventional starch ethanol production accounts for nearly three-fourths of total bioenergy production. At current levels of ethanol use, the United States is essentially at a blend wall—where the entire market for E10 (a blend of 10 volume percent ethanol and 90 volume percent gasoline) is met with conventional ethanol. Scenarios exist for moving beyond this blend wall—the Renewable Fuel Standard (RFS) and future plans for higher octane fuels create an opportunity to increase ethanol consumption. The best opportunities for near-term market expansion are increasing the use of E15 in 2001 and newer model year (MY) vehicles and increasing the use of E85 in flexible-fuel vehicles (FFVs). A longer-term possibility to increase ethanol consumption is deployment of vehicles with engines optimized to use high-octane fuel (e.g., research octane number 100), which could accommodate ethanol blends of 25% or greater or other high-octane biofuel. While E15 has not been available at many fuel stations, federal and industry funding efforts are expected to expand availability in the near future. More stations are expected to sell E85 for the nearly 20 million FFVs capable of using the fuel. The Corporate Average Fuel Economy (CAFE) has been a primary motivator for auto manufactures to make FFVs. However, the long-term future for E85 is unclear as recent policy changes require vehicle manufacturers to prove FFVs are using E85 to receive a credit in the CAFE regulation. This may result in manufacturers producing fewer or no FFVs in future years.

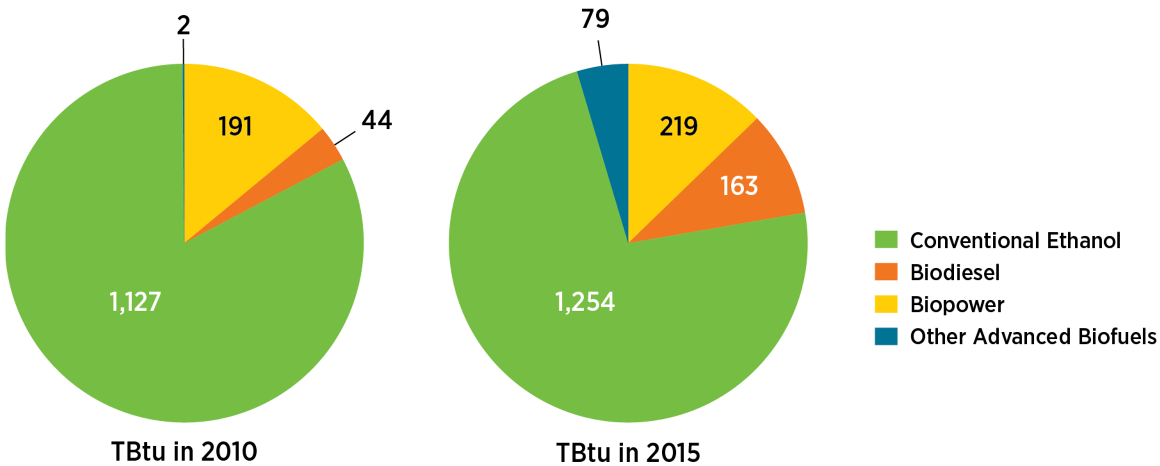

Figure 1. U.S. bioenergy market (1,400 trillion Btu [TBtu][4] total in 2010 and 1,700 TBtu total in 2015)

Sources: Conventional Ethanol and Biodiesel: EIA 2016a, Tables 10.3 and 10.4; Biopower: EIA 2016b; Other Advanced Biofuels: EPA 2016a. Other advanced biofuels include renewable diesel, heating oil, and naphtha, as well as small volumes of imports used to meet federal requirements for advanced biofuels. Note: This figure only includes the energy content of the product fuels and power, and not the associated co-products.

[4] One trillion Btu is equivalent to 0.001 quads.

2 Biofuels Markets

The primary market driver for U.S. biofuels production and consumption is the RFS. The RFS is a federal program that requires transportation fuel sold in the United States to contain a minimum volume of renewable fuel. Congress created the RFS program to reduce reliance on imported oil and expand the nation's renewable fuels sector while reducing greenhouse gas (GHG) emissions (EPA 2016c). The RFS originated with the Energy Policy Act of 2005 and expanded under the Energy Independence and Security Act of 2007 (EISA) (U.S. Congress 2007).

The RFS program requires renewable fuel to be blended into transportation fuel in increasing amounts each year, escalating to 36 billion gallons by 2022.[5] There are four overall RFS nested categories (Figure 2 and Figure 3): (1) renewable fuel, which is largely satisfied by conventional corn grain ethanol; (2) advanced biofuel; (3) biomass-based diesel, which is largely satisfied by biodiesel; and (4) cellulosic biofuel. Figure 3 illustrates how Renewable Identification Number (RIN) designations allow fuels to meet more than one RFS category. For example, cellulosic diesel represents the overlap between cellulosic biofuel and biomass-based diesel.

In order to meet the fuel blend requirements, the RFS program assigns obligated parties (fuel refiners and importers) a renewable volume obligation (RVO), which is the volume of renewable fuels the party is obligated to blend based on a percentage of the company's total fuel sales. There is no specific requirement for starch-based ethanol, although this fuel accounts for the majority of fuel in meeting the RFS—it falls under the overall requirement of renewable fuel. The RFS program requires renewable fuels to emit lower levels of GHGs than the petroleum fuel they replace. Specific GHG emission reductions are 20% for renewable fuel (conventional ethanol); 50% for advanced biofuel and biomass-based diesel; and 60% for cellulosic biofuels from cellulosic feedstocks.[6] In Appendix A, Table A-1 includes more detailed definitions for the RFS biofuel categories.

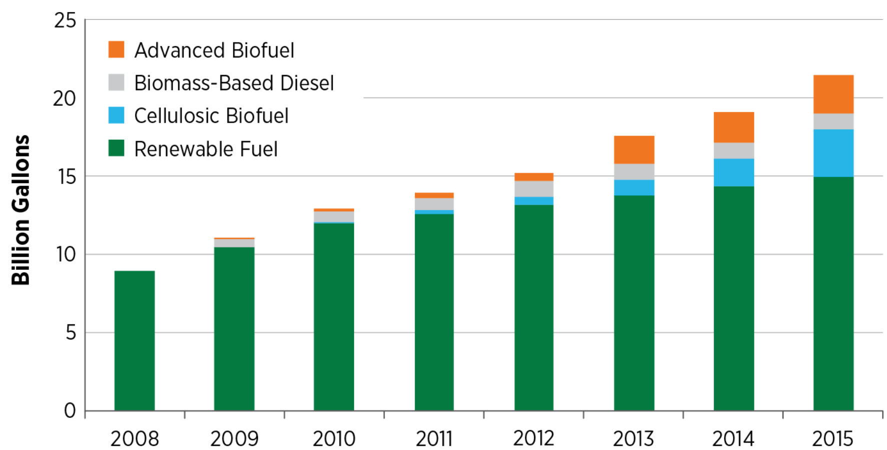

Figure 2. Nested annual RFS volumes from 2008 to 2015

Source: U.S. Congress 2007.

[5] RFS gallons are ethanol equivalent gallons except for biodiesel, which is actual gallons.

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

The U.S. Environmental Protection Agency (EPA) manages and tracks RFS compliance through RINs. RINs are the mechanism for tracking annual renewable fuel blend requirements across the various biofuel categories. In Appendix A, Table A-2 includes data on RIN generation in 2015 (EPA 2016a). 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 can be used to demonstrate a company's RVO compliance to EPA and then is retired. RINs also may be sold or saved for meeting RVO compliance in the compliance year after generation. Most RIN prices are determined by market factors typical of other commodities, while the EPA rules can have a large influence over the cellulosic biofuel RIN price due to offering cellulosic biofuel waiver credits (EPA 2016a). In 2015, RIN prices were typically around $0.7/RIN, but, depending on the day, prices ranged from about $0.3/RIN as the lowest price for the renewable fuel RIN to about $1.10/RIN as the highest point for the cellulosic biofuel RIN (OPIS 2016).

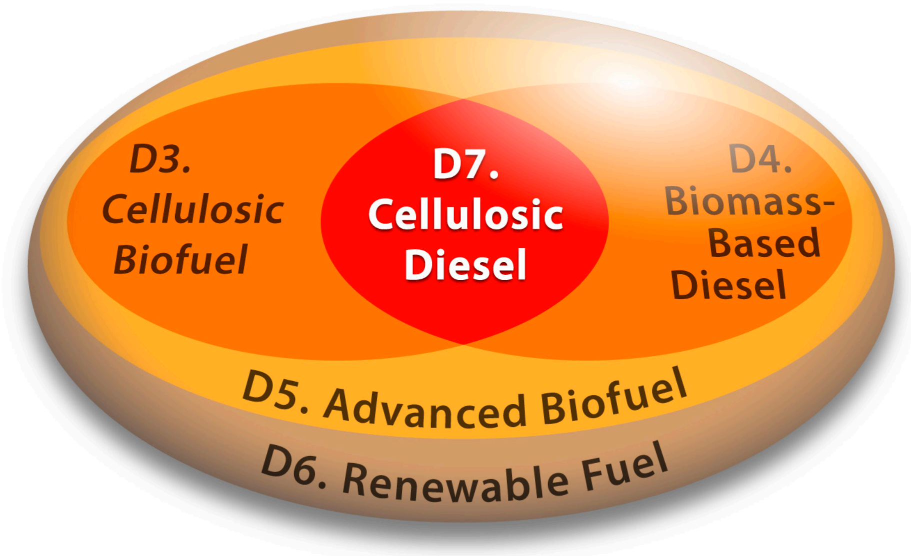

Figure 3. Nesting of biofuel categories under the RFS

See Appendix A for definitions for each biofuel category. Cellulosic biofuel (D3) and biomass-based diesel (D4) are both nested within advanced biofuel (D5), which is nested within renewable fuel (D6). Note: Diagram not to scale.

Figure 4 compares EISA legislated volumes versus EPA annual RVO volumes, based on anticipated production versus RIN generation. The fuel producers have met EPA annual RVOs every year but the RVO amount was less than the legislated volumes that were adjusted down in 2014 and 2015 due to limited cellulosic biofuel production.

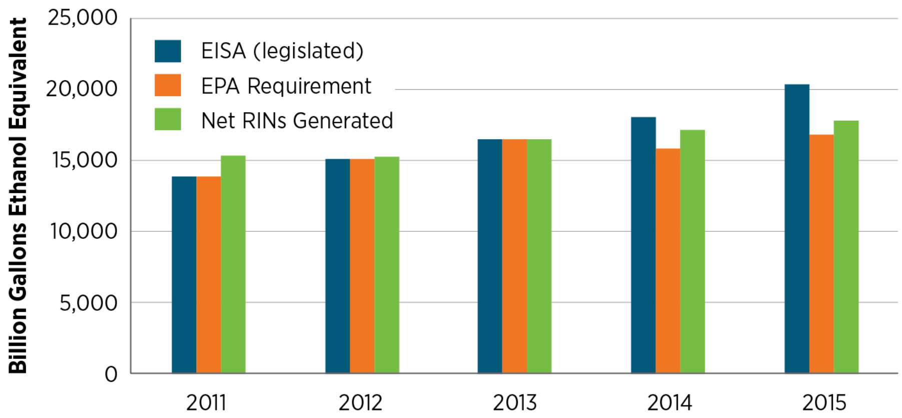

Figure 4. RFS comparison of EISA, annual RVO Requirements, and RIN generation

Source: U.S. Congress 2007; EPA 2016a; EPA 2016d.

Figure 5 shows production for ethanol, biodiesel, and other advanced biofuels (including biogas, cellulosic diesel, cellulosic ethanol, imported sugarcane ethanol and other advanced ethanol, naphtha, renewable diesel, renewable gasoline, renewable heating oil, renewable compressed natural gas, and renewable liquefied natural gas). The biofuels market is dominated by conventional starch-based ethanol. The market for biodiesel has remained stable over the past few years. Production and consumption of renewable diesel and RNG (which accounts for the majority of the cellulosic biofuel) have grown significantly. Renewable diesel and RNG RIN generation in 2015 were 513 and 139 million gallons, respectively (EPA 2016a). Several cellulosic ethanol refineries came online in 2015, increasing production from approximately 0.7 million gallons in 2014 to more than 2 million gallons in 2015 (EPA 2016a).

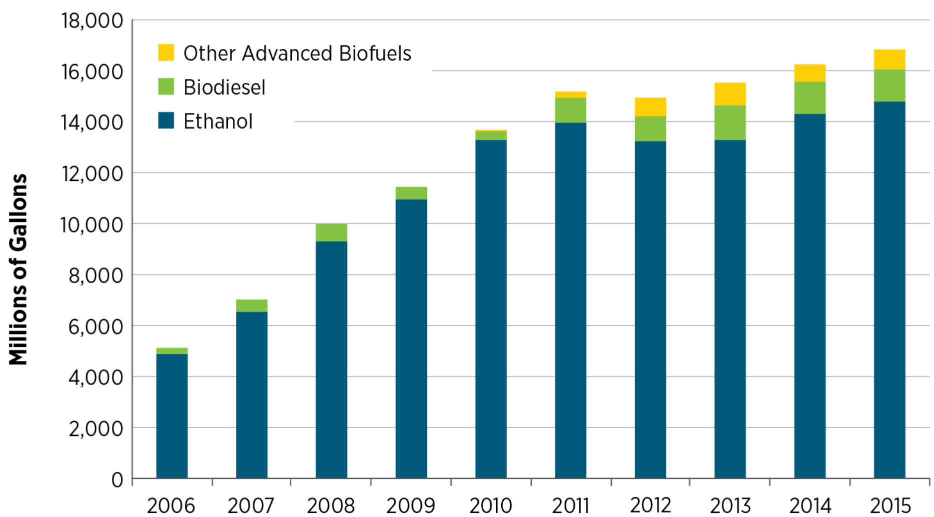

Figure 5. U.S. renewable liquid fuels market

Sources: Ethanol and Biodiesel: EIA 2016a, Tables 10.3, 10.4; Other Advanced Biofuels: EPA 2016a (2010 data is for July through December only). Other advanced biofuels include biogas, cellulosic diesel, cellulosic ethanol, imported sugarcane ethanol and other ethanol qualifying as advanced, naphtha, renewable diesel, renewable heating oil, renewable compressed natural gas, and renewable liquefied natural gas.

2.1 Ethanol

Ethanol is a widely used biofuel made from corn grain and other plant materials. In 2015, 98% of domestic ethanol production was from corn grain (RFA 2016a). As the commercial cellulosic ethanol market has begun to develop over the last few years, cellulosic ethanol represents 0.015% of the ethanol production market. Ethanol has a long history of use in the United States dating back to the introduction of motor vehicles. It became more common as an oxygenate additive and octane enhancer in gasoline after passage of major amendments to the Clean Air Act in 1990 that required oxygenates to be used in reformulated gasoline. Production and use grew dramatically to meet these standards. Another oxygenate, methyl tertiary-butyl ether (MTBE), was the primary product used to meet the standard until it was found to contaminate ground water, and some states banned the use or proposed banning its use. Ethanol was voluntarily used to replace MTBE in these areas, and production and consumption increased dramatically. 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 vary regionally. Many of these products are sub-octane, meaning they have a lower octane than is required for sale to consumers at the pump. Ethanol has a higher octane number than gasoline, and refiners provide a gasoline blendstock that, when blended with ethanol, will meet octane specifications necessary to meet vehicle performance needs. Ethanol is delivered to terminals or blenders by rail car, tanker truck, or barges and is blended with gasoline for delivery to stations for end users.

The benefits of ethanol include a higher octane number than gasoline, which provides increased engine power and performance. As a domestically produced biofuel, ethanol reduces reliance on petroleum products and foreign imports and provides jobs in rural areas. In 2005, 60% of petroleum products were imported; however, that was reduced to less than 25% in 2015 because of increased domestic crude oil and ethanol production, as well as decreased gasoline consumption (RFA 2016a). Under the RFS, corn grain ethanol meets the renewable fuel 20% GHG-emission reduction threshold and is currently the main contributor to this fuel category (EPA 2010; EPA 2016a; EPA 2016c). Imported sugarcane ethanol meets the advanced biofuel 50% GHG-emission reduction threshold (EPA 2010; EPA 2016a; EPA 2016c). Cellulosic ethanol meets the cellulosic biofuel 60% GHG-emission reduction threshold and is currently a minor contributor to this fuel category (EPA 2010; EPA 2016a).

More than 97% of gasoline sold in the United States contains ethanol, and nearly all ethanol is sold as E10 (10% ethanol, 90% gasoline) (RFA 2016b). Another long-available blend is E85—containing 51% to 83% ethanol, depending on geography and season—for use in FFVs. At the end of 2015, E85 was available at nearly 3,000 fueling stations, and nearly 20 million FFVs were registered nationwide. In 2011, EPA approved E15 (10.5%–15% ethanol blended with gasoline) for use in MY 2001 and newer vehicles. The number of stations offering E15 grew from 1 in 2012 to 180 in 2015 (RFA 2016b). The U.S. Department of Agriculture's (USDA's) Biofuels Infrastructure Partnership is funding ethanol infrastructure at nearly 1,500 retail fuel stations in 20 states, which is expected to extend the availability of E15 and E85 (USDA 2015).

The primary drivers of ethanol prices are the cost of corn grain and the gasoline prices for which ethanol serves as a substitute product. In the past 10 years, ethanol prices have fluctuated in correlation with gasoline or corn grain prices. When corn grain was relatively inexpensive and petroleum prices were increasing (from 2004 through 2010), ethanol futures traded based on gasoline prices. As ethanol began to consume a larger percentage of corn grain production, its price increasingly moved in sync with corn grain prices when domestic supply of corn was tight. More recently, as corn grain prices have dropped lower, ethanol prices have been based at a discount to gasoline prices. Figure 6 compares ethanol and gasoline futures prices with corn grain prices. The correlation between corn grain and ethanol prices is expected to decline once substantial volumes are produced from cellulosic feedstock.

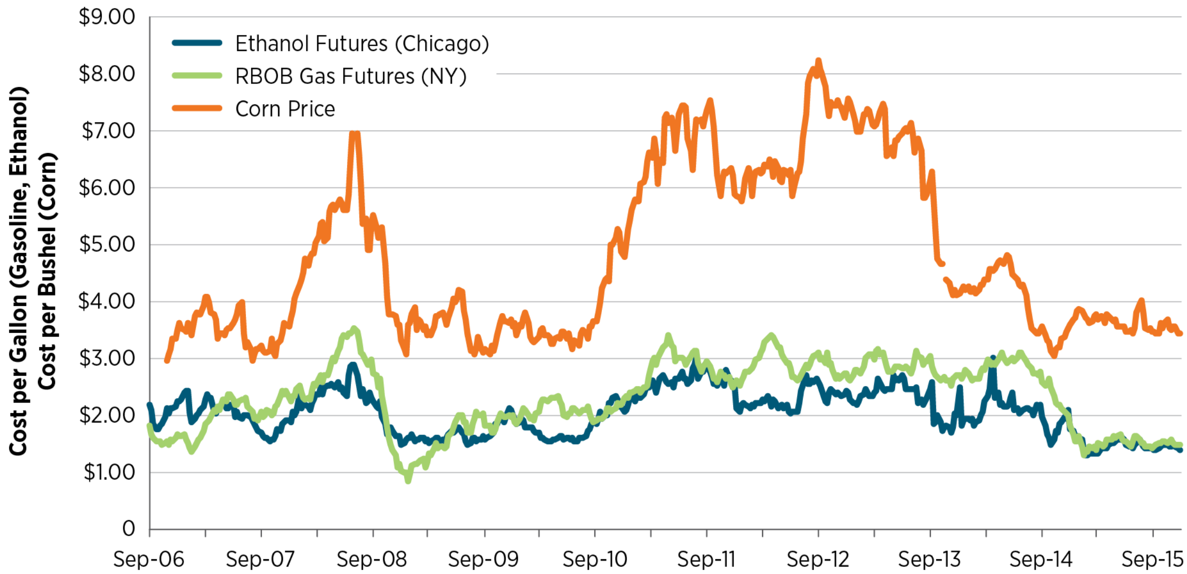

Figure 6. Historic ethanol and gasoline futures prices and corn grain prices

Sources: Ethanol and Corn Grain: CME Group 2016; Gasoline: EIA 2016d. Ethanol and gasoline are price per gallon, not energy equivalent.

