


DOVETAIL PARTNERS

BIOENERGY UPDATE: A U.S. OUTLOOK

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EXECUTIVE SUMMARY

In this time of transition to alternative energy sources, all sectors are under pressure to reduce their GHG emissions. Research is underway on many fronts with the result that placing bets regarding winners and losers in the future energy picture is risky. Within this environment, the future role of biomass in contributing to future needs for energy and industrial chemicals is open to question.

Heat and power, liquid fuels, industrial chemicals – all are areas wherein biomass-derived energy and chemicals play a current role. With regard to chemical feedstocks, it is technically possible to obtain from biomass almost all of the industrial chemicals now derived from fossil fuels. But faced with competition from other means of producing energy and chemicals, will biomass play an ever-greater role in the future or will prospects dim going forward?

Our assessment suggests a bright near- to mid-term future for biomass, especially regarding liquid fuels for commercial transportation. However, with the exception of aviation fuel, we see an uncertain and less promising future for biomass in both energy and industrial chemical markets over the long term.

INTRODUCTION

In 2000 biomass accounted for over 73% of U.S. renewable energy consumption. Hydropower accounted for 23% while wind and solar combined accounted for less than 2%. The subsequent domestic focus on renewable energy development has resulted in a significant shift in renewable energy sources (Table 1 and Figure 1). In 2023 biomass[1] remained the dominant source of renewable energy, although at a reduced share of 60% (Figure 2), this despite substantial development of corn and soy-based biofuels over the preceding decade. The greatest change was in the contribution of wind and solar, up from less than 2% to over 28%. Overall, the portion of total primary consumption provided by biomass remained at about 5% from 2010 onward (Figure 3).

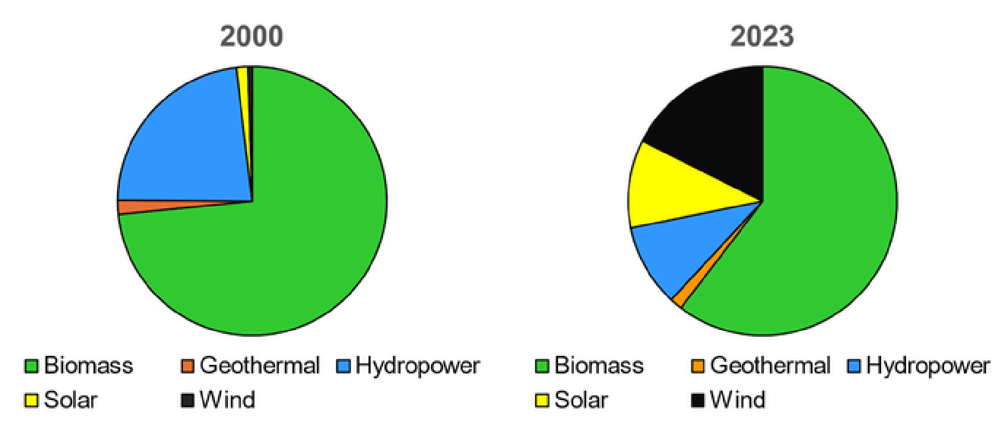
The declining trend in biomass' contribution to renewable energy raises a question about the future role of biomass in the nation's energy picture. This report examines the various energy applications of biomass in the present and seeks to shed light on what the future may hold.

TABLE 1: SHARE OF RENEWABLE ENERGY PRODUCED

Renewable Energy Source	Share of Renewable Energy	
	2000	2023
Biomass	73.4	60.4
Geothermal	1.7	1.5
Hydropower	23.0	9.9
Solar	1.4	10.6
Wind	0.5	17.6
Renewables share of total U.S. primary energy consumption	4.2	8.8
Biomass share of total U.S. primary energy consumption	3.1	5.3

* EIA. 2012. Annual Energy Review 2011, Table 10.1. DOE/EIA-0384, Sept.
** EIA 2023. Monthly Energy Review, Apr.

