Biofuel Production and Greenhouse Gas Reduction Potential

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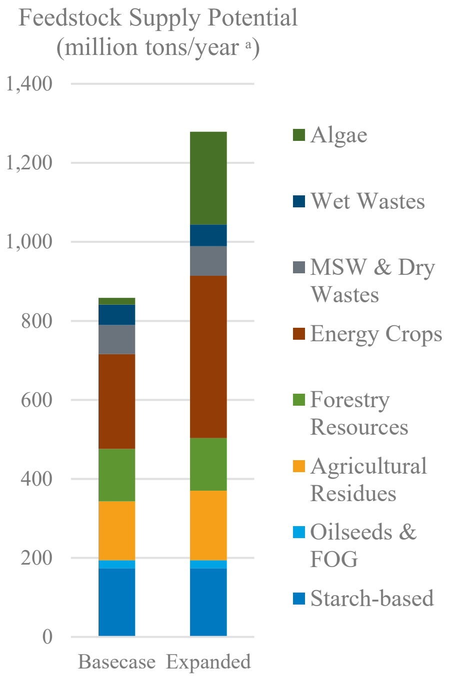
Executive Summary

This study uses two sustainable biomass supply scenarios to demonstrate the potential of biofuels to replace petroleum-based fuels and mitigate greenhouse gas (GHG) emissions in hard-to-electrify transportation sectors by 2050.

1. **Base case scenario – 858 million tons of sustainable biomass supply.**
   - Dry feedstock[1] and algae feedstock volumes are based on the U.S. Department of Energy's (DOE's) *2016 Billion-Ton Report* (BT16) **2030 base case** (DOE 2016).
   - DOE's 2017 *Biofuels and Bioproducts from Wet and Gaseous Waste Streams* report (BETO 2017) and U.S. Census Bureau projections of population growth are used to estimate volumes of wet waste.
   - Starch-based, oilseed, and waste fat, oil, and grease (FOG) feedstock volumes are based on Renewable Fuels Association (RFA) and U.S. Energy Information Administration (EIA) projections of fuel ethanol, renewable diesel, and biodiesel production.
2. **Expanded supply scenario – 1,279 million tons of sustainable biomass supply.** In addition to the above, we include longer-term potential of:
   - Energy crops based on the BT16 **2040 base case.**
   - Algae feedstock volume based on DOE's 2017 Algae Harmonization Study (ANL, NREL, and PNNL 2017).



[a] Dry and wet waste feedstocks are reported on a dry basis. Algae feedstock is reported on an ash-free dry weight basis. Starch-based, oilseed, and waste FOG are reported on an as-received basis.

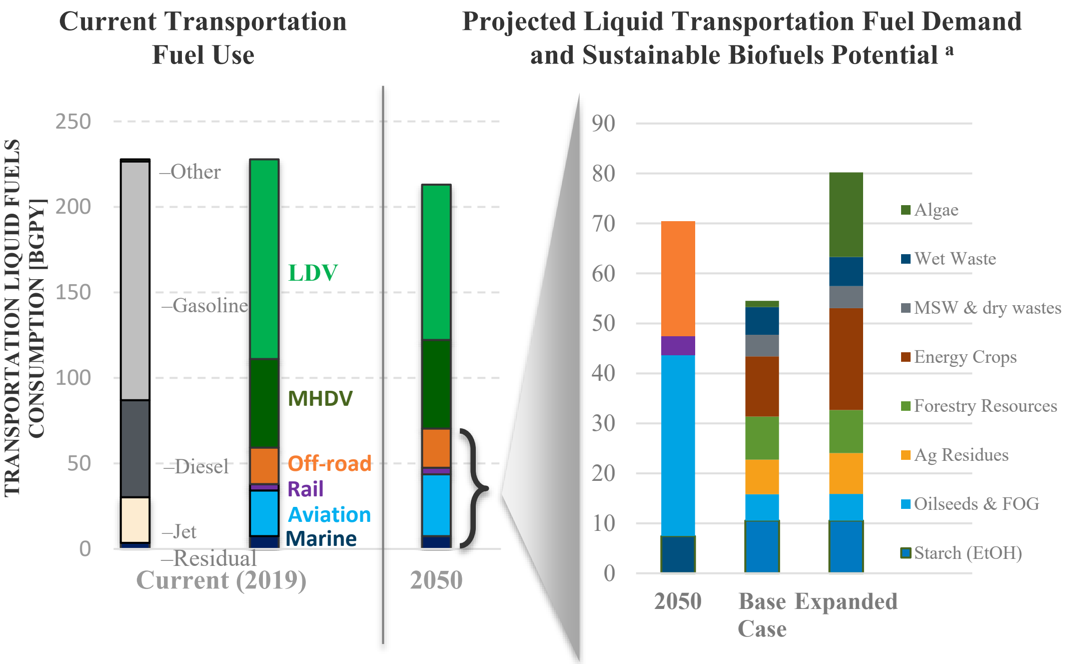
[1] Dry feedstocks include forest resources, agricultural residues, purpose-grown energy crops, municipal solid waste (MSW), and other dry wastes.

Executive Summary

Based on EIA (EIA 2020), U.S. Environmental Protection Agency (EPA) (EPA 2021), and Federal Aviation Administration (FAA) (FAA 2021) projections, approximately 70 billion gallons per year (BGPY) of liquid transportation fuels will be needed in "hard-to-electrify" aviation, marine, rail, and off-road sectors by 2050.

Under the two biomass supply scenarios and conversion pathways modeled in this study:

- 55 and 80 billion gallons of gasoline equivalent (GGE) per year of sustainable biofuel could be produced by 2050.
- Replacing equivalent volumes of petroleum-based fuel with sustainable biofuel would result in 410 and 640 million metric tonnes (Mt) of carbon dioxide equivalent (CO_2e) per year of life cycle GHG reductions—a total 68%–73% reduction in GHG emissions over petroleum-based fuels.
- The external hydrogen required is estimated to be 3.1 and 5.2 Mt/year, respectively. If this natural-gas-derived hydrogen[1] were replaced with hydrogen derived from renewable sources, additional respective GHG reductions of 35 and 60 Mt CO_2e/year could be realized.



[a] The Base case and Expanded scenario bars above are reported on a GGE basis

[1] Hydrogen inputs are assumed to be sourced from steam reformed natural gas without carbon capture and sequestration.

Executive Summary

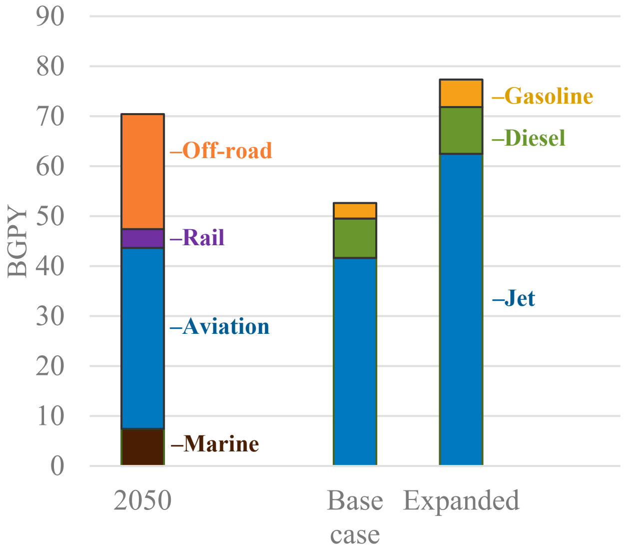
Most of the anticipated growth in hard-to-electrify transportation is due to increased air travel. Despite anticipated improvements in aircraft technology and operations, the FAA projects domestic jet fuel uplift will grow from 23 BGPY in 2019 to 34 BGPY by 2050 (FAA 2021).

Based on the base case and expanded supply scenarios modeled in this study, along with conversion pathways and process conditions selected to favor sustainable aviation fuel production, up to 42 and 63 BGPY of jet fuel could be produced, respectively.

This study provides estimates of biofuels production and GHG reduction **potential**. These are not projections but should be viewed as upper bounds based on the assumptions described in the report. There are many factors discussed in the report that could limit this potential. Likewise, there are feedstocks and processes not considered that could increase this potential.

This is the first iteration of this analysis. Future iterations will address sensitivity to the assumptions and pathway selections used in this analysis. Future analysis will also consider additional and updated data sources for feedstock volumes. Forthcoming updates to the billion-ton and algae harmonization studies will be incorporated.

Projected Liquid Fuel Demand in Hard-to-Electrify Transportation [a] and Sustainable Biofuels Potential



[a] Projected 2050 fuel demand is based on EIA Annual Energy Outlook (EIA 2020) with adjustments based on EPA (EPA 2021) and FAA (FAA 2021) described in this report.

