U.S. DEPARTMENT OF ENERGY | Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

Chapter 03 | Waste Resources and Byproducts

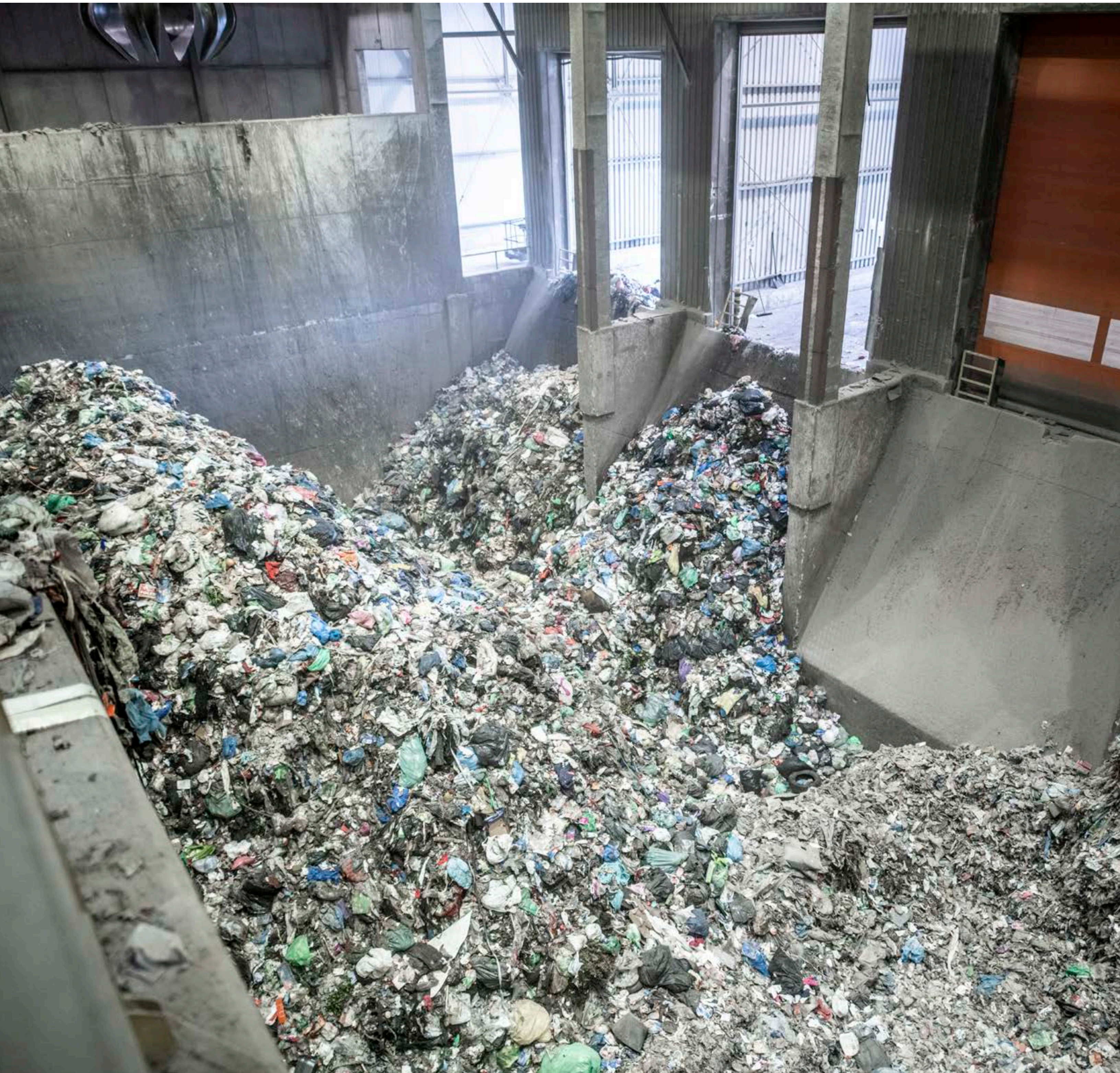

Table of Contents

3 Waste Resources and Byproducts

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Summary

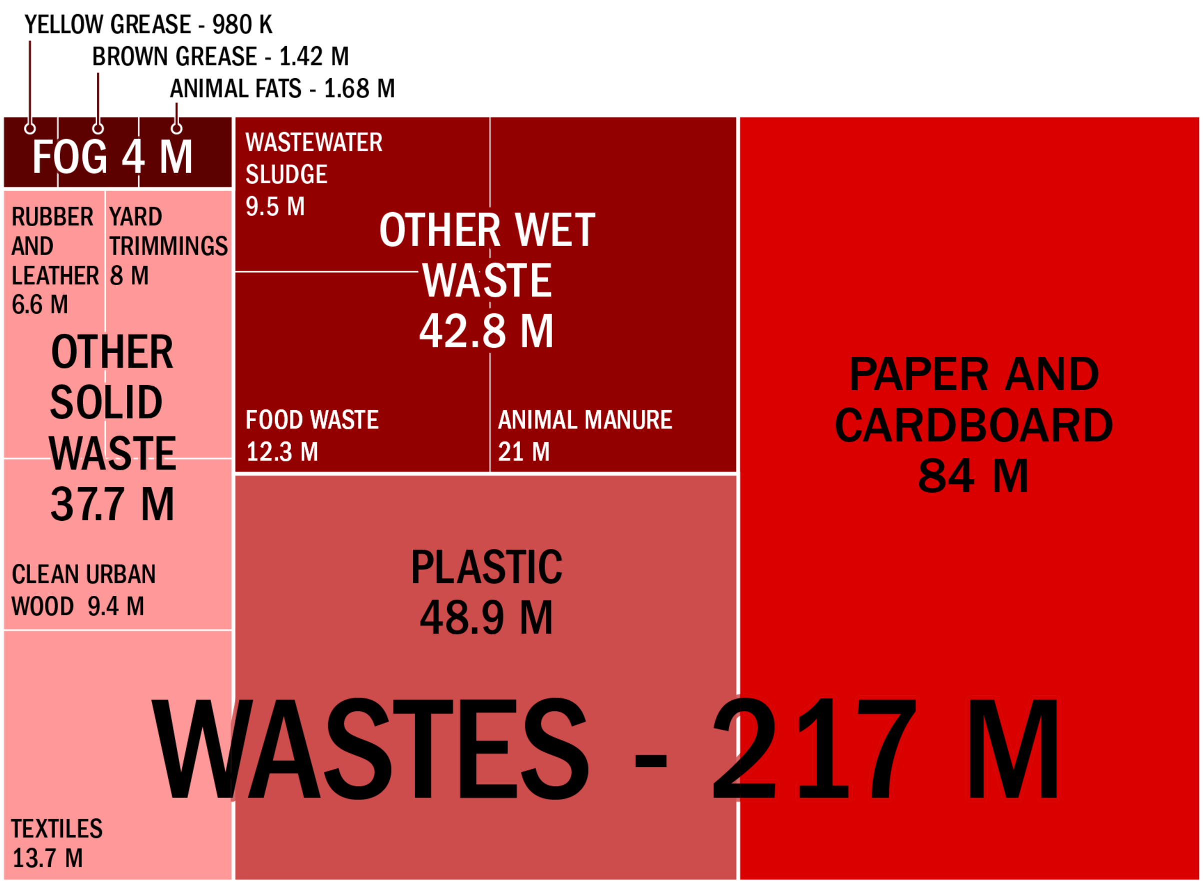