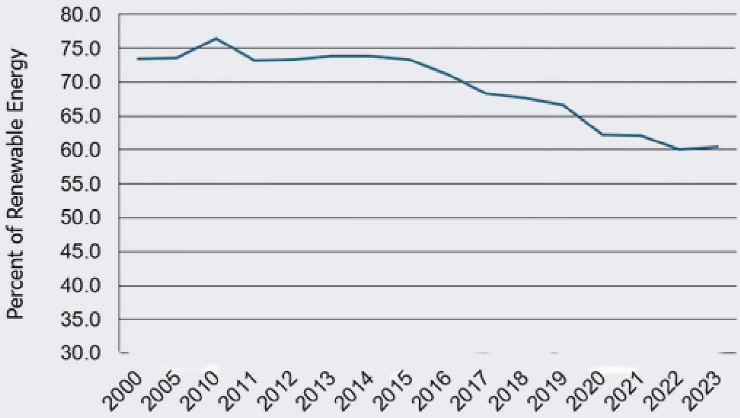
FIGURE 1: SHARE OF RENEWABLE ENERFY PRODUCED IN THE US



Source: EIA. (2025) Monthly Energy Review, Jan

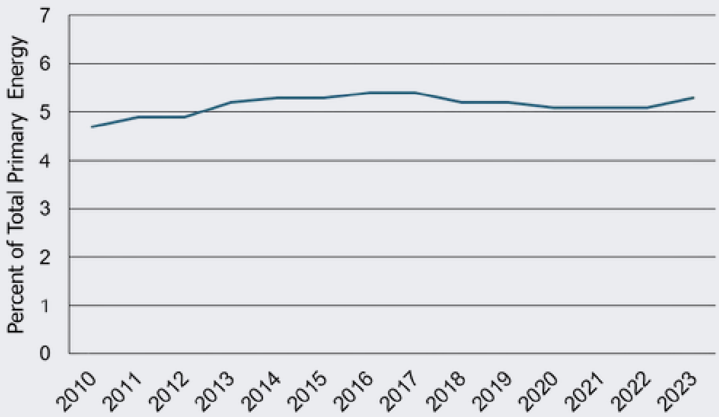
1 EIA (2012)

FIGURE 2: BIOMASS SHARE OF RENEWABLES ENERGY CONSUMPTION IN THE U.S., 2000-2023



Source: EIA. (2025) Monthly Energy Review, Jan.

FIGURE 3: BIOMASS SHARE OF TOTAL PRIMARY ENERGY CONSUMPTION IN THE U.S., 2000-2023



Source: EIA. (2025) Monthly Energy Review, Jan.

DIFFERENT FORMS AND USES OF BIOMASS ENERGY

In the early years of the 21st century the majority of biomass used for energy production was obtained from forests. In 2005 sawmill residues (bark, sawdust, chips), black liquor from pulp mills, and split firewood for home heating accounted for about two-thirds of biomass derived energy.[2] But by 2022, due to subsidy-driven growth of the corn ethanol and biodiesel industries, agriculture, and primarily corn starch, accounted for about half (49%) of energy derived from biomass, with wood wastes providing 44%.[3] The rest came from various waste streams such as municipal solid waste, and organics recovered from wastewater treatment.

Biomass is used in the production of transportation fuels and electricity and for home, industrial, and district heating. It also serves as a source of industrial chemicals – obviously not a form of energy, but as replacement for products currently derived from fossil fuels. What follows is a brief examination of each of the various forms and uses of biomass in the energy realm, current realities, and future scenarios.

2 Wright et al. (2006)
3 EIA (2023a)

BIOMASS AVAILABILITY

Around the year 2000 the U.S. Departments of Energy and Agriculture teamed up to study the volume of biomass that might be sustainably obtained on an annual basis for use in energy production. The result was the 2005 Billion Ton Report,[4] so named because investigation revealed the potential for gleaning over one billion tons of biomass each year without detracting from then current uses. Several updates were subsequently produced – in 2011 and 2016. A new update was issued in 2024,[5] described as a collective effort of numerous scientists from U.S. national laboratories, multiple government agencies — primarily the Departments of Energy and Agriculture — various universities, and industrial stakeholders. This report is referenced extensively in the following paragraphs.

The 2024 Billion Ton Report update identified capacity for production of as much as 1.5 billion tons of biomass and unutilized waste material annually without compromising current and anticipated requirements for food, feed, fiber, and export demand. For the near term (5-10 years), analysis indicates potential for utilization of about 350 million tons of biomass beyond the 342 million tons of biomass used for production of energy and bio-based chemicals in 2022. Supplies of biomass judged to be available in the near term include various forms of biomass waste that are collected but discarded without being utilized such as storm damaged urban trees and demolition debris. Additional volumes exist across farm and forest landscapes but would have to be collected to enable use.

For instance, current economic availability of corn stover excess of that needed for conservation tillage was estimated at about 134 million tons annually. The municipal solid waste stream could also provide a significant volume of combustible biomass; the volume of wastepaper and plastics[6] going to landfill was estimated at 105 million tons.

The 2024 Billion Ton Report update identified capacity for production of as much as **1.5 billion tons** of biomass and unutilized waste material annually without compromising current and anticipated requirements for food, feed, fiber, and export demand. Were this volume of biomass converted to energy at current rates of efficiency, the quantity of energy produced would be approximately equal to **28%** of 2022 U.S. primary energy production or **75%** of natural gas derived energy.

4 Stokes et al (2005)
5 U.S. Dept. of Energy/U.S. Dept. of Agriculture (2024)
6 While not biomass, waste plastics that are currently landfilled, and that have high potential energy content, were included in the Billion Ton analysis.