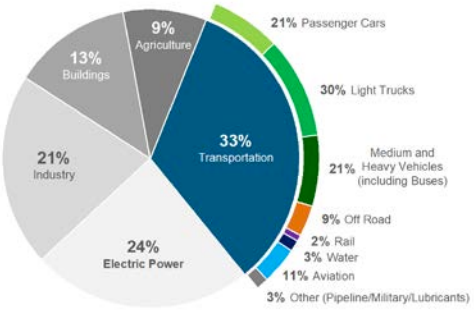
Contents

Introduction & Scope

Introduction | Background

- Transportation accounts for 33% of U.S. greenhouse gas (GHG) emissions, corresponding to 1,877 million metric tonnes (Mt) of carbon dioxide equivalent (CO_2e) per year (EPA 2021).
- Use of biofuels is a strategy to decarbonize all modes of transportation, especially hard-to-electrify sectors.
- Hard-to-electrify aviation, marine, rail, and off-road sectors consume 60 billion gallons per year (BGPY) of liquid fuels and represent 25% of current transportation GHG emissions (EPA 2021).
- Domestic fuel demand in hard-to-electrify sectors is expected to increase to 70 BGPY by 2050, due primarily to growth in air travel (see figure and data sources).[1]
- Despite anticipated improvements in aircraft technology and operations, the Federal Aviation Administration (FAA) projects domestic jet fuel uplift will grow from 23 BGPY in 2019 to 34 BGPY by 2050, with a corresponding increase in CO_2 emissions from 222 to 300 Mt CO_2/year (FAA 2021).
- Sustainable aviation fuel (SAF)[2] is critical to meeting net-zero emissions for the aviation sector by 2050 (FAA 2021). The SAF Grand Challenge established a goal of replacing 100% petroleum-based jet fuel with SAF by 2050 (BR&D 2023).

2019 U.S. GHG Emissions



2019 and Future U.S. Fuel Use

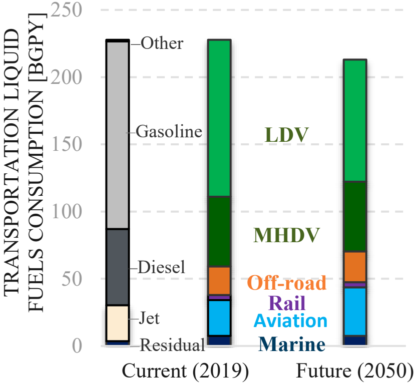


Figure sources
- EPA 2021
- EPA 2023
- EIA 2023c
- EIA 2020

Figure notes
- Off-road industry (2.3 quads) and off-road agriculture (0.5 quads) fuel use is reallocated to the transportation sector.
- Future projection based on AEO Reference case with adjustments for FAA projected jet use and inclusion of off-road allocations.
- Aviation and marine include emissions from international aviation and marine transport originating in the United States.
- Fractions may not add up to 100% due to rounding.

LDV: light-duty vehicle
MHDV: medium- and heavy-duty vehicle
Off-road: non-transportation mobility includes agricultural, construction and mining, lawn and garden, logging, and recreational equipment

[1] Annual Energy Outlook (AEO) reference case projections assume limited electrification or use of hydrogen in these hard-to-electrify sectors.
[2] SAFs are drop-in fuels created from renewable or waste materials (FAA 2021). To qualify as SAF under the SAF Grand Challenge, they must attain at least 50% GHG reduction over petroleum jet fuel.

Goal and Approach

Goal: Evaluate the potential of biofuels to replace projected petroleum consumption in "hard-to-electrify" transportation sectors and reduce GHG emissions by 2050.

Approach: Two Biomass Supply Scenarios

1. **Base case scenario**
   - Dry feedstock[1] and algae feedstock volumes are based on the U.S. Department of Energy's (DOE's) *2016 Billion-Ton Report* (BT16) **2030 base case** (DOE 2016).
   - DOE's 2017 *Biofuels and Bioproducts from Wet and Gaseous Waste Streams* report (BETO 2017) and U.S. Census Bureau projections of population growth were used to estimate volumes of wet waste.
   - Starch-based, oilseed, and waste fat, oil, and grease (FOG) feedstocks are based on data from Renewable Fuels Association (RFA) and U.S. Energy Information Administration (EIA) projections of fuel ethanol, renewable diesel, and biodiesel production.
2. **Expanded supply scenario**

   In addition to the above renewable carbon feedstocks, we also include longer-term potential of:
   - Energy crops based on the BT16 **2040 base case.**
   - Algae feedstock volume based on DOE's 2017 Algae Harmonization Study (ANL, NREL, and PNNL 2017).

[1] Dry feedstocks include forest resources, agricultural residues, purpose-grown energy crops, municipal solid waste (MSW), and other dry wastes.

Goal and Approach

Approach: Conversion Pathways

- A single, illustrative conversion pathway is selected for each feedstock based on:
  - Availability of published process design data.
  - Pathways currently qualified for commercial jet fuel production and use through ASTM D4054 (ASTM 2022).
  - Pathways with process designs and conditions that favor production of SAF.
  - Technology maturity (i.e., level of commercial readiness).
- GHG emissions values are based on the Greenhouse gases, Regulated Emissions, and Energy Use in Technologies (GREET) 2022 Aviation Module (ANL 2022) or International Civil Aviation Organization (ICAO) Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) (ICAO 2019) default values, where available. Otherwise, they are based on referenced Bioenergy Technologies Office (BETO) design reports or GREET's Well-to-Wheel (WTW) Calculator 2022, Version 1 (ANL 2023).

Key Assumptions & Limitations

This study estimates biofuels *potential* based on these key assumptions:
Terrestrial feedstock volumes based on BT16 2030 and 2040 base case scenarios at <$60 per dry ton (DT) farm-gate pricing.
Algae feedstock volumes based on BT16 2030 base case and Algae Harmonization Study at <$700/ton ash-free dry weight (AFDW).
Use of "excess" biomass, defined as biomass beyond that currently and projected to be used for food, feed, fiber, and timber.
Starch-based feedstock volume based on RFA's estimate of current ethanol industry capacity. The corresponding feedstock volume remains constant through 2050.
Oilseed and waste FOG feedstock volumes based on EIA projections of renewable diesel and biodiesel production through 2050. The corresponding feedstock volume remains constant through 2050.
A single, illustrative conversion pathway for each feedstock to biofuels.
Conversion pathways and process designs that favor the production of SAF.

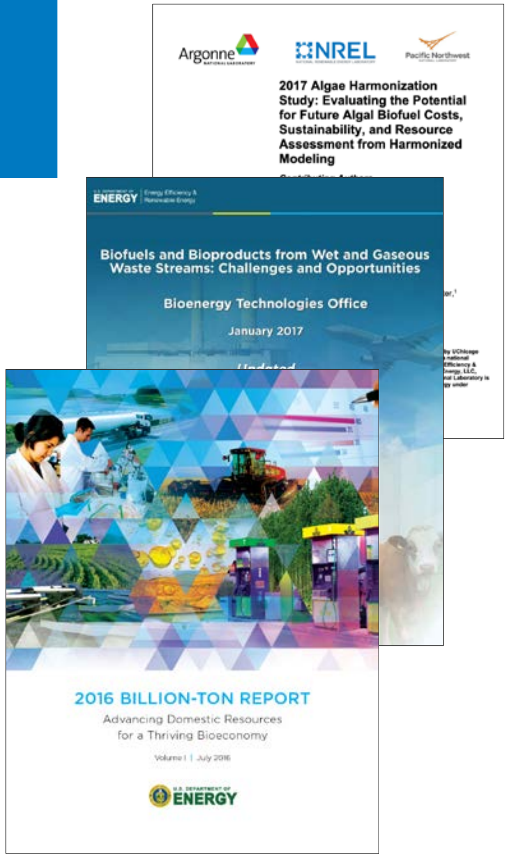
This study does not:
Evaluate competing uses or cost of the biomass supply.
Evaluate the quality and logistics requirements of biomass for conversion to fuels.
Consider additional renewable carbon feedstocks such as direct air CO_2 capture, oilseeds from cover crops, biogas, or macroalgae.
Consider additional BT16 biomass volumes available at >$60/DT or from high-yield scenarios.
Consider the cost of conversion or the delivered cost of fuel.
Evaluate multiple pathway options for conversion of each feedstock.
Optimize the pathway selections or process designs.
Consider the use of renewable hydrogen and/or power to improve carbon conversion efficiencies of selected pathways.

Feedstock Volumes

Feedstock Volume Estimates

Feedstock Volume Estimates Overview

- The primary data source used for feedstock volume projections is DOE's ***BT16 report*** (DOE 2016). Feedstocks include forestry and woody wastes, agricultural residues, purpose-grown energy crops, MSW, other dry wastes, and algae (for the base case supply scenario).
- The ***2017 Algae Harmonization Study*** report (ANL, NREL, and PNNL 2017) is used for algae volume projections in the expanded supply scenario.
- The ***2017 Biofuels and Bioproducts from Wet and Gaseous Waste Streams*** report (BETO 2017) is used for wet waste volume projection. Wet waste feedstocks include municipal wastewater solids, manure, and food waste.
- RFA and EIA projections of fuel ethanol, renewable diesel, and biodiesel production are used to estimate volumes of starch-based, oilseed, and FOG feedstocks that will be available.
- Potential feedstocks not considered include BT16 high-yield scenario, biogas, CO_2 from direct air capture, macroalgae, and additional starch-based or oilseed feedstock production (e.g., from cover crops).



