

Supply Chain Sustainability Analysis of Renewable Hydrocarbon Fuels via Indirect Liquefaction, Ex Situ Catalytic Fast Pyrolysis, Hydrothermal Liquefaction, Combined Algal Processing, and Biochemical Conversion: Update of the 2020 State-of-Technology Cases

Energy Systems Division

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by

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1 INTRODUCTION

The Department of Energy's (DOE) Bioenergy Technologies Office (BETO) aims to develop and deploy technologies to transform renewable biomass resources into commercially viable, high-performance biofuels, bioproducts, and biopower through public and private partnerships (U.S. Department of Energy, 2016). BETO and its national laboratory teams conduct in-depth techno-economic assessments (TEA) of biomass feedstock supply and logistics and conversion technologies to produce biofuels. There are two general types of TEAs: A *design case* outlines a target case (future projection) for a particular biofuel pathway. It enables identification of data gaps and research and development needs and provides goals and benchmarks against which technology progress is assessed. A *state of technology* (SOT) analysis assesses progress within and across relevant technology areas based on actual results at current experimental scales relative to technical targets and cost goals from design cases, and includes technical, economic, and environmental criteria as available.

In addition to developing a TEA for a pathway of interest, BETO also performs a supply chain sustainability analysis (SCSA). The SCSA takes the life-cycle analysis approach that BETO has been supporting for about 20 years. It enables BETO to identify energy consumption, environmental, and sustainability issues that may be associated with biofuel production. Approaches to mitigate these issues can then be developed. Additionally, the SCSA allows for comparison of energy and environmental impacts across biofuel pathways in BETO's research and development portfolio.

This technical report describes the SCSAs for the production of renewable hydrocarbon transportation fuels via a range of conversion technologies in the 2020 SOTs: (1) renewable high octane gasoline (HOG) via indirect liquefaction (IDL) of woody lignocellulosic biomass (note that the IDL pathway in this SCSA represents the syngas conversion design [Harris et al. 2021]); (2) renewable gasoline (RG) and diesel (RD) blendstocks via ex situ catalytic fast pyrolysis of woody lignocellulosic biomass [Abhijit et al. 2021]; (3) RD via hydrothermal liquefaction (HTL) of wet sludge from a wastewater treatment plant; (4) renewable hydrocarbon fuels via biochemical conversion of herbaceous lignocellulosic biomass (Davis et al. 2021; Lin et al. 2021); (5) renewable diesel via HTL of a blend of algae (Davis and Klein, 2021) and woody biomass (Hartley et al. 2020); and (6) renewable diesel via combined algae processing (CAP) (Wiatrowski and Davis, 2021). This technical report focuses on the environmental performance of these six biofuel production pathways in their 2020 SOT cases. The results of these renewable hydrocarbon fuel pathways in these SCSA analyses update those for the respective 2019 SOT cases (Cai et al. 2020). They also provide an opportunity to examine the impact of technology improvements in both biomass feedstock production and biofuel production that have been achieved in 2020 SOTs on the sustainability performance of these renewable transportation fuels. The SCSA results also reflect updates to Argonne National Laboratory's Greenhouse gases, Regulated Emissions, and Energy use in Technologies (GREET[®]) model, which was released in October 2020 (Wang et al. 2020). These GREET updates include the production of natural gas, electricity, and petroleum-based fuels that can influence biofuels' supply chain greenhouse gas (GHG) (CO₂, CH₄, and N₂O) emissions, water consumption, and air pollutant emissions. GHG emissions, water consumption, and nitrogen oxides (NO_x) emissions are the main sustainability

metrics assessed in this analysis. In this analysis, we define water consumption as the amount of water withdrawn from a freshwater source that is not returned (or returnable) to a freshwater source at the same level of quality. Life-cycle fossil energy consumption and net energy balance, which is the life-cycle fossil energy consumption deducted from the renewable biofuel energy produced, are also assessed.

Figure 1 shows the stages in the supply chain that are considered and the data sources used in the SCSA of HOG via IDL, RG and RD from CFP, and RD from biochemical, algae HTL, algae CAP, and sludge HTL conversion. In this analysis, we consider the upstream impacts of producing each energy and chemical input to the supply chain.

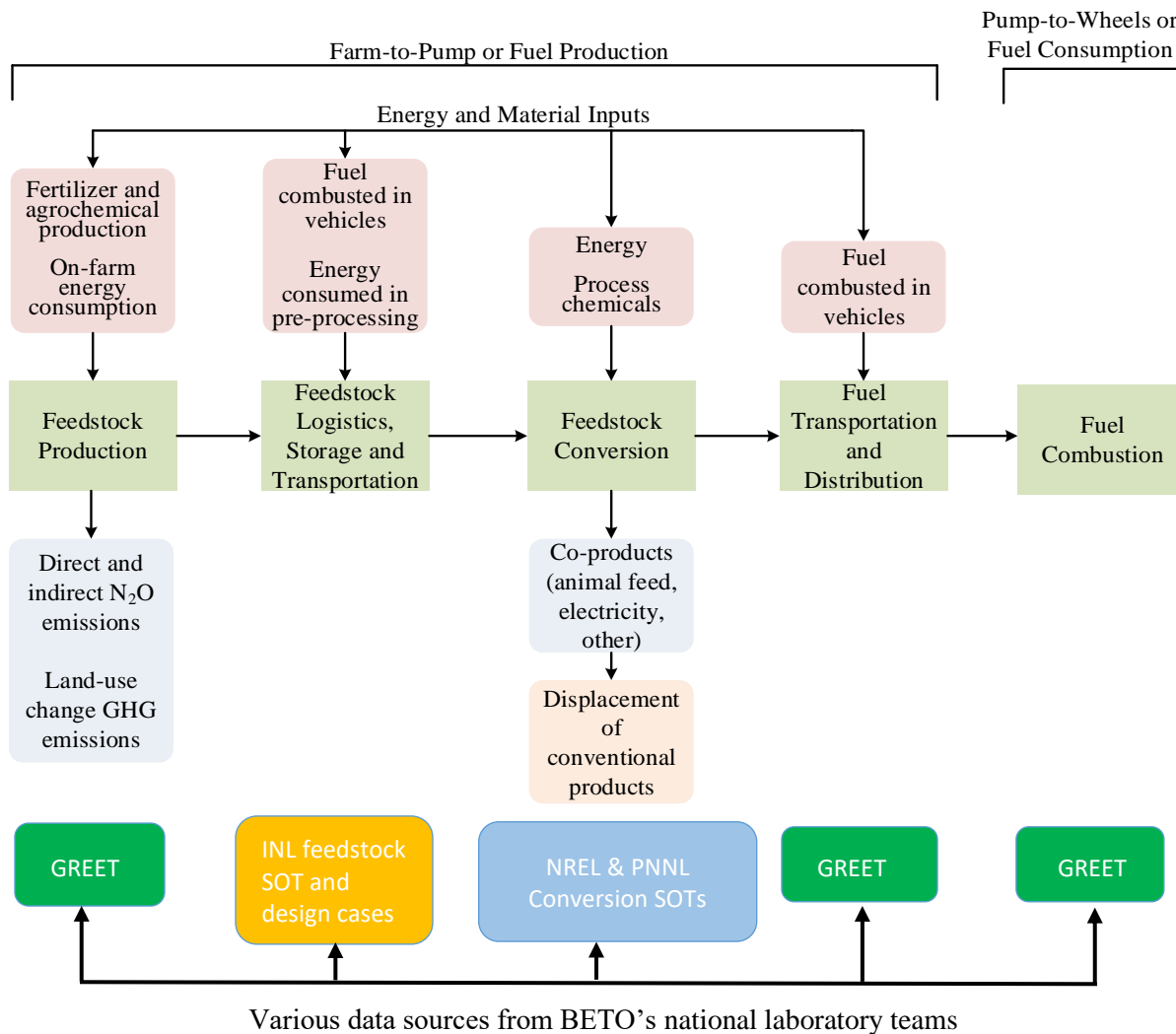


Figure 1 General Stages Considered and Data Sources Used in the Supply Chain Sustainability Analyses for HOG via IDL, RG and RD from CFP, and Renewable Fuels from Biochemical Conversion

2 METHODS AND DATA

Argonne National Laboratory's GREET model was used to generate the SCSA results for the 2020 SOT cases of the six biofuel pathways. The GREET model, developed with the support of DOE, is a publicly available tool for the life-cycle analysis of transportation fuels, and permits users to investigate the energy and environmental impacts of numerous fuel types and vehicle technologies. GREET computes fossil, petroleum, and total energy use (including renewable energy in biomass), GHG emissions, water consumption, and emissions of six air pollutants: carbon monoxide (CO), volatile organic compounds (VOCs), NO_x, sulfur oxides (SO_x), and particulate matter with an aerodynamic diameter below 10 micrometers (PM₁₀) and below 2.5 micrometers (PM_{2.5}), in the various fuel production pathways. Regular updates and expansion of the GREET model enable timely characterization of recent technology development and any modifications and improvement in the supply chain operations of energy and chemical products that are required for the biofuel production analyzed in this report.

2.1 Co-Product Handling Methods

BETO and its national labs have been developing new integrated biorefinery concepts that co-produce hydrocarbon fuels and value-added bio-based chemicals. These biorefinery designs aim to improve the economic viability, to enhance biomass resource utilization efficiencies, and to maximize potential greenhouse gas (GHG) emission reductions. Unlike biorefineries producing hydrocarbon fuels only, these biorefinery designs may co-produce a significant amount of bio-based chemicals, bearing emission implications for specific biorefinery products and the biorefinery as a whole.

As shown in Figure 2, several co-product handling methods could be considered to address the co-product effects, including allocation-based methods at the system level or process level, a displacement method, and a system expansion method to address biorefinery-level impacts (Cai et al. 2018). For pathways with significant co-product outputs, including the biochemical conversion, the algae CAP, and the algae/stover HTL pathways, we are addressing the co-product effects with three co-product handling methods in the SCSAs. These include

- 1) The process-level allocation method using the masses and market values of the finished products as the allocation basis.
- 2) The displacement method that attributes all the supply chain emission burdens to the fuel product, but also attributes all avoidance of emissions that otherwise would have taken place with the incumbent technology to produce the co-product, or co-product displacement credit, to the fuel product.
- 3) A biorefinery-level method that assesses the total emissions from producing both the biofuel and non-fuel bio-based co-products as well as the total emission reduction from both the biofuel and co-products, displacing their respective incumbent counterparts.