2.1.1 Conventional Ethanol

Conventional ethanol dominates the current ethanol market, and in nearly all cases it is made from corn grain (98%) with a few plants using milo (grain sorghum) or food/beverage wastes (RFA 2016a). This fuel meets the overall renewable fuel category of the RFS (D6 RIN).

The majority of ethanol is produced using dry-mill technology (90%); a small number of larger plants use a wet-milling process (10%) (RFA 2016a). Dry milling is a process that grinds corn grain into flour and ferments only the starch component into ethanol with co-products of distillers grains (an animal feed substitute) and carbon dioxide. Wet-mill plants primarily produce corn grain sweeteners, along with ethanol and several other co-products (such as corn oil and starch). Wet mills separate starch, protein, and fiber in corn grain prior to processing these components into ethanol and other products.

2.1.1.1 Feedstocks

The United States is the world's largest corn grain producer. Corn grain accounts for more than 90% of total feed grain production and use (USDA-ERS 2016a). Corn grain is grown in most states, but production is primarily concentrated in Iowa, Minnesota, Nebraska, North Dakota, and Illinois (USDA 2016). Corn grain is also exported and processed into a wide range of industrial products. In 2015, corn grain used for ethanol accounted for about 44% of total corn grain production (AFDC 2016b).

2.1.1.2 Historical Production, Consumption, and Capacity

Figure 7 highlights the tremendous growth in production and consumption of ethanol since 2006. The past few years saw production plateau due to the blend wall. Figure 8 illustrates the rapid build-out of plants and capacity between 2005 and 2011. The number of plants operating at any given time is a function of economics and demand, and plants may idle at different times during the year depending on ethanol and corn grain prices.[7] Installed capacity is capable of meeting the overall RFS renewable fuel category of 15 billion gallons.

[7] The Renewable Fuels Association maintains a continuously updated list of installed and operating ethanol plants: http://www.ethanolrfa.org/resources/biorefinery-locations/.

As of December 2015, there were 214 fuel ethanol plants in 29 states, with an installed capacity of 15.6 billion gallons producing 15.1 billion gallons (Figure 9). Plant ownership is not consolidated—there are more than 120 ownership organizations, but there are four companies that own 29% of plants and 39% of installed capacity: POET (27 plants; 1.6 billion gallons), Archer Daniels Midland (ADM) (8 plants; 1.7 billion gallons), Valero (11 plants; 1.2 billion gallons), and Green Plains Renewable Energy (14 plants; 1.2 billion gallons). Only seven ownership groups are traded publicly, and they account for 29% of plants and 41% of installed capacity (RFA 2016c).[8]

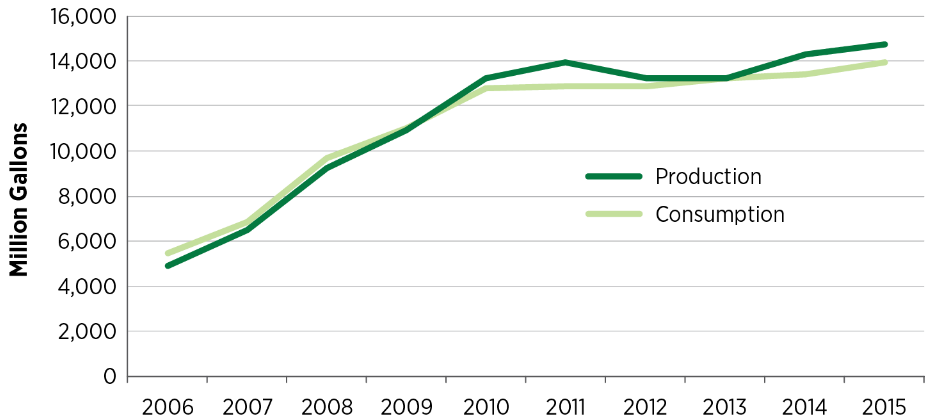

Figure 7. U.S. historical ethanol production and consumption

Source: EIA 2016a, Table 10.3.

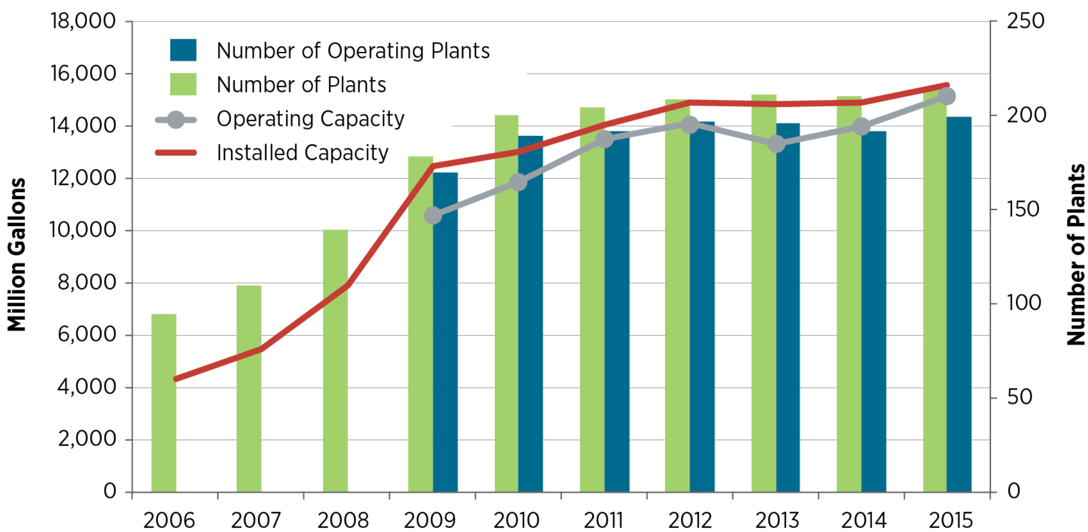

Figure 8. U.S. historical ethanol plants and capacity

Source: RFA 2016b.

[8] Public ethanol plants ownership companies include: Abengoa, Aemitis, ADM, CHS Inc., DuPont, Green Plains Renewable Energy, Pacific Ethanol, REX American Resources, The Andersons Inc., and Valero.

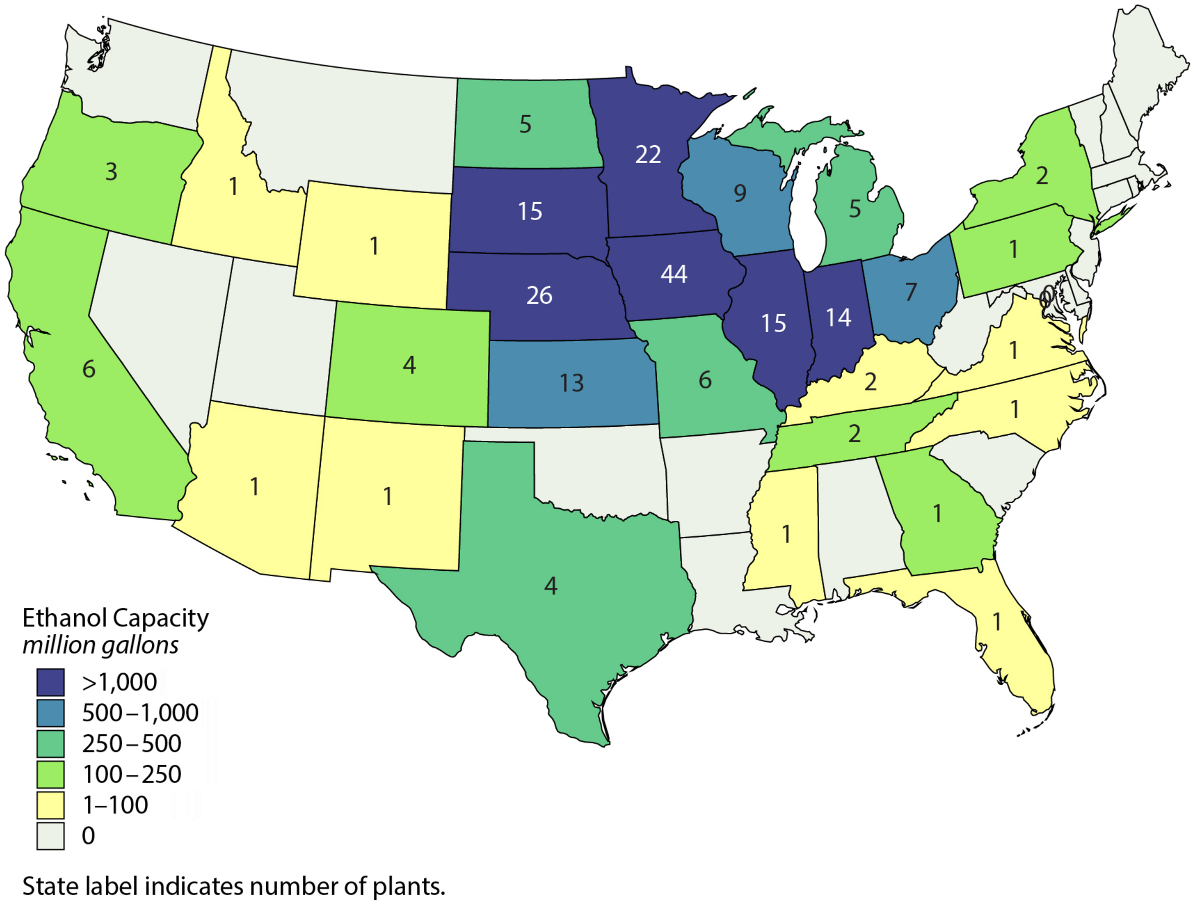

Figure 9. Ethanol plants by state (as of January 2016)

Source: RFA 2016b.

2.1.1.3 Production Cost

Because of the scarcity of data on the actual production cost of corn grain ethanol, economic models were developed to estimate production cost and track ethanol profitability. A model created by Iowa State University can be 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 2016a). The plant represents similar facilities built around 2007 in Iowa, but may not be representative of plants in other regions (Hofstrand 2016a). The estimated production cost, as shown in Figure 10, takes into account fixed costs, non-feedstock variable costs (e.g., natural gas, chemicals, and labor), feedstock costs, and revenue contribution from co-product(s) (dry distillers grains assumed by the model); the estimate production cost varied from \$1.35/gallon to \$3.47/gallon between 2006 and 2015 (Hofstrand 2016a).

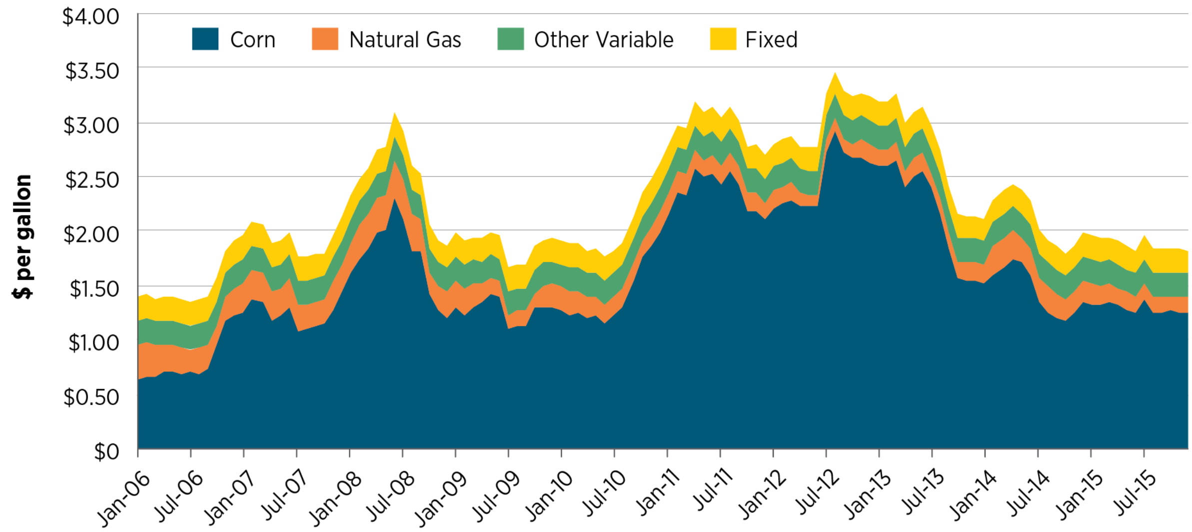

Figure 10. U.S. corn grain ethanol production cost trends

Source: Hofstrand 2016a.

The single largest cost in the production of ethanol from corn grain is the cost of corn (Figure 10). Corn grain prices vary from year to year and have ranged from $3.04/bushel to $4.46/bushel in the last decade (from 2006–2015) (USDA-ERS 2016a).[9] Another major production cost contributor is the price of natural gas or other sources of heat needed for the conversion process. The market price of ethanol does not necessarily reflect the cost of ethanol production.

The largest ethanol markets are located on the East and West Coasts of the United States, outside of the primary corn grain production region. The majority of ethanol produced in the United States is shipped on trains to those markets because ethanol is not shipped by pipeline due to fuel properties. While these distribution costs are minimal, they may increase due to tank cars transitioning to new safety standards and ethanol competing with newly discovered domestic oil fields. Ethanol prices are typically lowest in the Midwest and increase as a function of transportation costs when shipped to other domestic markets.

2.1.1.4 Co-Product Overview

Fuel ethanol co-products from dry mills include distillers grains,[10] corn oil, and carbon dioxide. Corn grain is approximately two-thirds starch, which is converted into ethanol and carbon dioxide; the remaining one-third is protein and fat that are converted into distillers grains. Distillers grains are the highest volume co-product and are sold as livestock feed either wet (46 pounds/bushel at 65% moisture) or dry (18 pounds/bushel at 10% moisture). Approximately 85% of ethanol plants have added dry fractionation technology at the front end of their plant to extract non-edible corn oil at a rate of about 0.5 pounds/bushel, which is most often used as a feedstock for biodiesel plants (RFA 2016a; Jessen 2013a).[11] Only 36 ethanol plants sell carbon dioxide (6.6 pounds/gallon of ethanol) to industry for use in food and pharmaceutical products, and prices for raw carbon

[9] 1 bushel of corn grain = 56 pounds; 1 bushel of corn grain yields approximately 2.8 gallons of ethanol.

[10] Distillers grains are sold in two forms: wet distillers grains and dried distillers grains with solubles. 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.

[11] Corn oil extraction rates range from 0.4 to 0.9 pounds per bushel (Jessen 2013b); however, many ethanol plants do not go for higher extraction rates because distillers grains customers expect a certain oil content.

dioxide gas range from $5–$25/ton (Rushing 2011). More plants would likely sell carbon dioxide if they were near the end user; however, most ethanol plants are located in rural areas.

Benchmarking studies have found that the co-product contribution to revenues has increased in recent years—largely due to corn oil—going from an average of 16.5% of revenue contribution in 2008 to 23% in the first half of 2012 (Jessen 2013b). Pricing for distillers grains and corn oil is a function of corn grain price and is driven by demand in the markets ethanol producers serve. Distillers grains export markets have grown over time to supplement corn grain exports with 33% of production exported to more than 50 countries in 2015 (RFA 2016a) (Figure 11). Ethanol plant production data for corn oil is unknown and may vary with the extraction rates of various technologies. USDA reports a market year 2014/15 inedible corn oil price of 26.8 cents/pound (USDA-ERS 2016b).

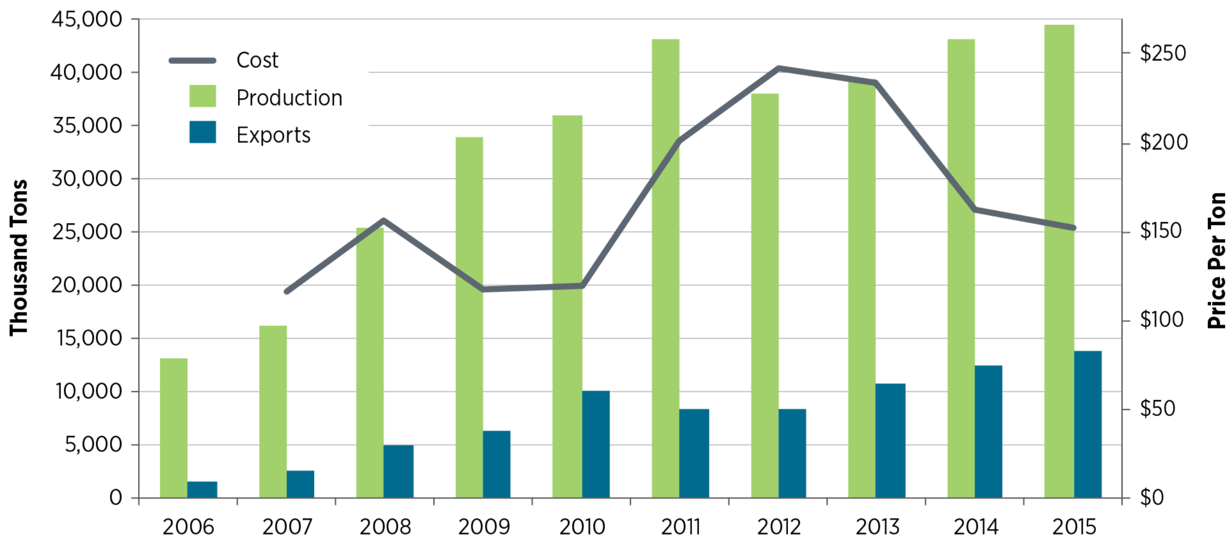

Figure 11. U.S. starch ethanol distillers grains production, trade, and price

Sources: Production: RFA 2016d; Exports: RFA 2016e; Prices at Production Facilities (annual average of prices at production facilities in Iowa, Illinois, Nebraska, South Dakota, and Wisconsin): USDA-ERS 2016c.

2.1.1.5 Economic Impacts of Conventional Ethanol

The economic impact of corn grain ethanol is significant, particularly among the states where ethanol plants are located and corn grain production increases partially because of rising demand for ethanol production. Processing raw corn grain into ethanol adds value to the feedstock through activities that support the necessary investment in processing, marketing, construction, and research and development.

The ethanol industry funds annual studies to determine the impacts of ethanol production on the economy (most recently Urbanchuk 2016). These studies applied an economic input-output model known as IMPLAN, or IMpact analysis for PLANning, 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.

- Ethanol contribution to gross domestic product increased from $17.7 billion in 2005 to $44 billion in 2015.
- The number of direct jobs has remained somewhat level, with 87,883 during the rapid build-out of plants in 2005 and 85,967 in 2015.
- The contribution of federal tax revenue grew from $1.9 billion in 2005 to $4.8 billion in 2015. State and local government tax revenue was $3.9 billion in 2015.