Figure 3.1. National waste resources, mature-market medium scenario, all prices

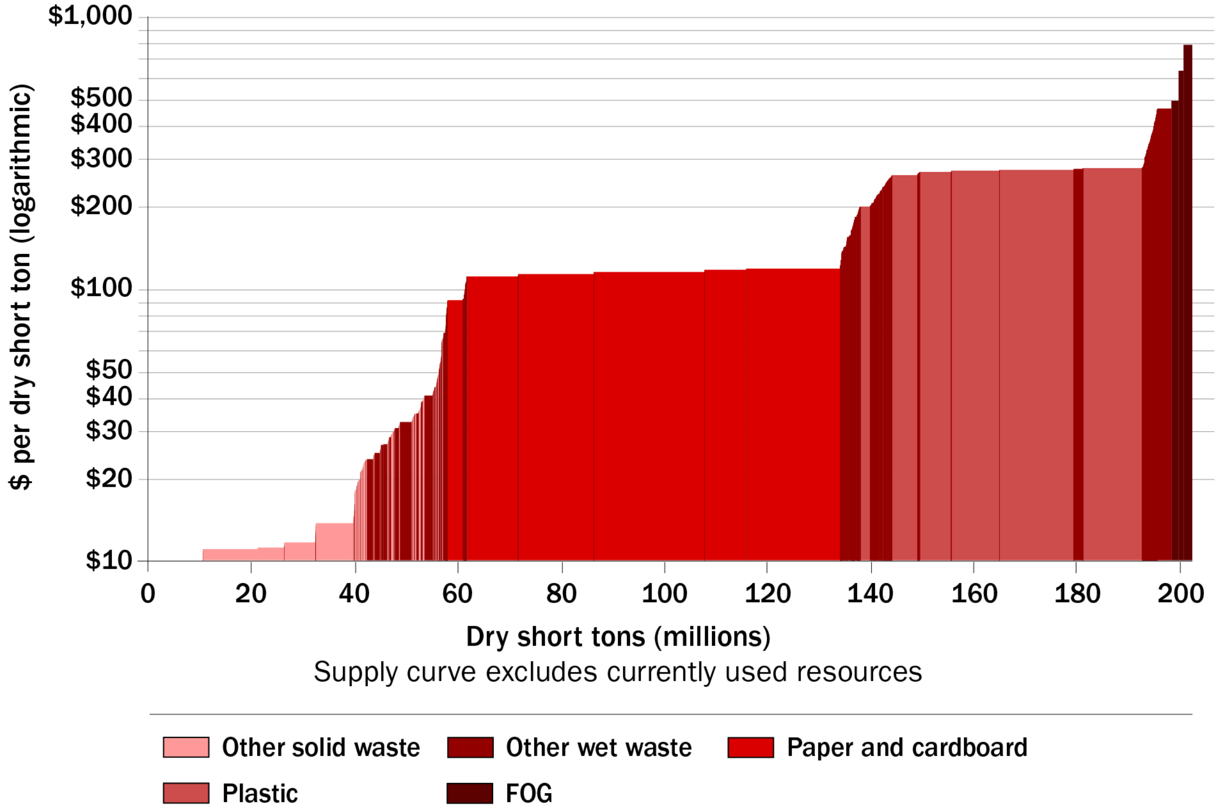


Figure 3.2. Stepwise supply curve of waste resources, mature-market medium scenario

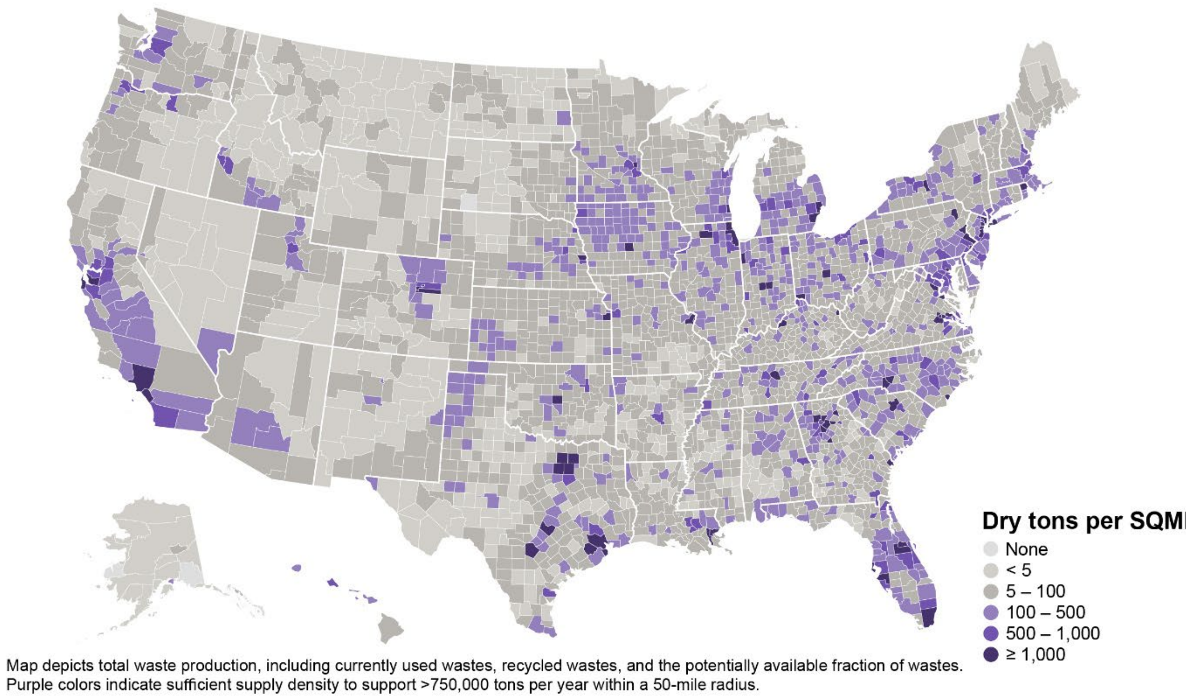


Figure 3.3. Spatial distribution of waste resources, mature-market medium scenario, all prices

