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# 2016 BILLION-TON REPORT

## Advancing Domestic Resources for a Thriving Bioeconomy

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A Study Sponsored by U.S. Department of Energy  
Office of Energy Efficiency and Renewable Energy  
Bioenergy Technologies Office

### **Volume 1:**

Economic Availability of Feedstocks

July 2016

*Prepared by*

OAK RIDGE NATIONAL LABORATORY  
Oak Ridge, Tennessee 37831-6335 managed by  
UT-Battelle, LLC  
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## Additional Information

The U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy's Bioenergy Technologies Office and Oak Ridge National Laboratory provide access to information and publications on biomass availability and other topics. The following websites are available:

[energy.gov](http://energy.gov)

[eere.energy.gov](http://eere.energy.gov)

[bioenergy.energy.gov](http://bioenergy.energy.gov)

[web.ornl.gov/sci/transportation/research/bioenergy/](http://web.ornl.gov/sci/transportation/research/bioenergy/)

Front cover images courtesy of ATP<sup>3</sup>, Oak Ridge National Laboratory, Abengoa, Solazyme, and BCS, Incorporated.

### DISCLAIMER

The authors have made every attempt to use the best information and data available, to provide transparency in the analysis, and to have experts provide input and review. However, the *2016 Billion-Ton Report* is a strategic assessment of potential biomass. It alone is not sufficiently designed, developed, and validated to be a tactical planning and decision tool, and it should not be the sole source of information for supporting business decisions. This analysis provides county by county estimates of the feedstocks at a selected cost, yet users should use associated information on the Bioenergy Knowledge Discovery Framework ([bioenergykdf.net/billionton](http://bioenergykdf.net/billionton)) to understand the assumptions and ramifications of using this analysis. The use of tradenames and brands are for reader convenience and are not, nor does their use imply, an endorsement by the U.S. Department of Energy or Oak Ridge National Laboratory.

The foundation of the agricultural sector analysis is the USDA Agricultural Projections to 2024. From the report, "projections cover agricultural commodities, agricultural trade, and aggregate indicators of the sector, such as farm income. The projections are based on specific assumptions about macroeconomic conditions, policy, weather, and international developments, with no domestic or external shocks to global agricultural markets." The *2016 Billion-Ton Report* agricultural simulations of energy crops and primary crop residues are introduced in alternative scenarios to the 2015 USDA Long Term Forecast. Only 2015-2024 Billion-Ton national level baseline scenario results of crop supply, price, and planted and harvested acres for the 8 major crops are considered to be consistent with the 2015 USDA Long Term Forecast. Additional years of 2025-2040 in the *2016 Billion-Ton Report* baseline scenario and downscaled reporting to the regional and county level were generated through application of separate data, analysis, and technical assumptions led by Oak Ridge National Laboratory and do not represent nor imply U.S. Department of Agriculture or U.S. Department of Energy quantitative forecasts or policy. The forest scenarios were adapted from U.S. Forest Service models and developed explicitly for this report and do not reflect, imply, or represent U.S. Forest Service policy or findings.

The biomass supply projections presented in this report are policy independent and estimate the potential economic availability of biomass feedstocks using specified market scenarios and guiding principles intended to be conservative and to reflect certain environmental and socio-economic considerations. For example, some principles aim to maintain food availability and environmental quality, including improved tillage and residue removal practices, exclusion of irrigation, and reserved land areas to protect biodiversity and soil quality. In this sense, this report (volume 1) and related analyses on environmental effects (forthcoming in volume 2) may differ from other efforts seeking to depict potential biomass demand and related market, environmental and land use interactions under business-as-usual or specific policy conditions.

The federal government prohibits discrimination in all its programs and activities on the basis of race, color, national origin, age, disability, and, where applicable, sex, marital status, familial status, parental status, religion, sexual orientation, genetic information, political beliefs, reprisal, or because all or part of an individual's income is derived from any public assistance program.

# 02

Biomass  
Consumed in  
the Current  
Bioeconomy





## 2.1 Introduction

This chapter reviews and expands upon the large variety of biomass-based resources identified in the 2005 *BTS* and 2011 *BT2* that are currently used for fuels, heat, and power production. Biomass is a feedstock for a broad range of primary and secondary energy applications, from home heating to industrial power generation. This section will review primary energy consumption, along with a compilation of estimates of secondary biomass consumption, with attention to the quantification of biomass as a feedstock for energy uses.

### Text Box 2.1 | Data Sources and Definition of Currently Used Resources

In this chapter, 2014 values of biomass energy consumption are used as much as possible; however, the wood-derived energy, MSW, and landfill gas values from EIA's 2015 *Electric Power Annual* are from 2013. These values were chosen as the best and most current source of data.

The *Electric Power Annual* was selected, as opposed to EIA's *Monthly Energy Review*, because it breaks down the feedstock categories to a more granular level and attributes energy to both electric and thermal end uses (unlike the *Monthly Energy Review*). The *Electric Power Annual* also provides information regarding MSW and landfill gas in thousand dry tons and million cubic feet, respectively.

In the 2011 *BT2*, projections of biomass consumption from EIA's *Annual Energy Outlook* provided the basis for growth in supply for existing biomass-to-energy pathways (EIA 2015a). This report deviates from this approach using two simplifying assumptions about future demand and supply. First, it is assumed that demand is constant for all existing uses identified in this chapter throughout the projection period to 2040. Second, future supply of biomass to meet existing uses equals demand. The representation of "currently used resources" in reporting the billion-ton potential is reported alongside potential future supply to highlight the growth in biomass potential supply without confounding estimates of growth in demand from biomass energy.

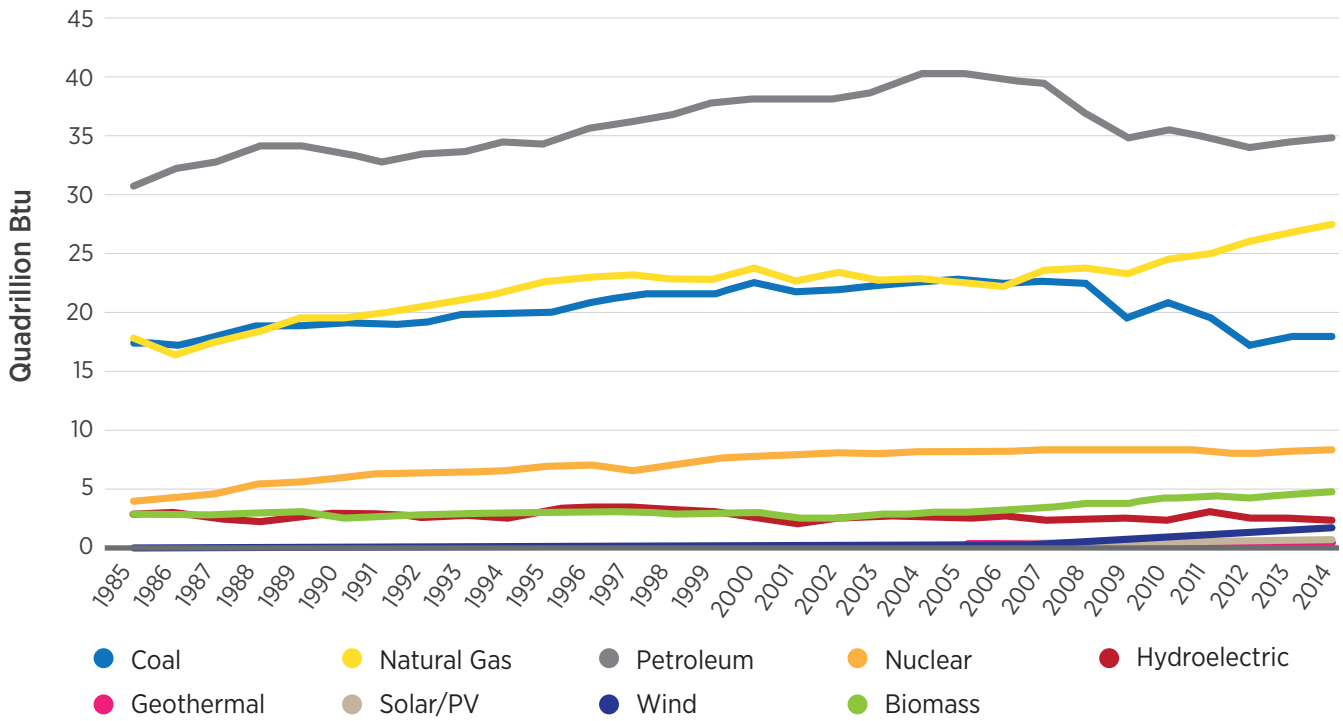
## 2.2 Primary Energy Consumption

According to EIA, combined energy consumption rose from a low of 76 quadrillion Btu in 1985 to a high of 101 quadrillion Btu in 2007 (EIA 2015b; see fig. 2.1). Around 2006, there is a clear inflection point marking downward trends in the use of coal and petroleum. Natural gas has shown the largest growth, although biomass, wind, solar, and other renewables are also trending upward. The use of renewable energy will continue to increase as the United States attempts to meet emissions reduction targets and transition toward a more diverse energy portfolio.