Over a longer horizon there is considerable potential for establishment of energy crop plantations of perennial herbaceous plants including switchgrass, miscanthus, and woody plants such as fast-growing short-rotation poplar or willow (Figure 4). If planted on marginal agricultural lands comprising 8 to 11% of current agricultural land, and grown without irrigation, such crops could provide 440 to 740 million tons of biomass. Extensive analysis indicates that doing so would leave 8% of agricultural land unused, and as noted previously, would not adversely impact current or projected needs for food, feed, or fiber, or capacity to serve agricultural export markets.

FIGURE 4: EXAMPLES OF ENERGY CROPS

Switchgrass

DeLucia. 2015. "How BioFuels Can Cool Our Climate and Strengthen Our Ecosystems"

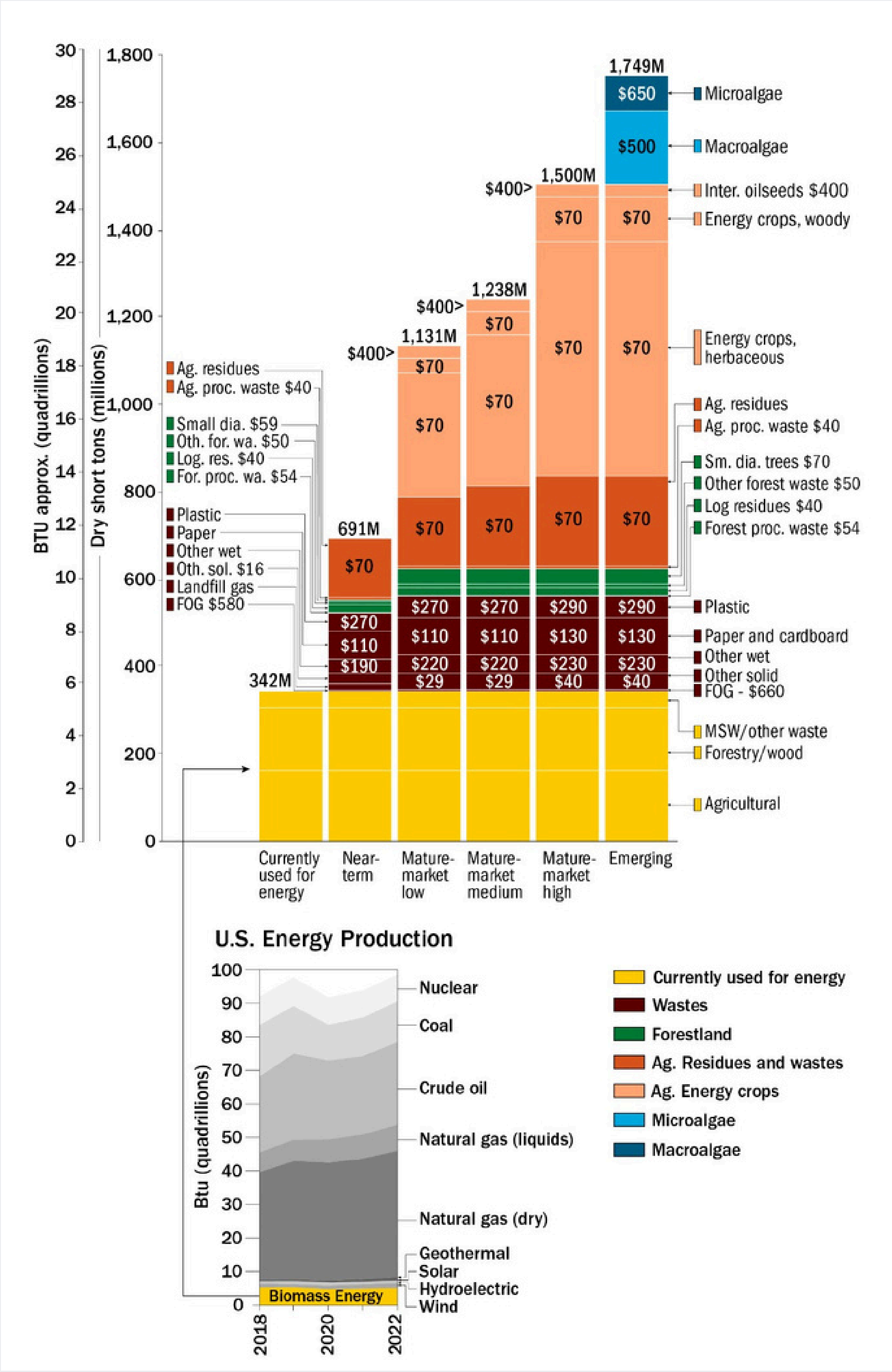
Short Rotation Willow

Abramhamson/Volk. 2022. "USDA Biomass Crop Assistance Project for Willow in Northern NY: Why Willow?"