Two Feedstock Supply Scenarios

Feedstock Category	Base Case Supply Scenario	Expanded Supply Scenario
Forestry, agricultural, energy crops, MSW, and dry wastes	BT16 2030 baseline at <$60/DT	BT16 2040 baseline at <$60/DT
Wet wastes	2017 wet waste study scaled with population growth to 2030	2017 wet waste study scaled with population growth to 2040
Algae	BT16 freshwater scenario at <$700 per ton AFDW	2017 Algae Harmonization Study *saline* scenario at <$700/ton AFDW
Oilseed and waste FOG	Based on EIA projections of biodiesel and renewable diesel production through 2050	
Corn- and starch-based	Based on RFA estimate of current ethanol industry production capacity.	

- This study assumes all excess biomass is converted to biofuels. Excess is defined as biomass beyond that currently and projected to be used for food, feed, fiber, and timber.
- This study does not evaluate competing uses for excess biomass or consider quality requirements for use of the excess biomass in the chosen conversion pathways.

BT16 "Dry" Feedstocks

This study's base case and expanded supply scenarios for "dry feedstocks" are derived from the BT16 2030 and 2040 base case[1] projections, respectively, at a cost of <$60/DT.[2] **This results in respective projections of 597 and 796 million DT of biomass.**[3] The following feedstock sources are included:

- **Forestry resources** after traditional timber uses are met:
  - Residues from logging for conventional forest products on both private and federal timberlands.
  - Whole trees harvested explicitly for biomass.
  - Removal residues and treatment thinnings on other forestland.
- **Agricultural residues** include corn stover, sorghum stubble, and wheat, barley, and oat straw.
- **Energy crops** include purpose-grown woody and herbaceous sources:
  - Woody: poplar, pine, willow, and eucalyptus.
  - Herbaceous: switchgrass, miscanthus, energy cane, and biomass sorghum.
- **MSW and other dry waste resources include unused portions of:**
  - MSW.
  - Forest product mill residues and urban wood wastes.
  - Secondary agricultural wastes.[4]

BT16 Category	Million Dry Tons at <$60/DT	
	Base Case	Expanded
Forestry resources	97	97
Agricultural residues	149	176
Woody energy crops	50	71
Herbaceous energy crops	190	340
MSW	55	55
Other dry waste	56	57
Total [2]	**597**	**796**

[1] The BT16 base case forestry scenario assumes moderate growth in housing starts, new southern plantation intensity, domestic and export forest products, and low growth in biomass for energy (including the wood pellet industry). The BT16 base case energy crop scenario assumes 1% annual yield improvement.

[2] The baseline cost of $60/DT (2014 $) does not include transportation from field or forest.

[3] The actual amount of biomass transported to and useable at the biorefinery may be less due to losses, screening and separation, and spoilage.

[4] Cotton field residue and gin trash, orchard pruning residue, rice straw and hulls, and sugarcane field trash.

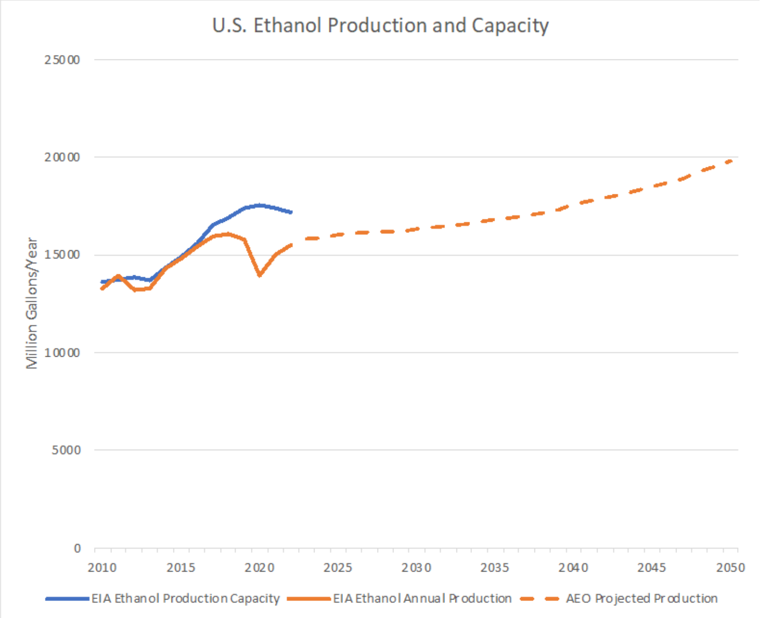
Starch-Based Ethanol Feedstock

For both scenarios in this study, we assume starch-based ethanol production will reach 18 BGPY and remain constant through 2050.

- 18 BGPY aligns with the RFA and EIA estimates of total installed capacity at the end of 2022 (RFA 2023b; EIA 2022b).
- AEO projects ethanol production will be close to 20 BGPY by 2050 (see figure) (EIA 2022a).

Based on a yield of 2.90 gal of ethanol per bushel of grain (RFA 2023a), 174 million tons of grain per year will be required to produce 18 BGPY.

- This represents an 18% increase over 2022 grain consumption for ethanol production.[1]



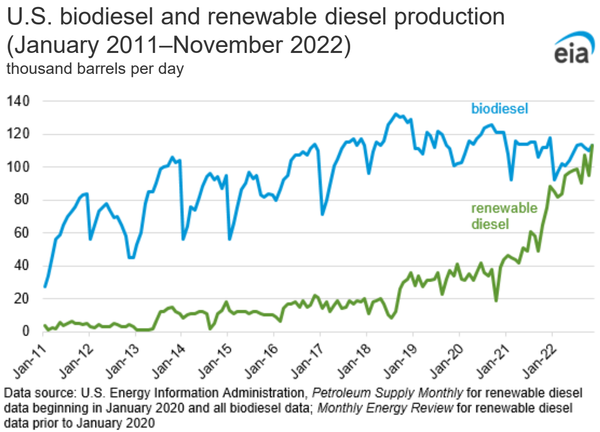
Source data: EIA (2022a, 2022b, 2023e)

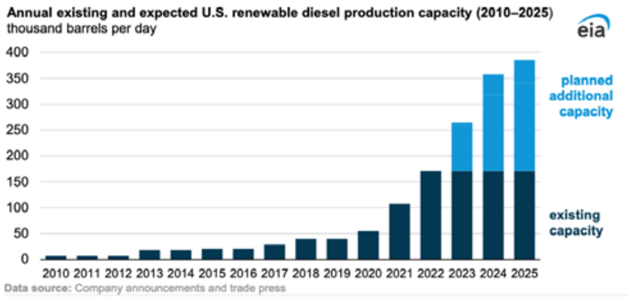
[1] In 2022, 5.214 billion bushels of grain were consumed in producing 15.12 billion neat gallons of ethanol.

Vegetable Oil & Waste FOG Feedstocks

For both scenarios in this study, we estimate available vegetable oil and waste FOG feedstock based on EIA projections of biodiesel (BD) and renewable diesel (RD) production.

- RD production has more than tripled in the past 3 years and is expected to continue rapid growth through 2025.
    - RD production surpassed biodiesel production in November 2022 (EIA 2023f).
    - EIA estimates U.S. RD production capacity was 2.6 BGPY at the end of 2022. Current announced projects could bring RD capacity to 5.9 BGPY by the end of 2025 (EIA 2023a).
    - EIA projects some of this new capacity may not be realized due to competition for constrained feedstocks and estimate RD production reaching 3.9 BGPY by the end of 2024 (EIA 2023f).
- BD production capacity has declined from a peak of 1.9 BGPY in 2018. Because BD competes with RD for the same constrained feedstocks, EIA projects biodiesel production will decline to 1.2 BGPY by the end of 2024 (EIA 2023f).
- EIA project combined RD and BD production will decline to 4 BGPY in 2030 and then increase back to 5 BGPY by 2050 (EIA 2023g).

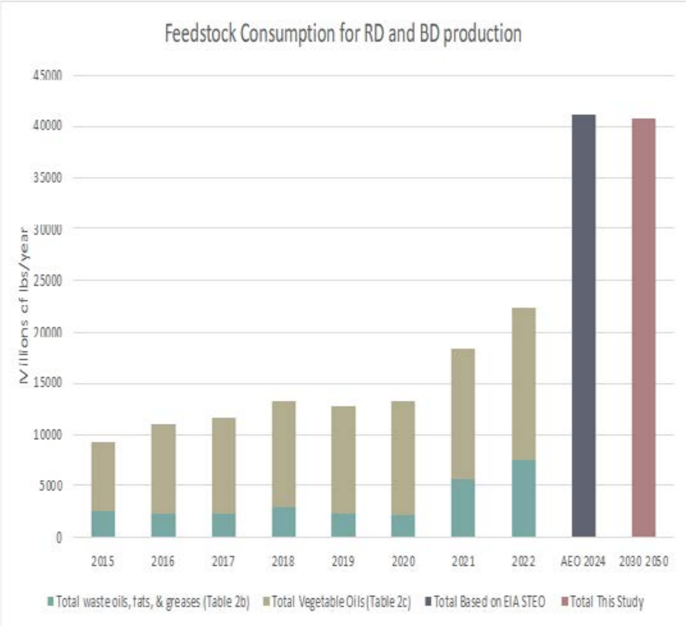




Vegetable Oil & Waste FOG Feedstocks

For both scenarios in this study, we assume:

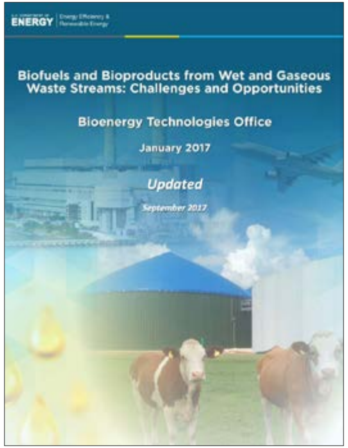
- The recent and projected rapid growth in RD capacity is not sustainable due to constrained oilseed and waste FOG supplies.[1]
- RD capacity will grow to 4 BGPY and remain constant through 2050.
- BD production will decline to 1 BGPY and remain constant through 2050.
- Based on the above assumptions, 40 billion lb/year of oilseed and waste FOG feedstock will be needed. This is nearly double the total consumed for combined BD and RD production in 2022 (see figure).