As shown in figure 2.2, cumulative renewable energy consumption has increased steadily since 2001, driven by growth in biofuels, wind, and solar production. It is interesting that the composite renewable energy total correlates closely with the largest sources, hydroelectric and biomass, up until 2001; after that, it grows according to the expansion of biofuels production from 2001 to 2014. Figure 2.3 provides a view of the 15-year historical consumption levels for the major components of renewable energy and a cross section of 2014 consumption by source.

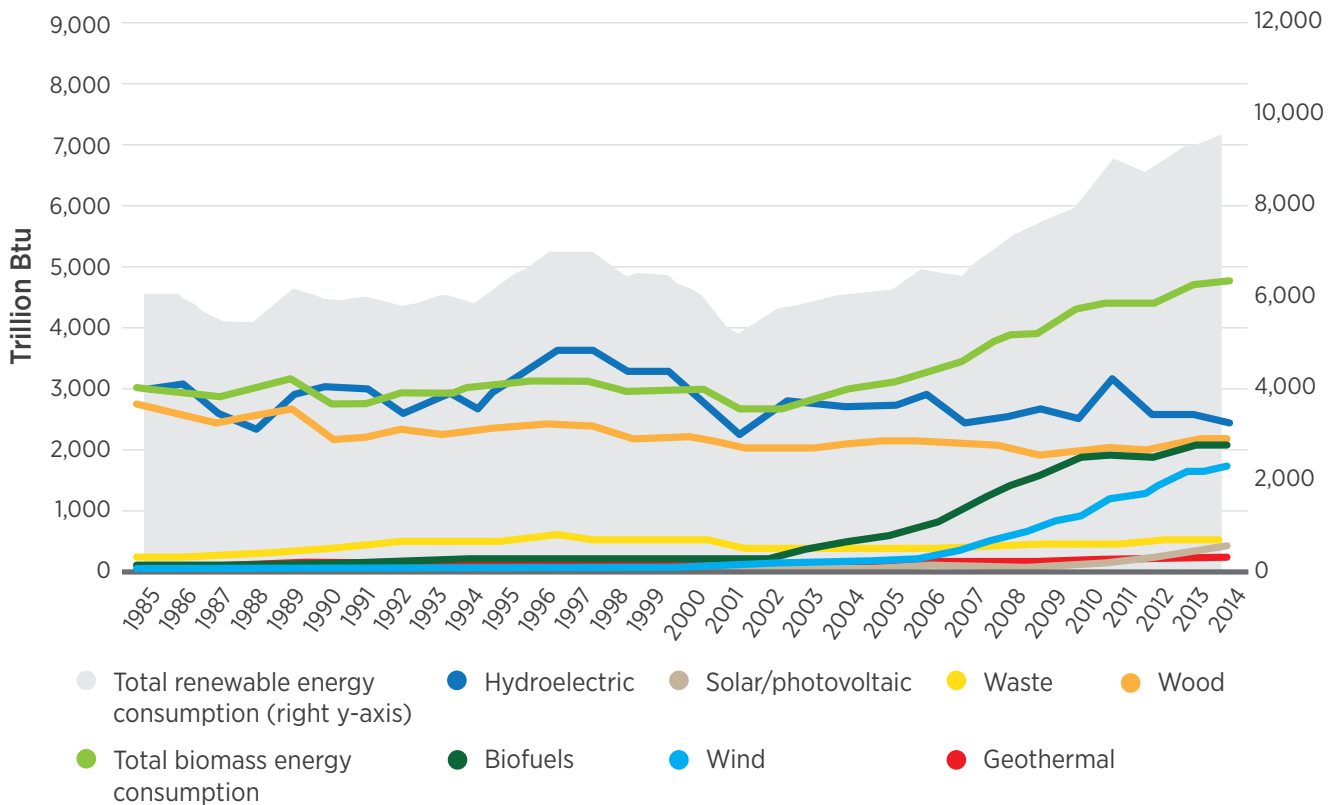
Biomass-based energy as a composite category of wood (23%), waste (5%), and biofuels (21%) contributes 50% of 2014 consumption.

**Figure 2.1** | Primary energy consumption by source (1985–2014)



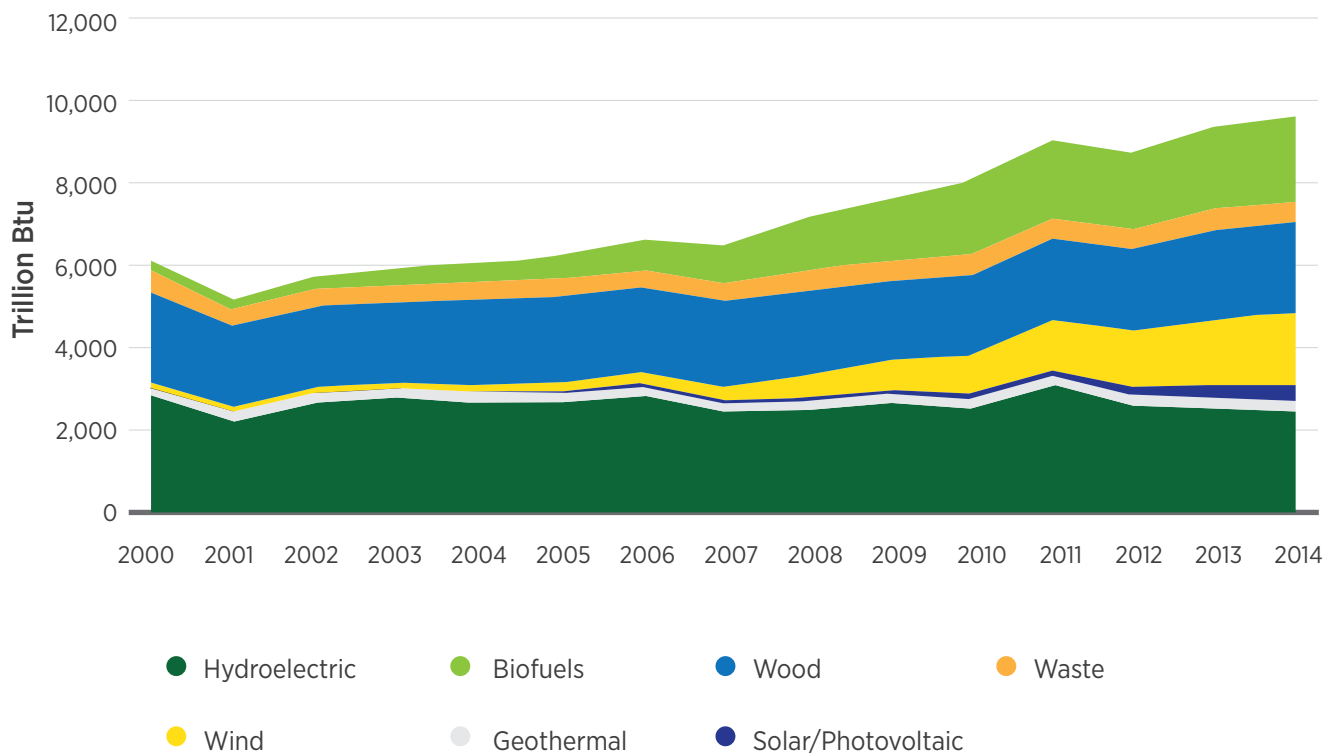
Source: Data from EIA (2015d).

**Figure 2.2** | Primary renewable energy consumption by source and total consumption (1985–2014)



Source: Data from EIA (2015d).