Another possible biomass source is rapidly reproducing algae that have been demonstrated to have capacity for a wide range of products and uses, from liquid fuels to dry biomass for heat and power generation, and for biochemical and bioplastics production. Biomass production capacity via algal cultivation is conservatively estimated at about 250 million tons. Still in the research stage, numerous challenges remain to be overcome before this form of biomass production reaches commercialization. Findings of the 2023 Billion Ton report are summarized in Figure 5.

FIGURE 5

Currently Used and Potential Future Biomass Resources UnderNear-Term, Mature-Market, and Emerging Scenarios.



*This figure is taken directly from the 2023 Billion Ton Report (Figure ES-1). 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 resource*s 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).

LIQUID FUELS

Ethanol

Of all the forms of renewable energy listed in Table 1 only one – biomass – can be used in making liquid fuels. As of this writing, bioethanol is found in 98% of gasoline sold in the U.S., typically in an E10 blend, meaning that the fuel is 10% ethanol and 90% gasoline. The blend rate may soon rise. In December 2023 the EPA proposed to the Office of Management and Budget (OMB) that permanent year-round sales of E15 be permitted in eight states that requested this change; this followed action by the agency earlier in 2023 to allow E15 sales nationwide in the summer months.

Gains in energy efficiency of ethanol production since 2008 indicate energy balances on the order of 2.1-2.3 and a reduction of GHG emissions by 39% relative to gasoline and 43% in comparison to natural gas.

Bioethanol was highly controversial early on, and in some quarters remains so today, based largely on subsequently debunked research showing negative energy balances in bioethanol production and the reality of relatively low average energy gain. Using data from 1996, a 2002 life cycle assessment of the net energy balance in bioethanol production, that included appropriate energy allocation for manufacturing byproducts, determined an average energy input/output ratio of 1.34, indicating an energy gain of 34%.[7] Controversy swelled again in 2008 following a pair of articles that appeared in the influential journal Science which reported higher greenhouse gas (GHG) emissions from production and combustion of ethanol than from an energy equivalent quantity of gasoline.[8,9] These reports spurred an extensive life cycle investigation into the GHG balance of ethanol production by the EPA. That analysis found a modest 21% GHG emissions reduction associated with ethanol production and use in comparison to gasoline on an energy equivalent basis.

Gains in energy efficiency of ethanol production since 2008 contributed to further energy and GHG balance advantage of ethanol over gasoline. The most recent USDA assessments indicate energy balances on the order of 2.1-2.3 and reduction of GHG emissions of 39% relative to gasoline and 43% in comparison to natural gas.[10,11]

7 Shapouri et al. (2002)
8 Searchinger et al. 2008)
9 Fargione et al. (2008)
10 Gallagher et al. (2026)
11 Rosenfeld et al. (2018)

Biodiesel/Renewable Diesel

Biodiesel is made from vegetable oils (primarily soy), animal fats, and recycled restaurant grease. Current rules allow blending of up to 5% biodiesel concentrations (B5) in regular diesel fuel without a labeling requirement. A more common blend is 20% biodiesel to 80% regular diesel (B20). The Department of Energy reports that B20 use yields similar fuel consumption, horsepower, and torque in comparison to engines running on petroleum diesel.[12]

Renewable diesel is different from biodiesel in that these two fuels are produced using different processes. Made from soy or canola oil or from fats and waste cooking oils, renewable diesel is made using the same refining processes as petroleum diesel. It can be either blended with petroleum diesel (as biodiesel is) or simply used as a replacement fuel.[13] A limitation to use is that renewable diesel production costs are higher than for biodiesel.

There were early reports of cold weather problems with biodiesel, but subsequent experience has shown that although there can be complications in extremely cold weather, similar difficulties have long existed with petroleum diesel. In both fuels, anti-gel and cold-flow enhancers can be used to avoid problems.

As is the case with bioethanol, use of biodiesel is associated with considerable reduction of GHG emissions. An assessment[14] of three soy-based diesel fuels using various calculation methods found that use of 100% (B100) biodiesel resulted in a 66-94% reduction in GHG emissions relative to petroleum-based fuels. Emissions reductions with renewable diesel were found to be as high as 130% (57-130%). The greater than 100% reduction possible with renewable diesel is attributed to emissions reductions in coproducts as well as in the fuel itself.

Aviation Fuel

The aviation sector is aggressively seeking ways to reduce its GHG emissions. Research is underway on several fronts, including plant-based fuels, hydrogen/electric, and battery electric powered engines.