Sources: EIA (2021) (2015–2020); EIA (2023b) (2021–2022); 2024 projection based on EIA (2023d) for RD and BD production of 3.9 and 1.2 BGPY, respectively, at assumed 239-gal/ton yield.

[1] The U.S. Department of Agriculture and private agriculture are developing cover crops such as camelina, carinata, and pennycress. These crops could produce addition oilseed feedstock that would enable additional capacity. That is a topic for further investigation beyond the scope of the current analysis.

Wet Waste Feedstocks



Wet waste volumes are derived from BETO's 2017 ***Biofuels and Bioproducts from Wet and Gaseous Waste Streams: Challenges and Opportunities*** report (BETO 2017). Wet wastes include wastewater residual solids, animal wastes, and food waste.

For the purposes of this study:

- We include only the potential excess volumes beyond those currently or projected to be utilized for other beneficial uses.
- We assume the excess wet waste volumes in BETO's 2017 report increase proportional to population growth.[1]

Based on this, **we estimate 52 and 55 million DT of wet waste is available in 2030 and 2040, respectively.**

Million Dry Tons	2017 Report			2030	2040
	Currently Used	Potential Excess	Total	Potential Excess	Potential Excess
Population growth		*Baseline*		*9.1%*	*14.8%*
Wastewater residuals (solids)	7.1	7.7	14.8	8.4	8.8
Animal waste (i.e., manure)	15.0	26.0	41.0	28.4	29.8
Food waste (excludes FOG)	1.3	14.0	15.3	15.3	16.1
Subtotal	**23.4**	**47.7**	**71.1**	**52.0**	**54.8**

[1] Population growth is a key driver for anthropogenic waste volume growth. The U.S. Census Bureau estimates U.S. population will increase by 9.1% and 14.5% from 2017 to 2030 and 2040, respectively (U.S. Census Bureau 2017).

Algae Base Case (BT16)

For the base case scenario, we used algae feedstock input based on the BT16 report.

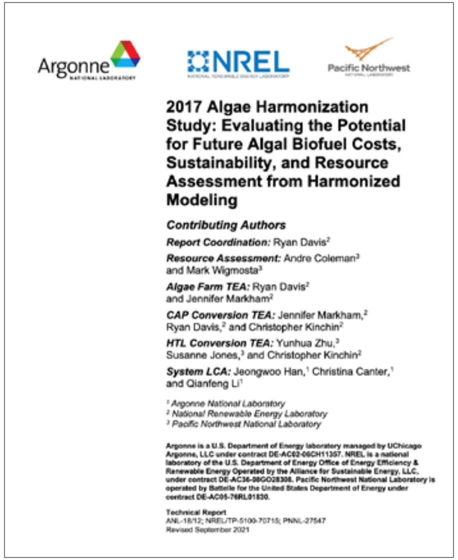
- Key BT16 algae production assumptions included:
  - 1,000-acre algae farms are collocated at flue gas sources and ethanol plants.
  - Bulk, low-pressure flue gas is transferred to the algae farms.
  - Only coal- and natural-gas-fired power plants were considered as flue gas sources.
  - Ethanol production facilities were considered as high-purity CO_2 sources.
  - Both freshwater and saline cultivation scenarios were evaluated. **These are not mutually exclusive** because both scenarios used many of the same flue gas sources.
- At a threshold of <$700/ton AFDW[1] with productivities set at a future target of 25 $g/m^2/day$, the BT16 analysis indicated:
  - 17 million tons AFDW/year production potential for freshwater ponds **or**
  - 12 million tons AFDW/year production potential for saline ponds.
- For the purposes of the base case analysis, we chose to use the freshwater scenario because it represented the higher overall biofuels production potential.

[1] BETO's *2017 Algae Harmonization Study* used <$700/ton AFDW as the maximum algae biomass cost that could enable achieving BETO's fuel cost goals of <$3 per gallon of gasoline equivalent (GGE) (ANL, NREL, and PNNL 2017).

Algae | 2017 Harmonization Study

BETO's *2017 Algae Harmonization Study* (ANL, NREL, and PNNL 2017) addressed the key collocation constraint imposed in the BT16 report by allowing for the use of flue gas carbon capture. Carbon capture helps overcome the key scalability, technical, and logistical hurdles of the BT16 collocation approach by producing high-purity CO_2 at supercritical pressures, which:

- Enables substantial expansion of the economic transport range and more flexible location of algae farms.
- Avoids high capital expenses of large-diameter (4–6-ft) piping networks and compressors needed to move low-pressure flue gas from source to ponds.
- Enables expansion of CO_2 sources to additional point sources including cement plants, fertilizer and ammonia plants, chemical and hydrogen plants, petroleum and natural gas processing, pulp and paper mills, and metal production.


2017 Algae Harmonization Study: Evaluating the Potential for Future Algal Biofuel Costs, Sustainability, and Resource Assessment from Harmonized Modeling

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Argonne is a U.S. Department of Energy laboratory managed by UChicago Argonne, LLC under contract DE-AC02-06CH11357. NREL is a national laboratory of the U.S. Department of Energy Office of Energy Efficiency & Renewable Energy Operated by the Alliance for Sustainable Energy, LLC, under contract DE-AC36-08GO28308. Pacific Northwest National Laboratory is operated by Battelle for the United States Department of Energy under contract DE-AC05-76RL01830.

Technical Report
ANL-18/12; NREL/TP-5100-70715; PNNL-27547
Revised September 2021

At a threshold of <$700/ton AFDW, **the *Algae Harmonization Study* projected 104 and 235 million tons AFDW/year of algae feedstock potential for freshwater and saline scenarios, respectively**.[1] For the purposes of the expanded supply scenario in this study, the saline scenario was chosen based on the higher total biomass-based fuel production potential.

Source	Scenario	Biomass Potential, million tons AFDW/year	Cost, $/ton AFDW
BT16	Saline	12	<$700
	Freshwater	**17**	**<$700**
Harmonization Study	**Saline**	**235**	**$617–$684**
	Freshwater	104	$443–$522

[1] The freshwater and saline scenarios are not mutually exclusive and use many of the same point sources.

Potential Feedstocks Not Considered

Potential renewable carbon feedstock sources not considered in this analysis could add substantial biofuel production and GHG reduction potential beyond that reported here. These include:

- BT16 high-yield scenario: Identifies an additional 300 million DT of energy crop potential.
- BT16 cost scenarios at >$60/DT.
- CO_2 from direct air capture (i.e., “e-fuels”).
- Biogas.
- Additional oilseed from cover crops.
- Macroalgae (e.g., seaweed).

BETO is producing an update to the BT16 report that will include most of these additional feedstock sources. The update is expected to be released in early 2024.

Updates to this study will be published when the updated Billion-Ton report is available and when additional and/or better feedstock supply data sources are identified for the sources not considered here.

Conversion Pathways

Key Conversion Pathway Assumptions

- A single, illustrative conversion pathway is selected for each feedstock based on:
  - Availability of published process design data.
  - Pathways currently qualified for commercial jet fuel production through ASTM D4054 (ASTM 2022).
  - Pathways with process designs and conditions that favor production of SAF.
  - Technology maturity (i.e., level of commercial readiness).
- Conversion yields and hydrogen consumption are based on published sources including BETO design cases and/or corresponding state-of-technology updates (DOE 2023). Some values are derived from conversion pathways developed with the support of BETO funding (e.g., syngas fermentation to ethanol and alcohol-to-jet [ATJ] upgrading) or other published data sources.
- GHG emissions values are based on GREET 2022 Aviation Module (ANL 2022) or ICAO CORSIA default values (ICAO 2019), where available. For pathways where these are not available, we use published values from BETO design cases or GREET's WTW Calculator 2022, Version 1 (ANL 2023).
- Where ethanol is an intermediate, we assume it is produced in distributed facilities and processed into jet fuel at centralized ATJ upgraders.