2.1.2 Cellulosic Ethanol Production

As the corn grain ethanol industry has matured, interest has moved toward using non-food cellulosic feedstocks, such as crop residues, waste wood, municipal solid waste (MSW), and dedicated energy crops to produce ethanol. Ethanol made from cellulosic feedstock meets the same ASTM International fuel quality standards as conventional ethanol and has the same performance in vehicles. After decades of technology development, the cellulosic ethanol industry is now reaching commercial production. Commercial deployment of cellulosic biofuels has been hampered by the economic downturn as financial investment was constricted, particularly due to the high startup risks for these new technologies. These risks include feedstock availability, collection, and delivery; pretreatment technology costs; higher capital costs; and technology scale-up challenges.

Cellulosic ethanol is produced via biochemical, thermochemical, and hybrid technology pathways. In the biochemical pathway, cellulose and hemicellulose in the feedstock are deconstructed into simple sugars through various pretreatment processes and enzymes. Microbes are used to ferment the sugars into ethanol. The thermochemical pathway uses heat to transform the feedstock into a synthesis gas (syngas) comprised of hydrogen and carbon monoxide that is catalytically converted to ethanol, other alcohols, and oxygenated intermediates. Hybrid technologies use a combination of biochemical and thermochemical operations—for example, syngas fermentation thermochemically deconstructs the feedstock into syngas, which microbes ferment into fuel or bioproducts.

Despite challenges in technology development, investment constraints from the 2008 recession, and market conditions for ethanol, the industry is seeing the first commercial-scale cellulosic ethanol plants being built. EPA reports (Figure 12) small volumes of cellulosic ethanol production, with 2,181,000 gallons in 2015 (EPA 2016a).

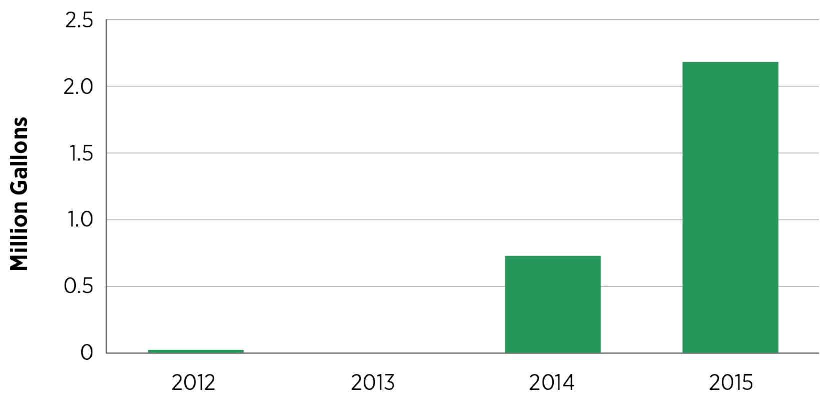

Figure 12. U.S. historical cellulosic ethanol production

2.1.2.1 Feedstocks

Cellulosic ethanol can be produced from various food and non-food cellulosic feedstocks, such as corn kernel fiber, crop residues, woody materials (e.g., forest residues), MSW, and dedicated energy crops. The *2013 Bioenergy Market Report* illustrates that about 400 million dry tons of cellulosic biomass resources were generated in 2012 (Schwab et al. 2016). The *2016 Billion-Ton Report* provides estimates on feedstock quantity and price from 2017 to 2040 under several alternative assumptions about achievable future yields (DOE 2016a).

2.1.2.2 Commercialization of Cellulosic Ethanol

A survey of U.S. non-starch ethanol producers was conducted to understand the status of the cellulosic ethanol industry at the end of calendar year 2015 (Schwab et al. 2016).

Several U.S. facilities began producing cellulosic ethanol during 2015 that resulted in the assignment of D3 RINs (EPA 2016a). In 2015, almost 2.2 million gallons of cellulosic ethanol were produced. Table 1 summarizes the U.S. commercial cellulosic ethanol capacity identified during this survey. Eight of the commercial facilities identified in this survey were scheduled to become operational sometime after the end of 2015. These anticipated operational start dates represent forward-looking projections from the survey, which will be updated in future studies after these facilities become operational. Some facilities are pursuing innovative routes for cellulosic biofuel production. Three commercial facilities are pursuing routes to extract additional fuel from conversion of corn kernel cellulose. One commercial facility owned by Front Range Energy is pursuing potential suppliers of cellulosic sugars from Sweetwater Energy Inc. as an alternative feedstock to corn starch.

Table 1. Status of U.S. Commercial-Scale Cellulosic Ethanol Capacity at the End of 2015

Company	Project Location	Technology Pathway	Feedstock Category	Capacity [MMGY]	Operational Year (Anticipated)
Abengoa	Hugoton, KS	Biochemical	Crop Residues	23	2015 (idled in 2015)
Ace Ethanol (Sweetwater Energy, Inc.)	Stanley, WI	Biochemical	Corn Kernel Cellulose	3.5	(2017)
Beta Renewables Inc.	Clinton, NC	Biochemical	Dedicated Energy Crops	20	(2017)
Canergy	Brawley, CA	Biochemical	Dedicated Energy Crops	25	(2017)
DuPont	Nevada, IA	Biochemical	Crop Residues	30	2015
Enerkem	Pontotoc, MS	Thermochemical Gasification	Municipal Solid Waste	10	(2020)
Front Range Energy (Sweetwater Energy Inc.)	Windsor, CO	Biochemical	Cellulosic Sugars	3.6	(2017)
INEOS New Planet Bioenergy LLC[a]	Vero Beach, FL	Hybrid Biochemical/ Thermochemical	Municipal Solid Waste	8	(2016)
Pacific Ethanol (Sweetwater Energy Inc.)	Madera, CA	Biochemical	Corn Kernel Cellulose	3.6	(2017)
POET-DSM	Emmetsburg, IA	Biochemical	Crop Residues	25	2015
Quad County Corn Processors	Galva, IA	Biochemical	Corn Kernel Cellulose	3.8	2014
ZeaChem	Boardman, OR	Biochemical (EtOH)	Woody Biomass	22	(2017)

Source: Schwab et al. 2016. MMGY = million gallons per year.
[a] INEOS became operational in 2012 but was idle in 2015 while working on mechanical improvements and was expected to resume operations in 2016.

Figure 13 presents a summary of all the non-starch ethanol facilities included in the survey (Schwab et al. 2016). Two of the 29 non-starch ethanol facilities included in this report were under construction at the end of 2015, with the remainder of the facilities spread across the other stages of development. Ten of the facilities (four pilot-scale facilities, five demonstration-scale facilities, and one commercial-scale facility) were reported as idle at the end of 2015. The reasons for these facilities being idled largely varied and included a planned commercial facility being refocused on producing other products (e.g., biogas) (Sapp 2015), shifting demonstration-scale operations to a facility in a different location (Lane 2015a), and a facility sold as the previous owner divested from biofuels (Lane 2015b).

Scale of the Facility	Company Name Facility Location	Planning	Under Construction	Operating	Idle
Commercial	Abengoa_KS				+ (green)
	Ace Ethanol (Sweetwater Energy, Inc.)_WI	✱ (green)			
	Beta Renewables Inc._NC		× (green)		
	Canergy_CA	× (green)			
	DuPont_IA			+ (green)	
	Enerkem_MS	∇ (red)			
	Front Range Energy (Sweetwater Energy Inc.)_CO	O (green)			
	INEOS New Planet Bioenergy LLC_FL		∇ (purple)		
	Pacific Ethanol (Sweetwater Energy Inc.)_CA	✱ (green)			
	POET-DSM_IA			+ (green)	
	Quad County Corn_IA			✱ (green)	
	ZeaChem_OR	Δ (green)			
Demonstration	American Process Inc._GA			Δ (green)	
	American Process Inc._MI				Δ (green)
	BP_LA				× (green)
	DuPont_TN			+ (green)	
	Fiberight_VA				∇ (green)
	GeoSynFuels_WY				+ (green)
	ICM, Inc._MO			✱ (green)	
	Joule_NM			□ (orange)	
	Summit Natural Energy_OR				∇ (green)
	ZeaChem_OR			Δ (green)	
Pilot	Abengoa_NE				+ (green)
	Aemetis_MT				× (green)
	Algenol Biofuels Inc._FL			□ (orange)	
	Archer Daniels Midland_IL				+ (purple)
	LanzaTech_GA			Δ (red)	
	Logos Technologies (Edeniq, Inc.)_CA				✱ (green)
	POET_SD			+ (green)	

Technology Pathway
- Algae (EtOH) (orange)
- Biochemical (EtOH) (green)
- Thermochemical Gasification (EtOH) (red)
- Hybrid BC/TC (purple)

Feedstock Category
- □ Algae
- \+ Crop Residues
- Δ Woody Biomass
- × Dedicated Energy Crops
- ∇ MSW
- O Cellulosic Sugars
- ✱ Corn Kernel Cellulose

Figure 13. Characteristics of U.S. non-starch ethanol facilities at the end of 2015

Source: Schwab et al. 2016. EtOH stands for ethanol.

Most of the cellulosic ethanol facilities—23 of 29—use or will use a biochemical technology pathway, with 2 using a thermochemical gasification route, 2 using a hybrid biochemical/thermochemical technology, and 2 using an algal technology pathway for the direct production of ethanol. During this survey, each facility self-identified the conversion technology pathway that best describes their particular facility. Because companies typically employ a proprietary conversion process, there may be aspects of a company's process that incorporate elements of technology pathways other than the primary technology pathway indicated in Figure 13.

As shown in Figure 13, the facilities using a biochemical technology pathway used a range of feedstock materials. Of the 23 biochemical pathway facilities, 7 used crop residues, 4 used woody biomass, 5 used corn kernel cellulose, 4 used dedicated energy crops, 2 used MSW, and 1 facility did not report a specific feedstock beyond cellulosic sugars. The two thermochemical gasification facilities used either woody biomass or MSW as feedstock. Two facilities used a hybrid biochemical/thermochemical pathway, one utilized crop residues, and the other MSW as feedstock.

2.1.2.3 Production Costs and Economic Impacts

Available data on cellulosic ethanol production costs is limited due to the number of companies producing cellulosic ethanol. One study estimates that current fuel production costs for cellulosic ethanol are about $5.90/gge (ranging between $5.06 to $6.73/gge) and estimated potential costs are $4.69/gge (ranging between $4.18 to $4.88/gge) for 2025.

Due to limitations of current cost estimates, Figure 14 and Figure 15 illustrate modeled longer-term future cellulosic ethanol production costs. These figures illustrate how significant technology developments over the last few decades are enabling cost-competitive cellulosic ethanol to come to commercial-scale production. In 2012, researchers at the National Renewable Energy Laboratory (NREL), Pacific Northwest National Laboratory, and Idaho National Laboratory, funded through the U.S. Department of Energy (DOE), successfully modeled—at significant scale—two cellulosic ethanol production processes at a projected mature commercial-scale cost for the nth-plant.[12] The production of ethanol via lignocellulosic sugars derived from corn stover resulted in an nth-plant price of an estimated $2.45 per gallon (2014$), whereas the catalytic upgrading of syngas produced via indirect gasification of woody biomass resulted in an nth-plant model price of $2.34 per gallon (2014$) (Tao et al. 2014; Dutta et al. 2014). Based on the assumptions in these design case reports, calculated costs included feedstock harvesting, transportation, and integrated conversion. The modeled validated at integrated pilot scale and met the goals set by the DOE's Advanced Energy Initiative of 2006 to show that cellulosic ethanol could be cost competitive with corn grain ethanol and conventional fuels. Continued research may further decrease production costs. For example, in 2013, a partnership between INL and Iowa State University achieved critical corn stover feedstock processing targets that enable cost-competitive biofuels and identified best practices for replication with a variety of herbaceous feedstocks. DOE-funded industry research also has resulted in commercially viable strains of yeast, bacteria, and enzymes for biochemical conversion and catalysts for thermochemical conversion (Tao et al. 2014; Dutta et al. 2014). These and other such improvements are expected to be implemented in newly constructed cellulosic ethanol biorefineries.

[12] The nth plant represents the deployment of a mature technology once several plants have already been built and operated.

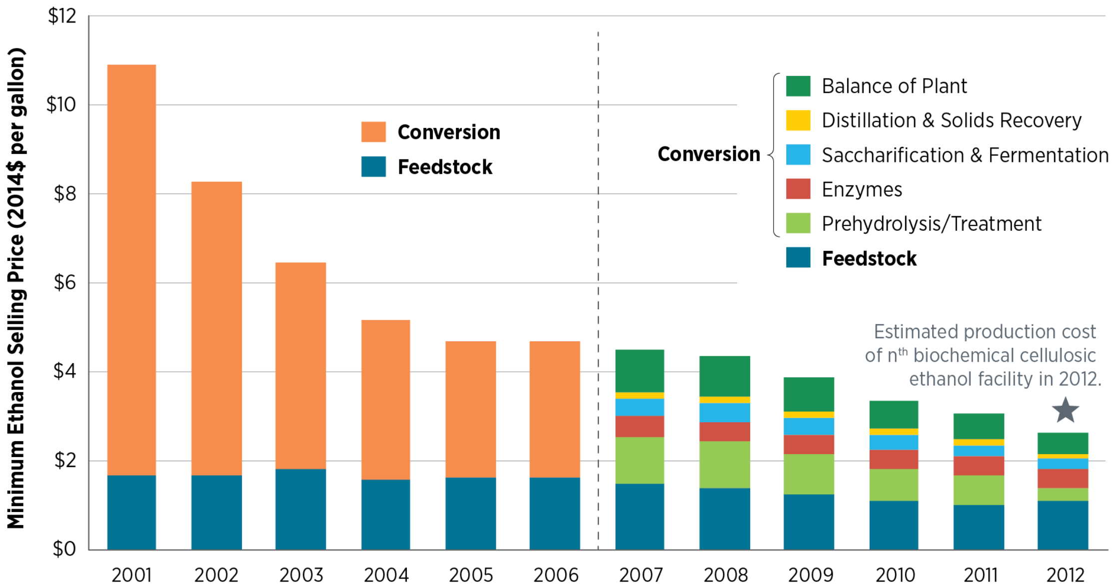

Figure 14. Biochemical cellulosic ethanol modeled production costs over time

Source: Schwab et al. 2016

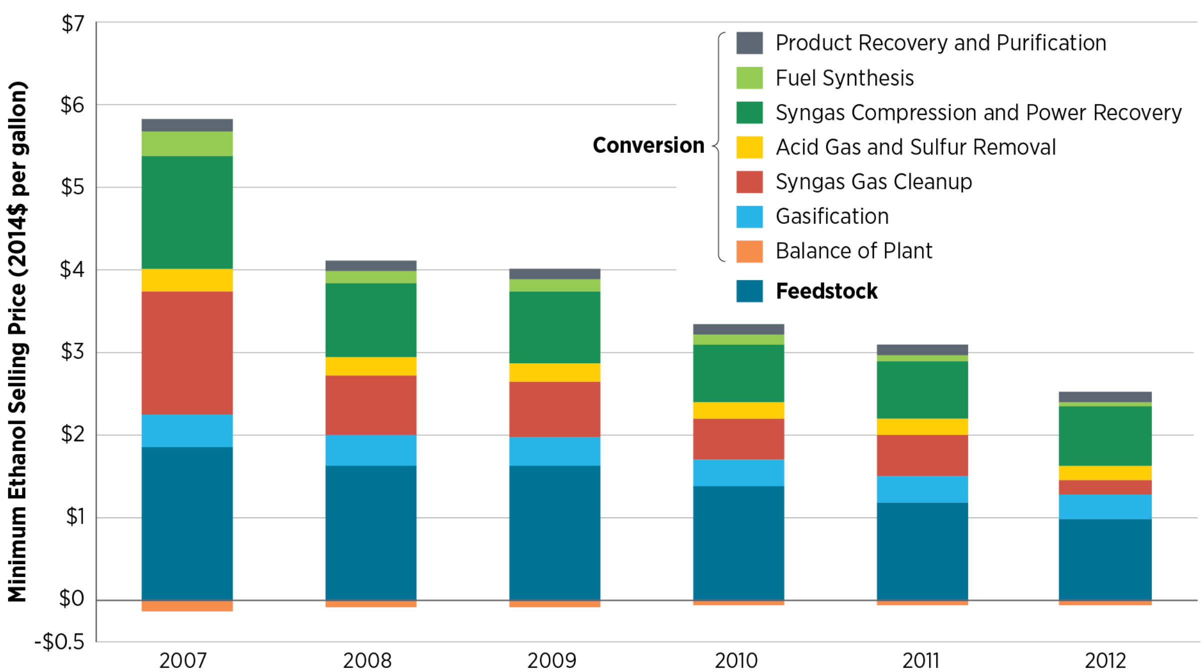

Figure 15. Thermochemical cellulosic ethanol modeled production costs over time

Source: DOE 2016b.

Techno-economic modeling analyses suggest that cellulosic ethanol facilities with a capacity of about 60 million gallons/year are expected to hire approximately 60 onsite workers for an nth-plant (Dutta et al. 2011; Humbird et al. 2011). Labor requirements will depend on which conversion process is employed, system configuration, size of the facility, and other factors, such as the feedstock type and handling. Cellulosic ethanol will also result in jobs for those gathering and delivering feedstock and other inputs and equipment to the plant.

2.1.2.4 Co-Products Overview

In current process designs for the biological conversion of cellulose- and hemicellulose-derived sugars to ethanol, lignin is burned to generate process heat and electricity, with any excess power produced being sold as a co-product. The exported electricity improves the profitability of the process and provides ancillary benefits by displacing fossil-derived electricity and potentially reducing GHG emissions (Wyman 2003; Humbird et al. 2011). For example, the INEOS facility in Florida is expected to produce 6 megawatts (MW) of renewable biomass power per year in addition to producing 8 million gallons per year of cellulosic ethanol (INEOS Bio 2013). As highlighted in a recent review article on lignin valorization, there are extensive opportunities for further improvements in the overall economic and environmental outcomes of a biorefinery complex via utilization of all of the components of biomass (Ragauskas et al. 2014). This potential economic and environmental improvement for an integrated biorefinery was investigated in the NREL design report (Davis et al. 2013) that focused on the biological conversion of cellulosic sugars to hydrocarbon fuels. In this study, the conversion of lignin to products including 1,4-butanediol and adipic acid resulted in improving the overall process economics, as well as potentially reducing the GHG emissions relative to the production of electricity from lignin (Davis et al. 2013). Continued research and development in catalysis and improvements in process integration may address the challenges and barriers for the conversion of lignin to fuels and chemicals.

2.1.3 Policies That Affect the Ethanol Market

Ethanol received significant government support under federal law in the form of mandated biofuel use, tax incentives, loan and grant programs, and other regulatory requirements.[13] The ethanol market has expanded due to both regulation and market factors. Federal regulations that have influenced the market include a series of federal and state tax incentives; the Energy Policy Act of 1978, which helped grow what was a small start-up industry; the RFS in the Energy Policy Act of 2005, which mandated blending 7.5 billion gallons of biofuel with gasoline annually by 2012; and EISA in 2007, which expanded the RFS to 36 billion gallons by 2022. Another significant market driver was the replacement of MTBE with ethanol as an octane source in gasoline blending. MTBE was previously used to increase octane, but concerns about groundwater contamination caused some states to ban its use in 2005 and 2006, leading to its discontinued use; it was replaced with ethanol. A sustained period of high gasoline prices and low corn grain prices led to a rapid expansion of ethanol production capacity (Tyner 2008). The federal incentives were provided in the form of a motor fuel excise tax exemption or a tax credit along with additional tax credit for small ethanol producers. In addition, a tariff on imported ethanol gave domestic producers a competitive advantage over foreign producers (Pelkmans et al. 2008).