**Figure 2.3** | Primary renewable energy consumption by source (2001–2014)



Source: Data from EIA (2015d).

Hydroelectric energy consumption follows with 26% of renewable energy consumption, followed by wind (18%), solar (4%), and geothermal (2%). Current consumption will be explained in more detail in the following sections.

### 2.2.1 Estimates from Previous Assessments

The 2005 *BTS* reports domestic biomass consumption for energy at 184 million dry tons per year based upon 2004 energy consumption. In the 2011 *BT2*, biomass consumption for energy increased to 214 million dry tons, with the increase largely attributed to biomass for ethanol as a transportation fuel.

These estimates understate the amount of biomass for energy as a result of incomplete reporting of all biomass-to-energy pathways. In this report, the approach to estimating the currently used sources of biomass for energy has been expanded and improved to include greater detail for biopower and secondary feedstocks contributing to energy generation in the industrial sector. Additionally, greater detail is included based on publicly available bioenergy feedstock production and energy use statistics, particularly for emerging consumption classes. In each section, the amount of product is reported from an estimated biomass feedstock quantity. In many cases, conversion factors are assumed based upon technical values

from industry, academic literature, and generally accepted renewable energy modeling assumptions. In this approach, the estimates are “bioenergy equivalent” amounts. All conversion factors to support the reported bioenergy production amounts are listed in appendix A.

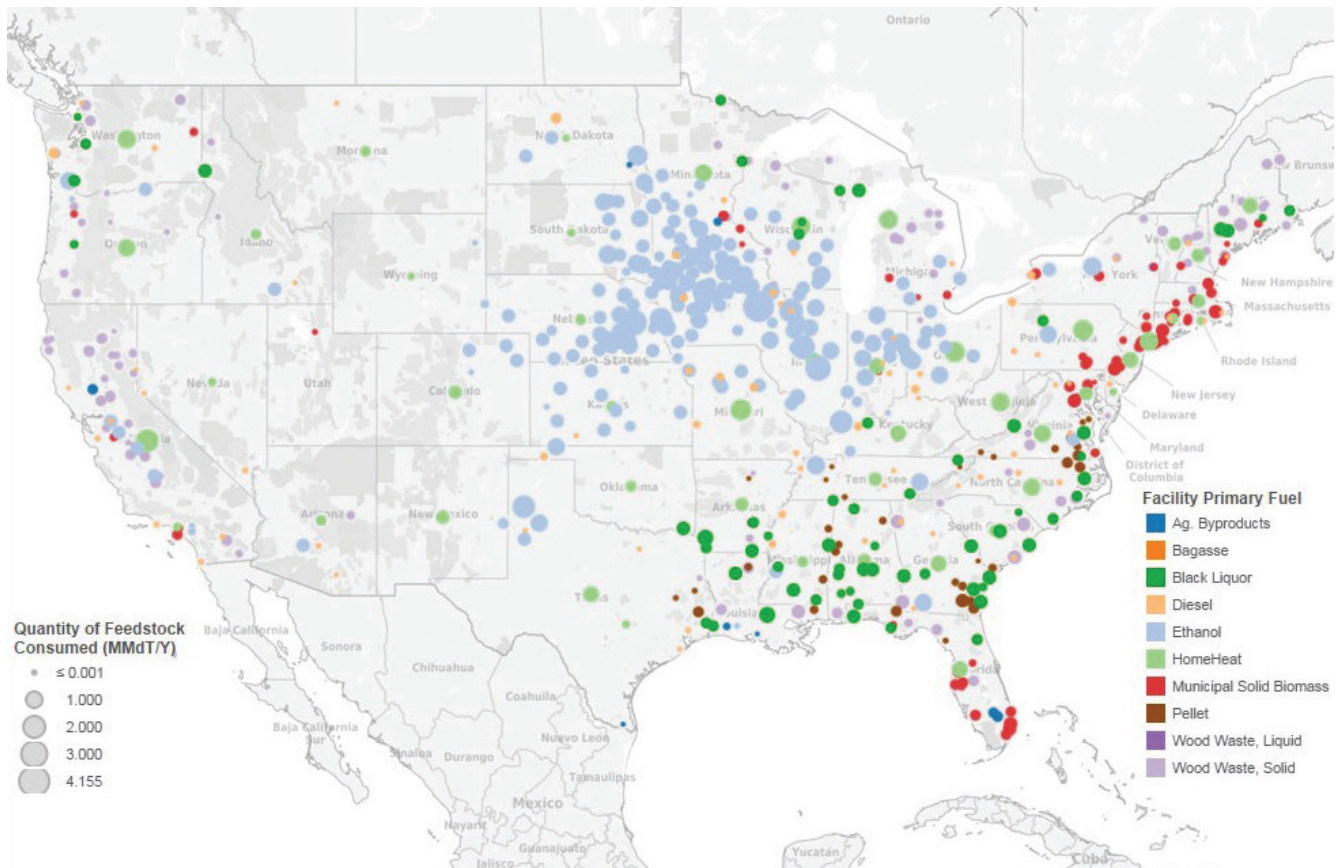
## 2.2.2 Spatial Distribution of Biomass Consumption

The current locations of facilities using biomass for energy and energy products are tightly coupled with the locations of the raw biomass sources (fig. 2.4). The current bioenergy economy is the most efficient in history, yet the majority of commercial applica-

tions reflect conventional systems based largely upon starch and waste resources with passive feedstock quality controls. The largest industry consumers of biomass are producers of corn-grain-based ethanol located throughout the Corn Belt, Northern Plains, and Southern Plains. The second-largest biomass use is production of electric and industrial power from wood and wood waste. Wood waste consuming facilities are clustered within the Southeast region, but facilities that consume woody biomass are located across the Lake States, Northeast, and Pacific.

The greatest distribution of incinerators burning MSW occurs near population centers predominantly in the Northeast, where most of the 84 current facil-

**Figure 2.4** | Spatial distribution of facilities that consume biomass for energy or energy products, by nameplate capacity in million bioenergy equivalent dry tons per year<sup>1</sup>



**Source:** Data from EIA (2015d); Forisk Consulting (2014); Biodiesel Magazine (2015); EIA (2015e); EPA (2015a); Renewable Fuels Association (2015).

<sup>1</sup> Interactive visualization: <https://bioenergykdf.net/billionton2016/2/2/tableau>



ities exist (ERC 2014). Smaller classes of biomass consumption are bagasse from sugar cane processing, agricultural byproducts, and a rapidly growing sector of wood pellets for export (wood pellets are discussed in detail in chapter 3). Figure 2.4 includes a nationwide map showing the major facilities that consume biomass for energy or energy products. The points representing facilities vary in size by the annual nameplate generation capacity in tons of bioenergy equivalent biomass per year.<sup>2</sup> The methodology used to generate the capacity is described in appendix A.

## 2.3 Transportation Fuels

The current primary biomass sources for liquid transportation fuels are predominantly corn grain for ethanol and soybean oil for biodiesel. In general, technologies that convert accessible sugars via fermentation for corn grain and transesterification for soybean oil to transportation fuel for blending are referred to as “first generation.” Ethanol is consumed primarily as motor fuel in the form of E10 (10% denatured ethanol by volume, 90% petroleum), and E15 (15% denatured ethanol) in 2001 and newer light-duty vehicles only. Flex-fuel vehicles can also take E85 (up to 85% ethanol). However, the overwhelming majority of ethanol (more than 99%) is sold as E10. E10 is essentially ubiquitous; so for more ethanol to enter the market, blends higher than 10% would need to be sold. The most common forms of biodiesel blends are B5 or B20 (5% and 20% biodiesel blended with petroleum); however, B100 (100% biodiesel) can be used by certain vehicles.

Under RFS2, EPA provides aggregated monthly data on RIN transactions and renewable fuel volume production. These data are used to determine current actual volumes for the production of ethanol, biobased gasoline blendstocks/naphtha, biobased jet/aviation

fuels, biobased diesel and heating oil, and biogas/compressed natural gas (CNG)/liquefied natural gas (LNG). These biofuel volumes are converted to tonnage and cross-referenced with reported information based on the USDA Feed Grains Database (USDA 2015) and the EIA Monthly Biodiesel Production Report to estimate the biobased fuel production by feedstock category, as shown in tables 2.1 and 2.2.

The following sections discuss current biobased fuel production and describe the references and assumptions used to estimate the amount of biomass resources consumed in conversion.

