Executive Summary

The following online companion materials are available:

- Report landing page: https://www.energy.gov/eere/bioenergy/2023-billion-ton-report-assessment-us-renewable-carbon-resources
- Data portal: https://bioenergykdf.ornl.gov/bt23-data-portal

Bioenergy provided the largest single source of renewable energy in the United States in 2022, comprising approximately 5% of U.S. energy produced (EIA 2023) (Figure ES-1). The mission of the U.S. Department of Energy (DOE) Bioenergy Technologies Office (BETO) is to develop and demonstrate technologies to accelerate net greenhouse gas emissions reductions through the cost-effective, sustainable use of biomass and waste feedstocks across the U.S. economy. This report assesses the potential for renewable biomass resources to support DOE goals by displacing fossil resources such as petroleum with renewable biogenic carbon resources that, when managed efficiently, have a lower climate impact than petroleum sources of carbon. Demand for renewable fuels is growing, especially for the aviation, marine, and rail sectors. For example, the Biden administration's Sustainable Aviation Fuel (SAF) Grand Challenge targets the production of 35 billion gallons per year of SAF by 2050, and the Clean Fuels & Products Shot™, whose target of developing cost-competitive carbon-based products at 85% less greenhouse gas emissions by 2035, can support delivery of approximately 440 million tons per year of low-carbon fuels and chemicals by 2050. Such targets raise the question: Does the United States have sufficient biomass supplies, within a practical range of environmental, economic, and resource constraints, to fill these needs? The answer is yes, provided adequate markets can be established, and that environmental safeguards are established to ensure sustainable outcomes. This report aims to inform stakeholders of the types and quantities of biomass resources that could potentially be available in the future and under what conditions. The report provides a detailed assessment of current and potential biomass production capacity in the United States at defined price points and under conditions that protect food production and environmental integrity.

This report is the latest in a series of national biomass resource assessments supported by BETO (Perlack et al. 2005; DOE 2011, 2016, 2017). Each report represents an advancement in the understanding of biomass resources in terms of production capacity, spatial distribution, and economic accessibility. While the reports have consistently found that the United States could sustainably produce about 1 billion tons of biomass per year under some scenarios, that was not a goal or target; it was merely one outcome of analyses based on available data. Goals of this report are to update the latest available input data (e.g., costs, yields, economic conditions) and improve accessibility of the latest biomass resource data and results. New resources in this report include:

- Intermediate (i.e., off-season) oilseeds

- Western forest fuels (as case studies, not included in national totals)
- Macroalgae and point-source waste carbon dioxide (CO_2).

Market pull is needed to realize the production of biomass resources reported here. In this report, we emphasize this precondition by presenting resource potential in terms of market demand scenarios. The market scenarios used in this report are characterized in Table ES-1 and detailed in Chapter 1. Another key factor in biomass resource availability is the price offered for biomass. Reference prices[1] are used to summarize supply potential, as shown in Figure ES-1, but readers are encouraged to explore the range of potential resource availabilities under different price assumptions at https://bioenergykdf.ornl.gov/bt23-data-portal.

[1] Prices here (and unless otherwise specified) are as raw biomass on a dry-weight, with-ash basis, in 2022 dollars, at the farm gate for agricultural land resources; chipped into a van roadside for timberland resources; collected and sorted for waste resources; after harvest, dewatering, and seasonal storage for microalgae resources; and after harvest and transportation to the nearest port for macroalgae resources. For comparison, the reference price of the previous report (DOE 2016) was $60 per dry ton in 2014 dollars—i.e., approximately $74 per dry ton in 2022 dollars. Biomass resources currently used for energy have varying market prices and are not reported here.