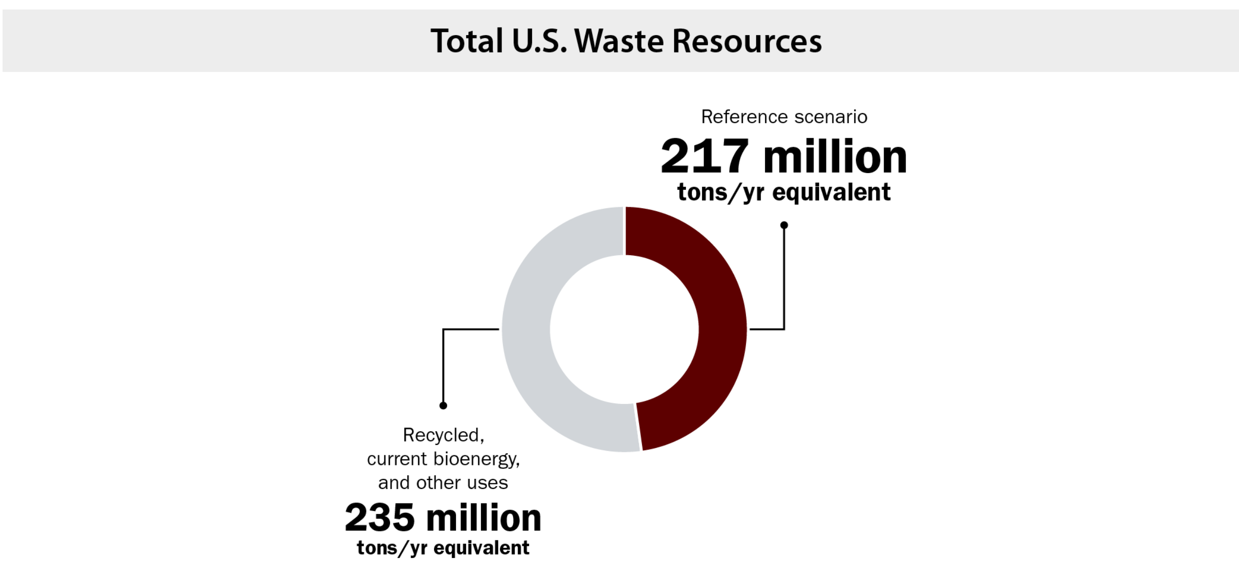


Figure 3.4. Waste resources reported as available in mature-market medium scenario in proportion to total production

- On average, about 161 million dry tons (415 million wet tons) per year of wet and solid waste resources are available above current uses in the near term. 217 million dry tons per year are estimated to be available above current uses in mature-market scenarios.

- Wastes are diverse with potentially low prices, but prices vary with feedstock and market conditions.
- Some of these materials may not be economically obtainable due to collection challenges and preprocessing required such as separation, sorting, dewatering, and depackaging.
- Waste supplies are not intrinsically linked to demand and are therefore expected to change little with demand. Thus, a mature-market scenario may result in little change in supply but higher prices compared to a near-term scenario.

3.1 Introduction

The waste resources and byproducts evaluated here can be categorized as follows: (1) wet waste resources such as animal manure, wastewater sludge, food waste, and inedible FOG; (2) solid waste resources entering the MSW stream such as paper/cardboard, plastics, wood, rubber/leather, textiles, and yard trimmings; (3) gaseous resources/intermediates (landfill gas [LFG]); and (4) byproducts, namely glycerol, black liquor, and distillers grains.

There are several factors making these resources different from the resources discussed in other chapters that affect their price and logistics. One is their geographic distribution. Except for animal manure and byproducts, generation of these resources follows population dynamics and is primarily concentrated near urban areas. This results in a close proximity to demand centers and access to labor and energy supply, and minimizes the cost of transporting feedstock to a processing facility. The concentration of these resources in a given area also provides an opportunity for their combined use (blending) in a processing facility and reduced costs through economies of scale for the utilization pathway. Another factor that makes these resources different from conventional biomass resources is that some are already commoditized (e.g., FOG, plastic waste, paper/cardboard waste, glycerin, distillers grains, and to some extent manure and urban wood). In other words, these waste materials have become standardized, marketable products with an economic value. Simultaneously, a large portion of these materials are viewed as waste by the entities generating them. In other words, they are not typically associated with a market value by these entities—but represent a liability, as they require disposal—and in some cases, their management must meet local environmental regulations. Even commoditized resources are sometimes treated as waste and disposed of at landfills, which represents a loss of their technical and market value. Conversely, from a user's perspective, waste resources are viewed as a valuable, underutilized feedstock for energy and resource recovery in the context of a circular economy. The balance between these different views on waste resources affects their economics—low demand and treatment as waste keeps their price low, but a high market demand increases prices.

3.2 Supply and Prices

Table 3.1 summarizes the total and available (subtracting current uses) waste resources and byproducts supply at the national level, their average prices, and inherent energy content under a near-term scenario. Future total supply and prices for wet and solid waste resources under a mature-market scenario are also presented. The estimated total wet and solid waste resources in the near term amount to about 290 million dry tons (876 million wet tons) annually, of which slightly more than half is available for bioenergy and other purposes considering current uses of these materials. While the estimated available supply is likely a reasonable estimate of overall generation, utilization of all these resources may not be economical due to preprocessing costs associated with activities such as separation, sorting, purification, dewatering, depackaging, and shredding. Competing demands for these resources (e.g., land application, composting, fertilizer, recycling, animal feed, pharmaceuticals, cosmetics, lubricants, export) also limit their availability for bioenergy purposes.

Table 3.1. Annual Waste Resources in Near-Term and Mature-Market Scenarios [a]

Waste Resources and Byproducts	Near-Term Total Annual Average Resources		Near-Term Available Annual Average Resources		Mature-Market Low/Medium/High Total Annual Average Resources		2022 Average Price in $/Wet Ton			2022 Average Price in $/MMBtu		
	Million Wet Tons/yr (Million Dry Tons/yr)	Energy Content (TBtu)	Million Wet Tons/yr (Million Dry Tons/yr)	Energy Content (TBtu)	Million Wet Tons/yr (Million Dry Tons/yr)	Energy Content (TBtu)	Near Term	Mature-Market Low/Medium	Mature-Market High	Near Term	Mature-Market Low/Medium	Mature-Market High
Wet Waste	622 (71)	1,027	273 (32)	450	668 (81)	1,166						
Animal manure [b]	417 (41.5)	540	167 (16.5)	215	422 (46)	598	$2.5	$2.5	$4.5	$1.8	$1.8	$3
Wastewater sludge	137 (13.7)	178	68.5 (6.9)	89	163 (16.3)	212	$21	$21	$23	$16	$16	$18
Food waste	61 (15.3)	77	35 (8.8)	44	75 (18.8)	94	$76	$76	$81	$61	$61	$65
FOG [c]	6.8	232	3	102	7.8	262	$554	$554	$568	$16	$16	$17
Animal fats	3.2	109	0.9	31	3.2	109	$686	$686	$706	$20	$20	$21
Used cooking oil/yellow grease	1.4	48	0.2	7	1.8	61	$550	$550	$571	$16	$16	$17
Trap/brown grease	2.2	75	2	68	2.7	92	$426	$426	$447	$13	$13	$13
Solid Waste	254 (219)	3,725	142 (129)	2,387	303 (261)	4,260						
Paper and cardboard [c,d]	121 (114)	1,624	68 (64)	910	142 (134)	1,903	$93	$93	$110	$7	$7	$8
Plastics [c,d]	48.6 (47.6)	1,334	41.6 (40.8)	1,142	56.8 (55.7)	1,560	$230	$230	$248	$8	$8.4	$9
Clean urban wood (MSW and construction and demolition [C&D]) [d]	22.6 (19.2)	307	5.6 (4.8)	76	28 (23.8)	381	$11	$21	$31	$0.8	$1.5	$2.3
Rubber and leather [d]	9.2 (8.7)	151	5 (4.7)	82	11.3 (10.6)	186	$11	$20	$29	$0.7	$1.2	$1.8
Textiles [d]	17 (15.3)	230	11.3 (10)	153	21 (19)	285	$11	$19	$28	$0.8	$1.4	$2
Yard trimmings [d]	35.4 (14.2)	79	10.5 (4.2)	24	43.9 (18)	101	$11	$14	$18	$5	$6.3	$8
Gaseous Resources/Intermediates												
LFG [e]	33 (836 BCF)	423	15 (383 BCF)	194	–	–	–	–	–	–	–	–