### 2.3.1 Fuel Ethanol

The rise in ethanol as a liquid transportation fuel in the early 2000s was due to its replacement of MTBE (methyl tert-butyl ether) as an oxygenate. The 2005 Energy Bill (including the RFS1) and EISA (including the RFS2) mandated an increase in the amount of corn grain-derived ethanol in fuel mixes. About 90% of corn ethanol is produced by the dry milling process (the other 10% comes from wet milling). In the past, the starch fraction was used to produce ethanol and the residual fractions were used to produce distillers grains (an animal feed). Preliminary reports as of November 2015 from the Agricultural Marketing Resource Center at Iowa State estimate that 43.64 million dry tons of dried distillers grains were produced in 2014 (Hoque and Hart 2015).

In 2014, renewable fuel ethanol production was 14.1 billion gallons. Mueller and Kwik (2013) report that dry mills produce an average of 2.82 gallons of ethanol per bushel of corn. At 56 lb of shelled corn per bushel and a 15.5% moisture content, this equates to 118 gallons/dry ton of corn (Rankin 2008). Thus, 14.1 billion gallons of ethanol at 118 gallons/dry ton represents about 120 million dry tons of corn (EPA 2015b). The USDA Feed Grains Database reports 5.2 billion bushels of corn were consumed in 2014 to

<sup>2</sup> Note that each state has one point representing residential power generation in the form of home heating. Facility data is represented for the most recent year of reporting, either 2014 or 2015.

**Table 2.1** | Biobased Fuel Production in the Current Bioeconomy (million gallons)

Biomass resource category	Ethanol	Gasoline blendstock/ naphtha	Jet/ aviation fuels	Diesel/ heating oil	Biogas, CNG, and LNG	Total
Corn grain	14,106.81	-	-	-	-	14,106.81
Vegetable oils	-	-	-	1,471.12	-	1,471.12
Other fats, oils, and greases	-	-	-	505.42	-	505.42
Feed for gasoline blendstock/ naphtha <sup>a</sup>	-	12.09	-	-	-	12.09
Landfill gas	-	-	-	-	52.95	52.95
<b>Total</b>	<b>14,106.81</b>	<b>12.09</b>	<b>-</b>	<b>1,976.54</b>	<b>-</b>	<b>16,095.44</b>

<sup>a</sup>Gasoline blendstocks and naphtha can be produced from a variety of feedstocks, including agricultural residues, forest residues, biogenic MSW, yard wastes, biogas, energy grasses, oil seed plants, and other cellulosic materials.

**Table 2.2** | Biomass Consumed for Fuel Production in the Current Bioeconomy (million bioenergy equivalent dry tons)

Biomass resource category	Ethanol	Gasoline blendstock/ naphtha	Jet/ aviation fuels	Diesel/ heating oil	Biogas, CNG, and LNG	Total
Corn grain <sup>a</sup>	119.55	-	-	-	-	119.55
Vegetable oils	-	-	-	5.51	-	5.51
Other fats, oils, and greases	-	-	-	1.89	-	1.89
Feed for gasoline blendstock/ naphtha <sup>b</sup>	-	0.22	-	-	-	0.22
Landfill gas <sup>c</sup> (bcf)	-	-	-	-	9.1	9.14
<b>Total</b>	<b>119.55</b>	<b>0.22</b>	<b>-</b>	<b>7.40</b>	<b>-</b>	<b>127.17</b>

bcf = billion cubic feet

<sup>a</sup>Corn grain consumed for ethanol production also creates 43.64 million dry tons of dried distillers grains (Wisner 2015).

<sup>b</sup>Gasoline blendstocks and naphtha can be produced from a variety of feedstocks, including agricultural residues, forest residues, biogenic MSW, yard wastes, biogas, energy grasses, oil seed plants, and other cellulosic materials.

<sup>c</sup>Bioenergy equivalent dry ton contributions from landfill gas are not added into the totals shown.

produce alcohol for fuel use, which at 56 lb of shelled corn per bushel and a 15.5% moisture content equates to 123 million dry tons of corn (USDA 2015). This value results in a slightly lower ethanol yield of 2.71 gallons per bushel, or 115 gallons of ethanol per dry ton. The 2% discrepancy between the number of dry tons of corn calculated from the RFS and that reported from the USDA Feed Grains Database is attributable to real-life variability in the assumed conversion efficiencies and feedstock moisture contents. Conversion efficiency has been rising over time, but there is an upper limit on the conversion rate based on the carbohydrate fraction of corn. Dry mills have also become more sophisticated, and most now also extract corn oil, which is used for either biodiesel production or animal feed.

Advanced technology now enables the production of ethanol from cellulosic biomass, including crop wastes, woody biomass, grasses, sorted MSW, and other sources. From 2013 to 2014, three pioneering facilities came online as first-of-a-kind integrated biorefineries capable of efficiently converting a broad range of biomass feedstocks into commercially viable second-generation biofuels, biopower, and other bioproducts. INEOS Bio's Indian River Bioenergy Center near Vero Beach, Florida, converts yard and wood waste into cellulosic ethanol.<sup>3</sup> POET-DSM's Project LIBERTY in Emmetsburg, Iowa, converts corn stover into cellulosic ethanol. Abengoa Bioenergy's biorefinery in Hugoton, Kansas, converts agricultural waste into cellulosic ethanol and renewable electricity.<sup>4</sup> In 2014, RFS2 reported the production of 728,000 gallons of cellulosic ethanol biofuel, which at 85 gallons per ton equates to about 10,000 tons of biomass. Combined, the three facilities mentioned are expected to take in up to 860,000 tons of agricultural residues and wood wastes to produce up to 53 million gallons of cellulosic ethanol and 27 MW of renew-

able electricity per year. These facilities may pave the way for additional investments in cellulosic ethanol, helping to advance U.S. competitiveness in clean energy technology while providing American farmers with an additional revenue stream.

### 2.3.2 Biodiesel

The second-largest type of liquid transportation fuels is biodiesel from vegetable oils, fats, and greases. Soybean oil makes up a little more than 50% of the feedstock for biodiesel. At present, about 25% of U.S. soybean oil production is used for biodiesel. Other feedstocks include yellow grease, canola oil, corn oil, white grease (lard), tallow, other recycled oils, poultry fat, other vegetable oils, palm oil, and miscellaneous other sources (EIA 2015c). Production in 2014 was 1.24 billion gallons, and the production capacity by the end of 2014 rose to 2.1 billion gallons (EIA 2015c). Although, historically, biodiesel has been produced via a chemical transesterification process, other technologies are also being used, such as enzymatic transesterification and hydrotreating. Hydro-treated oils and fats are called "renewable diesel," as opposed to biodiesel. Although biodiesel and renewable diesel can be made from the same feedstocks, biodiesel is chemically different from petrodiesel and renewable diesel because it contains oxygen atoms.

In 2014, EPA reported the production of 1,489 million gallons of biodiesel, 488 million gallons of non-ester renewable diesel, and 5,000 gallons of cellulosic diesel. Additionally, EPA reported 71,000 gallons of renewable heating oil and 50,000 gallons of cellulosic heating oil (EPA 2015b). Depending on the feedstock and conversion technology, the conversion rate may vary. We assume a conversion rate of 7.5 lb of oils/fats per gallon of biodiesel (or 267 gallons per ton) for biodiesel, renewable diesel, and

<sup>3</sup> Biofuels policy at the federal level dictates the eligibility of fuels to qualify for various subsidies and credits, such as RINs for advanced biofuels. Qualification is based upon a host of environmental performance and quality characteristics, one of which is the definition of eligible feedstocks.

<sup>4</sup> At the time of report publication, this plant was idle.

renewable heating oil, and 56 gallons per ton for the conversion of cellulosic biomass to diesel or heating oil. Based on these assumptions, it is estimated that more than 7.4 million tons of soybean oils, animal fats, and waste oils and nearly 1,000 tons of cellulosic biomass were consumed in 2014 for the production of fuel and heating oil. Cellulosic diesel production is entering the fuels market in small amounts. In 2014, the combined production of cellulosic diesel (for electric vehicle applications), renewable heating oil, and cellulosic heating oil was approximately 126,000 gallons from an estimated 2,265 dry tons of biomass.