At this point prospects for battery electric powered aircraft appear dim in large part because of the weight of batteries that would be required. In comparison to lithium-ion batteries, liquid jet fuels provide 43 times more energy than a battery with the same weight.[15]

12 U.S. Department of Energy (2023a)
13 U.S. Department of Energy (2023b)
14 Huo et al. (2008)
15 Diaz-Perez and Serrano-Ruiz (2020)

Hydrogen/electric is another focus of research. This pathway is promising because of the energy efficiency of hydrogen fuels production in comparison to production of plant-based fuels. Research has progressed to the point that in September 2023 a small experimental aircraft with a hydrogen-powered electric engine was flown for three hours by two Slovenian crew members. Major aircraft manufacturers as well as several start-up companies are pursuing this avenue of research. However, the hydrogen electric concept faces strong pushback from the global aviation industry because of the projected costs and timeline required for conversion of aircraft fleets and support systems to this technology.[16]

Neither bioethanol nor biodiesel are suitable for use as aviation fuel. However, liquid fuels made from the same feedstocks as current biofuels and crafted specifically for aviation use appear to have an inside track to future aircraft propulsion.[17] Jet fuel is highly refined kerosene, and it turns out that liquid fuels made from such materials as animal wastes and plant biomass are almost chemically identical to kerosene. As such, it is a drop-in substitute for conventional fuel requiring little adaptation by the airline industry. Test flights of all kinds of aircraft using pure and blends of biofuel date back to 2007; scores of tests have been conducted around the world since that time. A November 2023 Virgin Atlantic Boeing 787 flight from London to New York fueled entirely by waste fats and plant sugars underscores progress in aviation biofuels research. Yet, aviation biofuels remain expensive, explaining why in 2022 biofuels accounted for only 0.2% of fuels consumed by the global aviation sector.[18] Further work is also needed to ensure that aviation biofuels are consistently comparable in performance to present fuels.

Biofuels generally are rich in aliphatic components and contain fewer aromatics than petroleum fuels, resulting in cleaner burning and lower operating emissions and contrails. But as explained by MIT professor Yurly Román-Leshkov, the presence of some aromatic molecules is critical to achieving needed physical performance and combustion in the extreme low temperature conditions encountered in flight. He also pointed out that aromatics ensure that seals between various segments of an aircraft's fuel system are tight.

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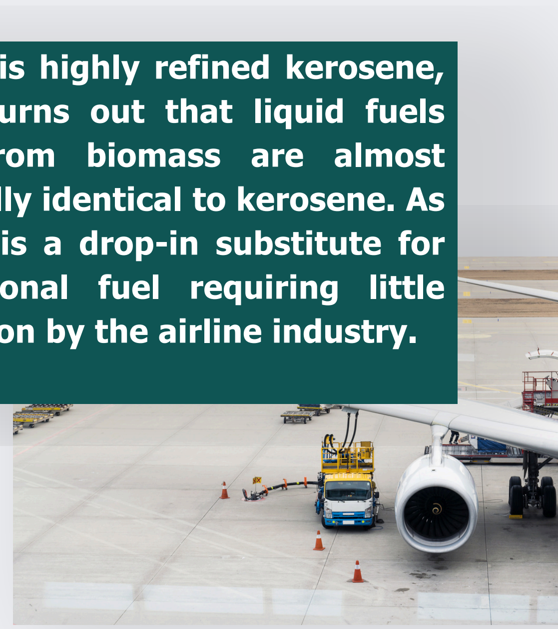


16 Schwagerl (2024)
17 Diaz-Perez and Serrano-Ruiz, J. (2020)
18 Schwagerl (2024)

He noted that “the aromatics get absorbed by the plastic seals and make them swell”, and “that if for some reason the fuel changes, so can the seals, and that’s very dangerous.” For over 5 years, he and his colleagues have been working on utilizing the lignin component of wood and other plants in production of aviation fuel in order to create an appropriately aromatics-rich product that is free of oxygen and chemically stable. It appears that his team is close to solving the problem, a development that could also lead to higher blend ratios and lower fuel costs for biofuels in general.[19]

In parallel with ongoing research aimed at increasing efficiency and lowering costs of renewable aviation fuels production, the aviation industry is also seeking changes in the public policy arena. In early 2024 formation of the Sustainable Aviation Fuel Coalition was announced.[20] This new organization is composed of major airlines and aircraft operators, agricultural enterprises, aircraft and aircraft equipment manufacturers, airports, technology developers, labor unions and biofuel producers, and was formed to advocate for incentives and policies to increase economic competitiveness of renewable aviation fuels, The coalition is also seeking to position for rapid scale-up of investment in sustainable fuels.

Liquid Fuels in Perspective

A 2023 study involving the U.S. Departments of Energy and Transportation, the Environmental Protection Agency, and Housing and Urban Development helps to put the potential of biomass energy into perspective. This study found that biofuels produced from a full suite of bioresources, including starch, vegetable oil, agricultural wastes, forest biomass, energy crops, municipal solid waste and wastewater organics could provide 100% of the combined fuel needs of the aviation, maritime, and rail sectors by 2050. Overall, in the unlikely event that all sustainably available biomass were applied to liquid fuels production, biomass could provide approximately 30% of total projected 2050 transportation fuel needs in a low carbon emissions system.[21]

Biofuels produced from a full suite of bioresources, including starch, vegetable oil, agricultural wastes, forest biomass, energy crops, municipal solid waste and wastewater organics could provide **100%** of the combined fuel needs of the aviation, maritime, and rail sectors **by 2050**.