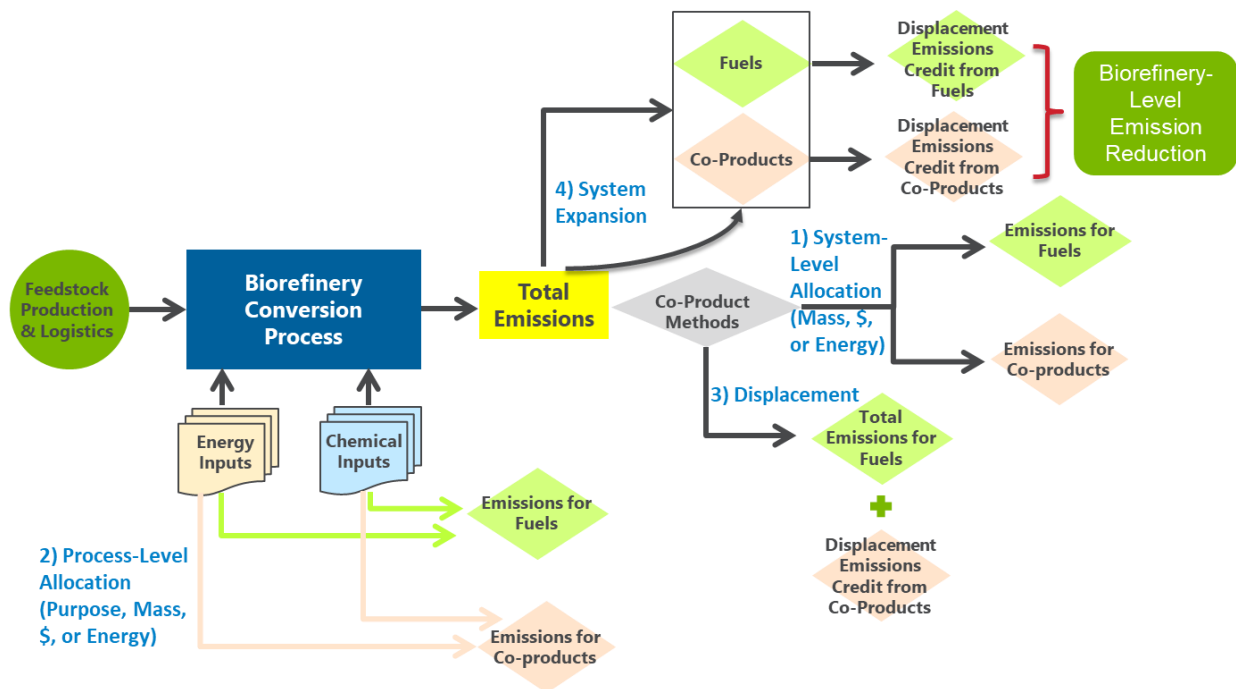


Figure 2 Co-Product Handling Methods to Address Co-Product Effects of Integrated Biorefineries: 1) System-Level Allocation, 2) Process-Level Allocation, 3) Displacement, and 4) System Expansion, or Biorefinery-Level Analysis

As discussed by Cai et al. (2018), each co-product method has its strengths and limitations. We present the SCSA results with all these methods and discuss their implications to illuminate and inform stakeholders of the significant sustainability effects of co-products in such biorefinery designs.

2.2 Material and Energy Requirement of Feedstock Production and Logistics

2.2.1 Herbaceous and Woody Biomass Production and Logistics

For the 2020 SOT case, Idaho National Laboratory (INL) modeled herbaceous feedstock and woody feedstock used by the biochemical conversion, IDL, CFP, and algae-woody blend HTL pathways (Lin et al. 2021; Hartley et al. 2020). The National Renewable Energy Laboratory (NREL) modeled an algal feedstock (Davis and Klein, 2021) used for the algae HTL and algae CAP pathways. Pacific Northwest National Laboratory (PNNL) modeled using wet sludge from wastewater treatment plants as feedstock for the sludge HTL pathway (Snowden-Swan et al. 2021).

The herbaceous feedstock blend comprises 70.37% two-pass corn stover, 29.63% three-pass corn stover in the 2020 SOT case. In the 2020 Herbaceous SOT, biomass availability is assumed to be same as in the 2019 Herbaceous SOT (Lin et al. 2021) in order to track the

economic impact of technical advancements from feedstock R&D. Biomass availability in the 2019 Herbaceous SOT was estimated by utilizing the projected 2019 supply curves from the BT16 report, modified to incorporate new models of the impact of implementing the Integrated Landscape Management (ILM) strategy in the supply shed and of the predicted grower participation rates with the implementation of ILM. The amount of feedstock required to be delivered to the biorefinery reactor throat is 725,000 dry tons/year in order to meet the feedstock cost (below \$71.26/dry ton [2016\$] in 2030) and quality (at least 59% carbohydrate content) targets.

The woody feedstock for the IDL and CFP pathways in the 2020 SOT case is 50% clean pine and 50% logging residue by mass.

Wet sludge for the HTL pathway is from a wastewater treatment plant (WWTP) that is co-located with an HTL plant. The wet sludge has a moisture content of 75%-80% and a dry matter content of about 15% that primarily consists of carbon, oxygen, and ash, with a small amount of hydrogen, nitrogen, phosphorus, and sulfur (Snowden-Swan et al. 2021).

The total energy and material requirements of each supply chain operation for the production of the herbaceous feedstock blend and the woody feedstock are summarized in Tables 1 and 2.

A series of logistics operations were used to harvest, collect, and preprocess corn stover in the 2020 SOT case. The use of supplementary fertilizer to maintain the soil fertility (to compensate for nutrients lost when corn stover is removed) is considered. Diesel is consumed for harvesting, collecting, and transporting corn stover. Corn stover handling at the depot consumes primarily electricity and diesel. Storage, preprocessing, and blending operations for corn stover consume only electricity. Preprocessing for corn stover size reduction, separation, and pelleting is an energy-intensive step.

The 2020 SOT case of the IDL pathway uses 50% logging residues and 50% clean pine as the feedstock blend. Both the logging residues and clean pine require logistics operations to collect, transport, and preprocess the biomass to be conversion-ready at the biorefinery gate. For the logging residues, diesel is consumed for collection by equipment such as excavator-base loaders or forwarders, for landing processing by chippers and loaders, for transportation by truck, and for storage by loaders, while electricity is consumed for receiving and handling the biomass by conveyors and truck tippers, and for depot preprocessing by dryers, conveyors, and dust collection operation. For the clean pine, diesel is consumed for pine silviculture and for pine harvesting and collection later on, for landing processing by delimiters and loaders, for transportation by truck, and for storage by loaders, while electricity is consumed for receiving and handling the biomass by conveyors, and for depot preprocessing by debarkers, grinders, dryers, conveyors, and dust collection operation.

The 2020 SOT case of the CFP pathway uses 50% logging residues and 50% clean pine as the feedstock blend. Both the logging residues and clean pine require logistics operations to collect, transport, and preprocess the biomass to be conversion-ready at the biorefinery gate. For the logging residues, diesel is consumed for collection by excavator-base loaders or forwarders,

for landing processing by chippers and loaders, for transportation by truck, and for storage by loaders, while electricity is consumed for receiving and handling the biomass by conveyors and truck tippers, and for depot preprocessing by dryers, conveyors, and dust collection operation. For the clean pine, diesel is consumed for pine silviculture, harvesting, and collection, for landing processing by delimiters and loaders, for transportation by truck, and for storage by loaders, while electricity is consumed for receiving and handling the biomass by conveyors, and for depot preprocessing by debarkers, grinders, dryers, conveyors, and dust collection operation. For the logging residues, diesel is consumed for collection, for landing processing by chippers and loaders, for transportation by truck, and for storage by loaders, while electricity is consumed for receiving and handling the biomass by conveyors, and for depot preprocessing by conveyors and dust collection operation. In addition, the drying steps consume natural gas.

Table 1 Energy Consumption, in Btu/Bone Dry Ton, Share of Fuel Type, and Fertilizer Application, in Grams/Bone Dry Ton, for Production and Logistics of Herbaceous Blends in the 2020 SOT Cases for the Biochemical Conversion Pathway (Lin et al. 2021; Canter et al. 2016)

	2020 SOT	
	3-Pass Corn Stover (29.6%)	2-Pass Corn Stover (70.4%)
Supplementary fertilizers and herbicides		
- Nitrogen	3,183 ^a	3,183 ^a
- P ₂ O ₅	2,273 ^a	2,273 ^a
- K ₂ O	13,641 ^a	13,641 ^a
Harvest and collection	89,040	108,560
- Diesel	100%	100%
Field storage	31	31
- Electricity	100%	100%
Depot storage	10,920	10,920
- Electricity	100%	100%
Preprocessing	326,280	326,280
- Electricity	100%	100%
Handling	7,720	7,720
- Diesel	89.50%	89.50%
- Electricity	10.50%	10.50%
Blending	440	440
- Electricity	100%	100%

^a Farming energy consumption and the fertilizer used for production of switchgrass are based on the 2016 Billion Ton Study (Canter et al. 2016).

Table 2 Energy Consumption, in Btu/Bone Dry Ton, for Clean Pine and Logging Residue Production and Logistics in the 2020 SOT Cases for HOG via IDL and RG via CFP (Hartley et al. 2020; Canter et al. 2016)

	IDL		CFP	
	Clean Pine (50%)	Logging Residue (50%)	Clean Pine (50%)	Logging Residue (50%)
Silviculture	144,177 ^a		144,177 ^a	
- Diesel	100%		100%	
Harvest and collection	139,910		139,910	
- Diesel	100%		100%	
Landing preprocessing	23,840	185,360	23,840	185,360
- Diesel	100%	100%	100%	100%
Receiving and handling	42	11,423	42	11,423
- Electricity	100%	100%	100%	100%
Storage	9,960	8,720	9,960	8,720
- Diesel	100%	100%	100%	100%
Preprocessing	232,730	160,960	1,262,420	1,190,650
- Natural gas	0%	0%	72%	77%
- Electricity	100%	100%	28%	23%

^a The silviculture energy consumption and the fertilizer used for production of pine are based on the 2016 Billion Ton Study (Canter et al. 2016).

Parameters used to determine energy consumed during feedstock transportation (which include transportation distance, truck payload, and feedstock moisture content, taken from the herbaceous and woody feedstock SOT cases) are shown in Tables 3 and 4. These data were incorporated into the IDL, CFP, and biochem pathways in the GREET model. Data for the last two stages of the supply chain (fuel transportation and distribution and fuel combustion) were obtained from GREET.

Table 3 Herbaceous Biomass Transportation Parameters, 2020 SOT Case (Lin et al. 2021)

			Truck Payload (Dry Tons)	Transportation Distance (Miles)	Transportation Moisture Content
2020 SOT	From fieldside to depot	3-Pass corn stover	17.7	22.8	20%
		2-Pass corn stover	17.7	46.3	20%
	From depot to biorefinery	3-Pass corn stover	20.9	58.2	11.4%
		2-Pass corn stover	20.9	50.8	11.4%

^{NN} Not needed.