### 2.3.3 Renewable Gasoline Blendstocks and Naphthas

Renewable gasoline blendstocks and naphthas represent a small but promising source of liquid transportation fuels. Renewable gasoline can be made from a variety of feedstocks, including agricultural residues, forest residues, biogenic MSW, yard wastes, biogas, and other cellulosic materials. Naphthas can also be made from a variety of biomass resources, including energy grasses such as miscanthus, switchgrass, and energy cane or oil seed plants such as *Camelina sativa*. Renewable gasoline and naphthas can be produced via hydrotreating and gasification processes. Renewable gasoline can also be produced by other thermocatalytic processes, pyrolysis, and direct biological conversion.

In 2014, EPA reported 29,000 gallons of cellulosic renewable gasoline blendstock and 12 million gallons of naphthas (EPA 2015b). Depending on the feedstock and conversion technology, the conversion rate may vary; however, we assume a conversion rate of

56 gallons per ton for the conversion of biomass to drop-in hydrocarbons.<sup>5</sup> Based on these assumptions, we estimate that more than 216,000 tons of biomass were consumed in 2014 for renewable gasoline blendstocks and naphthas.

### 2.3.4 Biogas

Biogas is produced from a variety of sources including landfills, municipal wastewater treatment facility digesters, and agricultural digesters. Biogas can be upgraded to renewable natural gas, which is comparable to conventional natural gas and can be injected into the pipeline network or used as an alternative fuel for natural gas vehicles. Renewable CNG and renewable LNG are both suitable for use in vehicles and can be used for light-, medium-, or heavy-duty applications. Although natural gas is a clean-burning alternative fuel, only about 0.1% is used for transportation fuel in the United States (DOE 2015b). Biogas may help to expand the natural gas vehicle fueling infrastructure in the United States.

In 2014, EPA reported the equivalent of nearly 53 million gallons of biogas and renewable natural gas were produced—more than 20 million gallons of biogas, 15 million gallons of renewable CNG, and 17 million gallons of renewable LNG.<sup>6</sup> By applying the lower heating value of propane as a proxy, 84,250 Btu/gallon, and a conversion factor of 0.488 trillion Btu (TBtu)/bcf, we estimate that the 53 million gallons is equivalent to 9.1 bcf of biogas.<sup>7</sup> Although biogas is produced from landfills, municipal wastewater treatment facility digesters, and agricultural digesters, a simplifying assumption is made that biogas used in transportation applications is currently from landfills.

<sup>5</sup> The estimated product yield for cellulosic biomass conversion to drop-in hydrocarbons of 56 gallons per dry ton is conservative relative to published values from National Renewable Energy Laboratory and Pacific Northwest National Laboratory design reports.

<sup>6</sup> 2014 RFS2 Data, <https://www.epa.gov/fuels-registration-reporting-and-compliance-help>.

<sup>7</sup> Conversion factor of 0.488 TBtu/billion cubic feet calculated using the 2015 EIA *Electric Power Annual 2013* (EIA 2015f), tables 5.6 A–F.



## 2.4 Heat and Power

The current primary biomass sources for heat and power are predominantly woody biomass and wood waste for home heating and for industrial use as fuel. Woody biomass/wood waste, the biogenic portion of MSW, and landfill gas also make contributions to the electricity sector. Animal manure can also be collected and converted to biogas via anaerobic digestion. This gas is recovered, treated, and used to generate energy for farm and wastewater treatment applications.

The 2015 EIA *Electric Power Annual* (EIA 2015f, tables 5.5, 5.6, 5.7, and 5.8) provides energy values by sector for the wood/wood waste, biogenic MSW, other waste biomass, and landfill gas consumed for electricity generation and useful thermal energy. The value for thermal energy consumed in the residential sector is obtained from table A17 of the EIA *Annual*

*Energy Outlook*. The AgSTAR Anaerobic Digester Projects Database provides basic information on anaerobic digesters on livestock farms in the United States (EPA 2015c). Estimates are extrapolated based on the digester type, end-use application, animal type, and animal population supplying the digester (using only reported values with no co-digestion). Table 2.3 shows the energy content of the biomass resources consumed to produce heat and power by end-use sector.

Several electrical and thermal conversion efficiencies are applied to the values in table 2.3 to estimate the useful electrical (in billion kWh) and thermal energy (in TBtu) output of each biomass resource by sector (shown in table 2.4). Depending on the technology and combustion method, electrical and thermal conversion efficiency may vary. Conservative estimates are used as much as possible when calculating estimates for the electrical and thermal energy output of the current bioeconomy.

**Table 2.3** | Inherent Energy of Biomass Resources Consumed for Heat and Power in 2013 (Tbtu)

Biomass resource category	Electricity		Industrial		Commercial		Residential		Farm use	Total		
	E	T	E	T	E	T	E	T	Total	E	T	Total
Wood/wood waste <sup>a</sup>	187.1	20.3	210.3	898.3	0.5	1.0	-	582.5		397.9	1,502.1	1,900.1
Animal manure <sup>b</sup>	-	-	-	-	-	-	-	-	34.8	-	-	34.8
Biogenic MSW <sup>a</sup>	115.9	4.1	0.1	1.5	19.8	9.5	-	-	-	135.8	15.2	150.9
Other waste biomass <sup>a</sup>	16.1	6.8	8.3	54.4	5.0	1.3	-	-	-	29.4	62.4	91.8
Landfill gas <sup>a</sup>	119.1	0.1	2.3	0.1	11.3	0.2	-	-	-	132.8	0.4	133.2
<b>Total</b>	<b>438.2</b>	<b>31.4</b>	<b>221.0</b>	<b>954.3</b>	<b>36.6</b>	<b>11.9</b>	<b>-</b>	<b>582.5</b>	<b>34.8</b>	<b>695.8</b>	<b>1,580.2</b>	<b>2,310.8</b>

**Note:** E represents biomass consumed for electricity generation, and T represents biomass consumed for thermal energy output.

<sup>a</sup>The EIA *Electric Power Annual*, tables 5.5, 5.6, 5.7, and 5.8 provide energy values for biomass consumed for electricity generation and useful thermal output by sector in billion Btu. Residential values are from table A17 of the 2015 EIA *Annual Energy Outlook*.

<sup>b</sup>Based on biogas estimates from the AgSTAR Anaerobic Digester Projects Database. Values were extrapolated based on the digester type, animal type, and animal population supplying the digester (using only reported values with no co-digestion).

**Table 2.4** | Useful Energy Output from Biomass (Forestry/Wood) Resources Consumed for Heat and Power in 2013

Biomass resource category	Electricity		Industrial		Commercial		Residential		Farm use		Total	
	E BkWh	T TBtu	E BkWh	T TBtu	E BkWh	T TBtu	E BkWh	T TBtu	E BkWh	T TBtu	E BkWh	T TBtu
Wood/wood waste <sup>a</sup>	13.7	12.2	15.4	539.0	-	0.6	-	349.5	-	-	29	901
Animal manure <sup>b</sup>	-	-	-	-	-	-	-	-	3.2	10.9	3	11
Biogenic MSW <sup>c</sup>	8.5	1.9	-	0.7	1.5	4.3	-	-	-	-	10	7
Other waste biomass <sup>c</sup>	1.2	3.0	0.6	24.5	0.4	0.6	-	-	-	-	2	28
Landfill gas <sup>d</sup>	10.5	0.1	0.2	0.1	1.0	0.2	-	-	-	-	12	0
<b>Total</b>	<b>33.9</b>	<b>17.2</b>	<b>16.2</b>	<b>564.2</b>	<b>2.8</b>	<b>5.6</b>	<b>-</b>	<b>349.5</b>	<b>3.2</b>	<b>10.9</b>	<b>56</b>	<b>947</b>

**Note:** Assumes a general conversion factor of 3,412 Btu/kilowatt hour (kwh). E denotes electric power generation; T denotes thermal power generation. BkWh = billion kilowatt hours. TBtu = trillion British thermal units.

<sup>a</sup>Wood/wood waste: Electric conversion efficiency of 25% and thermal conversion efficiency of 60%.

<sup>b</sup>Biogas from animal manure: 31.7% to electricity, 31.3% thermal energy, 37.0% loss based on AgSTAR end-use analysis.

<sup>c</sup>Biogenic MSW and other waste biomass: Electric conversion efficiency of 25% and thermal conversion efficiency of 45%.

<sup>d</sup>Landfill gas: Electric conversion efficiency of 30% and thermal conversion efficiency of 78%.