Waste Resources and Byproducts	Near-Term Total Annual Average Resources		Near-Term Available Annual Average Resources		Mature-Market Low/Medium/High Total Annual Average Resources		2022 Average Price in $/Wet Ton			2022 Average Price in $/MMBtu		
	Million Wet Tons/yr (Million Dry Tons/yr)	Energy Content (TBtu)	Million Wet Tons/yr (Million Dry Tons/yr)	Energy Content (TBtu)	Million Wet Tons/yr (Million Dry Tons/yr)	Energy Content (TBtu)	Near Term	Mature-Market Low/Medium	Mature-Market High	Near Term	Mature-Market Low/Medium	Mature-Market High
Byproducts												
Glycerin [c]	0.7	13	Negative	n/a	–	–	$218 (crude), $744 (refined)	–	–	$12 (crude), $41 (refined)	–	–
Black liquor	65	129	Negligible	n/a	–	–	$150–$350	–	–	$76–$177	–	–
Distillers grains [c]	36	564	0	n/a	–	–	$197	–	–	$12.6	–	–
Total Wet and Solid Waste Resources	876 (290)	4,752	415 (161)	2,837	971 (342)	5,426						

[a] Data sources and analysis methodology are presented in Section 3.3. In summary, wet waste resource quantity is adopted from Milbrandt et al. (2018), and wet waste resource prices are adopted from Badgett, Newes, and Milbrandt (2019). Paper and cardboard waste quantity and prices are summarized from Milbrandt et al. (2024), and plastic waste quantity and prices are summarized from Milbrandt et al. (2022). These data sources provide detailed resource breakdowns and further information. The data sources and methodology for estimating the quantity and prices for the remaining waste resources and byproducts are presented in Section 3.3.

[b] Total and available manure values are presented for 50 U.S. states and include dairy, beef, and swine manure. The downloadable spatial data are only available for 23 states, and therefore the data by county totals a lower value (341 million wet tons, or about 35 million dry tons).

[c] Commodities, 3-year (2019–2021) average price as reported, in $2022.

[d] The available amount represents landfilled quantity.

[e] LFG is produced from most resources listed above; thus, its potential should be viewed separately to avoid double counting. Future LFG generation is unknown and will depend on waste diversion rates.

n/a = not applicable; – = data not available.

The future quantity and prices of waste resources and byproducts will likely be influenced by several factors such as population growth, market demand, resource competition between industries, supporting policy (e.g., organic waste ban, zero-waste initiatives), and technology development (e.g., cost-effective sorting). Generation of waste resources is somewhat fixed and does not respond to shifts in market price or demand for the material. For a conventional market commodity, if the market demand increases, supply is likely to increase to meet this increased demand. As waste resources directly correlate with human and animal populations, their supply is linked to their dynamics and does not directly change in response to market drivers such as demand.

While supply dynamics for these resources are complex, changes in the utilization and market for these materials are likely to shift their prices. Previous work has estimated that some of these resources are available at negative prices, a situation where an entity using the waste could receive it for free or be paid to take the material (Badgett, Newes, and Milbrandt 2019). These negative prices are often referred to as "tipping fees" at the point of disposal, but from a waste generator's perspective would also include costs of collection and transport. Here, we do not attempt to forecast the occurrence of negative prices due to the forward-looking nature of the price projections provided in the mature-market scenarios. While negative prices are known to occur today in certain locations, the market, regulatory, and technological factors that could impact them in the future are highly uncertain. For example, the development of an advanced waste conversion pathway could drastically increase demand for waste feedstocks in the local area, shifting prices from negative to positive. Due to the high costs of transporting organic wastes with high moisture content, this new demand might only have a localized impact, and feedstocks generated farther away would not see price shifts. While these considerations are important for securing feedstock supply, they are beyond the scope of this analysis.

3.2.1 Wet Waste Resources

The wet waste resources considered here include animal manure (dairy, beef, and swine), wastewater sludge, food waste, and inedible FOG. The FOG category includes used cooking oil/yellow grease, trap/brown grease, and animal fats such as inedible tallow, choice white grease, and poultry fat, which is edible but widely used in technical applications including biofuels. The current/near-term supply of total wet waste resources amounts to about 622 million tons (71 million dry tons, excluding FOG) annually, of which roughly 45% is available considering current uses of these materials (Table 3.1); Milbrandt et al. (2018) provide more detailed information about this current/near-term supply. Future total supply is estimated at about 668 million tons (81 million dry tons, excluding FOG), and Figure 3.5 illustrates this supply by county. The analysis methodology for estimating future supply is presented in Section 3.3. More than half of this potential is generated by animal manure. As their collective name implies, these resources have high moisture content and thus are suitable for conversion processes able to handle this type of feedstock—such as anaerobic digestion, fermentation, and hydrothermal liquefaction. Despite widespread availability, their distributed nature, collection logistics, and compositional variability, among other nontechnical factors (e.g., lack of strong supporting polices in the past), have limited their utilization to date (DOE 2017). Although many of these resources are concentrated near urban areas (except animal manure), which allows for combined use in processing applications, such blending of resources is limited in existing installations. Future projections for wet waste generation suggest that these resources will continue to be concentrated near urban areas, with generation directly correlating with human population (and animal population for manure). While the U.S. population is projected to increase, certain areas are estimated to experience rapid population growth while others could see decreases in population.

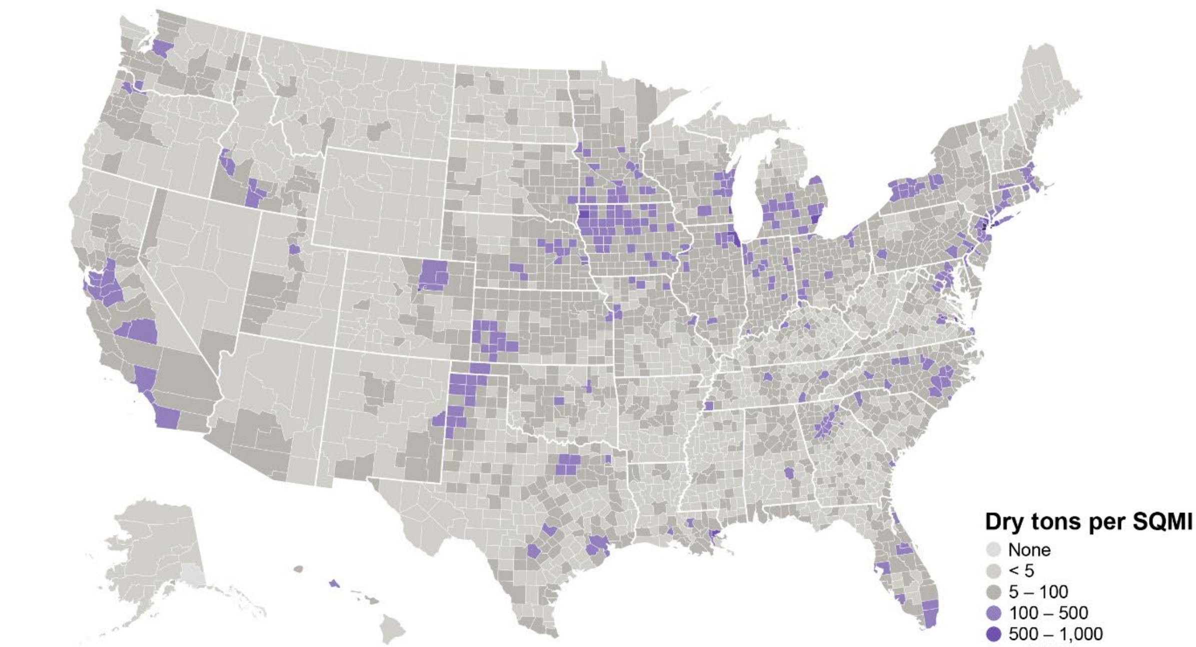


Figure 3.5. Total supply of wet waste resources in the United States under the mature-market scenario.