A number of federal incentives for ethanol producers and blenders expired at the end of 2011, including the volumetric ethanol excise tax credit (VEETC), small ethanol producer tax credit, and import tariff for fuel ethanol. Initially, the federal government subsidized ethanol by exempting ethanol gasoline blends from excise taxes and establishing a tax credit for ethanol use in the late 1970s. In 2004, the American Jobs Creation Act implemented the VEETC to replace the two historical subsidies as a combined excise tax exemption and tax credit (Taxpayers for Common Sense 2011). The tax credit was paid to ethanol blenders (petroleum companies) rather than ethanol plants, though the ethanol price was certainly impacted by the tax credit. The value of the tax credit was $0.51/gallon from 2004 through 2008 and $0.45/gallon between 2009 and 2011 (Kim et al. 2010). The VEETC was discontinued at the end of 2011 with the support of the ethanol industry because conventional ethanol had reached commercial maturity and the incentive was no longer necessary. Table 2 shows the historical VEETC federal support for ethanol based on production and VEETC payment per gallon.

[13] This section covers federal incentives and policies. States also may have incentives and policies. This information is available from the "Laws and Incentives" section of the Alternative Fuels Data Center (AFDC) website: http://www.afdc.energy.gov/laws.

Table 2. Historical VEETC Federal Investment

Year	VEETC (billion$)
2004	1.7
2005	2.0
2006	2.5
2007	3.3
2008	4.7
2009	4.9
2010	6.0
2011	6.3

Source: EIA 2016a, Table 10.3. Calculated by multiplying ethanol production by tax incentive ($0.51/gallon for 2004–2008 and $0.45/gallon for 2009–2011).

Cellulosic ethanol also has received significant government support under federal law in the form of biomass grower payments, mandated fuel use, tax incentives, loan and grant programs, and other regulatory requirements. The most significant incentive for cellulosic ethanol production has been the RFS. However, given the industry's slow startup, production has been lower than originally projected, resulting in yearly reductions by EPA of the cellulosic RVO. Other policy supports include grants through the DOE's Bioenergy Technologies Office (BETO) for first-of-a-kind biorefineries using biomass feedstocks, as well as payments to biomass feedstock growers under the USDA Biomass Crop Assistance Program.[14] Loan guarantees are available for cellulosic ethanol plants through DOE and USDA. A cellulosic biofuel production tax credit of $1.01/gallon expired at the end of 2013, and was extended retroactively through the end of 2014 when it once again expired. While the industry has received financial support in recent years, in 2015 there are fewer federal incentives for demonstration and deployment of cellulosic and algal biofuels than in recent years.

2.1.4 Ethanol Trade

Ethanol is both imported and exported as a function of demand or biofuel use requirements in other nations (Figure 16). The United States is the world leader in ethanol production, accounting for 57% of 2015 world production (RFA 2016b). In 2015, imports were from two countries, with 96% of the total 91 million gallons coming from Brazil and the balance from Canada (EIA 2016e). Sugarcane ethanol qualifies as an advanced biofuel in the RFS. The United States exported 844 million gallons in 2015 to 48 nations, and the United States' three largest trading partners are Canada (30%), Brazil (14%), and the Philippines (8%) (EIA 2016f). Exports to European Union (5%) member nations are limited due to an import tariff on U.S. ethanol.

[14] For more information on integrated biorefinery projects, visit http://www.energy.gov/eere/bioenergy/integrated-biorefineries.

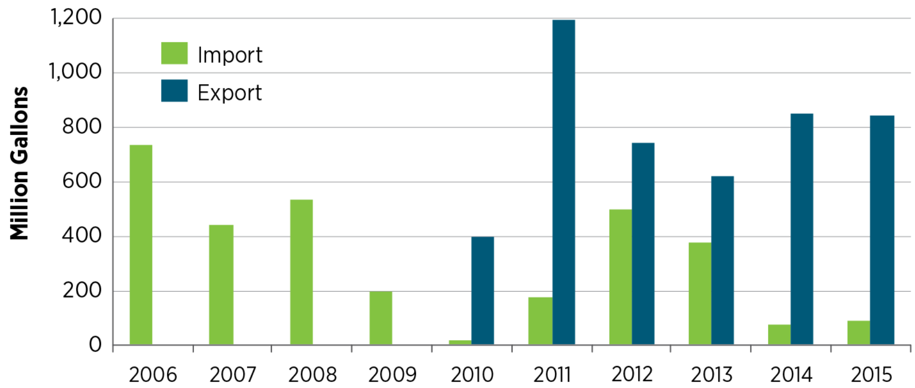

Figure 16. U.S. ethanol imports and exports

Source: EIA 2016e; EIA 2016f.

2.1.5 Infrastructure

Infrastructure is a critical part of the supply chain in deploying alternative transportation fuels. Significant research and outreach activities have resulted in blends above E10 being used in both specifically designed equipment and existing refueling equipment. Regulations have long accommodated the use of E10 in existing infrastructure. Blends above E10 require some specialized equipment to meet the patchwork of regulations that cover refueling infrastructure. Codes and standards for refueling agencies are developed and enforced by many organizations, including EPA's Office of Underground Storage Tanks, authorities having jurisdiction (typically fire marshals), Underwriters Laboratories (UL), the Occupational Safety and Health Administration, fire safety code organizations, and industry groups.

EPA's Office of Underground Storage Tanks is responsible for federal codes for fuel storage, and it updated federal code in July 2015 that requires stations to demonstrate compatibility when storing biofuel blends above E10 or B20 (20% biodiesel, 80% petroleum diesel).[15] The majority of installed tanks and pipes are compatible with ethanol blends up to E85 or E100, and UL-listed above-ground equipment for blends above E10 became available in 2010. 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 all steps and regulations and provides lists of compatible and UL-listed equipment.[16]

As of the end of 2015, E85 was available at 2,990 stations in 46 states (Figure 17 and Figure 18); however, there are often low densities of E85 stations in areas with high concentrations of capable vehicles (AFDC 2016b).[17] It is possible that E85 sales could increase if more E85 stations were located in areas with high concentrations of FFVs, but only when the price is discounted to reflect the lower energy density of ethanol compared with gasoline. As of January 2015, there were 180 stations in more than 20 states selling E15 (RFA 2016a).

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[15] 40 C.F.R. § 280.32 (2015). http://www.ecfr.gov/cgi-bin/text-idx?tpl=/ecfrbrowse/Title40/40cfr280_main_02.tpl.

[16] Clean Cities' *Handbook for Handling, Storing, and Dispensing E85 and Other Ethanol-Gasoline Blends* provides lists of compatible tanks, pipes, and associated underground storage tank equipment, as well as UL-listed dispensers and hanging hardware: http://www.afdc.energy.gov/uploads/publication/ethanol_handbook.pdf.

[17] TransAtlas shows locations of both alternative fuel stations and vehicles: http://maps.nrel.gov/transatlas.

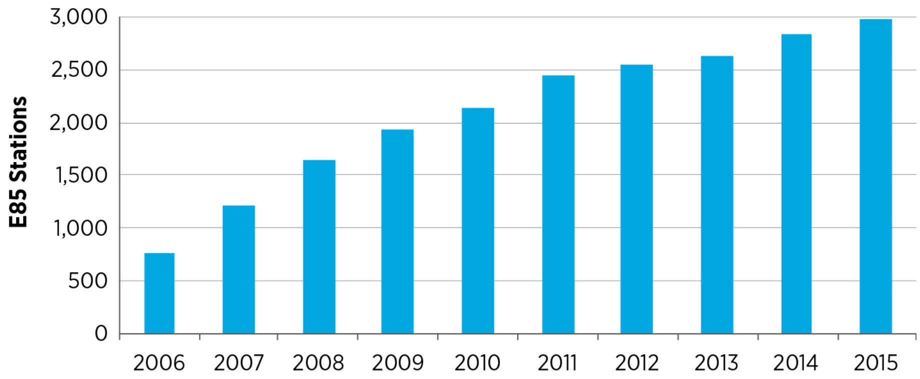

Figure 17. U.S. historical E85 stations

Source: AFDC 2016c.

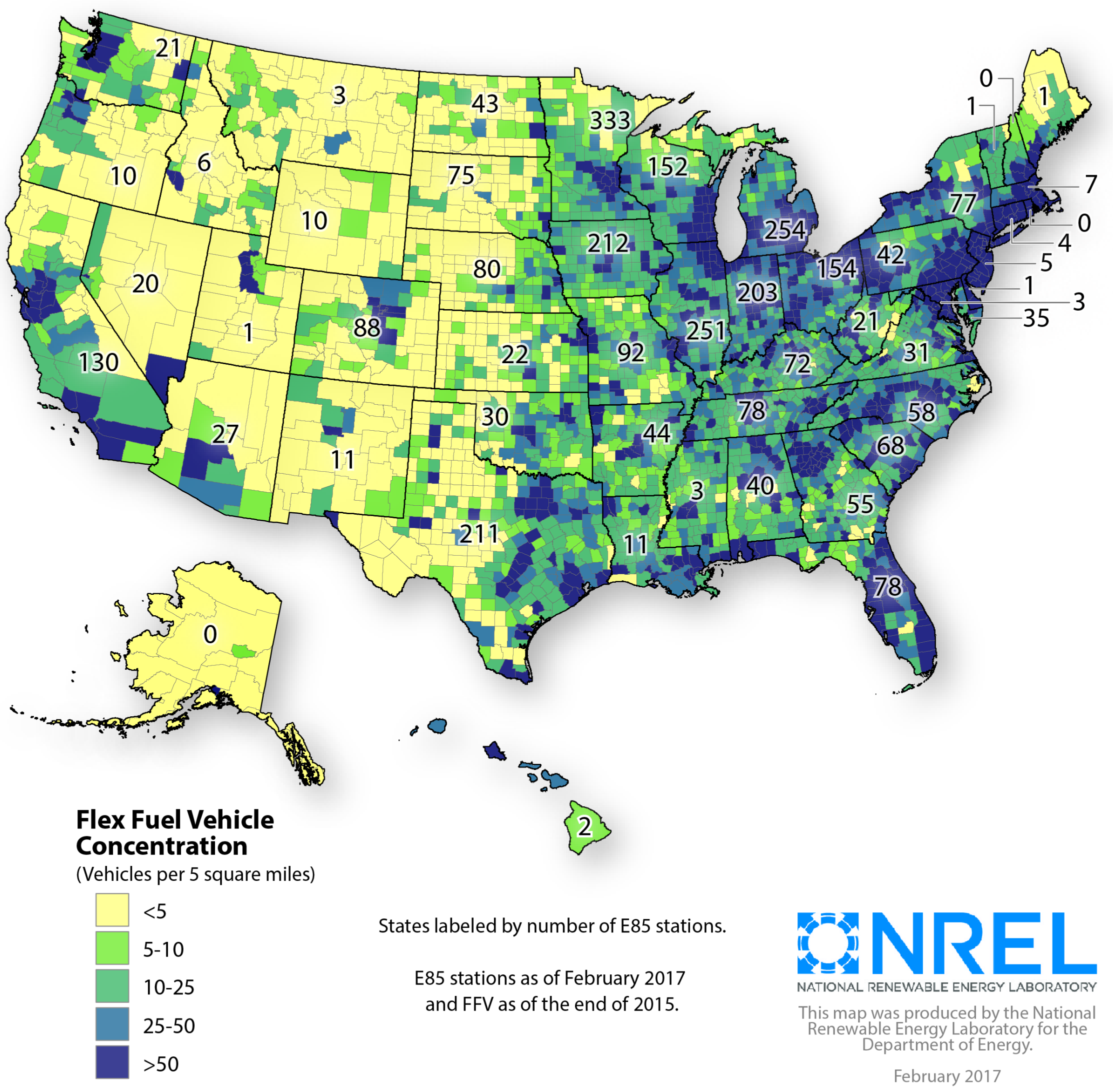

Figure 18. E85 stations and FFV locations by county

Sources: Vehicles: IHS Automotive (formerly Polk), https://www.polk.com; Stations: AFDC 2017.

2.1.6 End Use

All 264 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. At the end of 2015, 76% of the gasoline light-duty truck and vehicle population was MY 2001 and newer—however, some manufacturers approve the use of E15 in their vehicles while others do not.[18]

FFVs are capable of operating on any gasoline-ethanol blended fuel between E10 and E85, and there were nearly 20 million FFVs on U.S. roads at the end of 2015 (Figure 18 and Figure 19). For MY 2015, there were 103 models and configurations from seven manufacturers.[19] The National Highway Traffic Safety Administration establishes CAFE standards, and auto manufacturers receive a credit for each FFV sold, which helps them meet the overall regulation. Sales and production of FFVs are driven more by auto manufacturers' desire to obtain a CAFE credit than by demand from customers (Barrionuevo and Maynard 2006). FFV CAFE credits are set to expire at the end of 2016, and it is unclear if auto manufacturers will continue to offer FFVs in future years. Beyond 2016, there is still a CAFE credit if auto manufacturers can demonstrate FFVs are using E85. This requirement will be extremely difficult to meet as vehicles are not equipped with refueling data collection, and states generally track total ethanol sales (no differentiation between E10 and E85) for taxation purposes.

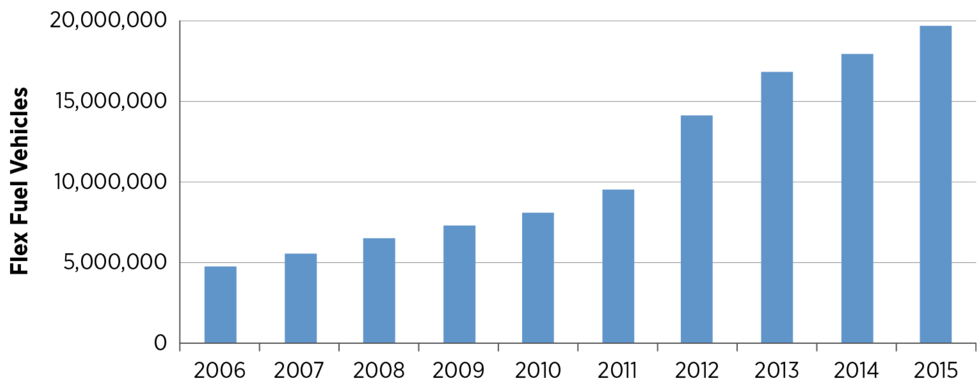

Figure 19. U.S. historical FFVs stock

Source: IHS Automotive, https://www.ihs.com/btp/polk.html (data purchased annually).

2.1.7 Outlook and Trends

In November 2015, EPA finalized RFS renewable biofuel requirements for 2014–2016.[20] EPA reduced both the total and advanced requirements originally set in EISA (EPA 2016d). The cellulosic requirement has been reduced each year because there has not been sufficient production of cellulosic ethanol or other cellulosic fuels to meet the EISA requirement. The total renewable fuel requirement is largely met by corn grain ethanol, and EPA bases volume requirements on fuel supplies.

The best opportunities for near-term market expansion are expanding the use of E15 for 2001 and newer MY vehicles and expanding the use of E85 for FFVs. A longer-term possibility to increase ethanol consumption is

[18] Vehicle populations were determined using 2015 IHS Automotive (formerly Polk) vehicle registration data purchased by NREL.

[19] Alternative Fuels Data Center (AFDC) Light-Duty Vehicle Search allows users to identify alternative fuel vehicle availability by MY and manufacturer: http://www.afdc.energy.gov/vehicles/search.

[20] View RFS final volumes here: https://www.epa.gov/renewable-fuel-standard-program/final-renewable-fuel-standards-2014-2015-and-2016-and-biomass-based.

deployment of vehicles with engines optimized to use high-octane fuel (e.g., research octane number 100), which could accommodate ethanol blends of 25% or greater or other high-octane biofuel. However, these optimized vehicles are currently in a research phase and will not be available in the near term (EERE 2017).

Other countries also have biofuel use requirements, which could provide additional markets for ethanol producers. Demand for exports will likely be impacted by the availability and price of sugarcane ethanol from Brazil.

2.2 Biobutanol

Biobutanol is a 4-carbon alcohol (butyl alcohol) produced from the same feedstocks as ethanol, including corn grain and other biomass. While there are four isomers of butanol, the most active commercialization work centers around isobutanol for blending with gasoline. There are two Clean Air Act provisions that allow for blending of up to 12.5% biobutanol with gasoline. Additionally, under the Octamix waiver, for which human health effects testing is ongoing, a 16% biobutanol blend is a legal fuel equivalent to E10 (GPO 2012). Biobutanol has an ASTM D7862 fuel quality standard for blends up to 12.5% with gasoline. It is important to ensure that biobutanol blended with ethanol-gasoline combinations does not result in an oxygen content exceeding the EPA limit of 3.7%. The benefits of biobutanol when compared with ethanol are that biobutanol is less miscible with water and it has a higher energy content and lower Reid vapor pressure. Under the RFS, corn grain butanol meets the renewable fuel 20% GHG-emission reduction threshold (EPA 2010; EPA 2016c).

One challenge for biobutanol is that more ethanol, on a volume basis, can be produced from a bushel of corn than biobutanol (Ramey 2007). Biobutanol companies produce transportation fuel and a range of high-value products with a goal of improving economic performance through diversification of product offerings. Primary co-products of biobutanol plants may include solvents/coatings, plastics, and fibers. Two companies pursuing biobutanol are Gevo and Butamax. Gevo retrofitted a corn ethanol plant in 2012. The plant is capable of producing either biobutanol or ethanol. The near-term outlook for biobutanol production is limited, as production has been minimal and intermittent since 2012. Approximately 12,000 gallons entered the commercial market in 2013 and none in 2014 and 2015 (EPA 2016a).

Oak Ridge National Laboratory has researched the compatibility of refueling equipment materials with biobutanol and has found that equipment compatible with ethanol blends would also be compatible with biobutanol. UL announced in late 2013 that equipment certified under testing subject 87A (for blends above E10) could also retain certification if used with biobutanol blends up to 16%. It is anticipated that biobutanol would be distributed by tanker truck and rail, with the potential for transportation in pipelines following research demonstrating its safety. Biobutanol is compatible with existing vehicles at blends of 16% or less with gasoline, and it provides the same fuel economy as E10 (Butamax 2014).

2.3 Biodiesel

2.3.1 Biodiesel Overview

Biodiesel is an alternative fuel manufactured from multiple feedstocks—including vegetable oils, animal fats, or yellow grease—for use in diesel vehicles. It is referred to as biomass-based diesel in the RFS along with renewable diesel, which is a different alternative fuel described later in Section 2.4. Biodiesel is produced by transesterification—a process that converts fats and oils into biodiesel and glycerin (a co-product). Biodiesel's physical properties are similar to those of petroleum diesel and they can be blended in any combination. Any 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 describes the properties 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 manufacturers warrant the use of B20. B100 (ASTM Standard 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 vehicles and infrastructure. In the first years of biodiesel production, fuel quality was an issue. Industry worked with ASTM to establish fuel quality standards and a voluntary quality assurance program known as BQ9000 to support higher-quality fuels in the market. Biodiesel is distributed by truck, train, and barge. While uncommon, biodiesel can be moved in pipelines; however, there are restrictions to consider if the pipeline also carries jet fuel.

The market for biodiesel is relatively small but has been growing over the past 5 years—it currently accounts for approximately 2.1% of the 60-billion-gallon annual diesel market (EIA 2016a; EIA 2016g).[21] Biodiesel demand is driven primarily by the RFS under two subcategories in the advanced biofuels requirements—biomass-based diesel and other advanced biofuels. 2013 was the first year biodiesel production and consumption exceeded the RFS requirement for biomass-based diesel, and excess production was used to meet the overall advanced biofuel requirement of the RFS. Several states also have biodiesel mandates. B5 has long been approved for use in home heating oil, and there is an opportunity for growth in this market, with ASTM International releasing a B20 home heating oil fuel quality specification in 2015.