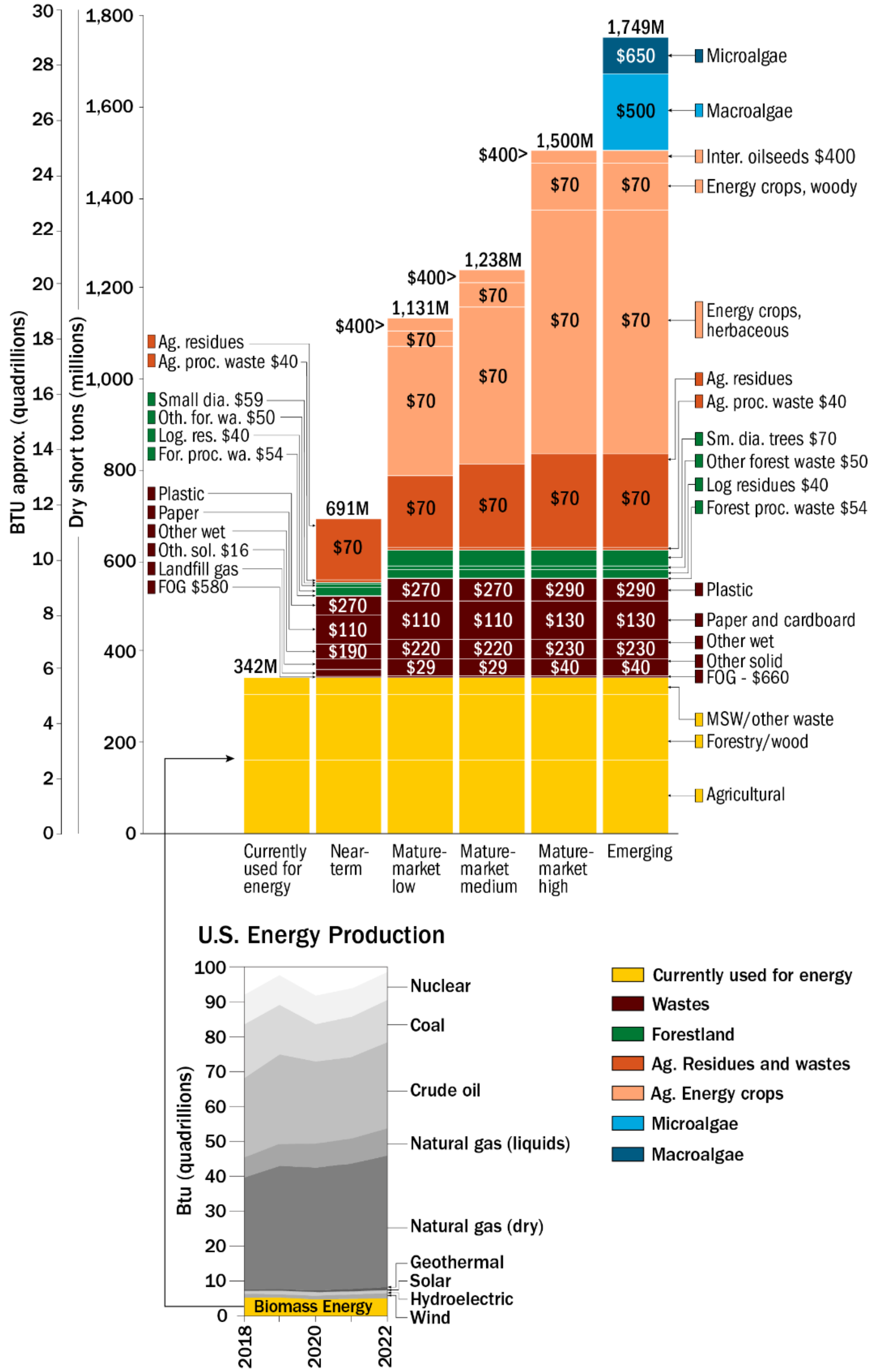

Figure ES-1. Currently used and potential future biomass resources under near-term, mature-market, and emerging scenarios. Reference prices are in dollars per dry ton, without transportation costs. Prices are reported as rounded weighted averages for wastes and marginal prices for all other resources. Market prices of currently used resources are not reported here. The energy equivalent does not account for conversion process efficiency. Values for 2018–2022 production are from the U.S. Energy Information Agency (2023). Select values are provided in Table ES-2. Underlying data for this figure and a version using alternate units can be found at https://bioenergykdf.ornl.gov/bt23-data-portal.

Table ES-1. Characterization of Market Scenarios Used in This Report (Attributes Detailed in Chapter 1 Table 1.2)

Market Scenario	Characterization
Current	Current uses of biomass for energy (i.e., power and fuels) and coproducts.
Near-term	Resources that are completely unused currently and can be used in the next 5–10 years, in addition to current uses.
Mature-market low	Low market pull, low supply push: business-as-usual (BAU) projections for the agriculture, forestry, and waste sectors, and no purpose-grown energy crop yield improvements, in addition to current uses.
Mature-market medium	Moderate market pull, moderate supply push: BAU projections and moderate (1%) purpose-grown energy crop yield improvements, in addition to current uses.
Mature-market high	High market pull and high supply push: 3% improvements of purpose-grown energy crops; conventional crop yields improve 1.5 times the USDA trend; BAU waste projections with higher waste demand increase waste prices, in addition to current uses.
Evolving and emerging resources	Potential future production of microalgae, macroalgae, and capture of point-source waste CO_2. These resources are considered as prospectively available, contingent upon future innovations, in addition to the mature-market high scenario.

Biomass resource availability is dependent in large part upon markets, and the timing and pace of market development is not known. Thus, this report provides estimates of biomass resource potential in response to market demand scenarios, rather than year-specific projections of biomass availability. Results here aim to indicate national biomass resource potential as estimated under the specific conditions and assumptions constructed in the analyses for each market scenario. Thus, resources reported here are less than the total raw biophysical potential for biomass production, but reflect the proportion thereof that complies with specified economic and environmental constraints (e.g., restricted land use change), and allow for satisfaction of conventional product demands, as illustrated in Figure ES-6. Results are based on national modeling simulations and are not intended to be predictive or precise, particularly for the county-level data provided in the data portal (https://bioenergykdf.ornl.gov/bt23-data-portal). The results are meant to provide general insights about the potential magnitude of biomass resource availability per specific conditions, which can be useful for resource allocation planning and future policy development. Local stakeholder innovation is expected to uncover synergistic practices that can increase both biomass potential and ecosystem services, which is not captured in this national analysis. Thus, this national assessment is approximate and probably conservative. The importance of market pull and the use of these data for decarbonization studies are explored further in Chapter 8. Key results of this national assessment follow.