Note: The map includes animal manure data for 23 states due to lack of geospatial data for the remaining states. However, these 23 states represent the majority of manure production: 94%, 76%, and 93% of confined cattle, dairy, and swine, respectively. For more information, please refer to Milbrandt et al. (2018).

Wet waste resource prices vary by geography and depend on whether a resource is commoditized or treated as waste (Badgett, Newes, and Milbrandt 2019). If a resource has been commoditized (e.g., FOG), its price is determined by market demand. Conversely, if a resource is regarded as waste, its price is driven by the cost of its disposal. In Table 3.1, for current/near-term and future market scenarios, we do not forecast negative prices for wet waste resources. However, we do factor in a price of zero for materials in certain locations where the avoided cost of disposal (i.e., landfill tipping fees) is likely to be high. In reality, some of these resources could be available at negative prices, meaning that a purchaser may receive these materials for free or be paid to accept them in some locations. This situation is highly localized and may not exist in all places with high wet waste generation. Resources with estimated prices of zero are not uniformly distributed and are most likely to occur in areas with organic waste disposal bans, high population densities, and high landfill tipping fees. Most FOG is commoditized, with an existing market as a biofuel feedstock and in other industries, which explains why the prices are higher than the price for other wet waste resources in Table 3.1. FOG prices do not vary greatly geographically; however, they do vary between types of FOG. Waste grease (used cooking oil and trap grease), for example, tends to be cheaper than animal fats (e.g., tallow and poultry fat).

Future wet waste resource prices reflect several key drivers that impact the markets for these materials. Mainly, these drivers include changes in generation of the resource and increasing market demand for the material. Increasing generation of wet wastes in locations with strong population growth can drive down the cost for diverting the material from its standard disposal pathway. Many waste conversion pathways can reduce costs through increasing economies of scale—in other words, the more waste the pathway manages, the lower the cost to manage said waste (Badgett and Milbrandt 2021). Through economies of scale with conversion pathways, increasing access and collection of generated waste can push management costs (and likely prices) lower in certain locations. Additionally, the high moisture content in wet waste resources makes the cost of transporting them high, requiring conversion facilities to be located close to the point of generation/aggregation or that the feedstock is dried to a lower moisture content. Currently operating waste management technologies such as landfills rely on economies of scale to minimize their capital and operational expenses per ton of waste. Diverting resources that are currently allocated to these existing technologies could favor the economics of the conversion pathway, but might also impact the economics of the currently operating waste management technology.

Market forces can also impact wet waste resource prices. While the supply of these resources is fixed to animal and human populations, their prices do respond to changing market forces. One of the most attractive aspects of utilizing waste resources is their potential to be available at low to negative prices. These low prices exist because these resources have not conventionally been utilized in bioenergy pathways and have instead been disposed of in accordance with waste management practices and regulations (Badgett and Milbrandt 2020). As with any material, if demand increases, the price is also likely to increase, suggesting that zero- to negative-price waste resources are not likely to always exist. If utilization of these resources in bioenergy pathways increases, prices are likely to increase in step with increased demand, as shown in the mature-market scenario (Table 3.1).

3.2.2 Solid Waste Resources

The solid waste resources considered here include the following materials entering the MSW stream: paper/cardboard, plastics, clean urban wood, rubber/leather, textiles, and yard trimmings. The current/near-term supply of total solid waste resources amounts to about 254 million tons (219 million dry tons) annually, of which roughly 56% is available considering current uses of these materials (Table 3.1). The available portion of these materials represents their landfilled quantity—in other words, materials sent to landfills that could be used beneficially, including in bioenergy applications. Most of the available quantity (about 85%) comprises paper/cardboard and plastic waste. The estimate for paper/cardboard waste is derived from Milbrandt et al. (2024)

and for plastic waste from Milbrandt et al. (2022). The data sources and methodology for estimating the quantity for the remaining solid waste resources are similar to those used in BT16 and are presented in Section 3.3. Future total supply is estimated at about 303 million tons (261 million dry tons), and Figure 3.6 illustrates this supply by county. The analysis methodology for estimating future supply is presented in Section 3.3.

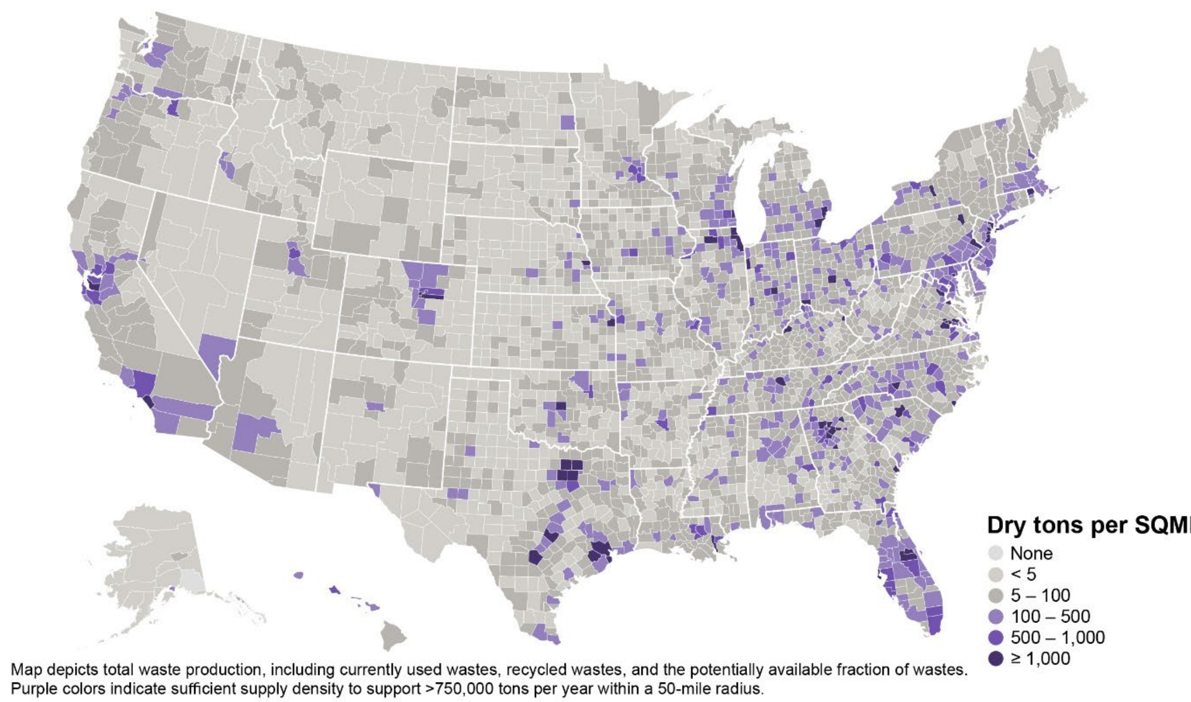


Figure 3.6. Total supply of solid waste resources in the United States under the mature-market scenario.