19 Stauffer (2023)
20 Biomass Magazine (2024)
21 U.S. Department of Energy (2023c)

THERMAL ENERGY

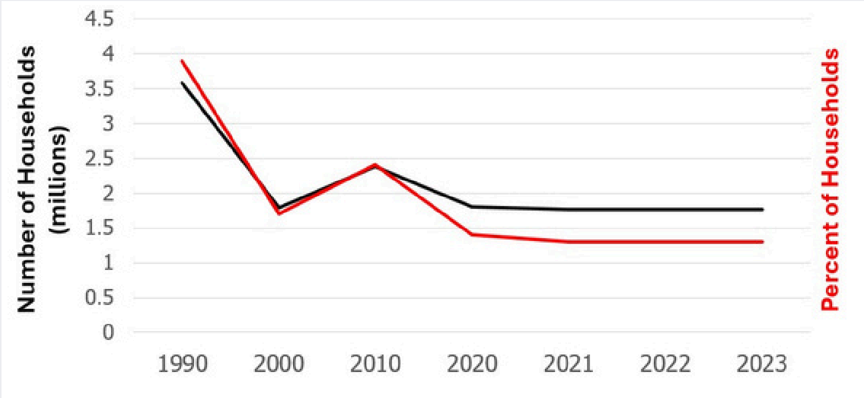
Most heat production in the U.S. is provided by fossil fuels, and dominantly natural gas. A small fraction of heat is derived from renewables, with wood and occasionally other forms of biomass in solid form (firewood, chips, fuel pellets, corn cobs) accounting for most (95%) of this.[22] Industry accounted for about two thirds of heat production from wood solids in 2022, used for both heating and process energy. Home heating largely accounted for the rest.[23]

Home Heating

In the mid-1800s, most households in the U.S. were heated by burning wood. Wood also was used to cook meals and heat water, a situation that prevailed through the late 1800s. Thereafter, wood was gradually displaced as a home heating fuel, first by coal and then by natural gas and heating oil. But then came the energy shocks of 1973/74 and 1978/79. The Three Mile Island nuclear reactor incident also occurred in 1979, further interrupting the normal availability of energy. What followed was nothing short of a revolution in the home heating market. Between 1973 and 1981 the percentage of households relying on wood as a primary source of heat jumped from 0.9% to 8.1%, with sales of wood stoves in the U.S. averaging 2 million annually in the early 1980s.[24]

The use of wood for home heating has been in slow decline in recent decades (Figure 6) both due to costs in comparison to fossil energy and increasing regulation of wood smoke in many regions of the U.S. Nonetheless, wood energy accounted for about 4.0% of residential sector end-use energy consumption and 2.5% of total residential energy consumption in 2022. An estimated 1.77 million households (1.3% of all households) nationwide continued to rely on wood as a primary source of home heating as of the winter of 2023/24,[25] with approximately another 9 million using wood as a supplemental source of heat.[26]

FIGURE 6: NUMBER AND PERCENT OF U.S. HOUSEHOLDS USING WOOD AS A PRIMARY SOURCE OF HEAT



Source: U.S. Census Bureau, Historical Households Tables and American Community Survey Household Heating.

22 U.S. Dept. of Energy/U.S. Dept. of Agriculture (2024), Table 2-4.
23 IEA (2021)
24 Alliance for Green Heat (2023)
25 EIA (2023c)
26 EIA (2023a)

Industrial Heat Production

The wood products and paper and paperboard industries rely heavily on wood derived energy and accounts for almost all production of heat and process energy from wood. Heat is produced from wood in the form of waste pulping liquor, bark, chips, and wood wastes. However, a 26% decline in domestic paper and paperboard manufacturing in recent decades,[27] combined with other factors, translated to a 20% reduction of space and process heat production from biomass by the industrial sector from 2014 to 2022.[28] Future trends in biomass energy production within the industrial sector will likely largely mirror developments in the wood and paper/paperboard industries.

Institutional Heating

As with home heating, limited energy availability and high costs in the 1970s and '80s inspired managers of institutions located in forested environs including schools, prisons, hospitals, and military and government facilities to consider conversion to wood as a primary or backup source of heat. A 2018 study identified 401 institutional wood heating systems in operation in the U.S. in 2014.[29] While information regarding the current situation nationally is not available, there is evidence of modest growth in the number of wood heat systems, especially in schools. With guidance and funding assistance provided by the U.S. Forest Service under the "Fuels for Schools" program,[30] wood heat is gaining traction. In Vermont, for example, 75 school systems had wood-fired heating systems in 2023, up from 60 in 2017.[31] Similar conversions of school heating systems have occurred or are underway in other states.