Table 4 Woody Biomass Transportation Parameters for Transportation from the Landing to the Biorefinery, 2020 SOT Case (Hartley et al. 2020)

	Truck Payload (Dry Tons)	Transportation Distance (Miles)	Transportation Moisture Content
Logging residue for IDL and CFP	17.7	104.0	25%
Logging residue for algae HTL	17.7	88	25%
Clean pine	17.6	51.0	30%

Dry matter losses of herbaceous and woody biomass during the storage and preprocessing steps, as shown in Table 5, mean that more biomass will be required initially to account for the losses along the supply chain and meet the biorefinery throughput target, thus increasing the upstream biomass operation burdens to deliver a unit ton of feedstock at the biorefinery throat. The GREET model is configured to fully account for the impacts of dry matter losses on additional unit operations and the associated energy requirement of delivering one dry ton of biomass to the biorefinery for conversion.

Table 5 Dry Matter Losses (in Percentage by Mass) of Herbaceous and Woody Biomass for Conversion Pathways, 2020 SOT Case (Hartley et al. 2020; Lin et al. 2021)

Feedstock	Pathway	Field Side Storage	Landing	
			Preprocessing	Preprocessing
Corn stover	Biochemical conversion	8.8%		2%
Logging residue	IDL		5%	
	CFP		5%	6%
	Algae HTL		5%	10%
Clean pine	IDL and CFP		5%	13%

2.2.2 Algae Biomass Cultivation

Algae cultivation for HTL and CAP conversion is modeled from the algae farm design report (Davis and Klein, 2021), which assumes sourcing of CO₂ through the capture of flue gas from coal-fired power plants. Energy requirements for algae cultivation assume a 5,000-cultivation-acre farm facility, a size selected based on optimal economy of scale considerations. All cultivation and conversion cases considered in this SCSA are based on the production of saline algae species in Florida (based on associated local seasonal evaporation rates) for consistency with prior SOT cases. This is overlaid with algal biomass productivity data that has reflected experimental cultivation trials at the ASU AzCATI test-bed site since the 2017 SOT.

In the 2020 SOT case (Davis and Klein, 2021), high purity CO₂ produced from carbon capture of flue gas from coal-fired power plants and other point sources is transported to the farm gate via a high-pressure pipeline. An energy demand of 0.63 mega-joules (MJ) per kilogram of CO₂ is assumed for CO₂ capture and pipeline delivery (attributed to advanced second-generation carbon capture technologies). The process assumes a continuous mode of cultivation and harvesting to maximize the on-stream utilization of all capital costs. Once harvested, the biomass is routed through three stages of dewatering to reach a final solids content of 20 wt% (ash-free dry weight, AFDW). The harvested biomass composition was set to a future target projection consistent with compositional attributes previously measured for mid-harvest, high-carbohydrate *Scenedesmus* (Davis and Klein, 2021). Figure 3 shows a general block-flow diagram of the process. Further details of the process design are given in the report (Davis and Klein, 2021). In these SCSAs, saline scenarios with minimally lined ponds are considered for the downstream conversion of algal biomass to fuels and co-products.

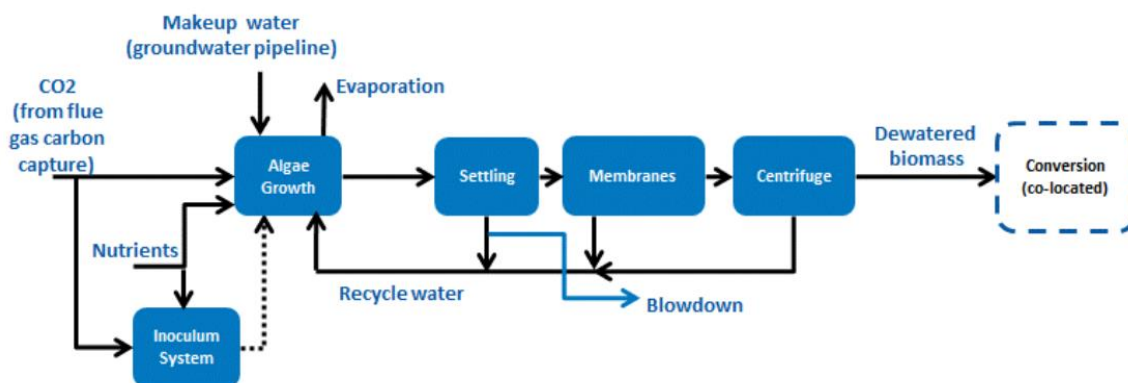


Figure 3 Process Flow Diagram of the Open Pond Algae Farm Model

Table 6 summarizes material and energy inputs and outputs of the 2020 algae farm model SOT. The input nutrient demands represent the gross requirements for cultivation, prior to accounting for any recycles from downstream conversion (these are credited in the respective algal conversion models instead).

Given that the algae strain assumed in the cultivation modeling (i.e., high-carbohydrate *Scenedesmus*) differs from that applied in the HTL conversion modeling (i.e., *Chlorella*), we adjusted the resource consumption, i.e., carbon, nitrogen in the form of ammonia and diammonium phosphate (DAP), and phosphorus in the form of DAP, and energy requirement at the cultivation step according to the algal chemical compositions and nutrient requirements for algae cultivation reflective of the *Chlorella* strain utilized for the HTL process and the recycled nutrients available in the HTL aqueous waste and recycled flue gas.

Table 6 Algal Biomass Production and Resource Requirement (Annual Averages, Hourly Net Rates Inclusive of Downstream Recycles Reflect Average Daily Rates Divided by a 24-Hour Day)

	2020 SOT	2020 SOT
	Algae for CAP	Algae for HTL
Products, kg/hr		
Algal biomass (AFDW)	13,246	13,246
Algal biomass (total including ash)	13,576	13,576
Make-up resource requirement, kg/hr		
CO ₂	29,441	0
Ammonia	265	910
Diammonium phosphate	128	180
Total process water input (saline water)	537,257	604,414 ^a
Electricity demand, kW	7,566	6,050 ^b
Algae lost in blowdown	5	5

^a Adjusted based on water content in the algae strain for CAP (80%) and water content in the algae strain for HTL (90%).

^b Resulting from a reduction of electricity demand by 184 kW due to centrifuge removal and by 1,332 kW due to removal of a CO₂ tank heater because the CO₂ comes directly from recycled flue gas and no heating is needed for the HTL case.

2.3 Material, Energy, and Water Requirements of Conversion Processes

2.3.1 Indirect Liquefaction (IDL)

The 2020 SOT case for the IDL pathway features a processing capacity of 2,205 U.S. short tons of dry feedstock per day at the biorefinery. The HOG yield at the biorefinery is 55.1 gallons, or 6.0 MMBtu per dry U.S. short ton of feedstock, which is an increase of 7% relative to the 2019 SOT case (Harris et al. 2021). Figure 4 shows a simplified process flow diagram (PFD) of the IDL pathway. The current research efforts focus on the DME-to-high-octane gasoline step in which DME undergoes homologation to form primarily branched paraffin hydrocarbons. For details regarding the conversion process, see the full report (Tan et al. 2019).

Table 7 lists the direct material, energy, and water consumption for the modeled IDL conversion process at the plant in the 2020 SOT case (Harris et al. 2021). Boiler feed water chemicals and cooling tower chemicals are not considered in the analysis due to a lack of information on their makeup. The impact of excluding such chemicals would likely be small, given their very low consumption levels (a combined 3.4 g/MMBTU of HOG).

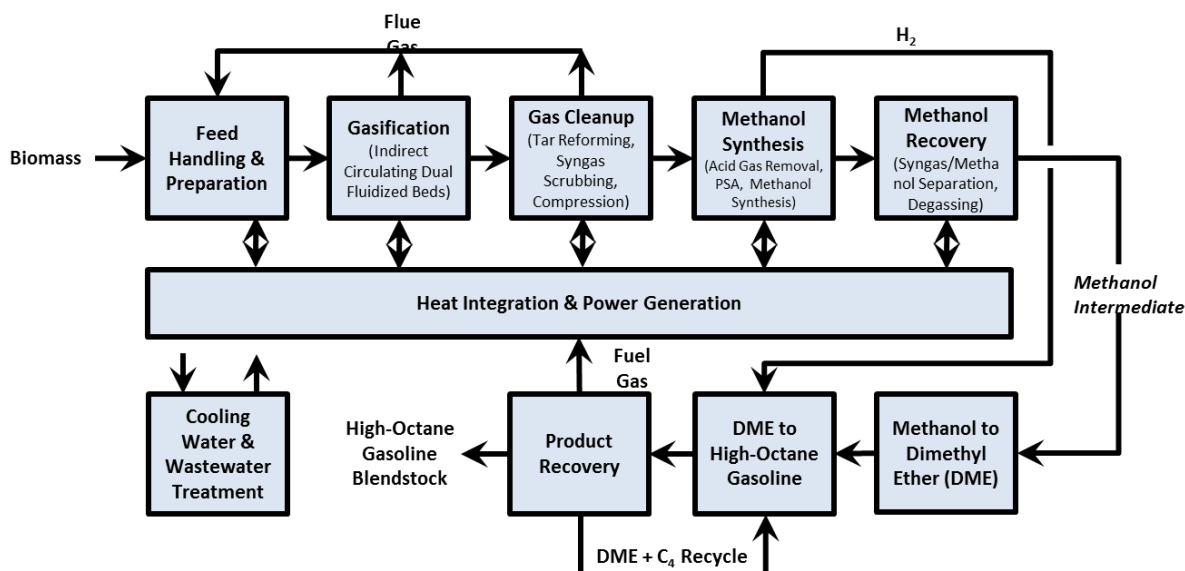


Figure 4 Process Flow Diagram for High Octane Gasoline via Indirect Liquefaction in the 2020 SOT (Harris et al. 2021)

Table 7 Key Indirect Liquefaction Process Parameters

	2020 SOT Value	Unit
HOG yield	6.0	MMBtu/dry ton feedstock
Surplus electricity	22	Btu/MMBtu of HOG
Diesel energy use	2,323	Btu/MMBtu of HOG
Char produced and combusted	795,552	Btu/MMBtu of HOG
Fuel gas produced and combusted	720,412	Btu/MMBtu of HOG
Magnesium oxide consumption	11.0	g/MMBtu of HOG
Fresh olivine consumption	445.8	g/MMBtu of HOG
Tar reformer catalyst consumption	7.9	g/MMBtu of HOG
Methanol synthesis catalyst consumption	3.8	g/MMBtu of HOG
DME catalyst consumption	7.3	g/MMBtu of HOG
Beta zeolite catalyst consumption	32.3	g/MMBtu of HOG
Zinc oxide catalyst consumption	2.0	g/MMBtu of HOG
LO-CAT chemicals	95.6	g/MMBtu of HOG
Dimethyl disulfide	1.7	g/MMBtu of HOG
Amine	3.5	g/MMBtu of HOG
Water consumption	28.1	gal/MMBtu of HOG

2.3.2 Ex Situ Catalytic Fast Pyrolysis (CFP)

Ex situ CFP converts woody biomass to infrastructure-compatible liquid hydrocarbon fuels including RD and RG. The 2020 SOT case for the ex situ CFP processes continues to use Pt/TiO₂ catalyst in a fixed bed as the base configuration, which showed significant yield improvements compared to using zeolite-based catalysts in previous experimental work (Dutta et

al. 2021). The CFP conversion features a processing capacity of 2,205 U.S. short tons of dry feedstock per day at the biorefinery. The hydrocarbon fuels consist of 50% RG and 50% RD by energy. The total RG and RD yields at the biorefinery are 7.1 MMBtu per dry U.S. short ton of biomass (50% clean pine and 50% logging residues by mass), about 3% increase in fuel yields compared to those in the 2019 SOT case. Surplus electricity is produced as a co-product (Dutta et al. 2021) and is assumed to be exported to the grid. In addition, two bioproducts, 2-butanone and acetone, are produced as co-products, with a yield of 10.1 and 58.4 lbs per dry ton, respectively. They are assumed to displace fossil-derived counterparts.