Under the RFS, biodiesel generally meets the biomass-based diesel 50% GHG-emissions reduction threshold, and it is currently the main contributor to this fuel category (EPA 2010; EPA 2016a; EPA 2016c). Use of biodiesel in older on-highway diesel engines also reduces emissions of unburned hydrocarbons, carbon monoxide, sulfates, polycyclic aromatic hydrocarbons, nitrated polycyclic aromatic hydrocarbons, and particulate matter. For 2010 and newer MY diesel engines, tailpipe emissions are controlled using catalysts and filters such that fuel composition has little effect on emissions. Biodiesel prices are directly correlated with petroleum diesel prices (Figure 20).

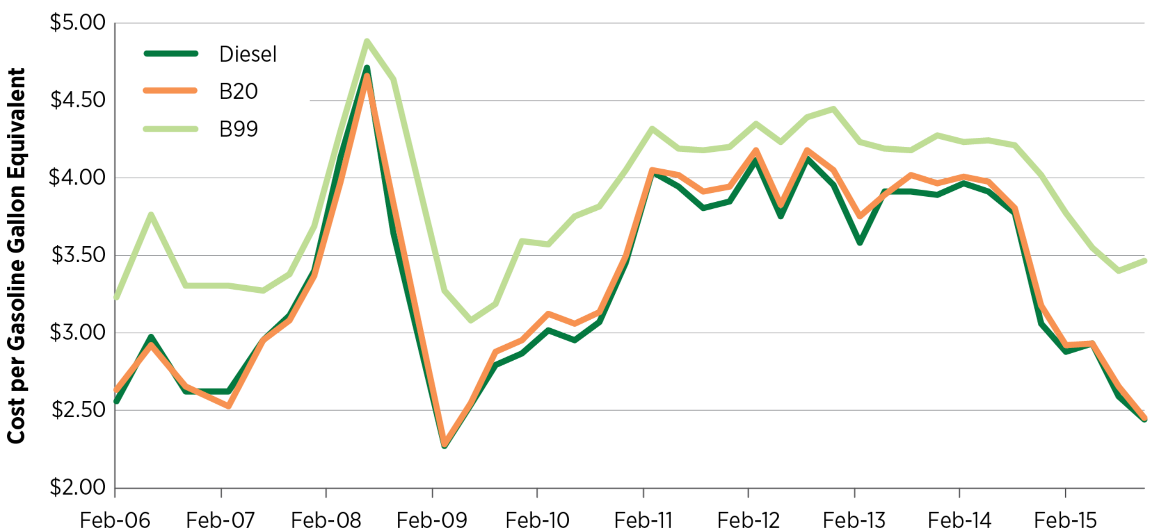

Figure 20. U.S. retail biodiesel prices

Source: DOE 2016c.

Research and development on biodiesel production has primarily focused on improved separation processes for product clean up and the development of inorganic heterogeneous (solid) and enzyme catalysts for the transesterification reaction. The majority of research on separation processes is proprietary and has been conducted by the biodiesel manufacturers, and this research has resulted in incremental improvements in the

[21] The diesel market of 60 billion gallons refers to No. 2 Distillate, which includes both fuel oil and diesel fuel—the two markets where biodiesel is used.

efficiency of their processes. Research on heterogeneous and enzyme catalysts has been published in the public domain, but none of these technologies has been adopted by biodiesel producers.

A major area of research sponsored by the biodiesel industry has been the performance of biodiesel blends in the fuel distribution system and in engines. This research has led to significant changes to the ASTM specifications for B100 and biodiesel blends that improved storage stability and cold weather operation. Additional research in these areas, as well as on the performance of biodiesel blends with emission control catalysts and filters, is ongoing.

2.3.1.1 Feedstocks

Biodiesel in the United States is produced from various lipid feedstocks, such as vegetable oils, animal fats, and waste greases. About 50% of the biodiesel plants do not rely on one type of feedstock and use multiple sources to ensure optimal feedstock supply security (Kotrba 2014).

Soybean oil is the most common biodiesel feedstock, providing more than 50% of the total input (Figure 21). About 4.9 billion pounds of soybean oil were used for biodiesel production in 2015, which is about 23% of the soybean oil produced that year (EIA 2016h; USDA-ERS 2016b).

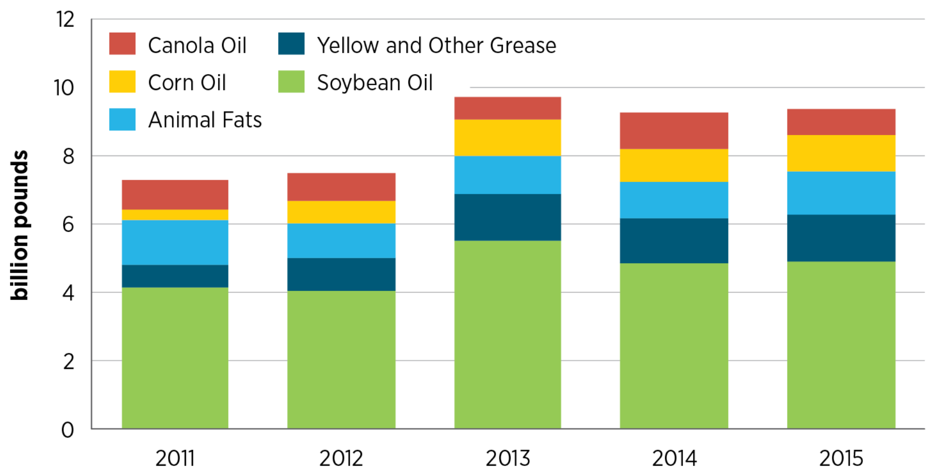

Figure 21. U.S. inputs to biodiesel production

Source: EIA 2016h.

About 745 million pounds of canola oil and just over 1 billion pounds of corn oil were used for biodiesel production in 2015 (Figure 21). In the past, corn oil had not been used as a feedstock; however, the production of low-cost, non-food-grade quality corn oil by many ethanol plants has resulted in a substantial increase in corn oil use for biodiesel over the past 5 years.[22]

The use of yellow grease (filtered used cooking oil) and other recycled oil feedstocks for biodiesel production has also increased due to low cost and resource availability. Consumption of yellow grease for biodiesel production was about 471 million pounds in 2011 and reached about 1.3 billion pounds in 2015, making it one of the main feedstock sources for biodiesel production. Animal fats provided about 14% of the total biodiesel feedstock supply in 2015, or about 1.3 billion pounds (EIA 2016h).

[22] Corn oil is a co-product at ethanol plants and does not impact the quantity of ethanol production.

2.3.1.2 Historical Production, Consumption, and Capacity

Both biodiesel production and consumption have expanded over the past decade, reaching a total production of 1.27 billion gallons in 2015 (EIA 2016a); however, there have been interesting market dynamics (Figure 22). Between 2007 and 2009, production exceeded domestic consumption and exports to European nations were common due to higher prices, but that opportunity declined in 2010 due to European Union legislation. Fuel companies were taking advantage of the U.S. production tax credit and exporting lower-cost biodiesel, prompting the European Union to issue a protectionist policy. This, likely combined with uncertainty about renewal of the federal biodiesel production tax credit, led to a period of lower production. EPA finalized RFS volume requirements for 2014 through 2017 in November 2015, which guarantees a market for biodiesel with an increase each year.[23] From 2013 through 2015, biodiesel consumption exceeded production due to biodiesel imports.

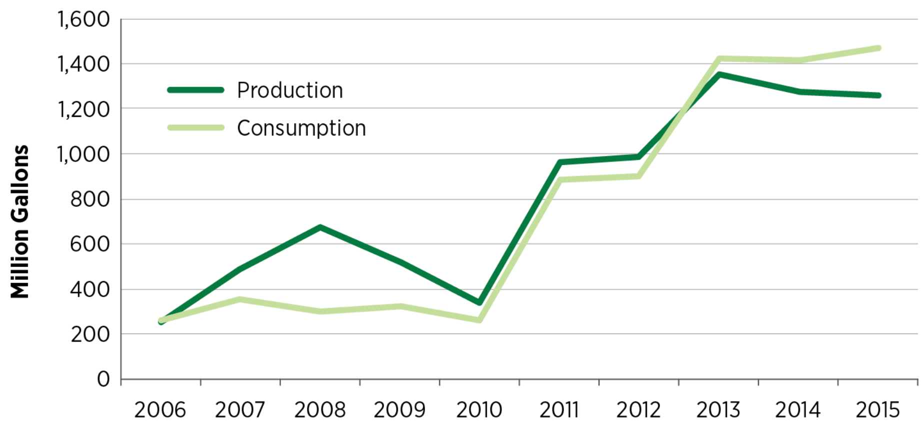

Figure 22. U.S. biodiesel production and consumption

Source: EIA 2016a, Table 10.4.

As of December 2015, there were 94 biodiesel plants with a total industry production capacity of more than 2 billion gallons in 36 states (Figure 23) (EIA 2016h). Biodiesel plant capacity ranges from less than 1 million gallons up to 180 million gallons. The average biodiesel plant size is 21 million gallons, and small plants are less able to deal with financial challenges than larger plants (EIA 2016h). In terms of production capacity, the largest biodiesel producer is Renewable Energy Group, which operates eight plants with a total production capacity of 357 million annual gallons ("USA Plants" 2015). Other large producers include traditional agricultural commodity processers and oleochemical producers: Ag Processing (120-million-gallon capacity), ADM (85-million-gallon capacity), and Louis Dreyfus (90-million-gallon capacity). Several companies focused exclusively on biodiesel production also have significant production capacity, including RBF Port Neches, which is the largest-capacity plant in North America at 180 million gallons.

As shown in Figure 24, biodiesel plants operate below capacity, but utilization of capacity has increased since 2012. The reason plants are idle or closed is typically related to economic conditions, where costs exceed market prices or periods when the federal biodiesel producer tax credit was unavailable. It has been challenging for biodiesel plants to remain profitable without the producer tax credit. Insufficient cash flow and limited or no access to credit also affect plants' ability to operate. Newer or upgraded plants may have greater efficiencies and the ability to use multiple feedstocks, which allows them the flexibility to use the most cost-effective feedstocks over time.

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[23] See RFS Final Volumes: https://www.epa.gov/renewable-fuel-standard-program/final-renewable-fuel-standards-2014-2015-and-2016-and-biomass-based.

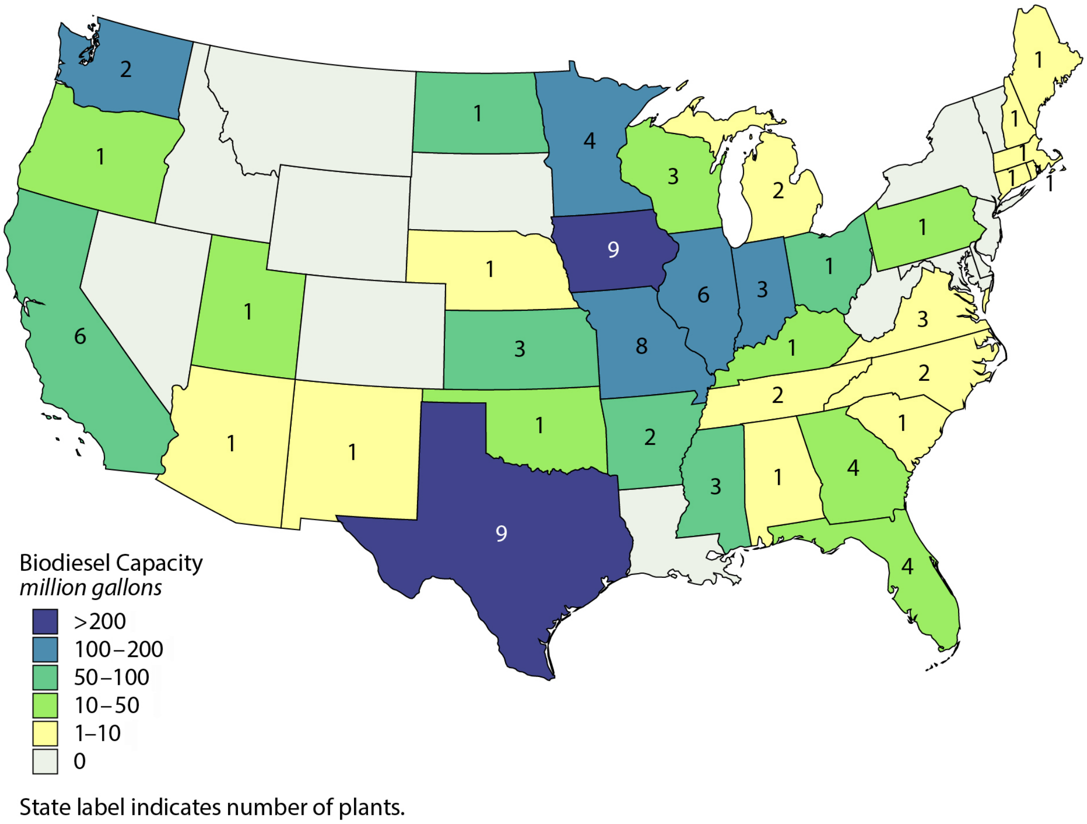

Figure 23. Biodiesel plants by state (as of December 2015)

Source: EIA 2016h, Table 4.

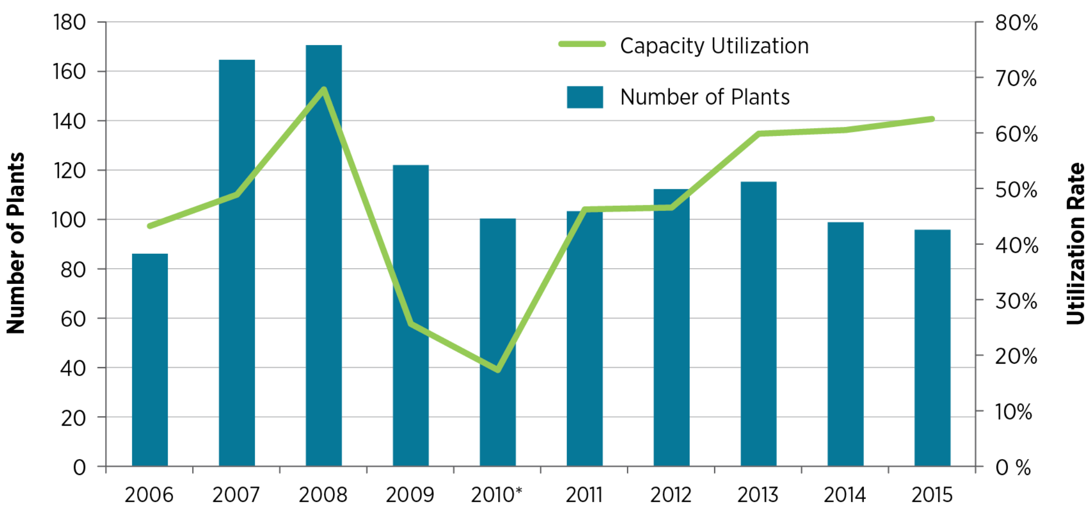

Figure 24. U.S. historical biodiesel plant capacity

Source: EIA 2106f, Table 4. Biodiesel producers and production capacity by state supplemented with data from National Biodiesel Board for years 2006–2008 and 2010. Capacity utilization is production divided by installed capacity from EIA 2016a, Table 10.4.

2.3.1.3 Production Cost

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 biodiesel profit margins and production costs over time based on Iowa biodiesel prices and costs for soybean oil and methanol, as well as other operating costs (Hofstrand 2016b). Over the past 8 years, soybean oil has accounted for 85% of operating costs at an average Iowa biodiesel plant, with lower costs for methanol and other operating costs. Production costs varied between $2.76 to $5.31 per gallon between April 2007 and December 2015 (Figure 25). 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). Energy costs are not significant and are not tracked separately as they are for ethanol.

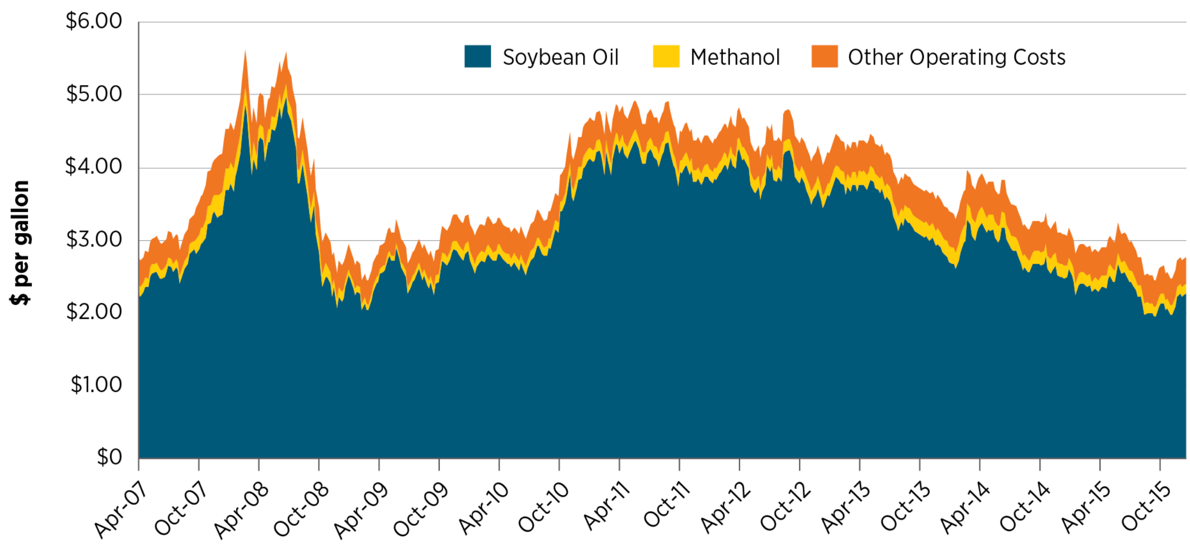

Figure 25. U.S. soybean-based biodiesel production cost trends

Source: Iowa State University 2016.

2.3.1.4 Co-Products Overview

The only co-product of biodiesel production is glycerin, which is used in food, hygiene, and pharmaceutical products. Each gallon of biodiesel produced results in 1.05 pounds of glycerin. Biodiesel production has resulted in an oversupply of glycerin for U.S. markets, leading to low prices for crude glycerin valued at $0.03 per gallon of biodiesel produced, with higher prices for upgraded or refined glycerin (Hofstrand 2016b). Research is focused on other uses for glycerin with an emphasis in the areas of algae, syngas, and yeast production.

One of DOE's technology transfer successes is ADM's 100,000-metric-ton renewable propylene glycol plant. ADM converts glycerin from biodiesel production into propylene glycol. The renewable propylene glycol is a component of several USDA-certified green product lines, mostly heat transfer fluids (Biddy, Scarlata, and Kinchin 2016).

2.3.1.5 Economic Impacts of Biodiesel

A recent study conducted for the National Biodiesel Board indicated that under assumptions in 2015 of 1.43 billion gallons of U.S. production and 670 million gallons of imports, there would be a contribution of $8.4 billion in economic activity and support of more than 47,400 direct jobs (NBB 2016).

According to the same National Biodiesel Board study, from 2005 to 2013, biodiesel production in the United States increased from 209 million gallons (747,000 tons) to 1.13 billion gallons (just more than 4 million tons). The gross impacts of this increased production include the following:

- The economic impact of biodiesel increased from $1.4 billion annually in 2006 to $8.4 billion in 2015.
- The number of direct jobs supported increased from just fewer than 7,000 in 2006 to more than 47,400 in 2015.
- Wage impacts increased from $260 million in 2005 to $1.9 billion, implying that the average job supported by the biodiesel sector paid a wage of approximately $39,300/year in 2015.