District Heating

Biomass fueled district heating systems, while relatively rare in the U.S., serve some locations. Examples are the cities of Minneapolis and St. Paul in Minnesota. A facility located in downtown Minneapolis converts 365,000 tons of garbage (municipal solid waste) each year into electricity (enough to power the equivalent of 25,000 homes) and also provides steam to downtown buildings via a district heating system for heating and cooling uses. Another system, fueled by biomass from urban tree trimming and other sources, produces electricity and provides hot water district heating and cooling services to many of the City of St. Paul's downtown buildings. Both facilities make use of biomass that would otherwise wind up in landfills.

27 Theo (2024)
28 U.S. Dept. of Energy/U.S. Dept. of Agriculture (2024)
29 Young et al. (2018)
30 The USDA-Forest Service Fuels for Schools program was initiated in 2011 as a way or creating a viable market for wood from forest thinning, with the dual objective of reducing catastrophic forest fire risk and reduction in reliance on fossil fuels.
31 Cooney (2023)

ELECTRICITY

Electricity can be generated from wood, agricultural residues, municipal solid waste (MSW), and other organics and from such sources as landfill gas. Basically, biomass is combusted to produce steam that is then used to power turbines that generate electricity. Combustion can be direct or follow intermediate steps such as gasification or anaerobic digestion.

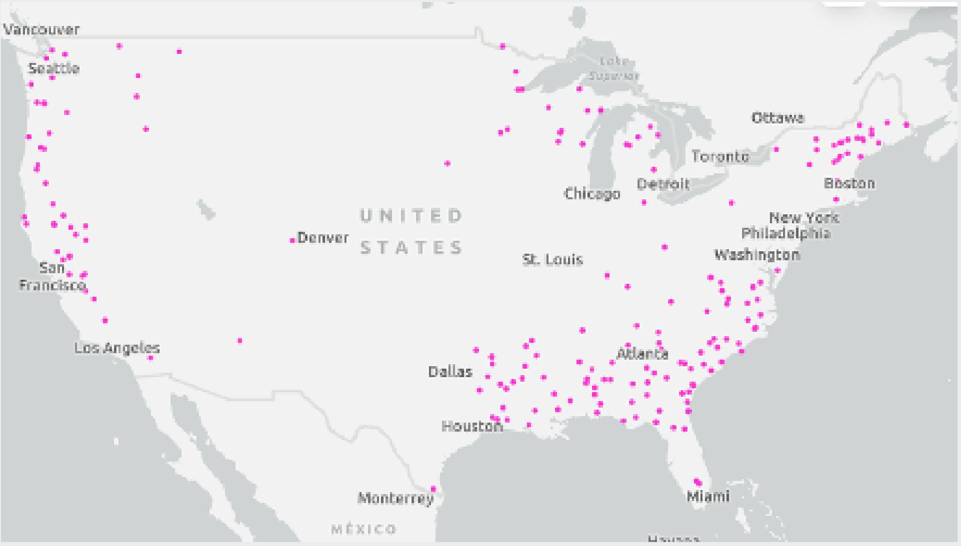
In 2023 1.1% (47 billion kWh) of electricity generated in the U.S. in utility scale generating plants was derived from biomass. Of the total, 31 billion kWh, or 65%, came from wood, with landfill and digester gas (17%) and municipal solid waste (13%) accounting for most of the rest.[32]

In addition to methane collected from landfills, gas for electricity generation was also obtained from anaerobic digesters processing animal wastes, and from municipal wastewater treatment facilities.

For MSW-powered generating facilities, whereas biomass materials were reported to comprise 61% of the weight of the combustibles, they accounted for only about 45% of the electricity generated. Non-biomass material, and primarily high-embodied energy plastics, accounted for the remainder.[33]

Various sources report different numbers of biomass-fired power plants in the United States. Synapse Energy Economics lists 183 such plants in the U.S., excluding Alaska, as of 2022 (Figure 7).[34] Another source[35] published a list of 145 biomass energy plants nationwide, again excluding Alaska, of which 72 are dedicated to power production from MSW. In either case the numbers are significant.

FIGURE 7
BIOMASS POWER PLANTS IN THE U.S.



Source: Synapse Energy Economics, Inc. (2022). Interactive Map of U.S. Power Plants.