Figure 5 shows a simplified PFD of the ex situ CFP pathway. For details of the conversion process, see the full SOT report (Dutta et al. 2021). The same biomass blending strategy developed in the 2019 SOT case is adopted in the 2020 SOT case. Diversified components provide an opportunity to strike a balance between feedstock quality and feedstock cost to meet performance, costs, and sustainability goals of this conversion pathway.

Table 8 lists the direct material, energy, and water consumption for the modeled ex situ conversion process at the plant in the 2020 SOT case (Dutta et al. 2021).

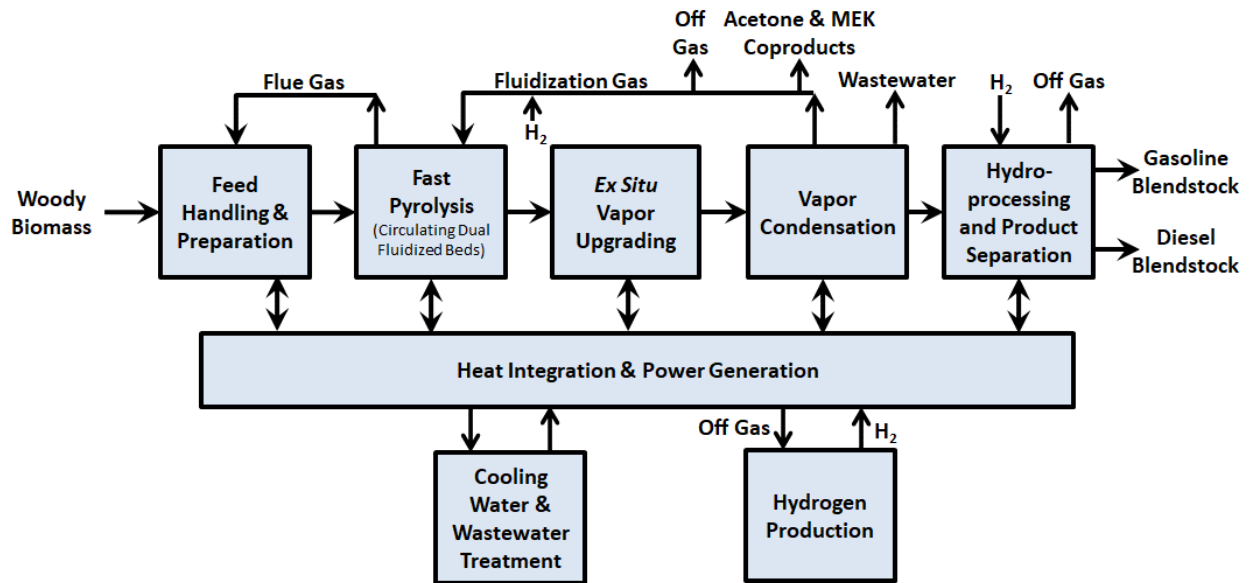


Figure 5 Simplified Process Flow Diagram for Fixed Bed Ex Situ Catalytic Fast Pyrolysis

Table 8 Key Ex Situ Catalytic Fast Pyrolysis Process Parameters

	2020 SOT Value	Unit
RG yield	3.6	MMBtu/dry ton feedstock
RD yield	3.6	MMBtu/dry ton feedstock
Co-produced 2-butanone	0.6	Kg/MMBtu of RG and RD combined
Co-produced acetone	3.7	Kg/MMBtu of RG and RD combined
Surplus electricity	137,498	Btu/MMBtu of RG and RD combined
Diesel energy use	1,990	Btu/MMBtu of RG and RD combined
Natural gas use	3,196	Btu/MMBtu of RG and RD combined
Fixed-bed VPU catalyst (0.5% Pt/TiO ₂)	0.05	g/MMBtu of RG and RD combined
Sand	110	g/MMBtu of RG and RD combined
ZnO	0.02	g/MMBtu of RG and RD combined
Steam reforming catalyst	0.04	g/MMBtu of RG and RD combined
Shift catalyst	0.05	g/MMBtu of RG and RD combined
PSA adsorbent	1.4	g/MMBtu of RG and RD combined
Caustic	100.7	g/MMBtu of RG and RD combined
Water consumption	9.7	gal/MMBtu of RG and RD combined

Table 9 Energy, Catalyst, and Water Consumption of Petroleum Refinery Co-Hydrotreating

	2020 SOT Value	Unit
Natural gas use	399,546	Btu/MMBtu of RG and RD combined
Electricity consumption	15,547	Btu/MMBtu of RG and RD combined
Co-produced steam, converted to natural gas consumption ¹	-9,697	Btu/MMBtu of RG and RD combined
Hydrotreating catalyst	11.2	g/MMBtu of RG and RD combined
Hydrocracking catalyst	2.8	g/MMBtu of RG and RD combined
Water consumption	8.6	Gal/MMBtu of RG and RD combined

¹: We assumed that it takes 180 BTU of energy to bring a pound of water to boiling and it takes another 970 BTU to vaporize it to steam.

The 2-butanone and acetone co-products account for about 14.9% of the total product slate by mass. We apply the displacement method to address the co-product effects. With this method, we need to address the supply chain energy use, water consumption, and emissions of producing these chemicals in the current industry practices, according to the life-cycle inventories (LCI) of the production. For 2-butanone, we collected and compiled the LCI from the U.S. Life Cycle Inventory (USLCI) Database. To account for the displacement credit of bio-derived acetone, (which displaces the petroleum-based counterpart), we take the energy use, water consumption, and emissions of petroleum-based acetone production that was modeled with GREET (Wu et al. 2007) in the calculations.

2.3.3 Sludge Hydrothermal Liquefaction (HTL)

HTL uses hot, pressurized water (e.g., 347°C and 20.5 MPa) in the condensed phase to convert biomass to a thermally stable oil product (also known as “biocrude”), which can then be thermocatalytically upgraded to hydrocarbon fuel blendstocks (Snowden-Swan et al. 2021). This technology has high carbon efficiency and can be applied to a wide range of wet feedstocks at similar processing conditions. The wet waste examined in the analysis is wastewater residuals (sludge) generated at wastewater treatment plants (WWTP). The configuration includes an HTL plant co-located with a WWTP and a larger scale biocrude upgrading plant for producing hydrocarbon fuel blendstocks. The SCSA of this pathway considers fuel production processes starting from biocrude production (HTL plant) followed by biocrude upgrading to RD (upgrading plant), and RD transportation and combustion in vehicles, as shown in Figure 6

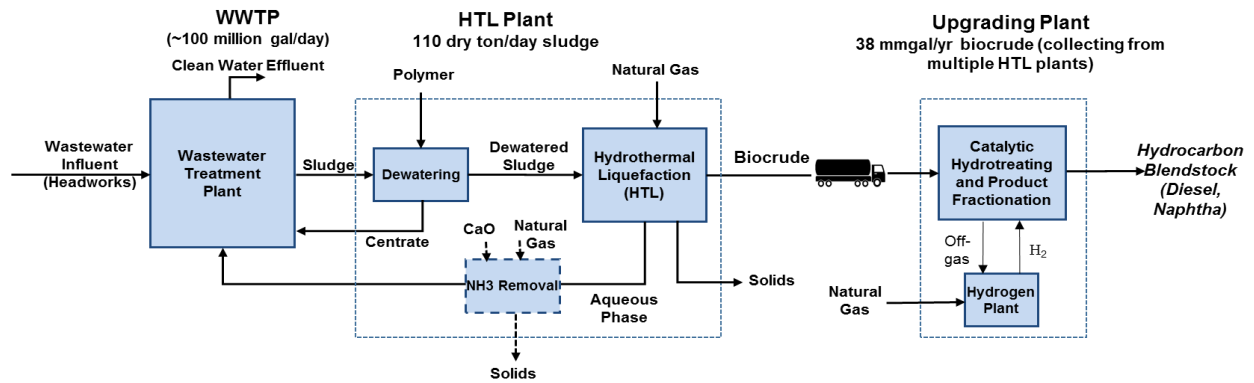


Figure 6 A Simplified Process Flow Diagram of the WWTP/HTL Plant and Centralized Biocrude Upgrading Plant Design

The operations at the HTL plant to produce biocrude and the subsequent biocrude upgrading operations in the 2020 SOT case remain the same. The only change from the 2019 SOT case is a decrease in natural gas consumption but an increase in electricity consumption at the HTL conversion step according to an updated Aspen process model by Pacific Northwest National Laboratory (PNNL). Table 10 summarizes major inputs and outputs of the HTL process for all the cases investigated. Table 11 presents the material and energy inputs and outputs of the upgrading plant.

Biocrude is assumed to be transported using trucks within a 100-mile radius to a large-scale centralized upgrading plant where it is converted to a hydrocarbon fuel blendstock.