2.3.2 Policies That Affect This Market

Biodiesel has been primarily impacted by three policies—the RFS and the biodiesel income and blending tax credit.[24] The biodiesel tax credit of $1.00/gallon was originally established by the American Jobs Creation Act of 2004; it has expired and been retroactively reinstated four times through other legislation, and it is set to expire at the end of 2016. The estimated cumulative federal investment for the biodiesel production tax credit since its inception is $6.9 billion (Figure 26).[25] The availability of the tax credit has influenced production—as production costs sometimes exceed the price paid for biodiesel (Figure 20, Figure 25). Between 2005 and 2011, there was a small producer tax incentive of $0.10/gallon for the first 15 million gallons of biodiesel production at facilities using pure vegetable oils as feedstock with capacity of 60 million or fewer gallons/year. Additional federal investment in the biodiesel industry was allocated through grants, loan guarantees, and tax credits to assist retail and fleet stations in costs to upgrade equipment to accommodate B20.

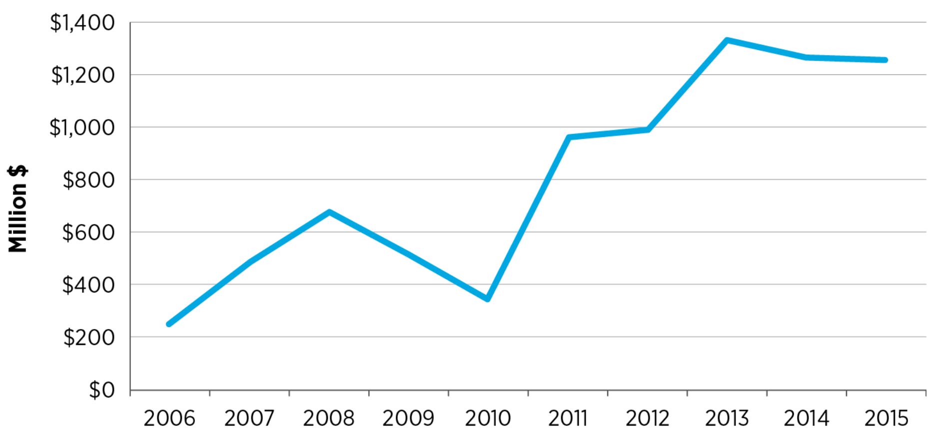

Figure 26. Estimated federal investment in the biodiesel tax credit

Sources: EIA 2016a, Table 10.4; AFDC 2016d. Calculated by multiplying biodiesel production by tax incentive of $1.00/gallon.

2.3.3 Biodiesel Trade

U.S. biodiesel trade (Figure 27) dynamics are largely affected by policies. The U.S. Energy Information Administration (EIA) reports that imports reached their highest level in 2013 but declined in 2014 due to uncertainty of RFS volumes (Hill 2016). Imports were from five nations; the majority came from Argentina (59%), with smaller amounts from Indonesia (17%) and Canada (13%) (EIA 2016f). Imports from Argentina were driven by EPA's approval of an RFS pathway in January 2015 allowing producers in Argentina to

[24] This section covers federal incentives and policies. States also may have incentives and policies. This information is available from the "Laws and Incentives" section of the Alternative Fuels Data Center (AFDC) website: http://www.afdc.energy.gov/laws.

[25] This is based on multiplying production by $1.00/gallon.

generate RINs (Hill 2016). The United States exported to five nations in 2015, with Canada and Mexico accounting for 85% and 13% of exports, respectively (EIA 2016f).

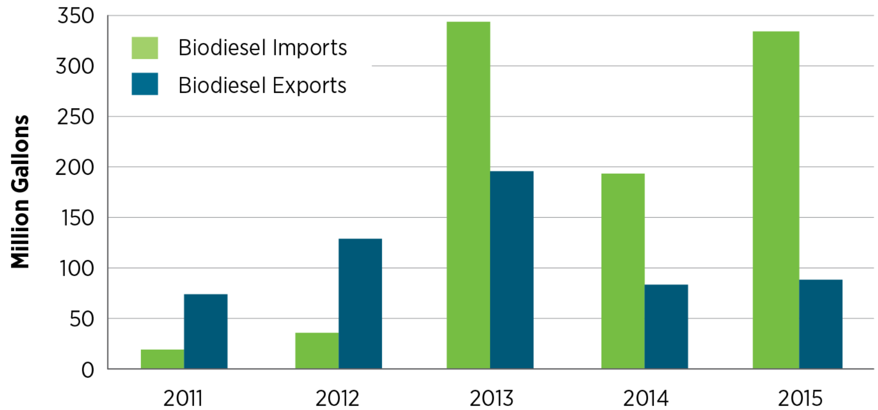

Figure 27. U.S. historical biodiesel exports

Source: EIA 2016e; EIA 2016f.

2.3.4 Infrastructure

The same patchwork of infrastructure regulation that applies to ethanol blends of more than E10 also applies to biodiesel blends of more than B5 for aboveground equipment and of more than B20 for belowground equipment (refer to Section 2.1.5). Federal code allows storage of up to B20 in existing tanks. 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.[26] UL-listed B20 aboveground equipment has been available since 2013.

Diesel use is predominately related to the trucking industry's consumption pattern and not personal vehicles. This is why many retail stations offering diesel are located along major trucking routes. This is also the reason biodiesel stations are located primarily in urban centers and along major highways. Those outside of these locations are typically private stations serving the fleets of the U.S. Department of Defense, other federal agencies, and local governments. Of the 721 refueling stations offering B20, 188 are open to the public (Figure 28). There is a growth opportunity for biodiesel at some of the 2,500 truck stops across the nation because less than 20 of these truck stops sold B20 as of December 2015.[27]

[26] A list of biodiesel-compatible tanks, associated equipment, and UL-listed dispensers and hanging hardware is available on the Alternative Fuels Data Center (AFDC) website: http://www.afdc.energy.gov/fuels/biodiesel_infrastructure.html.

[27] Based on NREL analysis of data from the AFDC Alternative Fueling Station Locator: http://www.afdc.energy.gov/locator/stations.

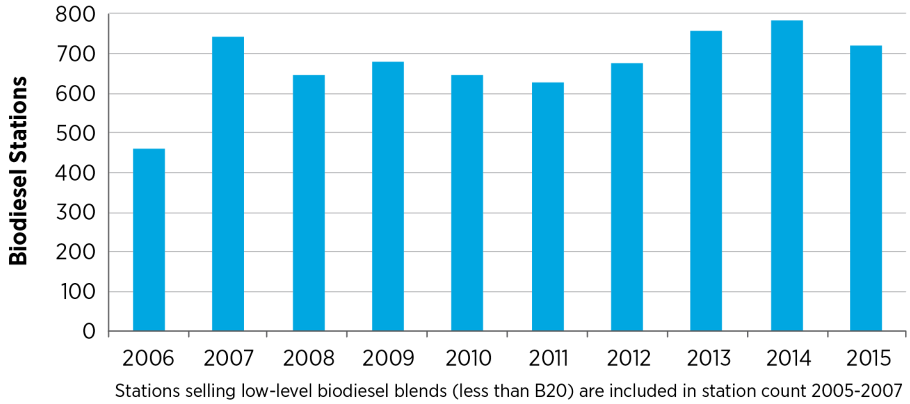

Figure 28. U.S. historical biodiesel (B20) refueling stations

Source: AFDC 2016c.

2.3.4.1 End Use

There are approximately 7.8 million light-duty diesel vehicles and 6.9 million medium- and heavy-duty diesel vehicles registered in the United States.[28] All of these vehicles can use B5 without any modifications to vehicles or infrastructure. There were 17 MY 2015 cars, pickup trucks, and vans approved by the manufacturer for use with B20 and at least 34 engines approved for B20 use in medium- and heavy-duty vehicles and trucks. The National Biodiesel Board provides information on biodiesel blend approvals for vehicles and engines for each MY.[29]

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 (National Oilheat Research Alliance [NORA]). B5 can be used in standard home heating oil equipment, and a NORA survey of 35,000 buildings using B5 reported no issues (NORA 2014). Since 2008, ASTM D396 Standard Specification for Fuel Oils has allowed a blend of up to B5 in home heating oil. NORA research results on blending B20 with standard and low-sulfur home heating oil showed no impact on heating equipment. This led to ASTM International approving the use of B6–B20 under ASTM D396 released in 2015.

2.3.5 Outlook and Trends

Federal policies are the primary drivers for biodiesel because it is not produced at a price competitive with petroleum diesel in current market conditions. Future growth of the biodiesel market will be highly dependent on the policy environment. The EPA RFS biomass-based diesel requirements for 2014–2017 exceed the minimum set by the original legislation, and biodiesel production above these requirements can be used to satisfy the total advanced and renewable fuel categories (EPA 2016b). As research on new feedstock sources comes to fruition, feedstock costs may stabilize or even decline, improving economics. Biodiesel producers are in competition with renewable hydrocarbon diesel producers for feedstock. There are no federal policies that promote the use of biodiesel in home heating oil—an area for potential market growth.

The outlook for biodiesel suggests industry consolidation and trends toward higher production at fewer, larger plants (Sims 2014). Because feedstock availability and price dominate the economics of biodiesel production,

[28] Data purchased from Polk (IHS Automotive). Medium- and heavy-duty vehicles are classified as vehicles with a gross weight of more than 14,000 pounds. Light-duty diesel data is as of the end of 2015, and medium- and heavy-duty diesel data is as of the end of 2013.

[29] National Biodiesel Board original equipment manufacturer information: http://www.biodiesel.org/using-biodiesel/oem-information.

larger producers have an advantage in that they have the financial resources to contract for feedstock on a large scale. Production companies may operate, but not necessarily own, multiple production plants to gain economies of scale and buying power in feedstock procurement. In many cases, smaller producers have been forced to purchase feedstock at higher prices on the commodity markets. There will continue to be a fairly large number of small producers utilizing waste grease collected from local restaurants and food processors.

2.4 Renewable Hydrocarbon Biofuels

Renewable hydrocarbon transportation fuels (also called “green” hydrocarbons, biohydrocarbons, drop-in biofuels, and sustainable or advanced hydrocarbon biofuels) are fuels produced from biomass sources through a variety of biological, thermal, and chemical processes. These products are similar to petroleum gasoline, diesel, or jet fuel in chemical makeup and, therefore, are considered fully infrastructure-compatible fuels. It is anticipated that these fuels can be used in vehicles without requiring engine modifications and can utilize existing petroleum fuel pipelines and retail distribution systems. This eliminates the infrastructure-compatibility concerns associated with ethanol and biodiesel.

Renewable hydrocarbon biofuels are produced from various biomass sources. These include lipids (vegetable oils, animal fats, greases, and algae) and cellulosic material (e.g., crops, crop residues, woody biomass, and others). Several conversion processes are being explored for the production of renewable hydrocarbon biofuels:

- Traditional hydrotreating used in petroleum refineries, which involves reacting the feedstock (lipids) with hydrogen under elevated temperatures and pressures in the presence of a catalyst
- Biological sugar upgrading, which uses a biochemical deconstruction process similar to that used with cellulosic ethanol and then organisms that convert sugars to hydrocarbons
- Catalytic conversion of sugars, which involves a series of catalytic reactions to convert a carbohydrate stream into hydrocarbon fuels
- Gasification, in which biomass is thermally converted to syngas and catalytically converted to hydrocarbon fuels
- Pyrolysis, which involves the chemical decomposition of organic materials at elevated temperatures in the absence of oxygen to produce a liquid pyrolysis oil that can be upgraded to hydrocarbon fuels, either in a stand-alone process or as a feedstock for co-feeding with crude oil into a standard petroleum refinery
- Hydrothermal processing, which uses high pressure and moderate temperature for chemical decomposition of biomass or wet waste materials to produce an oil that may be catalytically upgraded to hydrocarbon fuels.

Renewable gasoline, also known as biogasoline or “green” gasoline is a collection of gasoline-boiling-range hydrocarbons derived from biomass, suitable for use in spark-ignition engines and for meeting ASTM specification D4814 in the United States and EN 228 in Europe. Companies that have been working toward developing renewable gasoline include Cool Planet, Virent, Sundrop Fuels, and Mercurius Biofuels. Under the RFS, renewable gasoline from cellulosic feedstocks meets the cellulosic biofuel 60% GHG-emission reduction threshold (EPA 2010; EPA 2016c).

Renewable diesel, also called “green” diesel, is a transportation fuel derived from biomass sources suitable for use in diesel engines that meets the ASTM D975 specification in the United States and EN 590 in Europe. Renewable diesel is distinct from biodiesel. While renewable diesel is chemically similar to petroleum diesel, biodiesel is a mono-alkyl ester, which has different physical properties and, therefore, different fuel specifications (ASTM D6751 and EN 14214). The two fuels also are produced through very different processes. While biodiesel is produced via transesterification, renewable diesel is produced through various processes, such as hydrotreating/isomerization, gasification, pyrolysis, and other thermochemical and biochemical means. Moreover, biodiesel is produced exclusively from lipids whereas renewable diesel is produced from lipids and cellulosic biomass. Companies in the United States working toward developing renewable diesel include Amyris, AltAir Fuels, Honeywell International Inc.'s UOP, Cool Planet, Fulcrum BioEnergy, Red Rock Biofuels, and Emerald Biofuels, among others. Under the RFS, renewable diesel from cellulosic feedstocks meets the cellulosic diesel 60% GHG-emission reduction threshold (EPA 2010; EPA 2016c). Under the RFS, renewable diesel from biomass-based oils meets the biomass-based diesel 50% GHG-emission reduction threshold (EPA 2010; EPA 2016c). To be classified as a biomass-based diesel, renewable diesel production must not involve co-processed biomass-based oils with petroleum (EPA 2016c).

Renewable jet fuel, also called "biojet" or aviation biofuel, is a biomass-derived fuel that can be used interchangeably with petroleum-based aviation fuel. Certain biojet fuel can now be blended up to 50% with conventional commercial and military jet (or aviation turbine) fuel through requirements in the ASTM D7566 specification. The following synthetic paraffinic kerosene (SPK) fuel categories are approved by this standard:

- Hydrogenated esters and fatty acids (HEFA) fuels derived from used cooking oil, animal fats, algae, and vegetable oils (e.g., camelina) (HEFA-SPK)
- Fischer-Tropsch (FT) fuels using solid biomass resources (e.g., wood residues) (FT-SPK)
- Synthetic iso-paraffin (SIP) from fermented hydroprocessed sugar, formerly known as direct-sugar-to-hydrocarbon fuels. Blends of up to 10% are permitted for this fuel (SIP-SPK).
- Alcohol-to-jet (ATJ) fuels produced from isobutanol and blended to a maximum level of 30% (ATJ-SPK).

Blending of these SPK fuels is required because they lack sufficient aromatic hydrocarbons, which are present in conventional jet fuel. While aromatic hydrocarbons are limited in jet fuel to prevent smoke formation during combustion, a minimum aromatic content is needed to cause elastomer swell in aircraft fuel systems and increase fuel density.

Other processes in development include HEFA-derived synthetic kerosene with aromatics (SKA), FT-derived SKA, and ATJ-derived SKA.

Since 2008, several airlines (e.g., Lufthansa, KLM, United, Alaska Airlines, and others) and aircraft manufacturers (e.g., Boeing and Airbus) performed flight tests with various blends containing up to 50% of the approved forms of SPK biojet fuel, namely HEFA-SPK and FT-SPK. Additionally, flight tests were performed by military aircrafts of the U.S. Navy and U.S. Air Force. U.S. companies working toward developing renewable jet fuel include Amyris, Solazyme Inc., AltAir Fuels, Honeywell International Inc.'s UOP unit, LanzaTech, Fulcrum BioEnergy, Red Rock Biofuels, and others.

2.4.1 Commercialization of Renewable Hydrocarbon Biofuels

A survey of U.S. renewable hydrocarbon biofuel producers was conducted to understand the status of the renewable hydrocarbon biofuels industry at the end of calendar year 2015 (Schwab et al. 2016). As of the end of 2015, there were only two plants (the AltAir Fuels facility in California and the Diamond Green Diesel facility in Louisiana) producing renewable hydrocarbon biofuels at commercial scale (Table 3). One plant, KiOR, was producing in 2013, but it was idled in 2014. Another plant, operated by Renewable Energy Group Inc., was operating briefly in 2015 and then idled due to mechanical issues. The total installed U.S. commercial capacity for renewable hydrocarbons at year-end 2015 was approximately 255 million gallons per year; however, only 167 million gallons per year of capacity was operational at the end of 2015. EPA reports that about 513 million gallons of renewable hydrocarbon fuels (primarily renewable diesel) were supplied (i.e., produced and imported) in 2015 (EPA 2016a). Given the U.S. domestic operational capacity during 2015, most of this volume was met by import, primarily from Neste Corporation—the world's leading producer of renewable diesel. The company has three refineries (in Finland, the Netherlands, and Singapore) with a combined capacity of about 675 million gallons per year (CARB 2015). According to EIA, most renewable diesel imports (Figure 29) were from Singapore in 2015. This fuel is used predominately by fleets in California.

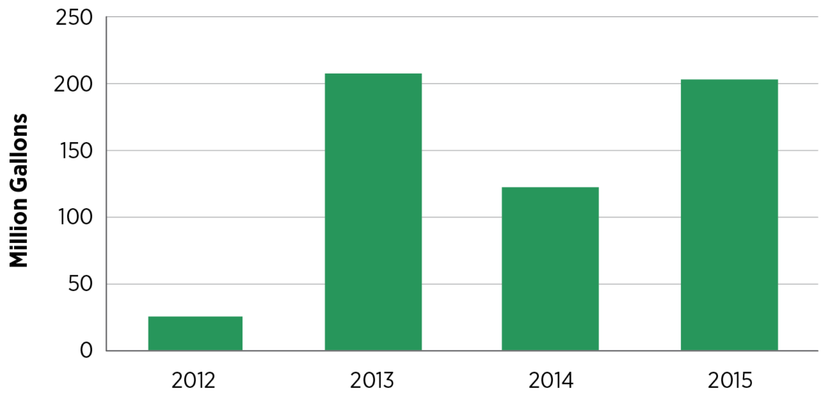

Figure 29. Renewable diesel imports

Source: EIA 2016e.

Table 3. Status of U.S. Commercial-Scale Renewable Hydrocarbon Capacity at the End of 2015

Company	Project Location	Technology Pathway	Feedstock Category	Capacity [MMGY]	Operational Year (Anticipated)
AltAir Fuels	Los Angeles, CA	Hydrotreating/ Isomerization	Vegetable Oils, Fats, and Greases	30	2015
Cool Planet Energy Systems[a]	Alexandria, LA	Thermochemical Pyrolysis	Woody Biomass	10	(2017)
Diamond Green Diesel	Norco, LA	Hydrotreating/ Isomerization	Vegetable Oils, Fats, and Greases	137	2013
Emerald Biofuels	Plaquemine, LA	Hydrotreating/ Isomerization	Vegetable Oils, Fats, and Greases	82	(2017)
Fulcrum BioEnergy	Reno, NV	Thermochemical Gasification	Municipal Solid Waste	10	(2017)
KiOR	Columbus, MS	Thermochemical Pyrolysis	Woody Biomass	13	2013 (idled in 2014)
Red Rock Biofuels	Lakeview, OR	Thermochemical Gasification	Woody Biomass	15.5	(2017)
Renewable Energy Group, Inc.	Geismar, LA	Hydrotreating/ Isomerization	Vegetable Oils, Fats, and Greases	75	(2016)
SG Preston	South Point, OH	Hydrotreating/ Isomerization	Vegetable Oils, Fats, and Greases	120	(2020)
SG Preston	Logansport, IN	Hydrotreating/ Isomerization	Vegetable Oils, Fats, and Greases	120	(2020)
Sundrop Fuels	Boyce, LA	Thermochemical Gasification	Woody Biomass	200	(2020)

Source: Schwab et al. 2016. MMGY = million gallons per year.
[a] This facility has reportedly been put on hold (Lane 2015c).