Note: The map includes available (landfilled) paper/carboard waste and plastic waste, not total, due to lack of geospatial data for total generation potential at the county level.

The solid waste resources considered here are typically constituents of the MSW stream, and therefore their generation, and to a large extent disposal, is associated with populated places. Despite their high energy density (Table 3.1), these resources' collection logistics, separation from mixed waste, and compositional variability, among other nontechnical factors (e.g., lack of supporting polices), have limited their utilization to date. Like wet waste resources, supply of solid waste material is expected to correlate with changes in population from location to location. Areas of the country with rapid population growth are likely to see increased supply of these resources, while areas with population declines are estimated to see decreases in supply.

Prices for these materials vary geographically and, similarly to wet wastes, depend on whether a resource has been commoditized or treated as waste. Prices for commoditized resources are determined by market demand. For resources regarded as waste, their price is driven by the cost of its disposal (local landfill tipping fees) or local market demand. Table 3.1 shows the average price for these materials. Prices for commoditized resources (plastic and paper/cardboard waste) include source separation cost and baling, which is why these prices are higher. For non-commoditized solid waste resources, prices correlate with regional landfill tipping fees and added costs for separating the resource. Locations with higher landfill tipping fees are estimated to have lower waste prices, as the avoided cost of sending these materials to landfills is significant. For example, if a construction company that generates wood waste must pay a landfill tipping fee of $100/ton to dispose of their wood waste, they might be willing to pay anything less than $100/ton to take their wood waste instead. What the bioenergy facility could charge or is willing to pay for its feedstock is dependent on the process economics and is beyond the scope of this resource assessment.

Price drivers for solid waste resources are similar to those discussed for wet wastes. Mainly, the low prices estimated for solid waste resources are likely to respond to increasing demand by increasing beyond the low values estimated here. This effect is captured in the MM scenarios, where prices for non-commoditized solid waste resources increase uniformly with projected increase in demand (Table 3.1) (Langholtz et al. 2022).

3.2.3 Gaseous Resources/Intermediates

LFG, a mixture of roughly 50% methane and 50% CO_2, is produced through decomposition of organic matter in landfills (EPA 2023a). Total LFG potential is estimated at about 33 million tons, or roughly 836 BCF (EPA 2023c). This potential accounts for the current LFG amount available at landfills that is currently or most likely able to support a project. The available LFG potential is estimated at about 15 million tons, or roughly 383 BCF, and represents the "total" value minus the gas flows to all operational, construction, and planned projects (i.e., the "used" LFG mentioned in Chapter 2). More information about the methodology for estimating LFG potential is presented in Section 3.3. It should be noted that the wet and solid waste resources discussed earlier are also disposed of at landfills and contribute to LFG generation. To avoid double counting, the total waste resource potential in Table 3.1 excludes LFG and includes only wet and solid waste resources. In addition, LFG is often considered an intermediate, not quite a resource (that would be the organic material) or a final product (e.g., power, heat, renewable natural gas [RNG]). We include its potential in this report as a reference.

3.2.4 Byproducts

This category includes materials generated as byproducts in various biomass processing applications, namely glycerin, black liquor, and distillers grains. These materials are mostly used locally by various industries, including bioenergy production, and are included here for completeness rather than contributors to the overall biomass resource potential. It is possible that in the future these materials may be utilized more for bioenergy purposes, given technological advances and market demand.

Glycerin, also known as glycerol, is a nontoxic, colorless, and odorless liquid used in a wide variety of applications (e.g., food, pharmaceuticals, cosmetics). Glycerin is a byproduct of soap and biodiesel production, with the latter being most common today (Goyal, Hernandez, and

Cochran 2021). Glycerin is initially produced in a crude form and can be further processed into refined or high-purity glycerin, a high-value product that is free of water and other impurities. Crude glycerin without further processing can be combusted to generate heat and power, gasified with other biomass resources to produce syngas (a mixture of CO and H_2), used in steam reforming for hydrogen production, fermented for alcohols (e.g., ethanol and butanol) and hydrogen, and co-digested with other organic wastes to produce biogas (He 2018). Production is about 700,000 tons annually (Table 3.1) (S&P Global 2021). Available potential is negative due to lower production than consumption and the deficit being supplied by imports.

Black liquor, a byproduct of the pulp- and paper-making process, is currently used to recover and reuse the valuable cooking chemicals and for electricity production on-site to offset energy costs. Therefore, nearly all of the estimated total resource (about 65 million tons annually; EIA 2018) is not available for higher-value bioenergy products such as fuels and chemicals (Table 3.1).

Distillers grains, a byproduct of the corn ethanol industry, are typically used as a protein-rich animal feed (Olson and Capehart 2019). Production was about 36 million tons in 2022 (Table 3.1) (USDA 2022a). For local markets, distillers grains are sold in wet form. For longer distances, distillers grains are dried to about 10% moisture to reduce weight (Olson and Capehart 2019). In addition to domestic use, dried distillers grains are also exported. Distillers grains can be used as fertilizer, for bioplastic production, and as a feedstock for transportation fuels production (Lei et al. 2011; University of Minnesota 2024). However, the probability of these other uses of distillers grains to occur is very low due to high demand of these materials as a livestock feed.

Table 3.2. Comparison with BT16

Resource	Same as BT16	Changes from BT16
Citrus residues		Reclassified to agricultural processing wastes
C&D wood		Updated BT16 method with latest EPA data (2018)
Cotton gin trash		Reclassified to agricultural processing wastes
Cotton residue		Reclassified to agricultural processing wastes
Food waste		Residential food waste included in addition to industrial, institutional, and commercial food waste
Hog manure		Detailed assessment by county
Dairy manure		Detailed assessment by county
Beef manure		Detailed assessment by county
FOG		Detailed assessment by county
MSW wood		Updated BT16 method with latest EPA data (2018)
Non-citrus residues		Reclassified to agricultural processing wastes

Resource	Same as BT16	Changes from BT16
Other forest residue		Reclassified to forest processing wastes
Other forest thinnings		Reclassified to forest processing wastes
Other MSW		Removed; all MSW materials amenable to bioenergy conversion have been included in the waste resources section
Paper and paperboard		Detailed assessment of available (landfilled) resources by county
Plastics		Detailed assessment of available (landfilled) resources by county
Primary mill residue		Reclassified to forest processing wastes
Rice hulls		Reclassified to agricultural processing wastes
Rice straw		Reclassified to agricultural processing wastes
Rubber and leather	Same BT16 method with latest EPA data (2018)	
Secondary mill residue		Reclassified to forest processing wastes
Sugarcane bagasse		Removed, is currently used
Sugarcane trash		Reclassified to agricultural processing wastes
Textiles	Same BT16 method with latest EPA data (2018)	
Tree nut residues		Reclassified to agricultural processing wastes
Yard trimmings	Same BT16 method with latest EPA data (2018)	
Glycerin		New in BT23
Black liquor	Using latest EIA data (2018)	
Distillers grains		New in BT23

3.3 Methods

The following assumptions were used in this analysis:

Moisture Content

- Manure: 87%–91%
- Sludge: 90%
- Food waste: 75%
- Paper/cardboard: 5.5%
- Plastic: 2%
- Wood: 15%

- Rubber and leather: 6% (rubber 2% and leather 10%)
- Textiles: 10%
- Yard trimmings: 60%
- Glycerin: 0.3%
- Black liquor: 85%
- Distillers grains: 10%.