The tonnage (or billion cubic feet) of each biomass resource category by heat and power end-use sector is shown in table 2.5. The 2013 values for the biogenic portion of MSW and landfill gas are reported in thousand tons and million cubic feet by the 2015 EIA *Electric Power Annual* (*Electric Power Annual*, tables 5.6 and 5.7, respectively). Several conversion factors (described in the footnotes of table 2.5) are used for the remaining biomass resource categories.

The following sections discuss current heat and power production and describe the references and assumptions used to estimate the amount of biomass resources consumed in those processes.

## 2.4.1 Woody Biomass and Wood Waste

Woody biomass and wood waste is reported as a single category—“Wood/Wood Waste”—by the 2015 EIA *Electric Power Annual*. Wood and wood-derived fuels include wood/wood waste solids (including paper pellets, railroad ties, utility poles, wood chips, bark, and wood waste solids), wood waste liquids (red liquor, sludge wood, spent sulfite liquor, and other wood-based liquids), and black liquor. Wood and wood-derived fuels are used primarily as thermal energy inputs for the industrial sector; however, they are also used in electric power production, in the commercial sector, and for residential purposes.

**Table 2.5** | Biomass Resources Consumed for Heat and Power in the 2013 Bioeconomy (million bioenergy equivalent dry tons)

Biomass resource category	Electricity	Industrial	Commercial	Residential	Farm use	Total
Wood/wood waste <sup>a</sup>	15.96	85.28	0.11	44.81	-	146.16
Animal manure <sup>b</sup>	-	-	-	-	10.50	10.50
Biogenic MSW <sup>c</sup>	15.03	0.20	3.65	-	-	18.87
Other waste biomass <sup>d</sup>	2.86	7.84	0.78	-	-	11.48
Landfill gas <sup>e</sup>	239.46	4.77	28.57	-	-	272.80
<b>Total</b>	<b>33.85</b>	<b>93.32</b>	<b>4.54</b>	<b>44.81</b>	<b>10.50</b>	<b>187.00</b>

<sup>a</sup>Wood/wood waste: 13 MMBtu/ton was selected as a conservative estimate based on various sources (EPAd 2015; DOE 2015a; INL 2014; NREL 2011).

<sup>b</sup>Animal manure: Applied GREET biogas assumptions applied by animal type to calculate 3.32 MMBtu/ton of total solids for manure digested in the current bioeconomy.

<sup>c</sup>Biogenic MSW: Reported directly from table 5.6 of the 2015 Electric Power Annual.

<sup>d</sup>Other waste biomass: 8 MMBtu/ton based on the values for biogenic MSW reported in the 2015 Electric Power Annual.

<sup>e</sup>Landfill gas: Reported directly from table 5.7 of the 2015 Electric Power Annual. Bioenergy equivalent dry ton contributions from landfill gas are not added into the totals shown.

In the projected bioeconomy, contributions from these individual wood resources are estimated at a more granular level.

Wood/wood waste, the largest category of biomass resource used for heat and power generation, is primarily used for residential heating and industrial use as fuel. Estimates from the 2015 EIA *Electric Power Annual* indicate that in 2013, the industrial sector consumed nearly 85.3 million dry tons of wood/wood waste to produce 15.4 billion kWh of electricity and 539.0 TBtu of thermal energy. In 2013, the residential sector consumed 44.8 million dry tons of wood/wood waste to produce 349.5 TBtu of thermal energy.

The two largest industrial consumers of biomass are the paper and wood products industries. In 2010, the latest year available, the Manufacturing Energy Con-

sumption Survey reported a consumption amount of 824 trillion Btu, or 63.4 million bioenergy equivalent tons per year, assuming 13 million Btu per ton (EIA 2013). In the 2012 Resource Planning Act database, the amount of mill residues reported as being consumed for fuel was 26 million tons, down from 36.7 million dry tons in the 2007 assessment (USDA-FS 2014). Most of the material (51%) consumed is bark, and the remainder is composed of fine (36%) and coarse (13%) materials by weight. As reported, these two categories contribute 89.3 million tons per year to the industrial use estimate of 93.2 million tons per year. However, because of the calculation approach taken to disaggregate EIA national statistics, additional assumptions would need to be applied to attribute pulp liquor and mill residues categories more precisely to the industrial use category.

## 2.4.2 Biogenic MSW

Biogenic MSW consists of organic nonfossil material of biological origin that is a byproduct or a discarded product. Biomass waste includes MSW from biogenic sources, landfill gas, sludge waste, agricultural crop byproducts, straw, and other biomass solids, liquids, and gases. It excludes wood and wood-derived fuels (including black liquor), biofuels feedstocks, biodiesel, and fuel ethanol.<sup>8</sup>

Biogenic MSW is primarily used in the electrical and industrial sectors. Estimates from the 2015 EIA *Electric Power Annual* (table 5.7 and table 5.8) indicate that in 2013, the electricity sector consumed more than 15.0 million dry tons of biogenic municipal waste to produce 8.5 billion kWh of electricity and 1.9 TBtu of thermal energy. The industrial sector was the largest consumer of waste biomass for thermal energy in 2013, using more than 8.0 million dry tons of various types of waste biomass to produce 25.2 TBtu of thermal energy.

Tables 5.6A through 5.8F of the 2015 EIA *Electric Power Annual* break down biogenic municipal waste by the electrical, thermal, and total contributions of landfill gas, other biogenic MSW, and other waste biomass. A conversion factor of 8 MMBtu per dry ton was calculated using tables 5.7F and 5.7C of the 2015 EIA *Electric Power Annual*. Electrical and thermal conversion efficiencies of 25% and 45%, respectively were applied to the energy content of the biomass to obtain estimates for the electrical and thermal energy output.<sup>9</sup>

## 2.4.3 Landfill Gas

Landfill gas is generated by decomposition of organic material at landfill disposal sites. The average composition of landfill gas is approximately 50% methane and 50% carbon dioxide and water vapor by volume. The methane percentage, however, can vary from 40% to 60%, depending on several factors, including waste composition (e.g., carbohydrate and cellulose content).

The methane in landfill gas may be vented, flared, or combusted to generate electricity or useful thermal energy on-site, or injected into a pipeline for combustion off-site. Landfill gas is primarily consumed in the electric sector. Estimates from the 2015 EIA *Electric Power Annual* indicate that in 2013, 239.5 bcf of landfill gas produced 10.5 billion kWh of electricity in the electric sector. Table 5.6 of the 2015 EIA *Electric Power Annual* provides the energy content (in billion Btu) and amount (in million cubic feet) of landfill gas consumed by the electricity, commercial, and industrial sectors. These reported values were used to calculate a conversion factor of 488 Btu/standard cubic foot (scf). Electrical and thermal conversion efficiencies of 30% and 78%, respectively, were applied to the inherent energy content of the landfill gas to obtain estimates for the useful electricity and thermal energy output.<sup>10</sup>

## 2.4.4 Anaerobic Digestion

Anaerobic digestion is a biological process that occurs when organic matter (in liquid or slurry form) is decomposed by bacteria in the absence of oxygen (i.e., anaerobically). The decomposition process releases biogas consisting of approximately 60% meth-

<sup>8</sup> EIA biomass waste data also include energy crops grown specifically for energy production, which would not normally constitute waste.

<sup>9</sup> Depending on the technology and combustion method, electrical and thermal conversion efficiency may vary. See appendix A for more information.

<sup>10</sup> Depending on the technology and combustion method, electrical and thermal conversion efficiency may vary. See appendix A-2 for more information.



ane and 40% carbon dioxide. This gas can be recovered, treated, and used to generate energy, replacing traditional fossil fuels. Anaerobic digester systems can be installed successfully at operations that collect manure as a liquid, slurry, or semi-solid. Existing farms use a variety of different types of digester designs—such as anaerobic sequencing batch, complete mix, covered lagoon, fixed film, induced blanket, and plug flow reactors, and energy use technologies—such as boiler or furnace fuel, cogeneration, electricity generation, or flaring.