Table 10 Energy and Material Balances (per lb of Biocrude Produced) at the HTL Plant

	Unit	With Ammonia Removal	Without Ammonia Removal
<i>Material and Energy Inputs</i>			
Dewatered sludge	(dry lb)	2.6	2.6
Natural gas	(Btu)	2,409	1,405
Electricity	(Btu)	1,137	1,105
Dewatering polymer	(lb)	0.007	0.007
Quicklime (CaO)	(lb)	0.281	0
Cooling water makeup	(gal)	0.00077	0.00077

Table 11 Material and Energy Inputs and Outputs, per MMBtu of Fuel Produced at the Upgrading Plant

	Unit	2020 SOT Case
<i>Material and Energy Inputs</i>		
Biocrude	lb	70.2
Natural gas	Btu	79,690
Electricity	Btu	10,286
Cooling tower chemical	g	0.3
Boiler chemical	g	0.2
Hydrotreating catalyst (CoMo/ γ -Al ₂ O ₃)	g	88.3
Hydrotreating catalyst (NiMo/ γ -Al ₂ O ₃)	g	62.1
Hydrocracking catalyst	g	0.2
Hydrogen plant catalyst (Ni)	g	0.3
Cooling water makeup	gal	5.4
Boiler feedwater makeup	gal	2.4

In order to evaluate the life-cycle GHG emissions associated with renewable diesel fuel, an energy allocation approach was applied in which GHG emissions are allocated between diesel (main product) and naphtha (co-product) based on their energy contents. The chemicals and catalysts required for the upgrading processes are incorporated into GREET to capture upstream energy use, emissions, and water consumption associated with their production. The production pathways of the materials listed in Tables 10 and 11 are available in GREET. Boiler chemical GHG emission burdens, however, were not included in the analysis because of lack of information. The impact of excluding such chemicals would likely be small, given their very low consumption levels.

2.3.4 Biochemical Conversion

As in previous SOT cases, the biochemical conversion pathway to produce renewable hydrocarbon fuels (primarily in the diesel range) includes two approaches that utilize carboxylic acids and 2,3-butanediol (BDO) as fermentation intermediates in the 2020 SOT. In the SCSAs,

we focused on the conversion scenario of both design case pathways that co-produce a significant amount of adipic acid by upgrading the lignin stream, as well as recovering sodium sulfate salt from the wastewater treatment step, which could displace conventionally produced sodium sulfate. Other conversion scenarios that could burn the lignin to produce process heat and steam are also included here to understand the sustainability implications of such alternative designs.

Figure 7 is a high-level PFD of the biochemical conversion design with lignin-derived adipic acid (AA) co-production. The design consists of deacetylation and mechanical refining (DMR) pretreatment, followed by enzymatic hydrolysis to deconstruct biomass carbohydrates into monomeric sugars, which are subsequently upgraded through fermentation to either carboxylic acids or BDO intermediates. The respective fermentation intermediate product is recovered and sent through a series of catalytic reaction steps to be upgraded to hydrocarbon fuels. The liquor from the deacetylation (mild alkaline extraction) step is combined with the residual lignin and other hydrolysate solids downstream and subjected to further alkaline deconstruction before being routed through fermentation to produce muconic acid. The muconic acid product is purified and hydrogenated to adipic acid, which is then further purified and sold as a value-added co-product. Alternatively, the SOT also considers a case without lignin upgrading to co-products, where residual solid lignin is burned in the boiler and deacetylation black liquor is routed to wastewater treatment. The process utilizes substantial quantities of caustic (sodium hydroxide) and acid (sulfuric acid) across several processing steps. The resultant sodium sulfate salt is assumed to be recovered for sale as an additional minor co-product (alternative options may be investigated in the future to recover and recycle the caustic/acid chemicals internally, thus avoiding the large caustic/acid makeup demands and resultant sodium sulfate co-product recovery). A key update implemented in the 2020 SOT was to make use of a new two-stage deacetylation step, first utilizing sodium carbonate, followed by standard sodium hydroxide deacetylation, which was found to enable better sugar yields while reducing sodium hydroxide demands by 70% via partial replacement with sodium carbonate (which is significantly more favorable both from a cost and GHG standpoint). Davis et al. (2021) provides more details on the process design, performance targets, and TEA results.

Given the significant amount of bioproduct co-product (AA) and its significant impact on the sustainability results, we took three co-product handling methods shown in Figure 2 (a purpose-driven, process-level allocation method, the displacement method, and the biorefinery-level analysis) to address the 2020 SOT case and the 2030 target case of the biochemical conversion pathway. Among these methods, the process-level allocation method allows us to separate the biorefinery inputs according to their purposes, namely, whether they are used for the fuel production, or used for the co-product production, or contribute to both. This ensures a plausible estimation of the sustainability impacts associated with different input streams that are purposefully contributing to different products. The results of the 2030 target case with the process-level allocation method serve as an alternative presentation of the results with the displacement method.

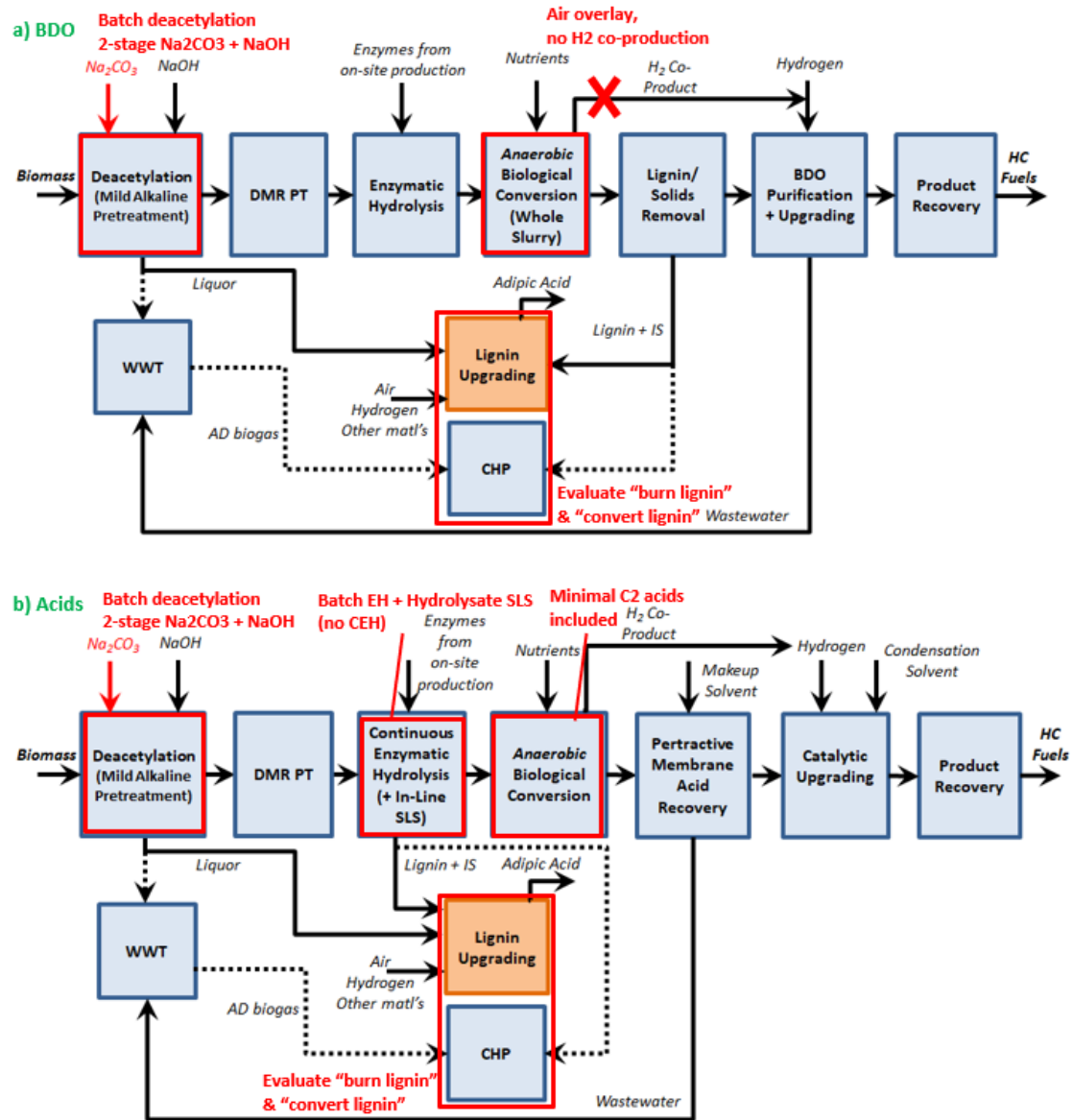


Figure 7 Process Flow Diagram of the Biochemical Conversion Design Case with Two Lignin Strategies: (1) Burn Lignin and (2) Convert Lignin to Adipic Acid. Modifications from the 2030 targets as reflected in the current 2020 SOT case are denoted in red (Davis et al. 2021)

With the purpose-driven, process-level allocation method, the inputs commonly shared by producing both the fuel and non-fuel products were allocated based on either the masses or the market values of the products. The mass-based yields of both products are informed by the process modeling, and the market prices for the renewable diesel and AA are assumed to be \$2.5/GGE and \$0.85/lb, respectively.

Tables 12 and 13 present the overall energy and material balances of the biochemical conversion pathway for both intermediate designs in the 2020 SOT and the 2030 target case. In addition, the allocated energy and material balances for fuel production only and for biochemical production only in the 2020 SOT and the 2030 target case, using the mass- and market value-based process-level allocation approach, are summarized in Tables A1-A4. Tables A5-A6 present the energy and material balances that are burdened to fuel production only, which are used to generate the results with the displacement method.

Table 12 Energy and Material Balances of the Biochemical Conversion Pathway for Both the Acids and BDO Intermediate Designs, 2020 SOT Case. Yellow inputs contribute to fuel production only, green inputs contribute to the biochemical production only, and blue inputs and outputs are shared by both the fuel and biochemical products.

	Via Acids		Via BDO		
	Burn Lignin	Convert Lignin Base	2020 SOT (Burn Lignin)	2020 SOT (Convert Lignin – Base)	
Products	Production Rate				
Hydrocarbon fuel	9,833	9,815	10,525	10,558	kg/hr
	103	103	111	112	MM
	410	409	442	444	kcal/hr (LHV)
					MMBtu/hr
Co-Products					
Adipic acid (polymer grade)	0	1,673	0	1,641	kg/hr
Recovered sodium sulfate salt from WWT	10,304	15,331	10,573	14,382	kg/hr
Resource Consumption	Flow Rate (kg/hr)				
Biomass feedstock (20% moisture)	104,167	104,167	104,167	104,167	
Sulfuric acid, 93%	9,235	12,477	9,235	11,542	
Caustic (as pure)	2,000	4,501	2,000	3,786	
	AA train	2,501		1,786	
	Both	2,000		2,000	
Sodium carbonate	6,667	6,667	6,667	6,667	
Ammonia	1,261	2,238	1,168	2,125	
	Fuel train	62		62	
	AA train	16		16	
	Both	2,160		2,047	
Glucose	1,312	1,312	1,312	1,312	
Corn steep liquor	1,226	1,226	918	918	
Corn oil	7	7	7	7	
Host nutrients	37	37	37	37	
Sulfur dioxide	9	9	9	9	

Table 12 (Cont.)