Energy Content (Btu/lb, dry weight)

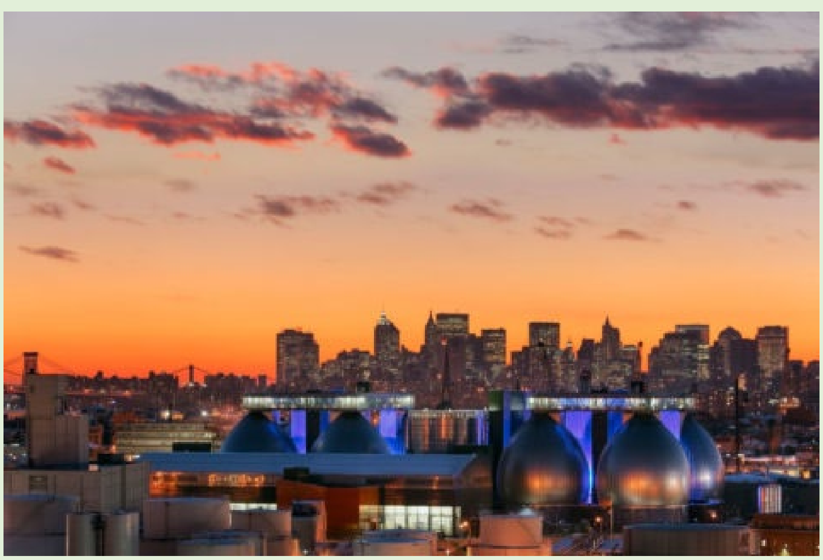
- Manure: 6,500
- Sludge: 6,500
- Food waste: 2,500
- FOG: 17,000
- Paper/cardboard: 7,100
- Plastic: 14,000
- Wood: 8,000
- Rubber and leather: 8,750
- Textiles: 7,500
- Yard trimmings: 2,800
- Glycerin: 9,000
- Black liquor: 6,600
- Distillers grains: 8,703.

Anaerobic Co-Digestion: Combining Various Organic Wastes to Generate Power

Anaerobic digesters process organic waste to reduce volume, the release of the global warming gas methane into the atmosphere and produce energy. Some facilities combine food waste with biowaste at wastewater treatment plants. In 2021, approximately 30 co-digestion facilities were operating in the United States (Dalke et al. 2021). Most of these are wastewater treatment plants that added preprocessing equipment to allow food waste to be added to the biowaste, processed in existing anaerobic digesters with extra capacity for the food waste. In almost all cases at the wastewater treatment plants, the produced biogas is used for combined heat and power generation to heat the digesters and partially power the facility.

One such facility, the Newtown Creek Wastewater Resource Recovery Facility in Brooklyn, New York, began co-digesting collected food waste from the New York City area in 2016. Food scraps from commercial, residential, and institutional sources, including schools and a curbside organics program run by the City of New York Department of Sanitation, provide the waste. Initially, the city collected approximately 30 tons of food waste per day, eventually increasing to more than 200 tons per day before temporarily dropping to 25 tons daily during the COVID-19 pandemic. In 2022, the plant processed about 130 to 140 tons of food waste per day (Karidis 2022). The biogas is used to heat the sites' boilers that provide heat to its buildings. The site, New York City's largest wastewater treatment facility, has partnered with the utility National Grid to clean the biogas to meet quality standards for injection into the natural gas pipeline network.

Other locations in dairy-centric areas such as Wisconsin and the northeast region utilize anaerobic digestion for cow manure combined with food waste. These locations also use the produced biogas for electrical generation or for combined heat and power. Lawnhurst Energy's anaerobic digestion facility in Stanley, New York, combines food waste, yogurt processing waste, and manure from dairy cows to produce combined heat and power. The facility, which began operations in 2014, provides power and heat to the buildings and for dairy processing needs, with excess electrical power being routed to the grid. At full capacity, the facility produces 541 kW of power and a heat output of 1,109 MMBtu per hour (EnviTec Biogas 2022).



Digester "eggs" at Newtown Creek Wastewater Resource Recovery Facility, Brooklyn, New York.
Photo courtesy of Newtown Creek Wastewater Resource Recovery Facility

3.3.1 Wet Waste Generation Estimates

Current/near-term total wet waste resource supply is based on previous work considering modeled and per-capita-derived estimates in 2017, except yellow and brown grease, which were updated to 2019 for this report using county population for that year from the U.S. Census Bureau. The amount of current/near-term available wet waste resources is estimated by subtracting currently used resources outlined in Milbrandt et al. (2018).

Future total supply for sludge, food waste, and FOG is based on generation increase approximated from percent change for population from 2017 to 2050 at the county level (Hauer 2021). Future total supply for animal manure is based on generation increase approximated from percent change for each manure type from 2021 to 2032 (USDA 2022b).

3.3.2 Wet Waste Price Estimates

The methods used to estimate current/near-term and future prices for wet waste resources are based primarily on previous work for wet waste price estimates (Badgett, Newes, and Milbrandt 2019). Cost models from this work were updated to account for inflation in equipment and management costs to 2022 dollars. Current/near-term price estimates use similar methodology to previous price modeling in updated dollar years. Additionally, a price ceiling and price floor are defined, where modeled prices that are lower than the price floor or higher than the price ceiling are assigned prices equal to the respective floor and ceiling values. We assume a price floor of $0.0/wet ton and ceiling of $100/wet ton across all scenarios.

Table 3.3. Methodology for Estimating Wet Waste Resource Prices for Current, BAU, and Mature-Market Scenarios

Scenario Dataset	Dollar Year	Feedstock Generation	Pricing Mechanism
Current/near term	2022 $	Current generation estimates	Supply curve model, updated to 2022 $ basis, price floor and ceiling defined
Mature-market low/medium	2022 $	Current generation updated with population projections	Supply curve model, updated to 2022 $ basis, price floor and ceiling defined, updated waste generation
Mature-market high	2022 $	Current generation updated with population projections	Supply curve model, updated to 2022 $ basis, price floor and ceiling defined, updated waste generation, 100% demand increase at $0.2/dry ton price increase per percent change in demand

These mechanisms are adopted to mitigate the effects of price model behavior in locations with low resource generation. For counties with very low waste generation, the cost to manage the waste ($/wet ton) can be extremely high. The price floor of $0/wet ton reflects uncertainty in the occurrence of negative prices in various locations. While negative prices for wet waste materials are possible and can exist in certain situations, forecasting the occurrence of these opportunities at a national-level analysis is highly uncertain. Detailed location-specific studies to identify these economically favorable situations are needed to confirm viability of negative prices and their elasticity to increased demand for the material.