Conversion Pathways Used in This Analysis

Feedstock	Conversion Pathway	ASTM 4054 Name/ D7566 Annex
Oilseeds and FOG	Hydroprocessing of esters and fatty acids (HEFA)	HEFA-SPK/Annex A2
Oilseeds	Transesterification to diesel	ASTM D975 – 22a
Starch-based	Fermentation with carbon capture, utilization, and storage (CCUS) + ATJ	ATJ-SPK/Annex A5
Forest resources, woody wastes, and woody energy crops	Gasification + syngas fermentation + ATJ	ATJ-SPK/Annex A5
MSW and dry waste	Gasification + Fischer–Tropsch (FT)	FT-SPK/Annex A1
Agricultural residues and herbaceous energy crops	Enzymatic hydrolysis + fermentation + ATJ	ATJ-SPK/Annex A5
Wet wastes	Hydrothermal liquefaction (HTL) + hydroprocessing	Not currently approved
Algae	Combined algae processing (CAP) + hydroprocessing	Partially approved [a]

[a] The portion of jet fuel produced from the lipid fraction via HEFA is eligible under D7566/Annex 2. The portion of jet fuel produced from carbohydrates is currently not approved but could be under ATJ-SPK/Annex A5 if the process is changed to convert algal carbohydrates to ethanol.

Oilseed & FOG Conversion

- For purposes of this analysis, we assume oilseed and FOG feedstocks are converted by HEFA and transesterification to biodiesel. We further assume:
  - 1 BGPY of fatty acid methyl ester (FAME) biodiesel is produced from oilseeds.
  - Growing demand and policy incentives shift RD production toward SAF.
- HEFA synthetic paraffinic kerosene (HEFA-SPK) is approved under ASTM D7566 Annex A2.

Key Assumptions Used for Conversion of Oilseeds and FOG

Feedstock	Process	Yield, GGE/ton	Liquid Hydrocarbon Distribution [a]			H_2 Use, g/GGE	WTW GHG, g CO_2e/MJ
			% SAF	% Diesel	% Gasoline		
Oilseed & FOG	HEFA	254 [b]	70%	5%	25%	86 [a]	42 [c]
Oilseed	Transesterification	283 [d]		100%		0	31 [e]

[a] Tao et al. (2017); the model used for the analysis in this reference estimates a range of yields, hydrocarbon distribution, and hydrogen use dependent upon oilseed and FOG feedstocks evaluated. For the purposes of this study, we assume the hydrocarbon distribution and hydrogen values shown in the table.
[b] Pearlson, Wollersheim, and Hileman (2013); all values converted to GGE basis.
[c] ANL (2022), based on soybean oil feedstock. Includes 9.3 g CO_2e/MJ for indirect land use change.
[d] EIA (2021); average biodiesel yield between 2015 and 2020.
[e] ANL (2023); GREET WTW Calculator 2022 Version 1, based on biodiesel produced from soybean oil.

Starch-Based Feedstock Conversion

- For purposes of this analysis, we assume starch-based feedstocks are converted to ethanol followed by ATJ upgrading to jet fuel. We further assume:
  - Electrification of LDVs, along with growing demand and policy incentives, will shift starch-based ethanol production capacity into ATJ production.
  - Ethanol production is distributed with centralized ATJ upgrading.
  - Due to its near-term potential, CCUS is applied during ethanol production (Xu, Lee, and Wang 2022).
- An ATJ process is undergoing commercial demonstration by LanzaJet (LanzaJet 2023).
- ATJ-SPK produced from ethanol is approved under ASTM D7566 Annex A5.

Key Assumptions Used for Conversion of Starch-Based Feedstocks

Feedstock	Process	Yield, GGE/ton	Liquid Hydrocarbon Distribution [a]			H_2 Use, g/GGE	WTW GHG, g CO_2e/MJ
			% SAF	% Diesel	% Gasoline		
Starch-based	ATJ	61 [b]	90%	10%		62 [c]	45 [d]

[a] Harmon et al. (2017); in their pilot demonstration project, LanzaTech produced 4,000 gal of jet fuel and 600 gal of diesel corresponding to the 90% jet/10% diesel split used here. In follow-up conversations with Pacific Northwest National Laboratory (PNNL), we confirmed their ATJ process is tunable with up to 90% jet fuel cut.

[b] Based on 103.6 gal ethanol per ton of grain (RFA 2022 production data) at 89% ATJ energy conversion efficiency. PNNL reports up to 90% ethanol conversion efficiency for their ATJ process (PNNL 2023).

[c] Han, Tao, and Wang (2017); 80.9 kJ H_2/MJ jet from Table 3 translates to 62 g H_2/GGE of fuel.

[d] ANL (2022); 76.6 g CO_2e/MJ for distributed ethanol-to-jet from corn dry mill with CO extraction. Xu, Lee, and Wang (2022) indicate between −31.2 and −31.4 g CO_2e/MJ for CCUS.

Woody Feedstock Conversion

- For purposes of this study, we assume forestry resources, woody wastes,[1] and woody energy crops are converted by gasification and syngas fermentation to ethanol followed by centralized ATJ upgrading (Handler et al. 2016; Harmon et al. 2017).
- Woody biomass gasification for fuel synthesis has been piloted and demonstrated. No commercial plants are in operation (Hrbek 2019a, Hrbek 2019b).
- Gas fermentation to ethanol has been commercialized on industrial off-gases (Harmon 2021).
- An ATJ process is undergoing commercial demonstration by LanzaJet (LanzaJet 2023).
- ATJ-SPK is approved under ASTM D7566 Annex A5.

Key Assumptions Used for Conversion of Oilseeds and FOG

Feedstock	Process	Yield, GGE/DT	Liquid Hydrocarbon Distribution [a]			H_2 Use, g/GGE	WTW GHG, g CO_2e/MJ
			% SAF	% Diesel	% Gasoline		
Forestry resources and woody wastes	Gasification + syngas fermentation + ATJ	65 [b]	90%	10%	0%	62 [c]	21 [d]
Woody energy crops							19 [d]

[a] Harmon et al. (2017); in their pilot demonstration project, LanzaTech produced 4,000 gal of jet and 600 gal of diesel corresponding to the 90% jet/10% diesel split. In follow-up conversation with PNNL, we confirmed their ATJ process is tunable with up to 90% jet fuel cut

[b] Handler et al. (2016); yield is derived from data in Table 1 for the forest residue scenario. We assume the same yield for woody wastes and energy crops.

[c] Han, Tao, and Wang (2017); Table 3 provides 80.9 kJ H_2/MJ jet for distributed ethanol-to-jet, which translates to 62 g H_2/GGE of fuel.

[d] ANL (2022); woody energy crop value (for poplar) includes −5.2 g CO_2e/MJ for U.S. indirect land use change based on the CORSIA default value.

[1] Includes forest product mill residues and urban wood wastes.

MSW & Dry Waste Conversion

- For purposes of this study, we assume MSW and other dry wastes[1] are converted by gasification followed by FT upgrading to fuels.
- A similar process is undergoing commercial deployment by Fulcrum BioEnergy (Fulcrum BioEnergy 2023).
- For sorted MSW, we assume 20% non-biogenic content and process yield the same as conversion of wood chips converted by gasification and FT upgrading to fuels (Tan et al. 2016).
- FT-SPK produced from MSW is approved under ASTM D7566 Annex A1.

Key Assumptions Used for Conversion of MSW and Dry Waste

Feedstock	Process	Yield, GGE/DT	Liquid Hydrocarbon Distribution [a]			H_2 Use, g/GGE	WTW GHG, g CO_2e/MJ
			% SAF	% Diesel	% Gasoline		
MSW and dry wastes	Gasification + FT	59 [b]	70%	15%	15%	0 [b]	33 [c]

[a] We assume up to 70% jet yield, with the balance split between diesel and naphtha cuts.
[b] Tan et al. (2016); for sorted MSW, we assume yield is similar to wood chips converted via gasification and FT pathway. All hydrogen requirements are met by reforming of FT tail gas.
[c] ANL (2022); based on MSW with 20% non-biogenic content and referencing the ICAO-MIT data set.

[1] Secondary agriculture wastes.

Herbaceous Feedstock Conversion

- Agricultural residues and herbaceous energy crops are converted to ethanol by dilute acid pretreatment, enzymatic hydrolysis, and fermentation (Humbird et al. 2011).
- Ethanol is upgraded to jet and diesel at centralized ATJ facilities (Han, Tao, and Wang 2017).
- ATJ-SPK from herbaceous feedstocks is approved under ASTM D7566 Annex A5.

Key Assumptions Used for Conversion of Herbaceous Feedstocks

<table>
<tr><th rowspan="2">Feedstock</th><th rowspan="2">Process</th><th rowspan="2">Yield, GGE/DT</th><th colspan="3">Liquid Hydrocarbon Distribution [a]</th><th rowspan="2">H_2 Use, g/GGE</th><th rowspan="2">WTW GHG, g CO_2e/MJ</th></tr>
<tr><th>% SAF</th><th>% Diesel</th><th>% Gasoline</th></tr>
<tr><td>Agricultural residues</td><td rowspan="2">Biochemical + ATJ</td><td rowspan="2">46.3 [b]</td><td rowspan="2">90%</td><td rowspan="2">10%</td><td rowspan="2">0%</td><td rowspan="2">62 [b]</td><td>20 [c]</td></tr>
<tr><td>Herbaceous energy crops</td><td>22 [c]</td></tr>
</table>

[a] Harmon et al. (2017); in their pilot demonstration project, LanzaTech produced 4,000 gal of jet and 600 gal of diesel corresponding to the 90% jet/10% diesel split. In follow-up conversation with PNNL, we confirmed their ATJ process is tunable with up to 90% jet fuel cut.