As of January 2015, AgSTAR estimates there are approximately 247 anaerobic digester systems operating at commercial livestock farms in the United States (EPA 2015c). Gas production estimates are available for only 94 of the operational systems reported in the AgSTAR database. Estimates for the remaining 153 digesters are made by extrapolating based on the digester type, animal type, and animal population supplying the digester (using only reported values with no co-digestion). Nearly 80% of these operational digesters are projects at dairy farms and 13% are at swine operations. Other digesters consist of mixed influent, beef, and poultry projects. An analysis of the AgSTAR database indicates that biogas is used for electricity generation (42%), cogeneration (41%), and boiler or furnace fuel (10%); is flared (2%); or is unknown/not reported (5%). Using these reported end uses, we calculate the energy distribution of the biogas to be 31.7% electricity, 31.3% thermal energy, and 37.0% loss.

Overall, the 247 operational anaerobic digesters are estimated to produce 3.2 billion kWh of electricity and 10.9 TBtu of thermal energy from 10.5 million tons of biomass (see appendix A for more information). Additionally, it is estimated that nearly 1.5 bcf of digester gas is flared each year. Using this gas for cogeneration could produce an additional 0.8 billion kWh of electricity and 0.4 TBtu of thermal energy.<sup>11</sup>

## 2.5 Biobased Chemicals

Biomass resources represent an important (and, in some cases, the only) option for sustainably replacing many of the petroleum-derived chemicals, plastics, and products relied upon today. Established by the Farm Security and Rural Investment Act of 2002 and strengthened by the Food, Conservation, and Energy Act of 2008, the USDA BioPreferred Program is charged with transforming the marketplace for biobased products and creating jobs in rural America. The 2015 USDA BioPreferred Report, *An Economic Impact Analysis of the U.S. Biobased Products Industry: A Report to the Congress of the United States of America*, 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 from energy, livestock, food, feed, and pharmaceuticals.

The BioPreferred program database includes about 20,000 biobased products; however, it does not include many forest products and traditional textile fiber products. The BioPreferred program estimates that because the latter two sectors have only recently been included, the actual number of biobased products is dramatically higher than the USDA BioPreferred report indicates, and 40,000 products would be a conservative estimate. Direct sales of biobased products in 2013 are estimated to total nearly \$126 billion.

The USDA BioPreferred report estimates that the starch produced from corn biorefineries in 2013 represented about 2% of the entire corn crop. In 2014,

<sup>11</sup> Cogeneration conversion efficiency: assumed energy outputs for cogeneration are 40% electrical energy, 50% thermal energy, and 10% loss (Clark Energy 2013).

according to the U.S. Feed Grain Database, 281.2 million dry tons of corn were produced for domestic use.<sup>12</sup> Assuming that the 2% relationship held true in 2014, and that this starch was used to manufacture biobased products, it is estimated that approximately 5.6 million dry tons of corn was consumed in 2014 to produce biobased products. Additionally, the BioPreferred report estimates that 0.6% of soybean and other oilseed processing was used to produce biobased products. Based on U.S. production and use forecasts for 2014, from table 3 of the 2015 *USDA Oilseed Yearbook* (ERS 2015), an estimated 0.32 million dry tons of soybeans were consumed in 2014 to produce biobased products.

Sufficient data to estimate the total number of individual “units” of biobased products is currently not available, and contributions from other feedstocks are not included within this report. We anticipate that the growth of these biobased sectors will continue to create both economic and environmental benefits for the United States.

## 2.6 Wood Pellets

Statistical information from the Forest and Agricultural Organization of the United Nations was used to estimate that 7.6 million dry tons of wood pellets were produced in 2014. Wood pellets are primarily produced for export to markets in the United Kingdom and Europe, which are strongly influenced by regulatory and political factors. Reports from the U.S. Forest Service (Abt et al. 2014) and the U.S. International Trade Commission (Goetzl 2015) anticipate that wood pellet export demand will plateau by 2020.

## 2.7 Emerging Sources of Biomass

Opportunities for near-term expansion of biomass resources for energy are found in waste streams, primary agricultural and forestry residues, and energy crops. This section explores in some detail commercialization of these resources for energy production across consumption sectors.

### 2.7.1 Biosolids and Wastewater Treatment

Wastewater treatment plants (WWTPs) represent another high-potential source of biogas. EPA reports that 1,484 WWTPs digest sludge to produce biogas (Bastian et al. 2011). Anaerobic digestion is a common technology for sludge treatment at WWTPs in the United States. The Water Environment Federation (WEF) released a phase 1 database that provides information about 1,241 U.S. WWTPs that operate anaerobic digestion systems and their biogas utilization (WEF 2014). WEF estimates that about 48% of the total wastewater flow in the United States is treated with anaerobic digestion (WEF 2013). However, less than 10% of facilities employ biogas for beneficial uses. Most biogas is flared, and only a small portion is used for on-site process heat and power production.

New technologies and digestion techniques are increasing the feasibility of transforming WWTPs into energy-positive water resource recovery facilities. One approach to enhancing anaerobic digestion at these facilities is through the co-digestion of biosolids with organic waste, resulting in higher methane yields, more efficient digester volume utilization, and reduced biosolids production. Combined heat and power (CHP) technologies such as internal combustion engines, microturbines, gas combustion turbines,

<sup>12</sup> 11,883.34 million bushels at 56 pounds of shelled corn per bushel and 15.5% moisture

and fuel cells may help to maximize the electrical and thermal energy output from a water resource recovery facility. Alternatively, biogas can be upgraded to renewable natural gas and can be injected into the pipeline network or used as an alternative fuel for natural gas vehicles.

A 2011 EPA report estimated that as of June 2011, CHP systems using biogas were in place at 104 WWTPs, representing 190 megawatts (MW) of electric power capacity and 18,000 MMBtu/day of thermal energy (Bastian et al. 2011). A March 2015 analysis from Argonne National Laboratory classifies the 1,241 WWTPs identified in the WEF phase 1 database into four categories based on average flow rates: plants with an average flow rate of 100–1,000 million gallons per day (MGD) (29 plants), 10–100 MGD (276 plants), 1–10 MGD (690 plants), and less than 1 MGD (96 plants) (Shen et al. 2015). Each rate category is broken down by biogas utilization, and biogas CHP technologies are further categorized by CHP technology type and whether there is power export. Overall, the Argonne analysis identified 282 operational CHP systems and 69 water recovery facilities that are exporting electric power to the grid.

Of the 29 facilities that process 100–1,000 MGD, Argonne found that 26 use biogas; 13 of those employ CHP technologies for energy generation, 6 export electric power to the grid, and 3 inject upgraded gas into natural gas pipelines. Of the 276 facilities that process 10–100 MGD, Argonne found that 238 use biogas; 123 of those employ CHP technologies for energy generation, 32 export electric power to the grid, and 12 inject upgraded gas into natural gas pipelines. Of the 690 facilities that process 1–10 MGD, Argonne found that 505 use biogas; 125 of those employ CHP technologies for energy generation, 30 export electric power to the grid, and 10 inject upgraded gas into natural gas pipelines. Of the 96 facilities that process <1 MGD, Argonne found that 55 use biogas; 21 of those employ CHP technologies for energy generation, 1 exports electric power to the grid, and none

inject upgraded gas into natural gas pipelines. Of the CHP technologies, the majority, 54%, are internal combustion engines. Microturbines make up 10%, fuel cells 2%, and gas combustion turbines 1%; 33% are categorized as “other.”

Both the 2011 EPA report and the Argonne analysis of the WEF phase 1 database indicate that there is significant potential to increase the utilization of biogas produced by WWTP digesters.

## 2.7.2 Biomass Crop Production

The commercialization of biomass crops for energy has increased since 2011, with deployment reaching up to 20,000 acres. Statistics for herbaceous energy crops are collected beginning with the 2012 census. The acreage is reported in table 2.6. These acres are underestimated; producers often do not report plantings of unique crops because they are not enrolled in federally subsidized programs, or the crops are grown on non-private agricultural lands (e.g., public universities, regional extension farms).

The regional statistics from the 2012 USDA census reported in table 2.6 represent production of switchgrass and miscanthus to supply multiple markets, such as power, fuels, and animal bedding; and they probably underestimate the gross production of all energy crop species. The data continue to improve for biomass production and consumption by use, reflecting the time lag due to the perennial nature of many of the dedicated species. Barriers to adopting these crops are being addressed through risk reduction measures such as crop insurance. Reporting of hybrid poplar acres in production increased from 211 acres in August 2014 to 2,554 acres in November 2014. In 2014 energy statistics, the use of dedicated herbaceous biomass for energy was reported in a mixed-waste category and is reported in the aggregated production amount. As of 2014, commercial primary crop residue collection for energy consumption is not reported in the USDA Census of Agriculture.