Future production capacity of more than 1 billion tons per year of biomass is identified, which could approximately triple the current U.S. bioenergy economy. More than 1 billion tons of biomass production capacity is identified nationally, while meeting projected demands for food, feed, fiber, and exports. As provided in the data portal, this supply increases at higher prices or with the inclusion of microalgae, macroalgae, or CO_2, which could be accessible if technological innovations are realized in the future. In the mature-market low scenario, approximately 1 billion tons of total biomass is identified, including current uses, whereas in the mature-market high scenario, approximately 1 billion tons of new biomass production is identified, above current uses (Figure ES-1). One billion tons per year of biomass is roughly enough biomass to produce approximately 60 billion gallons of fuel, or 1.7 times the quantity needed to achieve the SAF Grand Challenge. In the mature-market medium scenario, 1.5 billion tons of biomass per year is more than enough to meet the goals of the SAF Grand Challenge and the Clean Fuels & Products Shot™: Alternative Sources for Carbon-based Products. However, this analysis is agnostic with regard to end use.

Near-term resources can provide approximately 350 million tons per year of biomass above current uses, which would roughly double the current U.S. bioenergy economy (Figure ES-1 and Table ES-2). This "low-hanging fruit" of the biomass portfolio includes biomass resources that exist today, even in the absence of additional market pull for biomass, but are currently unused. Some of these resources, such as wastes, are already collected but then landfilled. Others, such as agricultural residues and timberland resources, exist in fields and forests but must be collected for use.

Table ES-2. Current and Potential Future Biomass Resources under Near-Term and Mature-Market Scenarios (million dry short tons per year). Market Scenario Assumptions Are Specified in Chapter 1.[a]

		Scenario			
Analysis Class [b]	Analysis Subclass [b]	Near-Term	Mature-Market Low	Mature-Market Medium	Mature-Market High
Currently Used for Energy and Coproducts	Agricultural	162	162	162	162
	Forestry/wood	144	144	144	144
	Municipal solid waste (MSW)/other wastes	37	37	37	37
Potential Waste and Byproducts [c]	Fats, oils, and grease (FOG)	3	4	4	4
	Gaseous resources	15			
	Other solid waste	24	38	38	38
	Other wet waste	32	43	43	43
	Paper	64	84	84	84
	Plastic	41	49	49	49
Potential Forestland Resources	Forest processing waste	1	1	1	1
	Logging residues	19	19	19	19
	Other forest waste	8	8	8	8
	Small-diameter trees	3	35	35	35
Potential Agricultural Land Resources	Agricultural processing waste	6	6	6	6
	Agricultural residues	134	158	183	205
	Energy crops, herbaceous		284	345	535
	Energy crops, woody		34	53	103
	Intermediate oilseeds		28	28	28
	Total [d]	691	1,131	1,238	1,500

[a] Currently used resources have a range of current prices not reported here. Waste quantities are reported at all modeled prices. Agricultural and forestry resource quantities are provided at up to $70 per dry ton. Prices in this table are reported as farm gate (i.e., at roadside), which includes costs of production and harvest but excludes transportation costs. Prices in this report are provided in 2022 dollars unless otherwise specified.
[b] Classes, subclasses, and resource are provided in the glossary.
[c] Waste totals do not match the sum of county-level data due to differences in the spatial resolution of data, as described in Chapter 3.
[d] Totals may not sum due to rounding.

Mature-market resources can provide approximately 800–1,200 million tons per year of biomass above current uses (Figure ES-1). The largest growth in the mature-market scenarios is due to the adoption of purpose-grown energy crops. Because future energy crop production can have interactions with conventional crop markets on agricultural lands, energy crop potential was assessed with an economic model as described in Chapter 5. Modeled scenarios of energy crop production require fulfilment of future demands for food, feed, fiber, and exports from the 2023 U.S. Department of Agriculture (USDA) baseline projection, which includes increased demand for conventional crops relative to previous projections. In response, the modeled potential of purpose-grown energy crops is down 3% (in the mature-market medium scenario) from the *2016 Billion-Ton Report* reference scenario (DOE 2016), but still shows potential of approximately 300–600 million tons across the three mature-market scenarios (Table ES-2). Modeling results for energy crops shown in Figure ES-1 and Table ES-2 are produced on 8%–11% of agricultural land while still meeting projected demands for conventional crops and leaving 8% of cropland unused. Results show purpose-grown energy crops having comparative economic advantage over other cropland use options primarily in the southern Plains, but not in highly productive agricultural regions where higher-value conventional crops dominate (Figure ES-4). Modeled increases on U.S. finished food prices associated with the energy crop production shown in Figure ES-1 are less than 1%; modeled increases in total farm net revenues range from 26% to 31% (Table ES-3). Changes in energy crop production would result in approximately proportional changes in these modeled effects.