[b] Han, Tao, and Wang (2017), based on data in Table 3. This corresponds to 79 gal ethanol/dry ton corn stover (Humbird et al. 2011) at 89% energy conversion in ATJ process. Table 3 provides 80.9 kJ H_2/MJ jet, which translates to 62 g H_2/GGE fuel.

[c] ANL (2022); based on distributed ATJ. The energy crop value is for switchgrass. For miscanthus the value would be −18 g CO_2/MJ.

Wet Waste Conversion

- For purposes of this study, we assume wet wastes are converted by HTL and hydroprocessing (Snowden-Swan et al. 2017).
- Wet waste conversion by HTL to jet fuel is not currently an ASTM-approved pathway.

Key Assumptions Used for Conversion of Wet Waste via HTL

Feedstock	Process	Yield, GGE/DT	Liquid Hydrocarbon Distribution [a]			H_2 Use, g/GGE	WTW GHG, g CO_2e/MJ
			% SAF	% Diesel	% Gasoline		
Wet wastes	Wet waste HTL	107 [b]	30%	47%	23%	35 [b]	27 [c]

[a] The conceptual design (Snowden-Swan et al. 2017) assumes 77% diesel and 23% naphtha split. Based on conversations with PNNL, we assume additional hydrocracking and distillation of the diesel cut could yield up to 30% jet fuel. Note that the hydrogen consumption is based on the conceptual design and does not include any additional hydrogen needed for production of the jet cut.

[b] Snowden-Swan et al. (2017); 135 GGE biocrude/ton AFDW × 0.95 GGE fuel/GGE biocrude with 15% ash gives 107 GGE/DT.

[c] Cai et al. (2021); WTW GHG value is based on 2022 wet waste HTL design case without NH_3 removal. Note that the GHG value is based on the conceptual design and does not include any additional hydrogen or natural gas input needed for production of additional jet cut.

Algae Conversion

- Algae feedstock is assumed to be converted to fuels and coproducts via CAP (ANL, NREL, and PNNL 2017; Davis et al. 2020).
- In the CAP design:
  - 50% of total algal lipids are upgraded to fuel via HEFA.
  - Carbohydrates are converted to fuel via fermentation followed by catalytic upgrading and hydroprocessing.
  - Significant volumes of coproduct are produced.[1]
- The portion of jet fuel produced from lipid via HEFA is approved under ASTM D7566/Annex 2.
- The portion of jet fuel produced from carbohydrates is currently not approved through ASTM.[2]

Key Assumptions Used for Conversion of Algae via CAP

Feedstock	Process	Yield, GGE/ ton AFDW	Liquid Hydrocarbon Distribution [a]			H_2 Use, g/GGE	WTW GHG, g CO_2e/MJ
			% SAF	% Diesel	% Gasoline		
Algae	CAP (HEFA of lipids)	38 [a]	70% [b]	5%	25%	100 [a]	9 [d]
	CAP (fermentation and upgrading of carbohydrates)	34 [a]	93% [c]		7%	91 [a]	

[a] Wiatrowski and Davis (2021); 2030 design projection for carboxylic acid pathway. Yield and hydrogen consumption are split between the lipid- and carbohydrate-derived fuel fractions based on the National Renewable Energy Laboratory's (NREL's) process model used in the design. Total yield is 72 GGE/ton, and total H_2 use is weighted average, or 96 g/GGE.

[b] Assume the hydrocarbon distribution from HEFA of lipid fraction is the same as used in the oilseed and FOG pathways.

[c] Davis et al. 2018; the catalytic upgrading of carboxylic acid produces predominantly a branched C14 molecule. We assume all C9–C16 hydrocarbons fall into the jet fuel cut.

[d] Cai et al. (2021); 2030 design projection for renewable diesel production via carboxylic acid pathway using the displacement method (Table 39). This method assigns significant GHG reduction credit to the fuel due to the displacement of petroleum-derived PU coproduct. Market- and mass-based allocation methods provide 32 and 52 g CO_2e/MJ emissions, respectively.

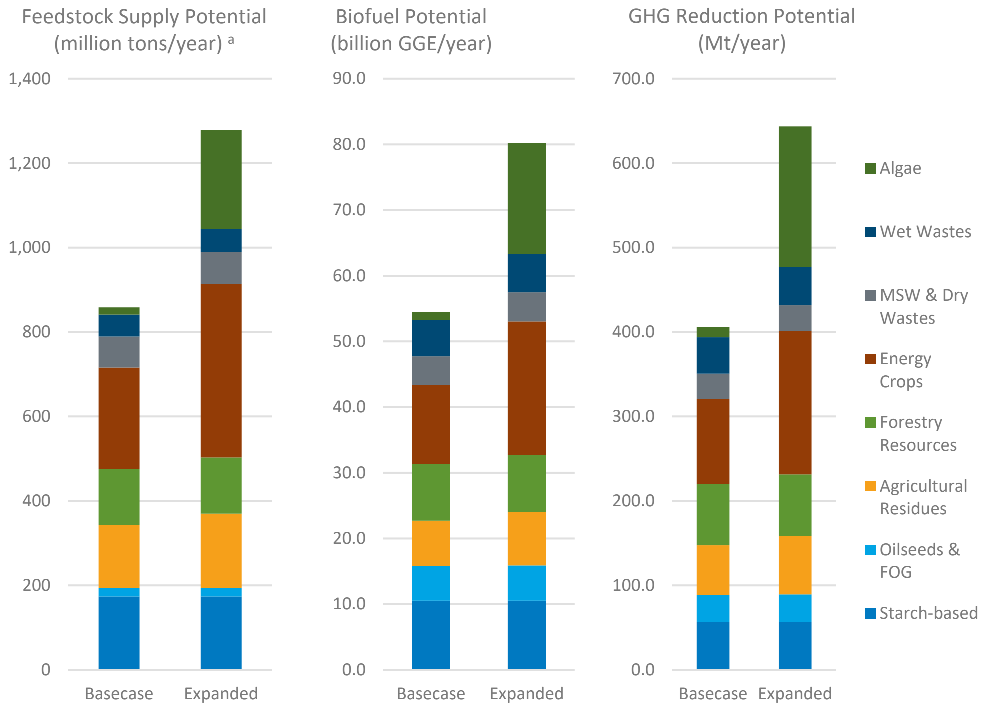
[1] In the reference design case, 50% of the extracted algal lipids are diverted to polyurethane (PU) production, resulting in 416 lb of PU per ton AFDW algae feed. For purposes of this analysis, we do not put a limit on market volume of coproducts.

[2] Though not included in the referenced design, carbohydrates could be fermented to ethanol (Davis et al. 2014), enabling ATJ upgrading that would be approved under ASTM D7566/Annex 5. This is being evaluated by BETO and NREL and may be a topic for a future iteration of this analysis.

Results

Feedstock Supply and Biofuel Potential

- For the base case scenario, a total of 858 million tons/year of potential biomass supply is available. This could be converted into 55 billion GGE/year of biofuel with the potential to reduce GHG emissions by 406 Mt/year.
- For the expanded supply scenario, 1,279 million tons/year of potential biomass is available. This could be converted into 80 billion GGE/year of biofuel with a GHG reduction potential of 644 Mt/year.

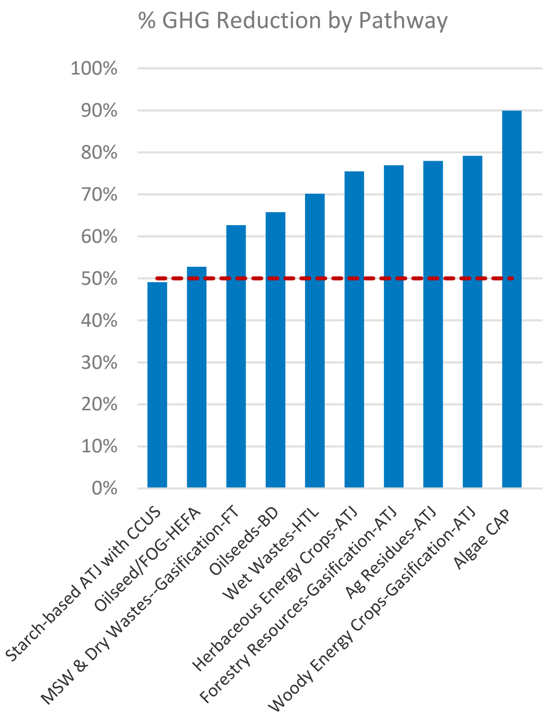


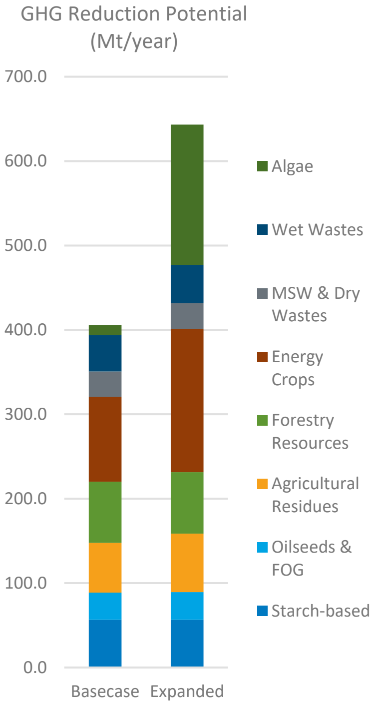
[a] Dry and wet waste feedstocks are reported on a dry basis. Algae is reported on an AFDW dry basis. Starch-based, oilseed, and waste FOG are reported on an as-received basis.