	Via Acids		Via BDO		
	Burn Lignin	Convert Lignin Base	2020 SOT (Burn Lignin)	2020 SOT (Convert Lignin – Base)	
Diammonium phosphate	169	273	103	206	
Fuel train		169		103	
AA train		105		104	
Flocculant	407	407	435	436	
Toluene solvent makeup	90	90	0	0	
Hydrogen	0	0	848	990	
Fuel train		0		844	
AA train		0		145	
Ethanol	0	13	0	13	
Boiler chemicals	0	0	0	1	
FGD lime	111	194	109	180	
WWT polymer	37	0	34	0	
Cooling tower chemicals	3	2	2	2	
Makeup water	330,952	239,435	134,676	112,362	
Natural gas for boiler	0	0	0	4,400	
Natural gas for hot oil system	39	39	0	0	
Grid electricity (net import)	7,019	53,859	17,894	42,759	MMBtu/hr
Fuel train		18,374		14,267	
AA train		3,386		3,125	
Both		32,099		25,367	kW

Table 13 Energy and Material Balances of the Biochemical Conversion Pathway for Both the Acids and BDO Intermediate Designs, 2030 Target Case. Yellow inputs contribute to fuel production only, green inputs contribute to the biochemical production only, and blue inputs and outputs are shared by both the fuel and biochemical products.

	Via Acids	Via BDO	
Products	Production Rate		
Hydrocarbon fuel	11,465	11,032	kg/hr
	504,671	486,293	MJ/hr (LHV)
Co-Products	478	461	mmBtu/hr
Adipic acid (polymer grade)	10,770	11,092	kg/hr
Recovered sodium sulfate salt from WWT	13,871	14,163	kg/hr

Table 13 (Cont.)

	Via Acids	Via BDO	
Resource Consumption		Flow Rate (kg/hr)	
Biomass feedstock (20% moisture)	104,167	104,167	
Sulfuric acid, 93%	10,531	10,835	
Caustic (as pure)	8,234	8,493	
	Both	5,833	5,833
	AA train	2,401	2,660
Ammonia	1,359	1,239	
	Fuel train	63	63
	AA train	81	86
	Both	1,215	1,090
Glucose	1,324	1,324	
Corn steep liquor	1,478	800	
	Fuel train	1,398	698
	AA train	80	102
Corn oil	7.3	7.3	
Host nutrients	37	37	
Sulfur dioxide	9	9	
Diammonium phosphate	714	626	
	Fuel train	190	71
	AA train	524	555
Toluene solvent makeup	90	0	
Hydrogen	0	816	
	Fuel train	0	408
	AA train	0	408
Ethanol	37	37	
Boiler chemicals	0.2	0.2	
FGD lime	97	103	
Cooling tower chemicals	3.4	2.1	
Makeup water	209,901	133,396	
Natural gas for boiler	0	1,300	
Natural gas for hot oil system	37.3	0	MMBtu/hr
Grid electricity (net import)	44,011	41,546	kW
Power Breakdown (Fraction of Total Facility Power Demand)			
A200 pretreatment	26.3%	31.7%	
A300 EH	25.0%	0.2%	
A400 enzymes	4.6%	5.5%	
A500 fermentation/upgrading	4.4%	18.9%	
A600 WWT	11.6%	13.3%	
A700 lignin	18.4%	22.7%	
A800 boiler	3.1%	2.4%	
A900 utilities	6.8%	5.3%	

About 97% of the toluene solvent makeup for the acids case ends up in the boiler and is combusted. The CO₂ emissions of toluene combustion are fully accounted for, and the emissions are considered fossil CO₂ emissions because toluene is made from fossil feedstock. CO₂ released upon acid neutralization of sodium carbonate (added in the 2020 SOT as part of the deacetylation step noted above) is also accounted for as fossil CO₂ emissions. Natural gas is used as a supplemental fuel in the boiler in the BDO intermediate route or in a hot oil heating system in the acids' intermediate route to meet process heat demands. Its use, as shown in Table 12, reflects the net gas inputs after accounting for burner efficiency losses. Grid electricity import is required for both fuel pathway designs, driven in part by high power/heat demands for the process and in part by diverting a portion of the residual solids (lignin) away from the boiler for adipic acid co-production.

2.3.5 Algae Hydrothermal Liquefaction (HTL)

This SCSA evaluates RD production from a blend feedstock consisting of algae and corn stover via HTL. An annual average blend of 58% saline algae and 42% corn stover by ash-free dry weight (AFDW) is formulated in the 2020 SOT case. Saline algae increases to 71% in the feedstock blend of the 2030 projection case, while corn stover accounts for 29% of the feedstock blend.

Figure 8 displays a simplified PFD for the algae/corn stover blend feedstock conversion via an HTL and upgrading system. Detailed process designs for co-feeding algae and corn stover in an HTL and upgrading system to make renewable diesel and naphtha-range fuels are given in Zhu et al. (2021). The major changes in the 2021 SOT case include blending corn stover (instead of logging residues) with saline algae as a feedstock blend, and producing lactic acid at a polymer grade (88 wt%) as a co-product via bioprocessing of carbohydrates extract from a two-stage sequential HTL reactor.

Given that the lactic acid co-product accounts for a significant portion (33%) of the total product slate by mass, we take the same purpose-driven, process-level allocation approach to evaluating the sustainability impacts of the renewable diesel product. At the same time, we apply an energy-based allocation method to allocate emission burdens between both liquid transportation fuels, the renewable diesel and the naphtha fuel products. With this method, we separate the biorefinery inputs dedicated to the fuel production, those dedicated to the co-product production, and those dedicated to both. For the inputs commonly shared by producing fuel and non-fuel products, we apply an allocation method based on either the masses or the market values of both products. The mass-based yields of both products are informed by process modeling, and the market prices for the renewable diesel and AA are assumed to be \$2.5/GGE and \$0.97/lbs (on a pure lactic acid basis).

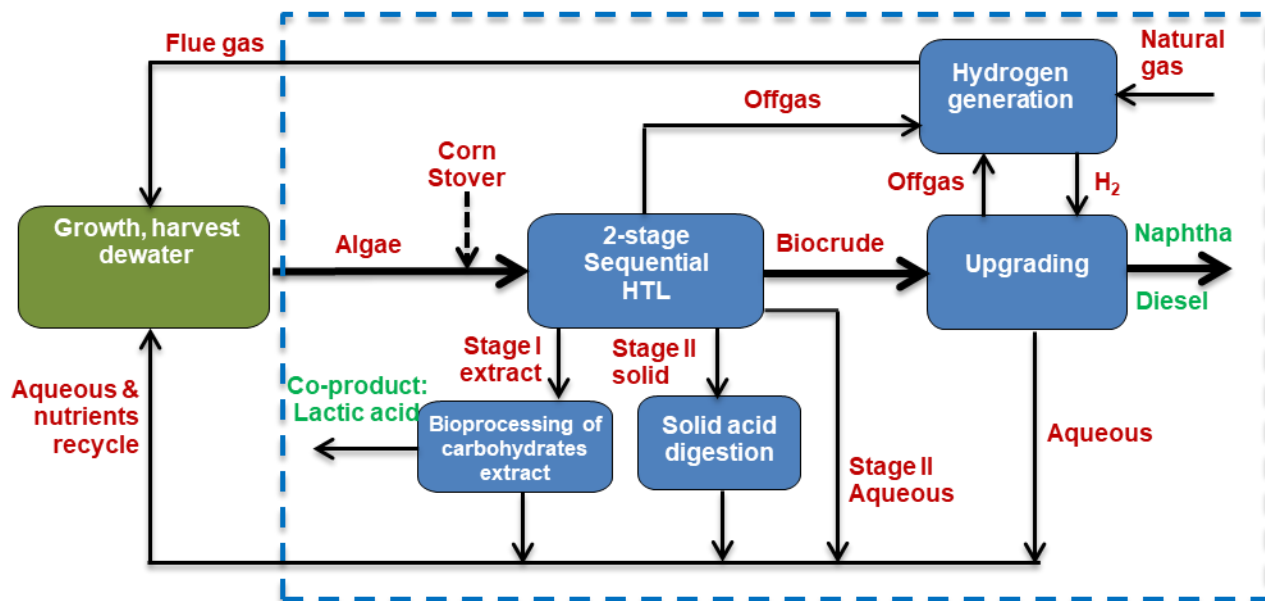


Figure 8 Process Flow Diagram for Hydrothermal Liquefaction of Co-Fed Algal and Corn Stover for Renewable Diesel Production in the 2020 SOT

Table 14 lists the overall material, energy, and water consumption for the modeled HTL conversion process at the plant in the 2020 SOT case and 2030 projection case. In addition, the allocated energy and material balances for fuel production only and for biochemical production only in the 2020 SOT and the 2030 projection case, using the mass- and market value-based process-level allocation approach, are summarized in Tables A7-A8. Table A9 presents the energy and material balances that are burdened to fuel production only, which are used to generate the results with the displacement method.

Table 14 Material, Energy, and Water Consumption for the Modeled HTL Conversion and Upgrading Process, 2020 SOT Case and 2030 Projection Case. Yellow inputs contribute to fuel production only, green inputs contribute to the biochemical production only, and blue inputs and outputs are shared by both the fuel and biochemical products.

	2020 SOT	2030 Projection	
Products	Production Rate		
Hydrocarbon Fuel			
Diesel	4,248	4,640	kg/hr
	173	189	MMBtu/h
Naphtha	2,256	2,464	kg/hr
	92	101	MMBtu/h
Co-products			
Lactic acid (polymer grade, 88 wt%)	3,133	4,791	kg/hr

Table 14 (Cont.)