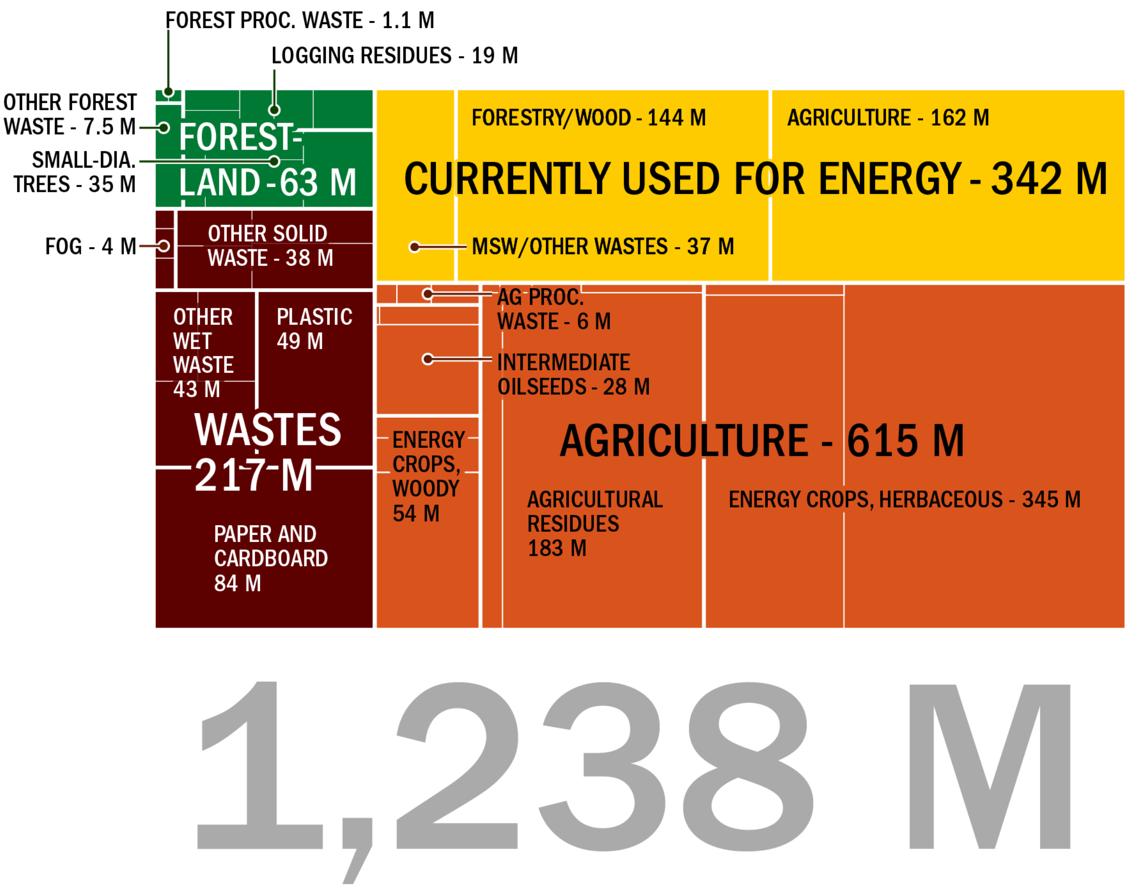

Figure ES-2. Biomass resources in the mature-market medium scenario, totaling 1.2 billion dry short tons per year (under reference prices shown in Figure ES-1). This figure for other scenarios and units is available at https://bioenergykdf.ornl.gov/bt23-data-portal.