**Table 2.6** | 2012 USDA Census Data for Herbaceous Energy Crop Production by Region

Farm production region	Acres harvested	Number of operations	Production (dry tons)
Appalachia	1,801	23	8,644
Southern Plains	979	4	1,178
Northeast	119	8	1,442
Other	0	13	0
<b>Total</b>	<b>2,899</b>	<b>48</b>	<b>11,264</b>

## 2.8 Summary

The total consumption of biomass resources for energy, including transportation, power, and heat, is reported in table 2.7. The primary sources of biomass in the current bioeconomy are agricultural resources and forestry/wood. The agricultural biomass is used predominantly for fuels and biobased chemicals. The

woody biomass is used to produce heat and power for the electrical, industrial, commercial, and residential sectors. Animal manure is digested to produce heat and power for farm use. The biogenic portion of MSW and other waste biomass is consumed to produce heat and power for various sectors. The flow of these resources from feedstock to end product energy is described in the Sankey diagrams in figure 2.5.

**Table 2.7** | Total Current Consumption of Biomass (2014) for Energy and Energy Products (million bioenergy equivalent dry tons per year)<sup>13</sup> 

Biomass resource category	Fuel	Heat and power	Biobased chemicals	Wood pellets	Total utilized biomass	Supply chain losses	Total biomass
<b>Agricultural</b>	127.18	10.50	5.94	-	143.30	13.91	157.21
Corn grain <sup>a</sup>	119.55	-	5.62	-	125.17	13.91	139.08
Vegetable oils	5.51	-	0.32	-	5.83	-	5.83
Other fats, oils, and greases	1.89	-	-	-	1.89	-	1.89
Feed for gasoline blendstock/naphtha <sup>b</sup>	0.22	-	-	-	0.22	-	0.22
Agricultural residues	0.01	-	-	-	0.01	-	0.01
Manure	-	10.50	-	-	10.50	-	10.50



**Table 2.7 (continued)**

Biomass resource category	Fuel	Heat and power	Biobased chemicals	Wood pellets	Total utilized biomass	Supply chain losses	Total biomass
<b>Forestry/wood</b>	-	146.16	-	7.61	153.76	17.08	170.85
Wood/wood waste	-	146.16	-		146.16	16.24	162.40
Wood pellets	-	-	-	7.61	7.61	0.85	8.45
Energy crops	-	-	-	-	-	-	-
Herbaceous energy crops	-	-	-	-	-	-	-
Woody energy crops	-	-	-	-	-	-	-
<b>MSW/other wastes</b>	-	30.35	-	-	30.35	-	30.35
Biogenic portion of MSW	-	18.87	-	-	18.87	-	18.87
Other waste biomass	-	11.48	-	-	11.48	-	11.48
<b>Landfill gas<sup>c</sup> (bcf)</b>	9.14	272.80	-	-	281.94	-	281.94
<b>Algae</b>	-	-	-	-	-	-	-
<b>Total Biomass</b>	<b>127.18</b>	<b>187.00</b>	<b>5.94</b>	<b>7.61</b>	<b>327.73</b>	<b>30.99</b>	<b>358.73</b>

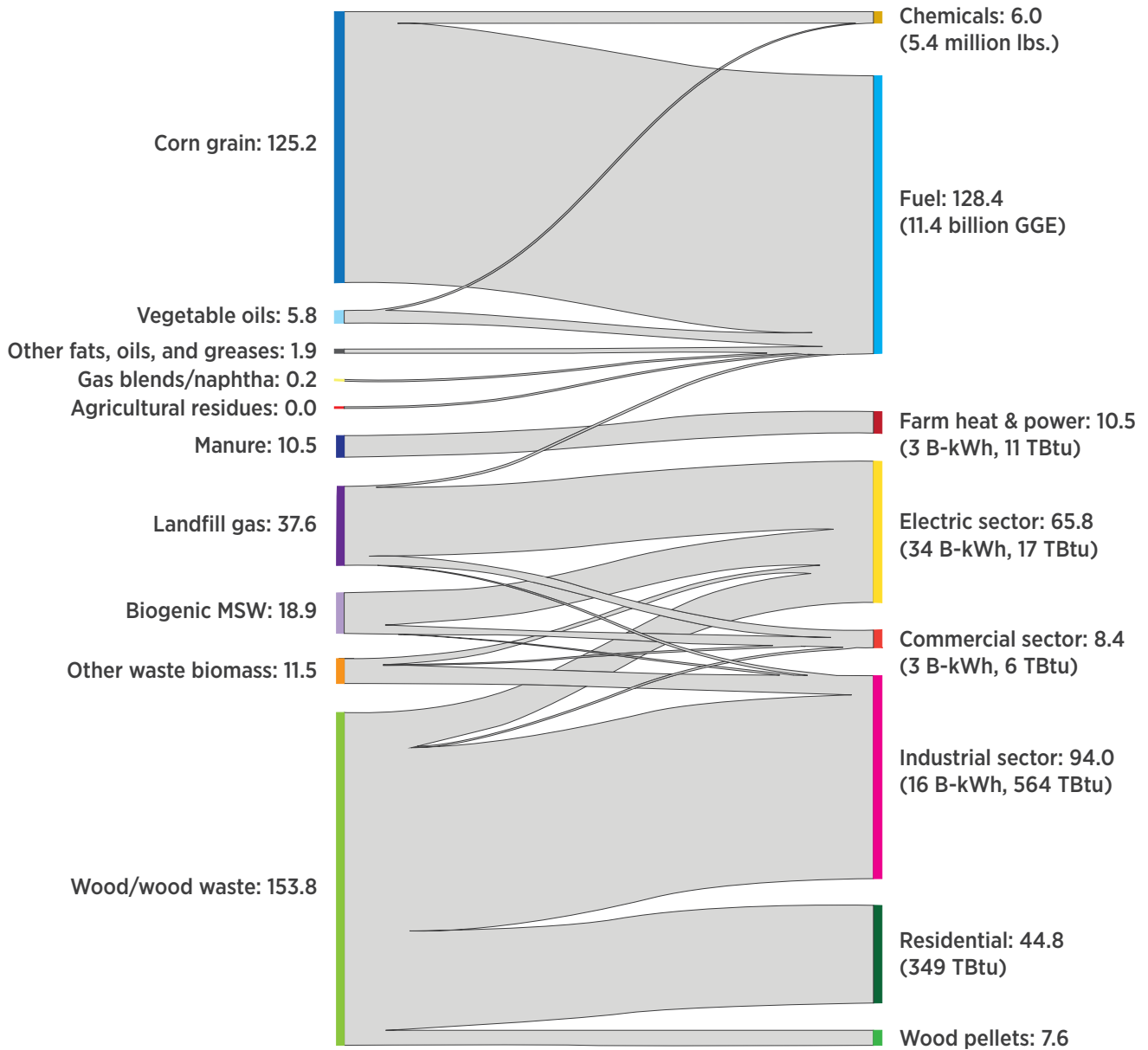
<sup>a</sup>Corn grain consumed for ethanol production also creates 43.64 million dry tons of dried distillers grains (Wisner 2015).

<sup>b</sup>Renewable gasoline blendstocks and naphtha can be produced from a variety of feedstocks, including agricultural residues, forest residues, biogenic MSW, yard wastes, biogas, energy grasses, oil seed plants, and other cellulosic materials. RFS2 does not provide clarity for the current sources of biomass.

<sup>c</sup>Bioenergy equivalent dry ton contributions from landfill gas are not added into the totals shown here but are represented in the Sankey diagram in figure 2.5 by applying a conversion factor of 0.2665 lb/scf.

<sup>13</sup> Interactive visualization: <https://bioenergykdf.net/billionton2016/2/1/table>

**Figure 2.5** | Sankey diagram of feedstock, sector consumption, and final product distribution, in million dry tons per year<sup>14</sup>



**Note:** Biomass resources are shown on the left and their allocations are shown on the right. The size of the flow is representative of the amount of biomass allocated to that end use. For this figure, contributions from landfill gas are represented as tons of biomass equivalent by applying a conversion factor of 0.2665 lb/scf.

<sup>14</sup> Interactive visualization: <https://bioenergykdf.net/billionton2016/2/3/sankey>

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