GHG Reduction Potential

Based on the data sources and assumptions used in this study:

- The total GHG reduction potential for the base case and expanded supply scenarios are 406 and 644 Mt/year, respectively.
- All pathways except starch-based ATJ exceed 50% reduction in GHG emissions relative to petroleum fuels.[1]
- With the application of CCUS, the starch-based ATJ pathway achieves 49% GHG reduction. There is potential to significantly further reduce GHG emissions for starch-based pathways (Xu, Lee, and Wang 2022).
- Algae achieves 90% GHG reduction because significant GHG credits are assigned to the fuel due to the displacement of petroleum-derived PU coproduct.[2]





[1] Jet petroleum reference value of 89 g CO_2e/MJ is based on CORSIA (ICAO 2019). Diesel and gasoline petroleum reference value of 91 g CO_2e/MJ is based on GREET 2022 WTW calculator (ANL 2023).

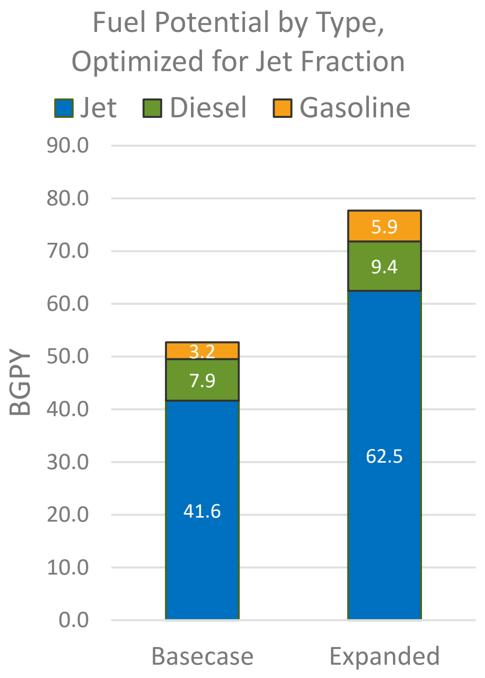
[2] Market- and mass-allocation methods provide 32 and 52 g CO_2e/MJ GHG emissions (Cai et al. 2021), respectively, for the CAP pathway. This would result in 64% and 42% GHG reduction and 119 and 77 Mt/year GHG reduction potential versus 166 Mt/year shown for algae in the expanded supply scenario.

Fuel Potential by Type

With few exceptions,[1] most biofuel pathways produce a distribution of hydrocarbon fuels. In some cases, this distribution can be adjusted through pathway selection and process design.

For the purposes of this study, we focused on pathway designs targeted at producing biofuels suitable for use in hard-to-electrify transportation sectors. Specifically, we chose pathways and applied assumptions favoring the production of jet fuel.[2]

- For the base case scenario, 42 BGPY of jet fuel and 8 BGPY of diesel could be produced.
- For the expanded supply scenario, 63 BGPY of jet fuel and 9 BGPY of diesel could be produced.



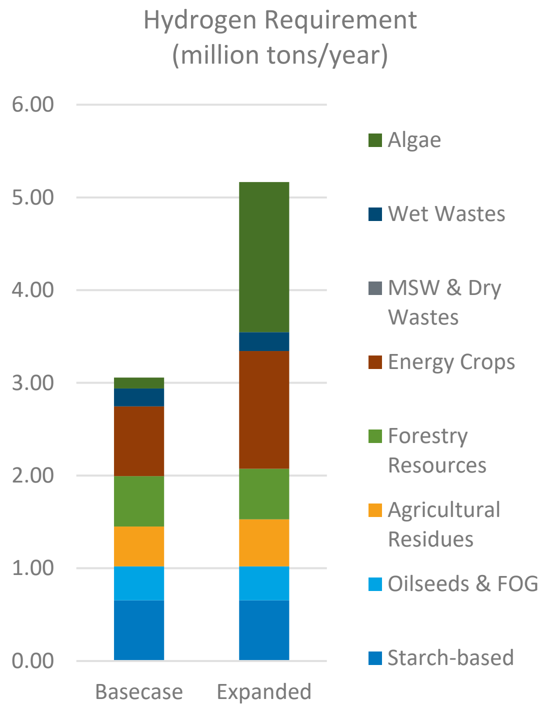
[1] Notable exceptions include pathways that ferment sugars to ethanol, hydroprocess fermented sugars to isoparaffins, or produce biodiesel via transesterification.

[2] We did not develop detailed process models or optimize the design for each of the pathways used in this study. Rather, we used existing data sources and applied practical engineering assumptions to adjust for hydrocarbon yield and distribution.

Hydrogen Requirement

Hydrogen input is necessary for biofuels production. The amount of hydrogen needed depends on feedstock and process design. For the purposes of this study, we estimate hydrogen demand based on the referenced process designs. For technical and economic reasons, these designs generally optimize for use of internal biomass-derived hydrogen first, with excess demand imported from external sources.

- For pathway designs used in this study, 3.1 and 5.2 million tons/year of external sourced hydrogen is needed for the base case and expanded supply scenarios, respectively.
- For the GHG calculations, this hydrogen is assumed to be derived from steam reformed natural gas.[1] If this fossil-based hydrogen were replaced with renewable hydrogen, an additional 35–60 Mt CO_2e/year of GHG reduction would be realized.
- Other studies have shown renewable hydrogen could replace the use of biomass-derived hydrogen in some pathways, resulting in significant biofuel yield improvements (Harris et al. 2021).[2]



[1] Without carbon capture and sequestration.

[2] Because this study relied on published sources and did not develop detailed process models, we did not estimate the impact on fuel yield or additional H_2 required. This may be a topic for a future iteration of this analysis.

Scenario Results Summary

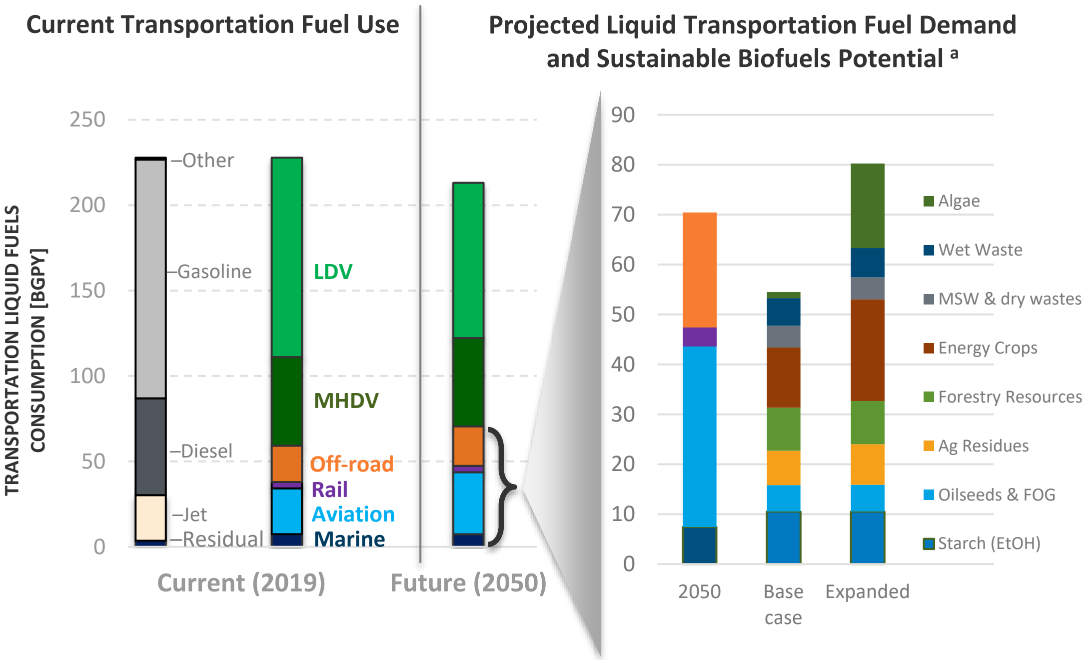
	Baseline	Expanded
Feedstock input, million DT/year	858	1,279
Hydrogen input, Mt/year	3.1	5.2
Total biofuel potential, billion GGE/year	55	80
SAF potential, BGPY	42	63
GHG reduction potential, Mt/year	406	644

Conclusions

Biofuels Potential for Hard-to-Electrify Transportation

This study demonstrates the potential of biofuels produced from sustainable biomass to replace petroleum-based fuels and mitigate GHG emissions in hard-to-electrify transportation sectors (aviation, marine, rail, and off-road).

- AEO estimates approximately 70 BGPY of liquid transportation fuels will be needed in these sectors by 2050.
- Biofuels from sustainable biomass resources have the potential to replace between 55 and 80 billion GGE/year of these fuels while eliminating 410–640 Mt/year of GHG emissions. This represents a total 68%–73% reduction in GHG emissions over petroleum-based fuels.



[a] The Base case and Expanded scenario bars are reported on a GGE basis.