Figure 30 summarizes the characteristics of the 32 renewable hydrocarbon facilities included in this survey report. Figure 30 also shows the various combinations of technology pathways and feedstocks being pursued at these renewable hydrocarbon facilities. The six feedstock types used across the six technology pathways indicate the diversity of the developing renewable hydrocarbon production capability in the United States.

Scale of the Facility	Company Name Facility Location	Planning	Under Construction	Operating	Idle
Commercial	AltAir Fuels_CA			✱ (cyan)	
	Cool Planet Energy Systems_LA	△ (purple)			
	Diamond Green Diesel_LA			✱ (cyan)	
	Emerald Biofuels_LA	✱ (cyan)			
	Fulcrum BioEnergy_NV	▽ (red)			
	KiOR_MS				△ (purple)
	Red Rock Biofuels_OR	△ (red)			
	Renewable Energy Group, Inc._LA		✱ (cyan)		
	SG Preston_IN	✱ (cyan)			
	SG Preston_OH	✱ (cyan)			
	Sundrop Fuels_LA	△ (red)			
Demonstration	Blue Sun_MO			✱ (cyan)	
	Cool Planet Energy Systems_CA			△ (purple)	
	Haldor Topsoe, Inc._IA				△ (red)
	KiOR_TX				△ (purple)
	REII_OH				△ (red)
	Renewable Energy Group, Inc._FL			○ (green)	
	Sundrop Fuels_ND				△ (red)
Pilot	Algae Systems_AL				□ (orange)
	Amyris_CA			○ (green)	
	BioProcess Algae_IA			□ (orange)	
	Envergent Technologies_HI				△ (purple)
	Frontline BioEnergy, LLC_TX	▽ (red)			
	KiOR_TX				△ (purple)
	Mainstream Engineering Corporation_FL			▽ (purple)	
	Mercurius Biofuels_ME	+ (brown)			
	Mississippi State University_MS			△ (purple)	
	Research Triangle Institute International_NC			△ (purple)	
	Sundrop Fuels_CO				△ (red)
	Thermochem Recovery International_NC			△ (red)	
	Versa Renewables LLC_GA			△ (purple)	
	Virginia Tech_VA				▽ (purple)

Technology Pathway
- Algae (HC) (orange)
- Hydrotreating/Isomerization (cyan)
- Thermochemical Gasification (HC) (red)
- Thermochemical Pyrolysis (purple)
- Biochemical (HC) (green)
- Biochemical Catalytic (brown)

Feedstock Category
- □ Algae
- + Crop Residues
- △ Woody Biomass
- ▽ MSW
- ○ Cellulosic Sugars
- ✱ Vegetable Oils, Fats, and Greases

Figure 30. Characteristics of U.S. renewable hydrocarbon biofuel facilities at the end of 2015

Source: Schwab et al. 2016.

In 2015, seven pilot-scale facilities were identified as operating, and two pilot-scale facilities were in the planning stage of development. Four of the seven operational pilot-scale facilities used a thermochemical pyrolysis technology. At the demonstration scale, three facilities were operating (each with a different technology pathway and feedstock combination), and none were currently under construction. At the commercial scale, two facilities were operational, both using the hydrotreating/isomerization technology on vegetable oils, fats, and greases. The survey documented five pilot, four demonstration, and one commercial facilities that were idle at the end of 2015.

Of the 10 idle facilities, 4 used the thermochemical gasification technology pathway, and 5 of the 10 idle facilities used the thermochemical pyrolysis technology. Development of these technology pathways continues at other facilities. Most of the thermochemical gasification and pyrolysis facilities used woody biomass as feedstock, with four facilities planning to use MSW. In 2015, the two operating hydrotreating/isomerization commercial facilities are using vegetable oils, fats, and greases as feedstock.

2.4.1.1 Production Costs

The costs for producing renewable hydrocarbon biofuels are not well known, and estimates range widely. Milbrandt et al. (2013) conducted a literature review of public sources and reported production costs for various production processes. The study reports costs for renewable diesel and jet fuel production via hydroprocessing of soybean oil at about $3.82–$4.39/gallon ($3.61–$4.15/gge) and $4.09–$4.69/gallon ($3.81–$4.37/gge) in 2010 dollars, respectively. The study also reports production costs of renewable diesel and gasoline produced via gasification of corn stover followed by FT synthesis at $4.50–$5.00/gge in 2007 dollars, depending on the operating temperature of the gasifier, along with another estimate of $6.45/gallon ($6.09/gge) in 2008 dollars. Biojet fuel production via gasification and FT synthesis is reported at $4.00/gge from corn stover, $5.50/gge from switchgrass, and about $5.80/gge from short-rotation woody crops in 2007 dollars. A selling price of $3.24/gge for the KiOR catalytic fast pyrolysis process was reported, although the source does not provide analysis details, and it is unclear what year the costs were indexed (Milbrandt et al. 2013).

2.4.2 Outlook and Trends

The outlook for renewable hydrocarbon fuels, based on market trends, is mixed. Investments in research and development on renewable hydrocarbon fuel pathways and the number of facilities being planned at various scales suggest continued interest and favorable longer-term trends toward producing renewable hydrocarbon biofuels. The number of idle facilities highlights the nearer-term operational challenges. As with cellulosic ethanol, the RFS is a significant driver encouraging hydrocarbon biofuel development. Due to the nested structure of the RIN categories, cellulosic renewable hydrocarbon biofuels are able to qualify for all categories of RINs—advanced biofuel, biomass-based diesel, cellulosic biofuel, and renewable fuel. For 2016, the EPA RFS volume is 3.61 billion gallons of advanced biofuels, which includes 230 million gallons of cellulosic biofuel production (EPA 2016d).

2.5 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 natural gas. RNG meets the 60% GHG-emission reduction threshold to qualify as a cellulosic biofuel under the RFS and is currently the main contributor to this fuel category (cellulosic ethanol provides a minor input) (EPA 2016c).

Biogas is produced from various biomass sources through a biochemical process, such as anaerobic digestion (AD), or through thermochemical means, such as gasification. Currently, most biogas in the United States is produced via AD of organic landfill waste, wastewater sludge, animal manure, and, to a lesser extent, food waste (American Biogas Council 2016). With minor cleanup (e.g., siloxane removal), 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.

EPA reports that about 81 million RINs or ethanol gallon equivalent (ege) of compressed RNG and about 58 million RINs or ege of liquefied RNG were produced in 2015 under the RFS2 program (EPA 2016a). Figure 31 shows the increase in RNG production over the past 5 years. The combined volume corresponds to about 93 million gge or roughly 10.8 trillion Btu. The overall RNG potential in the United States is much larger and underutilized. NREL estimates that the RNG potential from landfills, animal manure, wastewater, and food waste (industrial, institutional, and commercial organic waste) in the United States is about 8.7 million tons per year, equivalent to 431 trillion Btu (NREL 2013). Thus, only 2.7 % of the estimated RNG potential is currently utilized.

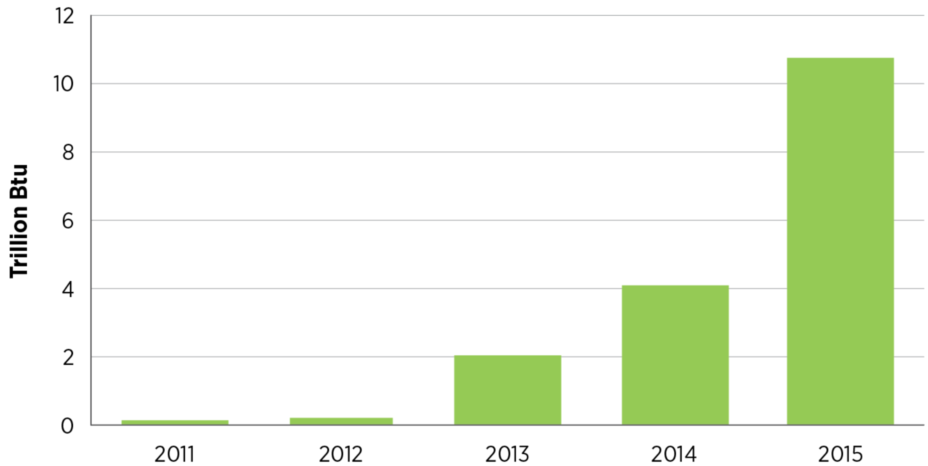

Figure 31. U.S. historical RNG production for transportation under the RFS

A literature review conducted by the National Petroleum Council estimates that the cost for RNG production via AD is between $5 and $13+ per million Btu or between $0.6 and $1.6 per gge (NPC 2012). The cost for producing RNG via thermochemical conversion (e.g., gasification) is estimated between $8 and $25+ per million Btu or between $1 and $3.1 per gge. The study notes that the 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.

RNG systems offer many socioeconomic benefits, including generating revenue streams and boosting the local economy. Along with generating revenues from the sale of renewable energy products, outputs from biogas systems can offer avoided costs of onsite electricity, heat, and transportation fuel (USDA et al. 2014). RNG systems create temporary jobs during the construction phase, while design and operation of the collection and energy recovery systems produce long-term jobs (USDA et al. 2014). Biogas energy projects involve engineers, construction firms, equipment vendors, and utilities or end users of the power produced; some materials for the overall project may be purchased locally, and often local firms handle construction, electrical, plumbing, and other services (USDA et al. 2014).

2.6 Biofuels Market Outlook

EIA, in its 2015 Annual Energy Outlook (AEO), provides forecasts of ethanol, biodiesel, and other advanced biofuels production through 2040 (EIA 2016k). AEO 2015 projects that overall renewable fuels production will increase modestly on average by 0.7% per year during the 2013–2040 period, with more rapid growth occurring during the first 10 years and then leveling off during the out-years. AEO 2015 (EIA 2016k) considers many of the different policies and regulations that can affect energy markets, including the RFS. In AEO 2015 (EIA 2016k), domestic ethanol production is expected to increase slightly, and biodiesel production is expected to increase through 2020 and decrease slightly for future years during the 2013–2040 forecast. It should be noted that AEO 2015 (EIA 2016k) assumes that the EPA RFS requirements for advanced biofuels will increase slowly after 2015 but will not reach the 2022 regulated values.

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, AD, 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 (CHP) 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. AD is a biological process in which microorganisms break down biodegradable material in the absence of oxygen. One of the end products of AD 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., CHP, AD, and gasification) at small scale used in off-grid, distributed-generation applications. Combustion, CHP, AD, 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 12% of all renewable energy generated in the United States and about 1.6% of total U.S. electricity generation (EIA 2016i). While the installed biopower capacity has been increasing over the past 10 years, biopower generation has remained almost flat during that period (Figure 32). The total number of biopower plants increased from 485 in 2003 to 760 in 2015 (EIA 2016j). In 2015, the top five states with the largest biopower generation were California, Florida, Georgia, Virginia, and Maine (EIA 2016i). California has adopted many policies and initiatives to promote bioenergy (e.g., California Renewables Portfolio Standard, California Integrated Waste Management Act of 1989, Assembly Bill 341, and CalRecycle's Anaerobic Digestion Initiative), which have resulted in the largest and most diverse biomass energy industry in the country. Florida has a large biomass resource base and, through industry-driven initiatives, has also become a major biopower producer (Stuart and El-Halwagi 2012).

According to Chum et al. (2011), biopower GHG emissions can potentially be reduced (on average) by about 95% relative to coal on a well-to-plant basis. The study also finds that potential GHG emission reductions are higher for forestry and crop residues and lower for energy crops.

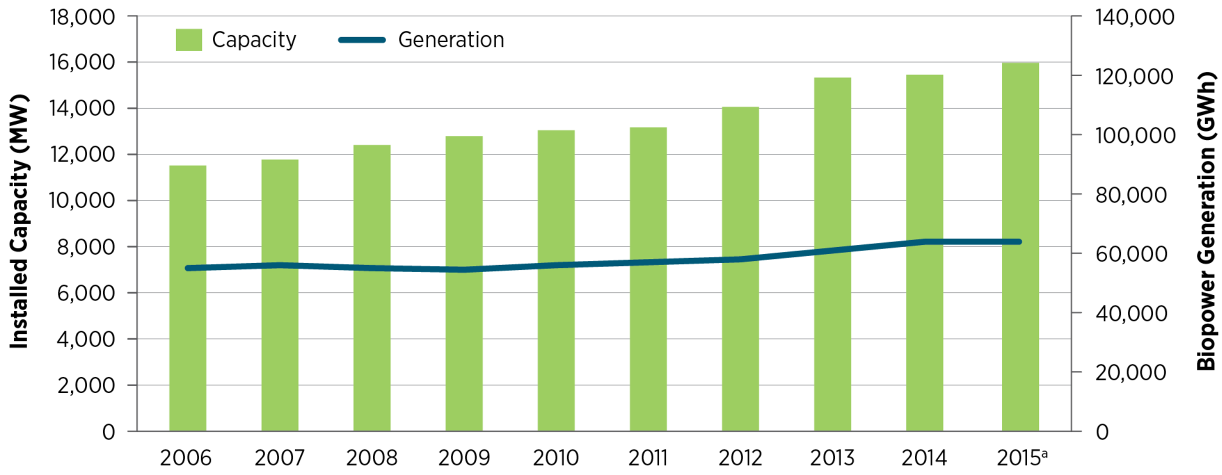

Figure 32. U.S. biopower capacity and generation

Sources: EIA 2016i; EIA 2016j. Note: Installed capacity includes both biogenic and non-biogenic MSW due to lack of separate data. Biopower generation does not utilize non-biogenic MSW, only biogenic MSW. GWh stands for gigawatt-hours.
[a] Early release, not final.

Biomass electricity is produced from various resources. These include cellulosic material (e.g., woody and crop materials, such as crop residues), 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 co-generation plants—such as pulp and paper mills or sawmills (EIA 2016c). Biogas is used to generate electricity for onsite use or sale to the grid and as a pipeline-quality gas (see RNG section). Solid wood and wood waste provided about 36% of total biomass power generation in 2015; black liquor provided 29%; and the organic portion of MSW provided 11% (EIA 2016c; Figure 33). According to EIA, while the use of these resources in biomass power applications has leveled over the past 10 years, the use of landfill gas (LFG) has been increasing—from 9.5% of total biopower generation in 2003 to about 18% in 2015. The use of other biomass sources—such as agricultural crop residues, sludge waste, other biomass solids, and gases—remains very small in comparison.

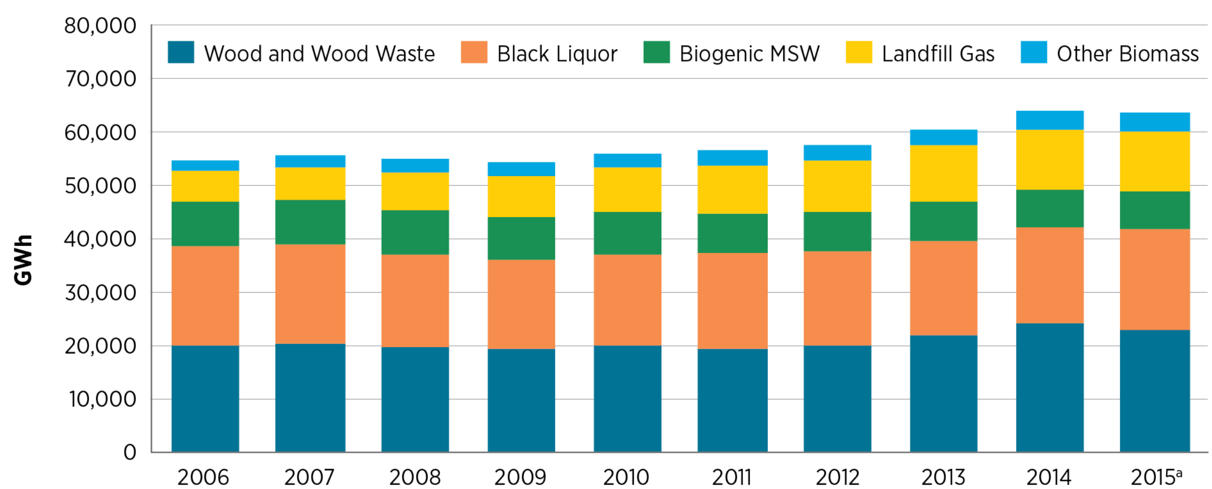

Figure 33. U.S. biopower generation sources

Source: EIA 2016c. Other biomass includes other biomass solids, other biomass gases, agricultural crop residues, sludge waste, wood-waste liquids, and other biomass liquids.
[a] Early release, not final.

Because of widely varying feedstock and conversion processes, there is a large range for the levelized cost of electricity (LCOE) of biomass power generation. LCOE is a calculation of the cost of electricity produced by a generator and includes capital costs, operations and maintenance, performance, and fuel costs (feedstock). The LCOE of biomass-fired power plants globally ranges from $0.04 to $0.29/kilowatt-hour (kWh) (IRENA 2012). Direct combustion is reported to have an LCOE of $0.06–$0.21/kWh; co-firing LCOE is between $0.04 and $0.13/kWh; LFG has an LCOE in the range of $0.09–$0.12/kWh; and the LCOE for digesters is between $0.06 and $0.15/kWh. The LCOE for CHP plants has an even wider range, for example, between $0.07 and $0.29/kWh for stoker-fired CHP facilities. Feedstock costs typically account for between 20% and 50% of the LCOE for power generation-only options, except co-firing (IRENA 2012). The wide range in feedstock costs is primarily due to transportation distances. For example, the feedstock cost can be zero for otherwise unusable byproduct materials that are produced onsite as a part of the industrial process (e.g., black liquor at pulp and paper mills or bagasse at sugar mills), and the use of these materials for energy avoids transport costs related to disposal; feedstock costs can be modest where agricultural crop residues can be collected and transported over short distances, and they can be high where significant transport distances are involved due to the low energy density of biomass (e.g., the trade in wood chips and pellets) (IRENA 2012). Operations and maintenance costs are typically between 9% and 20% of the LCOE for biomass power plants. They can be lower than that in the case of co-firing and greater for plants with extensive fuel preparation, handling, and conversion needs (IRENA 2012).

The biomass power industry provides many socioeconomic benefits, including gross job creation:

- It is estimated that a 50-MW dedicated biomass power plant utilizing direct combustion and using corn stover as feedstock can support about 25 direct, onsite jobs during its operation (NREL 2014).
- A typical 3-MW LFG electricity project can directly create 5 construction jobs and indirectly create another 20 to 26 direct jobs during the construction year (Pierson 2013). It also is expected to add more than $1.5 million in new project expenditures and increase the statewide economic output by $4.1 million.