		2020 SOT	2030 Projection	
Resource Consumption		Flow Rate (kg/hr)		
Feedstock				
	<i>Algae (AFDW basis)</i>	15,312	21,254	
	Fuel train	7,809	10,840	
	LA train	7,503	10,414	
	<i>Corn stover (AFDW basis)</i>	11,064	8,475	
	Fuel train	7,192	5,509	
	LA train	3,872	2,966	
Natural gas		4,157	5,214	
	Natural gas (for HTL)	1,389	2,200	
	Natural gas (for H ₂ production)	1,226	657	
	Natural gas (for bioprocessing)	1,542	2,357	
Sulfuric acid (93%)		7,741	8,710	
Na ₂ CO ₃		4,478	5,047	
Corn steep liquor		316	322	
NaOH		203	207	
Ethanol		30	46	
Ethylene glycol		50	76	
Reactive distillation catalyst		1.3	2.0	
Hydrotreating main bed catalyst		1.2	1.3	
HT guard bed catalyst		1.8	2.4	
Hydrocracking catalyst		0.02	0.02	
Boiler Chemicals		0.10	0.15	
	Fuel train	0.03	0.04	
	LA train	0.07	0.11	
Cooling Tower Chemicals		0.9	1.2	
	Fuel train	0.1	0.1	
	LA train	0.8	1.1	
Makeup water		6,834	7,702	
	Fuel train	6,151	6,932	
	LA train	683	770	
Electricity		7,871	8,704	kW
	Fuel train	2,991	3,308	kW
	LA train	4,880	5,397	kW

2.3.6 Combined Algae Processing (CAP)

The CAP model is based on NREL’s documented framework involving low-temperature biochemical fractionation of algal biomass into its respective constituents (lipids, carbohydrates, and protein) for subsequent upgrading of each constituent to fuels or products (Wiatrowski and Davis, 2021). In the process configurations evaluated here, a saline algae CAP model is configured to produce renewable fuels from lipids via extraction and upgrading and from sugars via either acid or BDO fermentation intermediates in the SOT and target cases (similar to the sugar fermentation concepts discussed previously for biochemical conversion). Protein and other residual fractions are routed to anaerobic digestion for combined heat and power generation as well as nutrient recycle credits back to the cultivation stage. In the 2020 SOT, a key update was the inclusion of a polyurethane (PU) co-product, produced from a fraction of the extracted algal lipids via epoxidation and ring opening to polyols, followed by reaction with isocyanates to produce PU foam (in part based on data furnished by UCSD under separate BETO project support). This inclusion significantly alters both the TEA and LCA outputs relative to prior SOT benchmarks that had not included chemical co-products in the CAP pathways. For future scenarios moving to 2030, this PU co-product inclusion is retained as a key means of supporting future cost targets. Figure 9 shows a block-flow diagram of the CAP conversion process. The 2020 SOT case reflects updated SOT algae farm model cultivation performance parameters, as well as higher dilute acid pretreatment sugar yields and the inclusion of the PU co-product train.

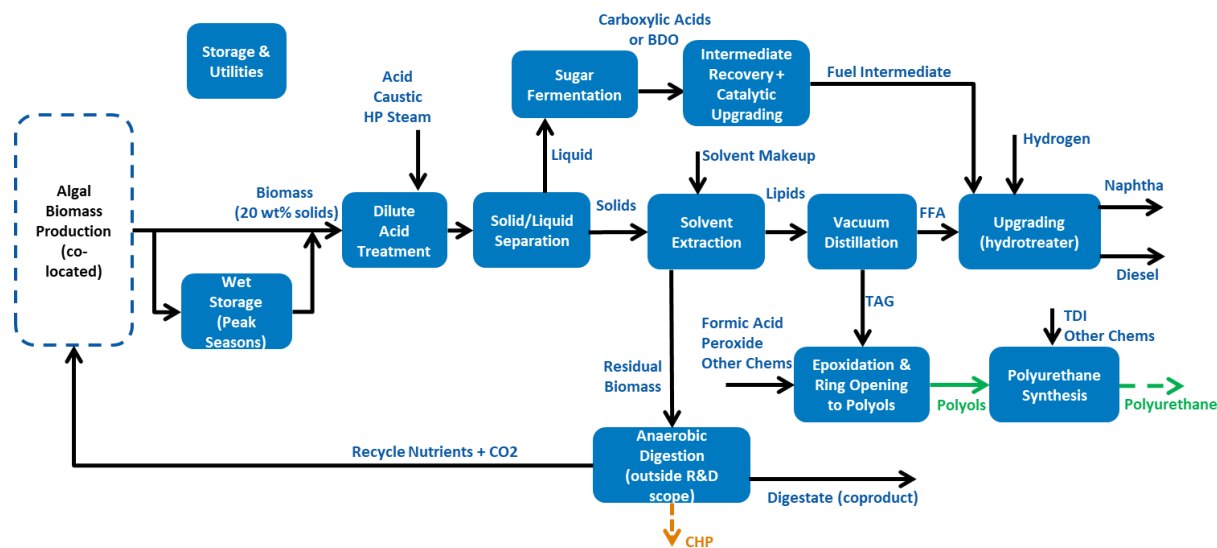


Figure 9 Block-Flow Diagram of the CAP Conversion Process as Reflected in the 2020 SOT

Given the significant amount of polyurethane (PU) co-product in the 2020 SOT case, which accounts for 54% by mass of the total product slate including RD, naphtha, and PU, we decided to take the same purpose-driven, process-level allocation method in this SCSA, as described above for other pathways involving non-fuel co-products. For the inputs that are commonly shared by production of both the fuel and non-fuel products, we apply an allocation method based on either the masses or the market values of both products. The mass-based yields

of both products are informed by the process modeling, and the market prices for the renewable diesel and PU are assumed to be \$2.5/GGE and \$2.04/lbs. We also allocate the surplus electricity that is generated from the entire conversion process between the fuel and non-fuel products. The surplus electricity accounts for about 1% of the total energy products by energy content. We apply the displacement method to evaluate its sustainability impacts. At the same time, we apply an energy-based allocation method to allocate emission burdens between both liquid transportation fuels, the renewable diesel and the naphtha fuel products.

To address the effects of the significant output of the PU co-product, we applied the purpose-driven, process-level allocation method to address the 2020 SOT case, as well as the 2025 and 2030 projection cases, in addition to the displacement method and biorefinery-level analysis.

Tables 15-17 list the overall energy and material inputs for the modeled CAP conversion process in the 2020 SOT case and future out-year projections (in 2025 and 2030), via either acids or BDO intermediate pathways for fuel production. Note that the life-cycle inventory data have been updated to reflect revisions to heat integration of the process-modeling since the publication of the 2020 SOT report (Wiatrowski and Davis, 2021), which affects the process energy balance. In addition, the allocated energy and material balances for fuel production only and for biochemical production only in the 2020 SOT and the 2030 projection case, using the mass- and market value-based process-level allocation approach, are summarized in Tables A10-A15. Tables A16-A18 present the energy and material balances that are burdened to fuel production only, which are used to generate the results with the displacement method.

Table 15 Overall Energy and Material Inputs and Outputs in the Modeled CAP Conversion Processes in the 2020 SOT Case via Acids and BDO as Intermediate Pathways. Yellow inputs contribute to fuel production only, green inputs contribute to the biochemical production only, and blue inputs and outputs are shared by both the fuel and biochemical products.

	Via Acids	Via BDO	
Products		Production Rate	
Hydrocarbon Fuel			
Diesel	2,133	1,921	kg/hr
Naphtha	837	1,034	kg/hr
Co-products			
Polyurethane	3,432	3,432	kg/hr
Power exported to grid	5,357	6,382	kW
Resource Consumption		Flow Rate (kg/hr)	
Feedstock (AFDW basis)	15,312	15,312	
Pretreatment			
Sulfuric acid (93% pure)	1,365	1,365	
Ammonia	441	441	

Table 15 (Cont.)

	Via Acids	Via BDO
<i>Lipid Extraction and Cleanup</i>		
Hexane requirement	80	80
Ethanol	32	32
Phosphoric acid (oil cleanup)	44	44
Silica (oil cleanup)	4	4
Clay (oil cleanup)	9	9
<i>Carboxylic Acid / 2,3-BDO Conversion</i>		
Corn steep liquor	694	103
Diammonium phosphate	72	13
Hydrogen		78
Flocculant	61	61
Dehydration catalyst		0.06
Oligomerization catalyst		0.1
Hydrotalcite	1	
Hexane	1	
Ketonization catalyst (ZrO ₂)	0.03	
Condensation catalyst (niobic acid)	0.2	
<i>Final Fuel Upgrading (HDO/HI)</i>		
Hydrogen	100	90
One-step HDO/HI catalyst (1% Pt/SAPO-11)	0.2	0.2
<i>Polyurethane Production</i>		
Formic acid	331	331
H ₂ O ₂	525	525
Catalysts and other chemicals	8	8
Nitrogen	50	50
Toluene diisocyanate	911	911
Diethanolamine	9	9
Surfactant	17	17
<i>Other Resource Consumption</i>		
Supplemental natural gas (total)	1,984	3,301
Supplemental natural gas (fuel+PU)	999	1,405
Supplemental natural gas (fuel)	106	728
Supplemental natural gas (PU)	879	1,168
Process water (total)	61,777	98,968
Process water (fuel+PU)	44,665	51,553
Process water (fuel)	94	30,395
Process water (PU)	17,019	17,019

Table 15 (Cont.)

Output Streams	Flow Rate (kg/hr)	
AD digestate cake (dry basis total flow)	3,541	3,374
AD digestate cake bioavailable N	18	17
AD effluent NH ₃	222	216
AD effluent DAP	105	74
Recycle water (excluding N/P nutrients)	99,883	102,324
CO₂ Recycle		
CO ₂ (biogenic)	8,775	8,647
CO ₂ (fossil)	5,981	9,594

Table 16 Overall Energy and Material Inputs and Outputs in the Modeled CAP Conversion Processes in the 2025 Projection Case via Acids and BDO as Intermediate Pathways. Yellow inputs contribute to fuel production only, green inputs contribute to the biochemical production only, and blue inputs and outputs are shared by both the fuel and biochemical products.

	Via Acids	Via BDO	
Products		Production Rate	
Hydrocarbon Fuel			
Diesel	3,150	2,901	kg/hr
Naphtha	1,250	1,643	kg/hr
Co-products			
Polyurethane	4,787	4,784	kg/hr
Power exported to grid	10,053	10,840	kW
Resource Consumption		Flow Rate (kg/hr)	
Feedstock (AFDW basis)	20,924	20,924	
Pretreatment			
Sulfuric acid (93% pure)	909	908	
Ammonia	294	293	
Lipid Extraction and Cleanup			
Hexane requirement	107	108	
Ethanol	43	43	
Phosphoric acid (oil cleanup)	61	61	
Silica (oil cleanup)	6	6	
Clay (oil cleanup)	12	12	
Carboxylic Acid / 2,3-BDO Conversion			
Corn steep liquor	953	158	
Diammonium phosphate	98	19	
Hydrogen		134	
Flocculant	80	80	
Dehydration catalyst		0.1	
Oligomerization catalyst		0.2	
Hydrotalcite	1		

Table 16 (Cont.)