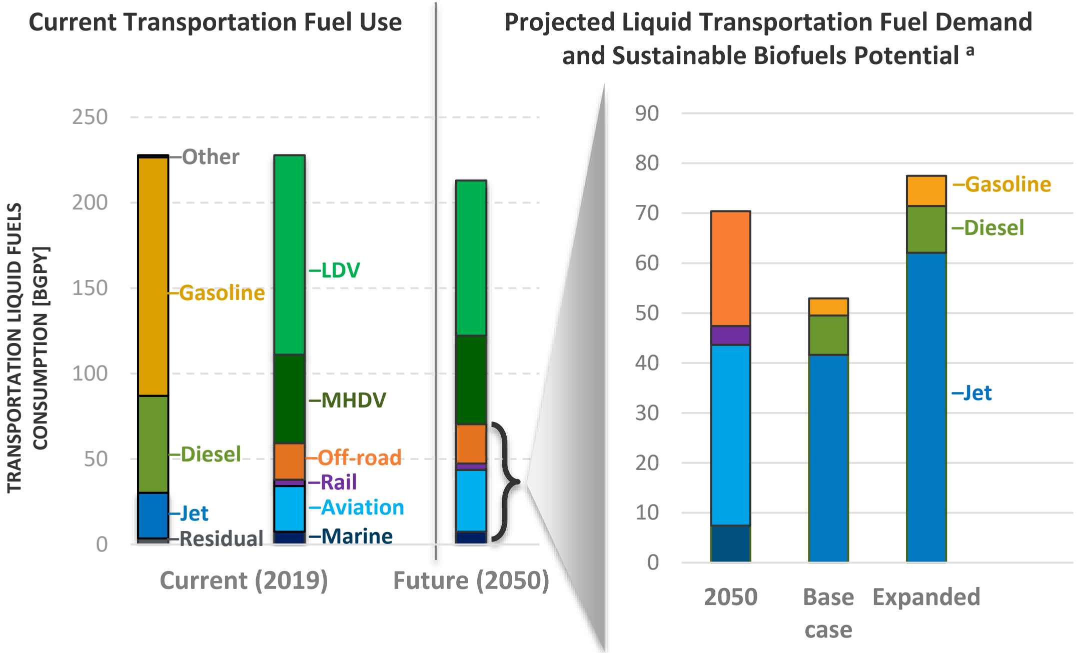
Biofuels Potential for Hard-to-Electrify Transportation

The SAF Grand Challenge set a goal of supplying 100% of domestic jet fuel use, or 35 BGPY by 2050 with SAF.

- Through pathway selection and assumptions favoring jet production, this study demonstrates the potential to produce between 42 and 63 BGPY of jet fuel by 2050.[1]

The external hydrogen required to produce 55 and 80 billion GGE/year of biofuel is estimated to be 3.1 and 5.1 Mt/year, respectively.

- If this hydrogen were replaced with hydrogen derived from renewable sources, additional respective GHG reductions of 35 and 60 Mt CO_2e/year could be realized.



[a] The Base case and Expanded scenario bars above are reported on a GGE basis

[1] 9 BGPY of this jet fuel is derived from starch-based feedstock through ATJ upgrading. With CCUS applied, this pathway achieves 49% GHG reduction. Additional GHG reductions would be required to meet the 50% GHG reduction needed to qualify as SAF.

Supplemental/Appendices

Base Case Scenario Results

Biofuel Production & GHG Reduction Potential (Base Case Feedstock Scenario)

Feedstock	Conversion Process	Feedstock Input MT/year+	Yield GGE/ton	Fuel Produced B GGE/year: Jet	Diesel	Gas	TOTAL	WTW GHG Emissions g CO2e/MJ	GHG Reduction Mt/year	%	Hydrogen Use Mt/year
Biomass input based on projedted ethanol and biodiesel production capacity											
Oilseed & FOG	HEFA	16.8	254	3.0	0.2	1.1	4.3	42	25	53%	0.37
Oilseed Oils	Transesterfication	3.6	283		1.0		1.0	31	8	66%	-
Corn & sorghum grain	Fermentation + ATJ w/CCS	174	61	9.5	1.1	0.0	10.5	45	57	49%	0.66
Biomass input based on Billion Ton Study 2016											
Forestry resources & woody wastes	Gasification + syngas fermentation + ATJ	133	65	7.8	0.9	0.0	8.6	21	73	77%	0.54
Woody energy crops		50	65	2.9	0.3	0.0	3.3	19	28	79%	0.20
MSW & other dry wastes	Gasification + F-T	74	59	3.0	0.7	0.7	4.3	33	30	63%	-
Agricultural residues	Enzymatic hydrolysis + Fermentation + ATJ	149	46	6.2	0.7	0.0	6.9	20	59	78%	0.43
Herbaceous energy crops		190	46	7.9	0.9	0.0	8.8	22	73	75%	0.55
Algae	CAP (HEFA of Lipids)	17	38	0.4	0.0	0.2	0.6	9	12	90%	0.06
	CAP (fermentation & upgrading of carbohydrates)		34	0.5	0.0	0.04	0.6				0.05
Biomass input based on Biofuels and Bioproducts from Wet and Gaseous Wastes 2017											
Wet Wastes	WWHTL	52	107	1.7	2.6	1.3	5.5	27	43	70%	0.19
TOTALS		***858***		***43***	***8***	***3***	***55***		***406***		***3.1***

+ Oilseed, FOG, and grain are input on an as-received basis. Algae is input on an AFDW basis. All other feedstock on a dry basis. Yields are reported on same basis as feedstock inputs.

Expanded Feedstock Scenario Results

Biofuel Production & GHG Reduction Potential (Expanded Feedstock Scenario)

Feedstock	Conversion Process	Feedstock Input	Yield	Fuel Produced B GGE/year				WTW GHG Emissions	GHG Reduction		Hydrogen Use
		MT/year+	GGE/ton	Jet	Diesel	Gas	TOTAL	g CO2e/MJ	Mt/year	%	Mt/y
Biomass input based on existing ethanol and biodiesel production capacity											
Vegetable Oils & FOG	HEFA	16.8	254	3.0	0.2	1.1	4.3	42	25	53%	0.37
Vegetable Oils	Transesterfication	3.6	283		1.1		1.1	31	8	66%	-
Corn grain	ATJ w/CCUS	174	61	9.5	1.1	0.0	10.5	45	57	49%	0.66
Biomass input based on Billion Ton Study 2016											
Forestry resources & woody wastes	Gasification + syngas fermentation + ATJ	133	65	7.8	0.9	0.0	8.6	21	73	77%	0.54
Woody energy crops		71	65	4.2	0.5	0.0	4.6	19	40	79%	0.29
MSW & other dry waste	Gasification + F-T	75	59	3.1	0.7	0.7	4.4	33	30	63%	-
Agricultural residues	Enzymatic hydrolysis + Fermentation + ATJ	176	46	7.3	0.8	0.0	8.1	20	69	78%	0.51
Herbaceous energy crops		340	46	14.2	1.6	0.0	15.7	22	130	75%	0.98
Algae input based on 2017 Algae Harmonization Study											
Algae	CAP (HEFA of Lipids)	235	38	6.2	0.4	2.2	8.9	9	166	90%	0.89
	CAP (fermentation & upgrading of carbohydrates)		34	7.5	0.0	0.6	8.0				0.73
Biomass input based on Biofuels and Bioproducts from Wet and Gaseous Wastes 2017											
Wet Wastes	WWHTL	55	107	1.8	2.7	1.3	5.8	27	45	70%	0.20
TOTALS		***1279***		***64***	***10***	***6***	***80***		***644***		***5.2***

+ Oilseed, FOG, and grain are input on an as-received basis. Algae is input on an AFDW basis. All other feedstock on a dry basis. Yields are reported on same basis as feedstock inputs.

List of Acronyms

AEO	Annual Energy Outlook
AFDW	ash-free dry weight
ANL	Argonne National Laboratory
ATJ	alcohol-to-jet
BD	biodiesel
BETO	Bioenergy Technologies Office
BGPY	billion gallons per year
BT16	*2016 Billion-Ton Report*
CAP	combined algae processing
CCUS	carbon capture, utilization, and storage
CO_2e	carbon dioxide equivalent
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
DOE	U.S. Department of Energy
DT	dry ton
EIA	U.S. Energy Information Administration
EPA	U.S. Environmental Protection Agency
FAA	Federal Aviation Administration
FOG	fats, oils, and greases
FT	Fischer–Tropsch
GGE	gallons of gasoline equivalent
GHG	greenhouse gas
GREET	Greenhouse gases, Regulated Emissions, and Energy use in Technologies
HEFA	hydroprocessing of esters and fatty acids
HTL	hydrothermal liquefaction
ICAO	International Civil Aviation Organization
LDV	light-duty vehicle
MHDV	medium- and heavy-duty vehicle

List of Acronyms

MSW	municipal solid waste
Mt	million metric tonnes (megatonne)
NREL	National Renewable Energy Laboratory
PNNL	Pacific Northwest National Laboratory
PU	polyurethane
RD	renewable diesel
RFA	Renewable Fuels Association
SAF	sustainable aviation fuel
SPK	synthetic paraffinic kerosene
WTW	well-to-wheel

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