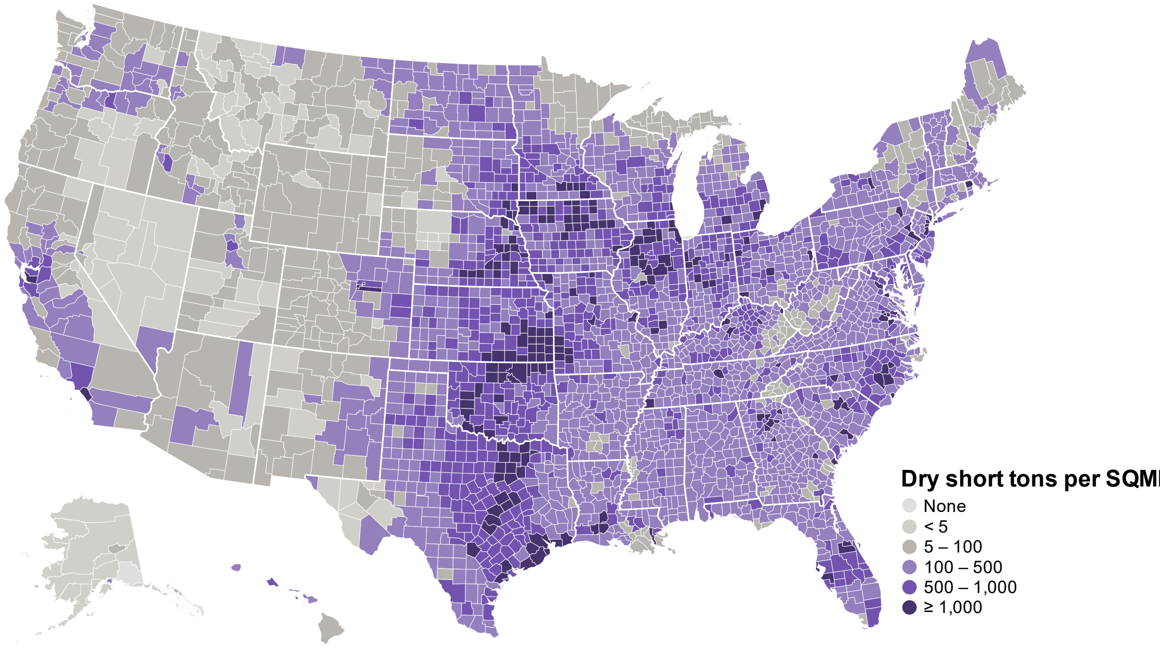

Figure ES-3. Spatial distribution of biomass resources from all sources shown in the mature-market medium scenario as specified in Figure ES-1, Figure ES-2, and Table ES-2, excluding currently used resources. Purple shades indicate adequate spatial density to support a facility of at least 725,000 dry tons per year within a 50-mile radius (i.e., at least 100 dry tons per square mile). Scenario- and class-specific versions of this figure are available at https://bioenergykdf.ornl.gov/bt23-data-portal.

The mature-market scenarios also carry forward resources from the near-term scenario with the following modifications:

- Waste quantities increase slightly, associated with projected increases in population over 20 years. Waste resources include urban wastes (e.g., MSW, FOG) and agricultural and forestry processing wastes (e.g., mill wastes).
- Demand for biomass from timberlands (i.e., logging residues and trees less than 11 inches in diameter at breast height) is increased to a sustained yield of 54 million tons per year, with market prices of up to $70 per dry ton.
- Agricultural residues increase to about 175 million tons per year in the mature-market medium scenario, up from about 130 million tons per year in the near-term scenario.