32 EIA (2024)
33 EIA (2023a)
34 Synapse (2022)
35 ISSUU (2024)

BIO-BASED CHEMICALS

From a technical perspective most or all of the industrial chemicals now derived from fossil fuels could be produced from biomass. Lubricants, solvents, surfactants, resins, drop-in fuels, and plastics and chemical feedstocks, such as polylactic acid and linear polyesters, can all be made from bioresources. While only a few biochemicals are commercially available in 2024 due to high production costs relative to products made from petroleum, the potential for producing virtually any petroleum-based chemical from bioresources has been established at demonstration or laboratory scale. And while the number of industrial chemicals and precursors made from biomass remains limited, the scale of market penetration is impressive. In 2020, global production of bio-based chemical and polymer production was estimated at 90 million metric tons, compared to world production of chemicals and polymers of 330 million metric tons from petrochemicals. [36]

It is technically possible to obtain almost all of the industrial chemicals now derived from fossil fuels from biomass. In 2020, global production of bio-based chemical and polymer production was estimated at **90 million metric tons**, compared to **330 million metric tons** from petrochemicals.

LOOKING FORWARD – THE FUTURE OF BIOMASS ENERGY

In the midst of what is nothing less than a revolutionary effort to change the world's energy systems it is difficult to predict what the new system will look like – which technologies will come to the fore, and which will be discarded. Whatever emerges will need to be robust.

The European Energy Agency (2023) succinctly summarized what will be required:

> "A future energy system needs to be resilient and adaptable to the inevitable impacts of climate change, such as droughts, heatwaves and storms. As the share of wind and solar power increases, the system also needs to be flexible enough to function well even when the wind does not blow, or the sun does not shine.
> A flexible power system can ensure a steady supply of energy and reduce peak demand. . ."

Additionally, a commentary from the Brookings Institution noted that alternative energy must be both affordable and environmentally sustainable.[37]

36 de Jong, E. et al. (2020)
37 Elkind, J. (2008)

What the mid-term (2025-2050) and longer (>2050) energy future looks like will be defined by numerous factors including:

- How rapidly and the level to which battery technology evolves.
- Whether critical metals will be available in sufficient volumes and at acceptable costs.
- How quickly the world's vehicle fleet can be converted to electric power.
- Potential emergence of new energy generation technologies.
- Whether focused development of wind and solar in combination with improvement of energy efficiency is likely to get society where it needs to be regarding emissions reduction quickly enough, versus a diversified energy portfolio.
- The extent to which primary energy generation systems may require backup.

In all of this, where does biomass energy fit?

In this regard, many view liquid fuels from biomass (bioethanol/biodiesel) as temporary "bridge" fuels that are helping to reduce reliance on fossil fuels as society transitions to a solar/wind powered electric energy future. These views are based on comparisons of photovoltaic (PV) and biomass energy production capacity from the same sized land areas in various locations that have shown production potential via PV to be 29-30 times greater than the biomass to energy route. In view of these analyses, it is possible and even likely that at some point biomass use for production of light transportation vehicle fuels will be phased out. If this is the case, then it becomes a matter of when this might occur.

There is a strong view on the part of many that a diversified approach to future energy production will be needed in order to have any chance of transitioning from fossil to alternative energy in a timely manner. The idea is to lower emissions as rapidly as possible using all available technologies. But will the need for diversification dim once targets are met, and if so, what technologies will be the winners and losers?

Our assessment is that liquid fuels will be needed for 2-3 decades or longer for at least some modes of transportation, and that conversion of the aviation sector from liquid fuels to an alternative, if ever achieved, will take much longer. Both conclusions suggest a prolonged market for biofuels, but one that may realize significant reduction at some point not too far into the future.

As to medium- to long-term prospects for utility-scale electricity and heat production from biomass in the U.S., we believe these to be dim as production costs are likely to be noncompetitive. Should this be an accurate view, this raises the question of whether there will be a market for forest biomass removed, especially in Western states, as part of forest thinning work to reduce wildfire threat. While this material has been demonstrated to be a viable raw material for production of aviation fuel, the future will again come down to the matter of raw material and production costs vs alternatives. An additional determinant of what will happen going forward is the extent of support for biomass energy and non-fossil materials development in the public policy arena. Absent more robust federal and state policies, including expanded research investment, to support biomass energy and biomass product development, the promise of biomass in providing energy and industrial materials solutions is likely to be significantly hampered.

THE BOTTOM LINE

In view of the current and important role of biofuels and bioenergy in general in helping to reduce greenhouse gas emissions, prospects for bioenergy in the near and medium future appear bright. Beyond 2050, however, assuming the ability of current and emerging alternative technologies to fulfill society's energy needs, efficiencies of these other energy generating technologies are likely to largely displace bioenergy. Only aviation fuels, and possibly energy generation from algae, appear to be likely candidates for the long term.

The future of biochemicals also appears uncertain. On the one hand, the International Energy Agency has described biochemicals as "an essential part of the transition to a circular economy" and painted a somewhat rosy future for them. On the other hand, a report in Chemical and Engineering News (Why the Future of Oil is in Chemicals, Not Fuels) outlines petrochemical industry efforts to refocus its investments on crude-to-chemicals production as demand for liquid fuels wanes. This strategy could make it extremely difficult for biochemicals to compete in industrial feedstock markets.

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