3.1 Biopower Outlook

In AEO 2015, EIA provides forecasts of renewable energy generating capacity and generation, including biomass, to 2040 (EIA 2016k). In its reference case, AEO 2015 projects that, during the 2013–2040 period, co-firing will have the highest annual average growth rate among all renewable energy technologies, about 12.7%. EIA assumes the existence and implementation of then-current state and federal regulations for emissions. The main driver for the projected increase in co-firing biomass is mostly economics, although in some cases it may be to comply with renewable portfolio standards (in some eastern states, co-firing is seen as potentially less expensive than building wind or solar facilities) (Namovicz 2014). In comparison, biopower generation by dedicated plants is projected to have an annual growth rate of 3.8%. EIA projects that biopower capacity for plants using wood and other biomass sources could grow at an annual average growth rate of 1.8%. Power generation from biogenic MSW is expected to remain almost flat during the period, with an annual growth rate of 0.8%. No significant increase in biopower capacity for plants using municipal waste is projected.

4 Bioproducts and Co-Products

Conventional bioproducts and emerging bioproducts are two broad categories used to classify products produced from biomass feedstock. Examples of conventional bioproducts include building materials, pulp and paper, and forest products. Examples of emerging bioproducts include bioadhesives, biopolymers, and biochemicals. Emerging bioproducts are active subjects of research and development, and these development efforts have been driven by the price of traditionally petroleum-based products, the environmental impact of petroleum use, and an interest in becoming more independent from foreign oil. Additionally, because biomass feedstocks are more oxygenated compared to petroleum feedstocks, many chemical products are functionally more similar to biomass than petroleum feedstocks (DOE 2015). Bioproducts derived from bioresources can replace (either directly or indirectly) some of the fuels, chemicals, plastics, etc., that are currently derived from petroleum.

If the bioproducts industry develops structurally like the existing petrochemical industry, it will utilize a platform-chemical approach to manufacturing. In the platform-chemical approach, a small number of chemical intermediates are first produced, and these intermediates are subsequently converted to a larger number of chemical products (Corma et al. 2007). Manufacturing would operate along a supply chain from lower-value/higher-volume biomass feedstocks to lower-volume/higher-value categories like polymers, specialty chemicals, and pharmaceutically active ingredients. Based on technical evaluations and inputs from industrial experts, DOE has previously compiled a list of platform chemicals that are particularly promising as biologically derived platform chemicals (Werpy and Peterson 2004). Subsequent studies have provided additional information and updates to this earlier study (Nikolau et al. 2008; Bomgardner 2014; Biddy, Scarlata, and Kinchin 2016). The most recent study reviewed a broad range of chemicals that can be produced from biomass, yielding a subset of 12 chemicals with prospects for near-term deployment. This study provided a detailed discussion of the existing markets and future potential for each of the selected bioproducts (Biddy, Scarlata, and Kinchin 2016). Thus, there is precedent to indicate that platform chemicals derived from biomass feedstock provide a promising approach for the development of a commercial bioproducts market.

Production of bioproducts (1) can enable the production of bioenergy feedstocks as co-products to improve the economics of the primary fuel product in an IBR (Biddy et al. 2016) or (2) can enable industrial learning to develop technologies and processes essential to the long-term production of biofuels and bioenergy. Within this context, this report considers four types of emerging bioproducts: platform and intermediate chemicals, lignin, biochar, and wood pellets.

4.1 Platform and Intermediate Chemicals

The biochemicals market is an emerging and immature market. 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. Many biochemicals manufacturers currently treat their production and pricing information as confidential as they pursue competitive advantages within this emerging market sector. Thus, at this point in time, publicly available biochemical production and pricing information is limited.

Examples of manufacturers producing platform and intermediate chemicals include DuPont Tate and Lyle’s 1,3-propanediol facility in Tennessee, NatureWorks’ polylactic acid facility in Nebraska, and the Myriant succinic acid facility in Louisiana (DOE 2015). Commercial production of biochemicals is developing to seek out cost advantages (relative to traditional petrochemical production routes), GHG-emission 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.

The 2015 USDA BioPreferred Report provides an analysis of specific biobased segments within the U.S. economy (Golden et al. 2015). The report evaluates agriculture and forestry, biorefining, biobased chemicals, enzymes, bioplastic bottles and packaging, forest products, and textiles as the seven major biobased product industries contributing to the U.S. economy. It specifically excludes contributions to the economy from energy, livestock, food, feed, and pharmaceuticals. Within this stated context, the 2015 USDA BioPreferred Report estimates that direct sales of biobased products in 2013 totaled nearly $126 billion.

Another recent study has estimated the current domestic market for biochemicals. Specifically, within the context of this study, biochemicals include renewable commodity chemicals, renewable polymers, and other materials produced from biomass that are not consumed as fuels (Nexant 2014). It is important to note that these biochemical production estimates exclude the traditional agriculturally based oleochemicals market and, thus, use a much different basis than the 2015 USDA BioPreferred Report. This study indicates a consumption of approximately 3 million dry tons of biomass feedstock to produce 1.1 billion pounds (0.5 million tons) of biochemicals per year, resulting in approximately $2.5 billion per year in sales revenue (Nexant 2014).

Target markets for biochemicals could include the $275 billion U.S. petrochemical industry (Nexant 2014), or the $164 billion U.S. organic chemical manufacturing industry (IBISWorld 2016). Given these market valuations, biochemical sales revenues of $2.5 billion represent a 1%–2% share of these markets. If biochemicals are able to successfully compete with and displace existing traditional chemical production, these figures indicate the potential for increasing market penetration.

A major distinguishing market factor between biofuels and biochemicals is policy support. While production of biofuels has been stimulated and supported by policy, analogous policy support for biochemicals has not existed through the end of 2015. However, policy mechanisms are in development.[30]

4.2 Lignin

Lignin is a component of woody biomass cell walls that gives wood its distinctive structure. A total resource availability of 300 billion metric tons of lignin exists in the biosphere, making it one of the most abundant natural polymers on earth (Gregorová, Košíková, and Moravčík 2006). Assuming a lignin energy content of 25 kilojoules per gram, this renewable resource is equivalent to nearly 8,000 quads of energy worldwide. (A quad is a unit of energy equal to 1.055 x 108 joules.) Of course, only some fraction of this theoretically maximum-available lignin can be captured for use in bioenergy or bioproduct applications without negatively affecting the environment and traditional markets (DOE 2015).

The use of cellulosic feedstock to produce biofuels is on the rise; however, the industry's focus is primarily on the sugars in this feedstock, i.e., the cellulosic and hemicellulose fractions, leaving a lignin byproduct stream. Currently, lignin is considered a byproduct that is typically burned for heat and power. However, lignin is a complex class of chemicals containing aromatic rings and heteroatom functional groups that could be upgraded and valorized.

Typically, lignin will comprise 15%–30% of the biomass feedstock stream in a lignocellulosic biorefinery (Linger et al. 2014). The ability to convert lignin into a higher-value bioproduct (compared to current heat and power utilizations) could improve profit margins for lignocellulosic biorefineries. Other smaller-volume applications of lignin include lignosulfonates used as additives and binders, agricultural dispersants, lignin-derived expanded polyurethane foam, and lignin-derived activated carbon (DOE 2015). Lignin valorization to higher-value bioproducts is currently a topic of active research and development (Linger et al. 2014; Ragauskas et al. 2014). Potential higher-value markets for this product include transportation fuels and fuel additives, carbon fiber, and plastic materials.

[30] The Iowa Renewable Chemicals Production Tax Credit program was signed into law on April 6, 2016.

4.3 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 co-product with biofuels produced via pyrolysis.[31] 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 (IBI 2015a).

Diversity in biomass feedstock materials, production technologies, and biochar end uses (including soil conditioners, building materials, water treatment, and industrial applications) creates a complex set of parameters whose interactions and synergies are still being investigated (Schmidt and Wilson 2014). Although purposely adding biochar to soils is an established practice in some parts of the world, biochar as a commercial product is an emerging concept—both in terms of research and of a formal biochar industry focused on promoting its adoption as a mainstream soil fertility management practice (IBI 2015b).

4.4 Wood Pellets

Wood pellets are generally 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 (WFI 2010). Chipping, shredding, and milling are typical first process steps to create a uniform, dough-like material (Fuller 2015), which 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 (Manomet Center for Conservation Sciences 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 (Tumuluru et al. 2011).

In 2015, there were 181 wood pellet plants in the United States with a total annual capacity of 20 million tons. Furthermore, there were an additional 21 wood pellet plants proposed (totaling a proposed 5 million tons of additional annual capacity), and 12 wood pellet plants were under construction, which is estimated to add an additional 2 million tons of annual capacity in the future ("Pellet Plants" 2015).

Production of wood pellets in the United States exceeded 5.6 million tons/year in 2012 and reached more than 8 million tons/year in 2015 (FAO 2016). The international trade of wood pellets as a renewable energy source has increased significantly since 2008, and the United States has established itself as the leading producer of wood pellets for export since 2012 (at the time, overtaking Canada as the lead exporter) (Table 4; Figure 34). While a steady quantity is still consumed within the United States, the main production capacity increases over the past years were mainly to fulfill the export market demand. By the end of 2015, 40% of U.S. wood pellet production was consumed within the United States, while the remaining share was exported—99% of which went to the European Union. As a result of this large increase in European Union imports, a sustainability assessment was commissioned by the European Commission to understand the environmental implications of increased reliance on U.S. wood pellets (ECDGE 2015). The Southeast is the primary wood pellet–producing region in the United States. Traditionally, tracking the international trade of wood pellets has been difficult, with trade statistics comingling sawdust, wood waste, and wood scrap in the form of logs, briquettes, pellet, or other product forms. However, in 2012, a harmonized tariff schedule code explicitly for wood pellets (4401.31) was added to the Harmonized Commodity Description and Coding System, which is the

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

international standard for trade nomenclature administered by the World Customs Organization. This change should lead to more consistency in international trade data for wood pellets (Lamers et al. 2012).

Table 4. Top Exporters of Wood Pellets (million tons)

Country	Year		
	2012	2013	2014
United States	1.9	2.9	4.0
Canada	1.4	1.6	1.6
Latvia	0.9	1.1	1.2
Russia	0.7	0.7	0.9
Portugal	0.6	0.8	0.7

Source: ITA 2015.

Wood pellet exports from the United States rose from 2012 to 2014 (as shown in Figure 34) and in 2015, primarily due to the demand created by bioenergy policies across northwestern Europe. A relatively stable cross-border trade of wood pellets, mainly for residential heating purposes, also exists between Canada and the United States.

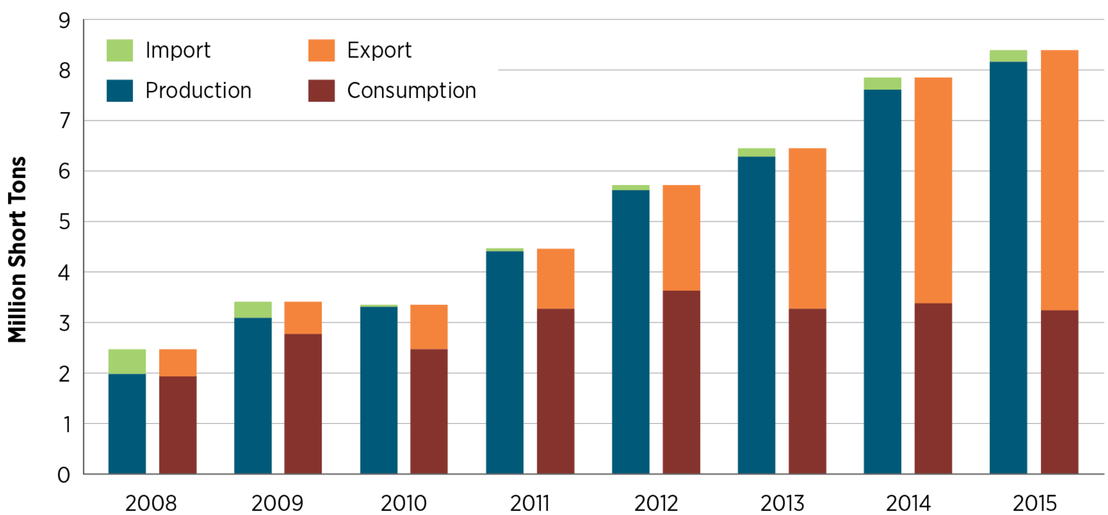

Figure 34. U.S. import, export, consumption, and production of wood pellets

Sources: Idaho National Laboratory, based on Lamers et al. 2012, REN21 2016, EUROSTAT 2016, FAO 2016, USDA-FAS 2016, and ITA 2015.

5 Future Work

The purpose of this market report is to synthesize and document the status of the domestic bioenergy and bioproduct markets and provide perspective on market trends over time. The data in this market report shows a flexible energy market adapting to emerging production of biofuels from a variety of feedstocks. It also documents the interplay of energy demand and regulatory aspects in driving the market. At the end of 2015, several companies were constructing biorefinery capacity capable of producing cellulosic biofuels at commercial scale. Emerging market trends and commercial developments such as this example will be documented and examined in future market reports, relative to the baseline established by this market report.

In future years, the trends and observations contained in this market report will be updated as new data sets and market information become available. The scope of future reports is also expected to expand to capture and document emerging market trends.

Appendix A

Table A-1. Renewable Fuel Standard (RFS) Biofuel Categories

Renewable Fuel Standard - Biofuel Category	D Code[a] Category	Biofuel Category Definition	Major Source(s) of RIN Generation in 2015 *(see Table A-2)*
Renewable Fuel	D6	Transportation fuel, transportation fuel additive, heating oil, or jet fuel that is produced from renewable biomass[b] and that is used to replace or reduce the quantity of fossil fuel present in a transportation fuel and has life-cycle (GHG) emissions that are at least 20% less than baseline life-cycle GHG emissions[c] unless exempted (e.g., grandfathered plants) pursuant to 40 Code of Federal Regulations (CFR) § 80.1403.	Ethanol derived from corn starch. Also defined as conventional biofuel. Biodiesel[d] or non-ester renewable diesel that has life-cycle GHG emissions that are less than 50% lower than baseline life-cycle GHG emissions.[e]
Advanced Biofuel	D5	Renewable fuel, other than ethanol derived from corn starch, which has life-cycle GHG emissions that are at least 50% less than baseline life-cycle GHG emissions.	Ethanol derived from sugar or starch (other than corn starch).
Biomass-Based Diesel	D4	Renewable and advanced fuel that is defined as biodiesel, non-ester renewable diesel, heating oil, or jet fuel and that has life-cycle GHG emissions that are at least 50% less than the baseline life-cycle GHG emissions.	Biodiesel or non-ester renewable diesel that has life-cycle GHG emissions that are at least 50% less than baseline life-cycle GHG emissions.
Cellulosic Biofuel	D3	Renewable and advanced fuel derived from any cellulose, hemicellulose, or lignin that is derived from renewable biomass and that has life-cycle GHG emissions that are at least 60% less than the baseline life-cycle GHG emissions.	Biogas (including landfill gas and sewage waste treatment gas) produced through the conversion of organic matter from renewable biomass. Ethanol derived from cellulose, hemicellulose, or lignin.
Cellulosic Diesel	D7	Any renewable and advanced fuel that meets both the definition of cellulosic biofuel (D3) and biomass-based diesel (D4).	Diesel or heating oil derived from cellulose, hemicellulose, or lignin.

[a] D codes signify the code number in the RIN indicating its biofuel category.

[b] See EPA's definition of feedstocks that qualify as renewable biomass (42 U.S. Code (USC) § 7545 (o)(1)(I)).

[c] The baseline is defined as the average life-cycle GHG emissions for gasoline or diesel (whichever is being replaced by renewable fuel) sold or distributed as transportation fuel in 2005 (42 USC § 7545 (o)(1)(C)). Gasoline contained a baseline level of 98 grams of carbon dioxide equivalent per megajoule, while diesel contained a baseline level of 97 grams of carbon dioxide equivalent per megajoule (EPA 2010).

[d] Biodiesel is defined as a mono-alkyl ester that meets American Society for Testing and Materials D 6751-09, Standard Specification for Biodiesel Fuel Blend Stock (B100) for Middle Distillate Fuels (40 CFR § 80.1401).

[e] Non-ester renewable diesel is defined as a fuel that can be used in an engine designed to operate on conventional fuel, or be heating oil or jet fuel and is not a mono-alkyl ester (40 CFR § 80.1401).

Table A-2. 2015 Renewable Identification Number (RIN) Generation

Fuel	Equivalence Value (EV)	Cellulosic Biofuel (D3)		Biomass-Based Diesel (D4)		Advanced Biofuel (D5)		Renewable Fuel (D6)		Cellulosic Diesel (D7)	
		RINs (ege)	Volume (gallons)	RINs (ege)	Volume (gallons)	RINs (ege)	Volume (gallons)	RINs (ege)	Volume (gallons)	RINs (ege)	Volume (gallons)
Ethanol	1	2,181,096	2,181,096	0	0	113,785,284	113,785,284	14,378,038,529	14,378,038,529	0	0
Biodiesel	1.5	0	0	2,273,251,369	1,515,484,489	0	0	111,679,662	74,453,091	0	0
Naphtha	1.5	0	0	0	0	23,988,365	15,992,239	0	0	0	0
Heating Oil	1.6	0	0	0	0	847,149	529,467	0	0	0	0
Non-Ester Renewable Diesel	1.6	0	0	6,877,749	4,298,593	0	0	0	0	0	0
Non-Ester Renewable Diesel	1.7	0	0	515,669,247	303,334,791	8,465,623	4,979,775	340,903,411	200,531,415	0	0
Cellulosic Heating Oil	EV application required	0	0	0	0	0	0	0	0	275,315	275,315
Renewable Compressed Natural Gas	n/a	81,490,266	81,490,266	0	0	5,022	5,022	0	0	0	0
Renewable Liquefied Natural Gas	n/a	58,368,879	58,368,879	0	0	0	0	0	0	0	0

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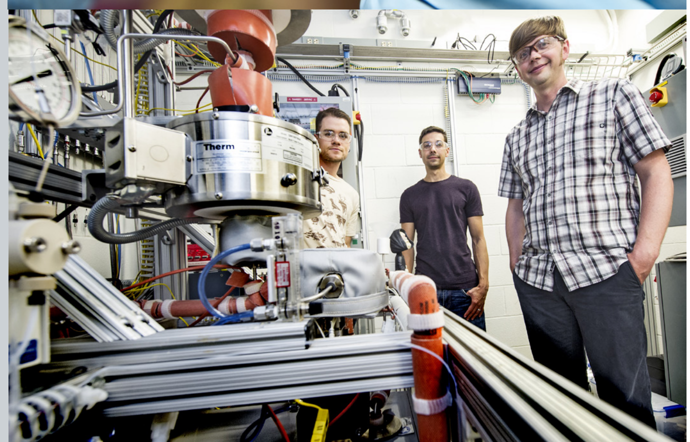

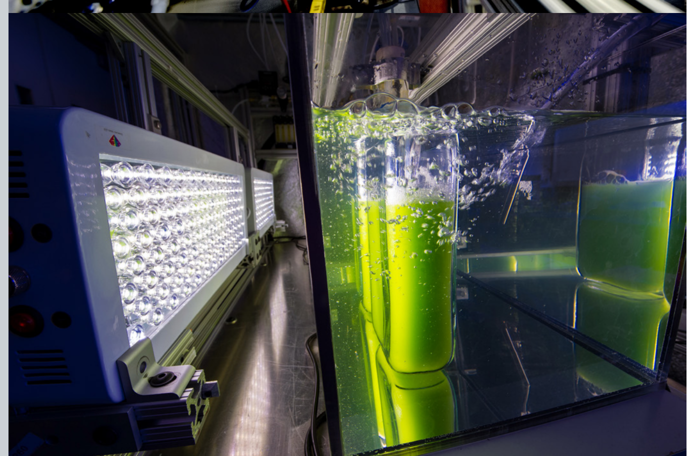

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