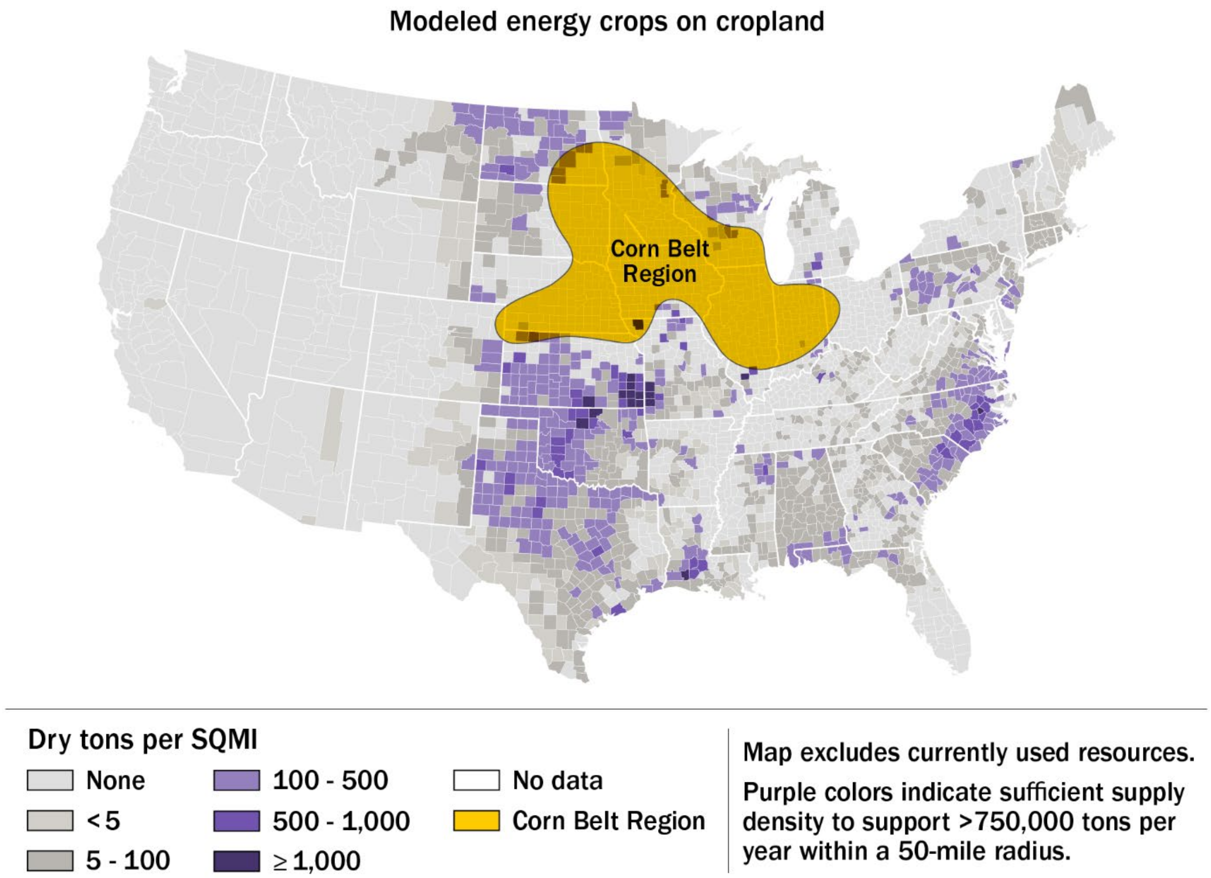

Figure ES-4. Spatial distribution of purpose-grown energy crops under the mature-market medium reference scenario on cropland, illustrating the comparative economic advantage of commodity crops in the corn belt. The orange region indicates a corn/soy production region as shown by the USDA National Agricultural Statistics Service (2023), where energy crops are largely excluded from cropland.

Table ES-3. Modeled Impacts of Energy Crop Scenarios on U.S. Commodity Crop Production, Commodity Crop Prices, Food Prices, and Farm Revenues. Future Yield Improvements Simulated in the Mature-Market High Scenario Mitigate Impacts on Conventional Production and Increase Biomass Production. Details Are Provided in Chapter 5.3.

Scenario [a]	Energy Crops Produced (million dry tons) [a,b]	Agricultural Residues Harvested (million dry tons) [c]	Production of Corn, Soy, and Wheat	Change in Finished Food Price	Total Farm Market Net Revenues
			Percent Change from Baseline, Mature Market		
Mature-market low	318	152	−3%	+0.6%	+26%
Mature-market medium	398	177	−3%	+0.7%	+31%
Mature-market high	638	200	−1%	+0.1%	+31%

[a] Mature-market scenarios are described in Chapter 5 and summarized in Table ES-1.
[b] Sum of modeled cellulosic terrestrial (i.e., excluding intermediate oilseeds and algae) purpose-grown energy crops within modeling constraints as summarized in Figure ES-1.
[c] Corn stover and wheat straw.

Resource quantities vary by price. The summaries above provide an illustration of potential biomass resources under specified market prices. However, different types and quantities of biomass resources are expected to be available at different prices. Biomass resource availability as a function of offered price for the mature-market medium scenario is illustrated in Figure ES-5. Users are encouraged to explore scenario-, price-, and resource-specific spatially explicit resource availability in the data portal.