FOG is priced separately from the other wet waste materials, as the market prices for various FOG subtypes are publicly available. We differentiate FOG prices for used cooking oil/yellow grease and animal fats from *Render* magazine (Johnson Downing 2022). Trap/brown grease prices were collected via survey of relevant collection and processing companies by staff at the National Renewable Energy Laboratory (NREL). These prices are applied to all FOG resources across the United States, as there is little geographic variability. FOG prices for the mature-market high scenario assume a similar 100% demand increase at $0.2/dry ton ($20/wet ton) increase per percent change in demand (Langholtz et al. 2022).

3.3.3 Solid Waste Generation Estimates

Current/near-term total and available supply for plastic waste is based on previous work considering modeled estimates in 2019. Milbrandt et al. (2022) provide more information and breakdown by material type—e.g., polyethylene terephthalate (PET) bottles/containers, high-density polyethylene (HDPE) bottles/containers, film/bags. Current/near-term total and available supply for paper and cardboard waste is based on previous work considering modeled estimates in 2019. Milbrandt et al. (2024) provide more information and breakdown by material type (e.g., cardboard, magazines, compostable paper). Current/near-term total supply for rubber/leather, textile, and yard trimmings is estimated using the same method as in BT16—per-capita generation derived from EPA's nationwide reporting and applied to county population—updated with the latest EPA estimate (2018) and 2018 county population from the U.S. Census Bureau (EPA 2020b). The current/near-term available supply for these materials represents their landfilled quantity; the data are obtained from the EPA and presented at the national level.

Current/near-term total supply for urban wood (MSW and C&D wood) is also estimated using per-capita generation derived from EPA's 2018 nationwide reporting and applied to 2018 county population (EPA 2020a, 2020b). We assume that 50% of MSW wood and one-third of C&D wood is clean (e.g., branches and stumps, clean lumber, most pallets and crates) and thus suitable for bioenergy conversions. Current/near-term available resources are estimated by subtracting the amount of wood that is recycled and combusted, assuming that only clean wood is used in these applications.

Future total supply for all solid waste resources is based on generation increase approximated from percent change for population from 2018/2019 to 2050 at the county level (Hauer 2021).

3.3.4 Solid Waste Price Estimates

Solid waste materials are priced using a separate methodology from wet wastes. If the waste has been commoditized, we report 3-year average (2019–2021) market prices for the material from RecyclingMarkets.net (recyclingmarkets.net/). This approach is applied to plastic and paper/cardboard waste for near-term and mature-market low/medium scenarios.

For the remaining materials where market prices are not readily available, we estimate a possible market price by considering the local landfill tipping fee and added costs for material separation in accordance with methodologies adapted from BT16 (DOE 2016):

$$price = sort\ cost - landfill\ tipping\ fee$$

The $sort\ cost$ can either be \$40/wet ton or \$60/wet ton, depending on the population in the county. This serves as a proxy for the scale of the separation and packaging equipment, assuming that higher-population counties are likely to leverage greater economies of scale and thus lower costs. Counties with greater than or equal to 250,000 people are assigned a $sort\ cost$ of \$40/wet ton, and those with populations below 250,000 people are assigned \$60/wet ton. Landfill tipping fees are aggregated at the state level.

As with wet waste materials, locations with estimated negative solid waste prices are set equal to zero. This price floor methodology reflects uncertainties around market development for waste materials discussed earlier.

Table 3.4. Price Estimation Methodology for Solid Waste Materials

Solid Waste	Dollar Year	Pricing Mechanism	Mature-Market Low/Medium Price Adder	Mature-Market High Price Adder
Yard waste	2022 $	Landfill price approximation + price adders for BAU/mature-market scenarios	$4.08/wet ton	$8.08/wet ton
Paper and paperboard	2022 $	Market prices + price adders for BAU/mature-market scenarios	$8.67/wet ton	$17.17/wet ton
Textiles	2022 $	Landfill price approximation + price adders for BAU/mature-market scenarios	$8.67/wet ton	$17.17/wet ton
Rubber and leather	2022 $	Landfill price approximation + price adders for BAU/mature-market scenarios	$9.18/wet ton	$18.18/wet ton
Urban wood	2022 $	Landfill price approximation + price adders for BAU/mature-market scenarios	$10.20/wet ton	$20.02/wet ton
Plastics	2022 $	Market prices + price adders for BAU/mature-market scenarios	$9.18/wet ton	$18.18/wet ton

For the mature-market scenarios, we assume an increase in demand for the solid waste materials that correlates to an increased market price. We assume a 50% increase in demand for the material for the mature-market low/medium scenario and a 100% demand increase for the mature-market high scenario with a \$0.2/dry ton increase in price per percent increase in demand across both mature-market low/medium and mature-market high (Langholtz et al. 2022). This price increase is added to initial mature-market low/medium prices to generate price estimates for the mature-market high scenario.

3.3.5 Gaseous Resources/Intermediates

Near-term total and available LFG production data were obtained from the EPA's Landfill Methane Outreach Program as of November 2023 (EPA 2023b). The total estimate considers current LFG amount available (or estimated for those with data gaps) at landfills that are currently or most likely able to support a project. It excludes landfills with only project records of "low potential" or "unknown" and includes landfills with or without a gas collection system. The available estimate considers the "total" value minus "currently used" (gas flows to all operational, construction, and planned projects). The available estimate includes the amount of gas flared at landfills that are only flaring, landfills with only a shutdown project, and landfills with or without a gas collection system. The hierarchy for LFG flow estimates is to use LFG flared, LFG collected, LFG generated, and then estimate from waste in place. For landfills with projects under construction or planned, it is assumed that all the LFG collected will go to the project. For the values in tons, the assumption was made that the LFG is 50% methane and 50% CO_2 for simplicity. In addition to filling some data gaps with estimates, EPA notes that most of the LFG values in their current database are for 2021, as they are still processing 2022 data.

3.3.6 Byproducts Generation and Price Estimates

Data for glycerin production, consumption, and prices were obtained from S&P Global's *Chemical Economics Handbook* published in July 2021 (S&P Global 2021).

Black liquor production data were obtained from EIA's latest Manufacturing Energy Consumption Survey, completed in 2018 (EIA 2018). Data for black liquor prices were obtained through personal communication with David Johnson, a retired NREL scientist with more than 30 years of experience in the field.

Distillers grains production, consumption, and price data were obtained from the USDA Economic Research Service in October 2022 (USDA 2022a).

Table 3.5. Comparison of National- and County-Level Supply Data

Category	Resource	National	County Level
Wet waste	Animal manure	Total, available (50 states)	Total (23 states)
Wet waste	Wastewater sludge	Total, available	Total
Wet waste	Food waste	Total, available	Total
Wet waste	FOG	Total, available	Total
Solid waste	Paper and cardboard	Total, available	Available (landfilled)

Category	Resource	National	County Level
Solid waste	Plastics	Total, available	Available (landfilled)
Solid waste	Clean urban wood (MSW and C&D)	Total, available	Total
Solid waste	Rubber and leather	Total, available	Total
Solid waste	Textiles	Total, available	Total
Solid waste	Yard trimmings	Total, available	Total
Gaseous	LFG candidate projects	Total	Total
Other waste	Glycerin	Total	n/a
Other waste	Black liquor	Total	n/a
Other waste	Distillers grains	Total	n/a

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