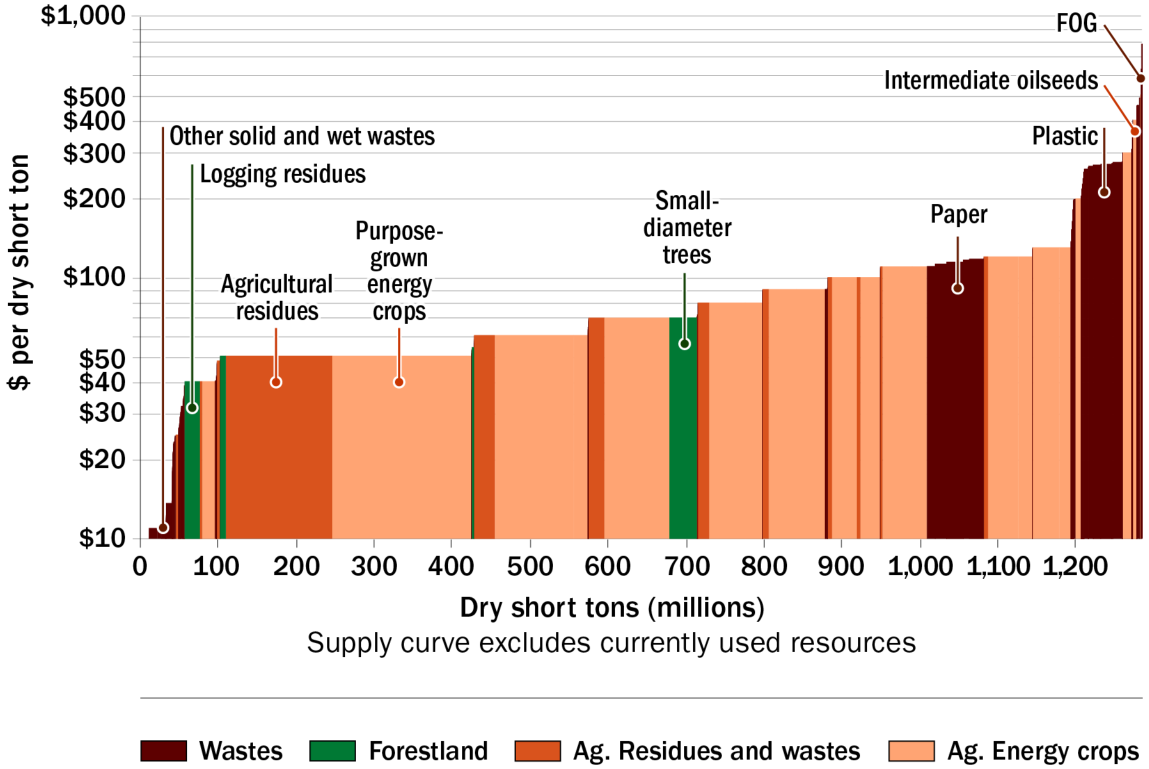

Figure ES-5. Supply curve of the mature-market medium scenario, excluding currently used resources and including agricultural resources above the $70 per dry ton price shown in Figure ES-1. Prices are reported as farm gate (i.e., after harvest and before transportation) in 2022 inflation-adjusted dollars. Interactive versions of this figure for other scenarios and units are available at https://bioenergykdf.ornl.gov/bt23-data-portal. Note that the y-axis is logarithmic.

Resource potentials reported here are not total national supplies "in field," but rather the economically accessible fraction within specified sustainability constraints (Figure ES-6). The economic and environmental constraints implemented in this report mean results are not maximum potential resource availability, but rather a fraction of resources that meet select sustainability constraints within specified prices. The results are representative of what is deemed accessible in potential futures if market demand is realized and other policy goals or conditions are met (such as food security or environmental integrity). For example, to meet modeled soil conservation constraints, about one-third of total national "in-field" agricultural residues are reported as available in the mature-market scenarios. Available waste resources represent about half of total national supplies after accounting for recycling and current uses.

Total timberland resource harvests, including for conventional wood products, are about one-third less than annual net forest growth, and less than 1% of total forest volumes. Purpose-grown biomass crops are not targeted to maximum production potential, but rather simulated to occupy 7% of cropland and 9% of agricultural lands in the mature-market medium scenario, where results indicate they have comparative economic advantage, within a mosaic of conventional agricultural uses. Changes in future costs, yields, or other factors (including policies and environmental and social conditions) would cause deviations from the estimated results in this report. Further, resources evaluated here are not exhaustive of all potential resources, which may include other sources of biomass from natural or anthropogenic activities such as winter herbaceous crops (Malone et al. 2023), storm debris, removals of beetle kill conifers or invasive exotics, realization of U.S. Forest Service forest fuel reduction goals, or purpose-grown energy crops produced on reclaimed mined lands or other underproductive lands (Field et al. 2023). The diversity of potential resources suggests that overestimation of some resource types is likely to be mitigated to some degree by underestimation of others. Ultimately, the market scenarios are provided to inform a range of future potential accessibility of national biomass resources. This analysis is not a prediction of what will be used, but rather an assessment of the possible economic accessibility of a portfolio of resources within specified constraints and modeled conditions, and with steady market development providing a demand "pull."

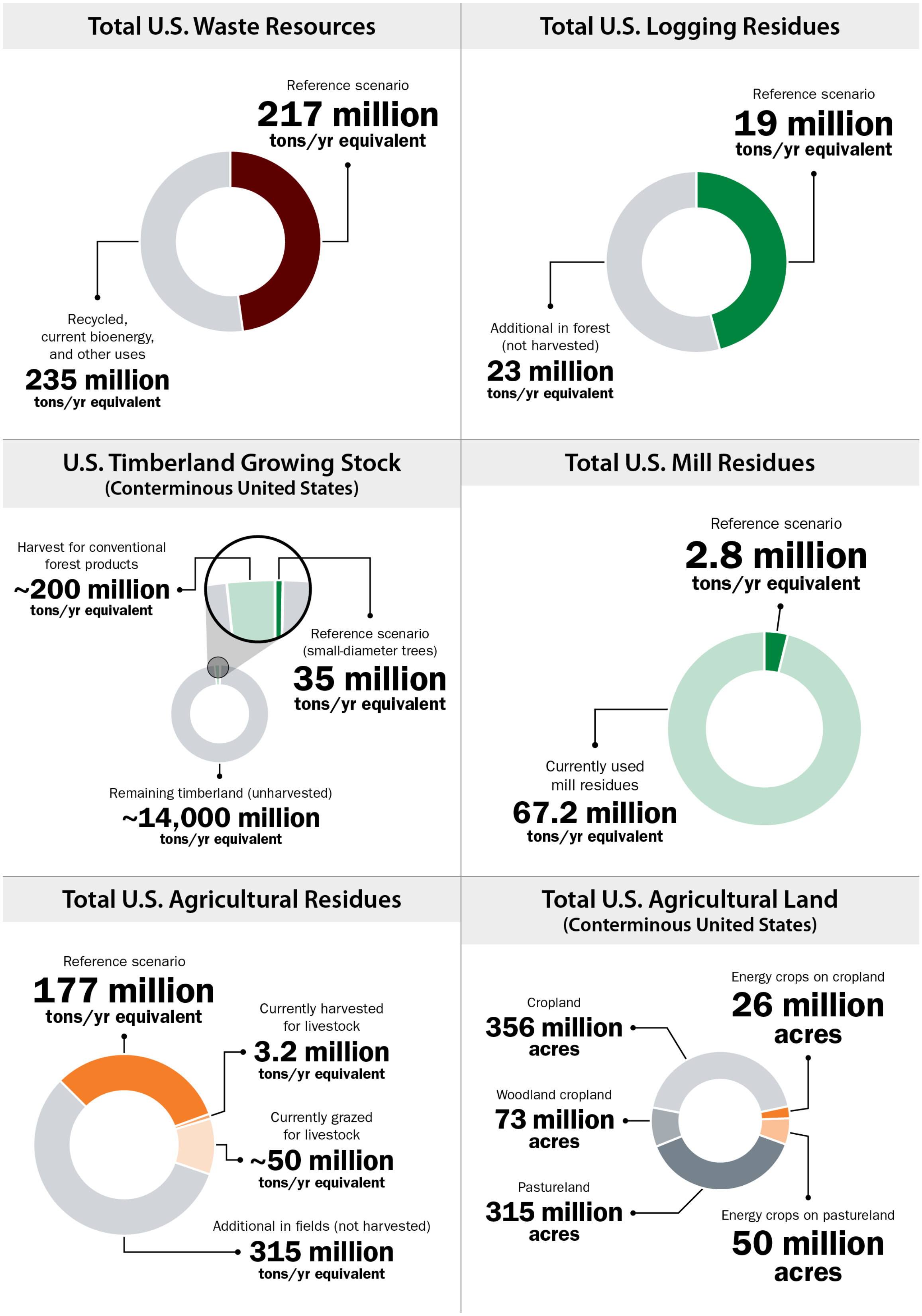

Figure ES-6. Available resources in the mature-market medium reference scenario in proportion to in-field supplies and competing uses.

Deviation from the sustainability constraints considered in this analysis could result in overharvesting and negative environmental effects. New in this report is an assessment of estimated risk of deviating from sustainability constraints used here. For example, relaxing agricultural residue retention constraints causes modeled residue harvest to nearly double, risking soil erosion or loss of soil carbon. Also, increasing biomass prices above $70 per ton at roadside, though currently cost prohibitive from a biofuels perspective, could incentivize harvest of some sawlog-class trees to be economically viable for bioenergy. Modeled prices higher than $70 per ton incentivize more production of purpose-grown energy crops and increase the market effects summarized in Table ES-3. Monitoring and evaluation are recommended to ensure that conservation practices are maintained, and consideration should be given to demand levels that might drive prices higher than evaluated here. Good practices that safeguard sustainability need to be appropriate for local conditions; consider practical, place-based opportunities and constraints; and be developed with stakeholders who are informed by reliable monitoring and evaluation data to support continual improvement. Biomass markets that provide performance-based incentives can support safeguards by promoting investment in technologies for more sustainable practices that reduce supply chain emissions and other detrimental effects. A discussion of the risk of deviating from modeling constraints is provided in Chapter 6.

Evolving and emerging resources represent additional potential. Chapter 7 in this report explores other resources that could be available at scale if technological innovations are realized. Microalgae (i.e., pond-grown algae) resources can be produced on underutilized lands using waste CO_2 streams and saline groundwater. Macroalgae (i.e., ocean-grown seaweed) can be cultivated in ocean farms with vast growth potential. CO_2 point-source waste streams can be targeted for decarbonization strategies. Combined, these resources could double or triple the billion-ton biomass resource potential reported here, but supplies vary greatly with price. An example of potential supplies at select prices is provided in Table ES-4. Perfect comparisons among resources are not possible with the data from this report alone. For example, economic results from the microalgae analysis include a 10% internal rate of return, whereas the macroalgae analysis is at breakeven cost. Microalgae is conversion-ready following harvest, dewatering, and seasonal storage (included in the economic results contributing on the order of about $100/ton to the presented microalgae biomass costs), whereas other resources still require transportation and preprocessing costs before conversion (not included in the economic results for those resources). Downstream factors of logistics and feedstock quality attributes, essential for comparing biomass resource options, are not included in this report.

Table ES-4. Emerging Resources at Reference Prices

Resource Category	Modeled Potential Supply at Specified Prices (million tons per year)
Microalgae (≤$650 per dry ton, with ash)	170
Macroalgae (≤$500 per ton, with ash)	80
CO_2 (high-purity)	47.2

Report organization. Chapter 1 provides background on the intent of this report and methods used in relation to previous billion-ton reports, including detailed descriptions of the market scenarios and sustainability constraints modeled. Chapter 2 details current uses of biomass for energy and coproducts. Chapters 3, 4, and 5 provide updated descriptions of the waste, forest, and agricultural biomass resource assessments, respectively. Chapter 6 explores sustainability issues in biomass resource production, including new quantitative analyses on food security impacts and the effects of relaxing sustainability constraints. Chapter 7 provides assessments of evolving and emerging feedstocks from microalgae, macroalgae, and CO_2 waste streams. Chapter 8 provides additional context on how this assessment can be used in decarbonization studies and priorities for future work, including modeling of energy crop production on marginal land and under future climate change.

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