	Via Acids	Via BDO	
Hexane	1		
Ketonization catalyst (ZrO ₂)	0.04		
Condensation catalyst (niobic acid)	0.3		
Final Fuel Upgrading (HDO/HI)			
Hydrogen	148	136	
One-step HDO/HI catalyst (1% Pt/SAPO-11)	0.3	0.4	
Polyurethane Production			
Formic acid	462	462	
H ₂ O ₂	732	731	
Nitrogen	70	70	
Toluene diisocyanate	1,270	1,269	
Diethanolamine	12	12	
Surfactant	23	23	
Catalysts and other chemicals			
Tin catalyst (stannous octoate)	8	8	
DABCO (1,4-diazabicyclo[2.2. 2]octane)	4	4	
Other Resource Consumption			
Supplemental natural gas (total)	3,064	4,632	
Supplemental natural gas (fuel+PU)	1,539	1,705	
Supplemental natural gas (fuel)	180	1,216	
Supplemental natural gas (PU)	1,344	1,711	
Process water (total)	123,749	175,648	
Process water (fuel+PU)	99,565	111,907	
Process water (fuel)	139	39,696	
Process water (PU)	24,045	24,045	
Output Streams		Flow Rate (kg/hr)	
AD digestate cake (dry basis total flow)	4,082	3,805	
AD digestate cake bioavailable N	25	24	
AD effluent NH ₃	319	310	
AD effluent DAP	146	107	
Recycle water (excluding N/P nutrients)	168,993	140,390	
CO₂ Recycle			
CO ₂ (biogenic)	11,897	11,761	
CO ₂ (fossil)	9,187	13,433	

Table 17 Overall Energy and Material Inputs and Outputs in the Modeled CAP Conversion Processes in the 2030 Projection Case via Acids and BDO as Intermediate Pathways. Yellow inputs contribute to fuel production only, green inputs contribute to the biochemical production only, and blue inputs and outputs are shared by both the fuel and biochemical products.

	Via Acids	Via BDO	
Products	Production Rate		
Hydrocarbon Fuel			
Diesel	3,315	2,999	kg/hr
Naphtha	1,302	1,670	kg/hr
Co-products			
Polyurethane	4,345	4,525	kg/hr
Power exported to grid	10,275	10,963	kW
Resource Consumption	Flow Rate (kg/hr)		
Feedstock (AFDW basis)	20,924	20,924	
Pretreatment			
Sulfuric acid (93% pure)	908	908	
Ammonia	293	293	
Lipid Extraction and Cleanup			
Hexane requirement	107	108	
Ethanol	43	43	
Phosphoric acid (oil cleanup)	61	61	
Silica (oil cleanup)	6	6	
Clay (oil cleanup)	12	12	
Carboxylic Acid / 2,3-BDO Conversion			
Corn steep liquor	953	158	
Diammonium phosphate	98	19	
Hydrogen		134	
Flocculant	80	80	
Dehydration catalyst		0.1	
Oligomerization catalyst		0.2	
Hydrotalcite	1		
Hexane	1		
Ketonization catalyst (ZrO ₂)	0.04		
Condensation catalyst (niobic acid)	0.3		
Final Fuel Upgrading (HDO/HI)			
Hydrogen	158	142	
One-step HDO/HI catalyst (1% Pt/SAPO-11)	0.3	0.4	

Table 17 (Cont.)

	Via Acids	Via BDO	
<i>Polyurethane Production</i>			
Formic acid	419	437	
H ₂ O ₂	664	692	
Nitrogen	63	66	
Toluene diisocyanate	1,153	1,201	
Diethanolamine	11	12	
Surfactant	21	22	
Catalysts and other chemicals			
Tin catalyst (stannous octoate)	7	8	
DABCO (1,4-diazabicyclo[2.2. 2]octane)	3	4	
<i>Other Resource Consumption</i>			
Supplemental natural gas (total)	3,052	4,618	
Supplemental natural gas (fuel+PU)	1,535	1,710	
Supplemental natural gas (fuel)	181	1,213	
Supplemental natural gas (PU)	1,335	1,695	
Process water (total)	123,166	175,151	
Process water (fuel+PU)	98,729	111,405	
Process water (fuel)	146	39,700	
Process water (PU)	24,292	24,045	
Output Streams		Flow Rate (kg/hr)	
AD digestate cake (dry basis total flow)	4,042	3,783	
AD digestate cake bioavailable N	25	24	
AD effluent NH ₃	319	310	
AD effluent DAP	146	107	
Recycle water (excluding N/P nutrients)	168,933	140,387	
<i>CO₂ Recycle</i>			
CO ₂ (biogenic)	12,007	11,841	
CO ₂ (fossil)	9,132	13,383	

Like the algae HTL case, a nutrient-rich effluent produced in the AD process can be recycled to the algae cultivation ponds. For the SCSAs, we assumed that the NH₃ and diammonium phosphate from the AD effluent reduce the nitrogen and phosphorus demand (as indicated by the algal farm model) and the bioavailable nitrogen from the AD digestate cake is sold as a nitrogen fertilizer and displaces synthetic nitrogen fertilizers on a kg for kg basis.

Like the algae HTL case, a nutrient-rich effluent produced in the AD process can be recycled to the algae cultivation ponds. For the SCSAs, we assumed that the NH₃ and diammonium phosphate from the AD effluent reduce the nitrogen and phosphorus demand (as

indicated by the algal farm model) and the bioavailable nitrogen from the AD digestate cake is sold as a nitrogen fertilizer and displaces synthetic nitrogen fertilizers on a kg for kg basis.

2.4 End-of-Life Implications of Bio-Based Chemicals

Value-added bio-based chemicals as co-products from integrated biorefineries contain biogenic carbon from the biomass feedstock and could serve as a biogenic carbon sink at the end of its service life, depending on its biodegradability. Furthermore, bio-based chemicals from the biorefinery could offer additional carbon reduction benefit comparable to its fossil-derived counterparts. In some cases, a bio-based chemical may contain a certain amount of fossil carbon during the chemical conversion processes. To holistically address the carbon emission impacts of bio-based chemicals as a biorefinery co-products, we consider both the source and fate of the carbon in the bio-based chemicals as well as those of the fossil-derived counterparts, as shown in Equations (1) and (2). The net carbon emission impacts of bio-based chemical relative to the fossil-derived counterpart can be calculated with Equation (3).

$$CO2_{bio} = M_{bio} \times [(1 - D\%_{bio}) \times BC\%_{bio} \times (-1) + (1 - D\%_{bio}) \times FC\%_{bio} \times 0 + D\%_{bio} \times BC\%_{bio} \times 0 + D\%_{bio} \times FC\%_{bio} \times 1] \times 44/12 \quad (1)$$

$$CO2_{fossil} = M_{fossil} \times [(1 - D\%_{fossil} \times FC\%_{fossil} \times 0 + D\%_{fossil} \times FC\%_{fossil} \times 1)] \times 44/12 \quad (2)$$

$$\begin{aligned} Net\ CO2_{bio-fossil} &= CO2_{bio} - CO2_{fossil} = \{M_{bio} \times [(1 - D\%_{bio}) \times BC\%_{bio} \times (-1) + (1 - D\%_{bio}) \times FC\%_{bio} \times 0 + D\%_{bio} \times BC\%_{bio} \times 0 + D\%_{bio} \times FC\%_{bio} \times 1] - \\ &M_{fossil} \times [(1 - D\%_{fossil}) \times FC\%_{fossil} \times 0 + D\%_{fossil} \times FC\%_{fossil} \times 1]\} \times \frac{44}{12} = \\ &\{M_{bio} \times [(1 - D\%_{bio}) \times BC\%_{bio} \times (-1) + D\%_{bio} \times FC\%_{bio} \times 1] - M_{fossil} \times \\ &[D\%_{fossil} \times FC\%_{fossil} \times 1]\} \times 44/12 \quad (3) \end{aligned}$$

Where:

$CO2_{bio}$ is the sum of fossil CO₂ emissions, if any, upon degradation of the bio-based chemical, plus any sequestration CO₂ emission credit for the bio-based chemical;

$CO2_{fossil}$ is the fossil CO₂ emissions, if any, upon degradation of the fossil-derived chemical;

M_{bio} and M_{fossil} are a unit mass of the bio-based and fossil-derived chemicals, respectively;

$D\%_{bio}$ and $D\%_{fossil}$ are the degradation rate of the bio-based and fossil-derived chemicals, respectively;

$BC\%_{bio}$ and $FC\%_{bio}$ are the biogenic carbon content and the fossil carbon content of the bio-based chemical, respectively;

$FC\%_{fossil}$ is the fossil carbon content of fossil-derived chemical; and

$Net\ CO2_{bio-fossil}$ is the net CO₂ emissions of the bio-based chemical relative to the fossil-derived counterpart.

In many cases, $BC\%_{bio}$ is the same as $FC\%_{fossil}$ when the bio-based chemical and fossil-derived counterpart have identical chemical compositions. In such cases, $D\%_{bio}$ and $D\%_{fossil}$ are assumed the same. In addition, when 100% of the carbon in bio-based chemical comes from biogenic sources, e.g., biomass feedstocks, the $Net\ CO2_{bio-fossil}$ is determined by biogenic carbon content of the bio-based chemical, regardless of its degradability. However, in some cases when fossil carbon, together with biogenic carbon, is involved in making the bio-based chemical, the $Net\ CO2_{bio-fossil}$ is determined by a set of parameters, including $BC\%_{bio}$, $FC\%_{bio}$, $FC\%_{fossil}$, $D\%_{bio}$ and $D\%_{fossil}$, as shown in Equation (3).

3 RESULTS AND DISCUSSION

The feedstock and conversion process model input/output inventories were furnished to the GREET model to calculate overall life-cycle metrics of the six renewable fuel pathways.

3.1 Indirect Liquefaction

The SCSA of the IDL pathway used a 50-50 blend of clean pine and logging residue in the 2020 feedstock SOT.

3.1.1 Supply Chain Greenhouse Gas Emissions

The GHG emission intensity of HOG production in the biorefinery is about 1.9 g CO_{2e}/MJ in the 2020 SOT case. Note that these conversion GHG emissions include both direct emissions from the combustion of intermediate process energy, such as biochar and fuel gas during the conversion stage, and upstream emissions associated with the production of catalysts used in the conversion. The energy self-sufficient design of the IDL conversion processes has contributed to the low emission intensity at the conversion step since the earlier SOT cases. With little contribution from energy consumption to GHG emissions from the IDL process, the production and use of catalysts is the major driver for the minimal GHG emissions from this supply chain step. Combustion of the fuel gas and char would produce CH₄ and N₂O, and these emissions are estimated through the application of emission factors in the GREET model developed for boiler combustion of refinery fuel gas and char.

The 2020 SOT case co-produces a small amount of surplus electricity. We used the displacement co-product treatment method to account for the energy, emission, and water credits resulting from transmitting the surplus electricity to the grid and displacing the U.S. average electricity. Figure 10 shows the supply chain GHG emissions.

The supply chain GHG emissions of HOG via IDL is 19 g CO_{2e}/MJ in the 2020 SOT case. Clean pine production and biomass logistics are the dominant contributors to the supply chain GHG emissions, accounting for 31% and 53% of the supply chain GHG emissions, respectively. The IDL conversion process contributes 10% of the supply chain GHG emissions. These do not change much compared to the 2019 SOT and 2022 design cases, given the same energy self-sufficient process design in these cases.

Compared with petroleum-derived gasoline, HOG via IDL offers a significant supply chain GHG emission reductions of 80% in the 2020 SOT case.

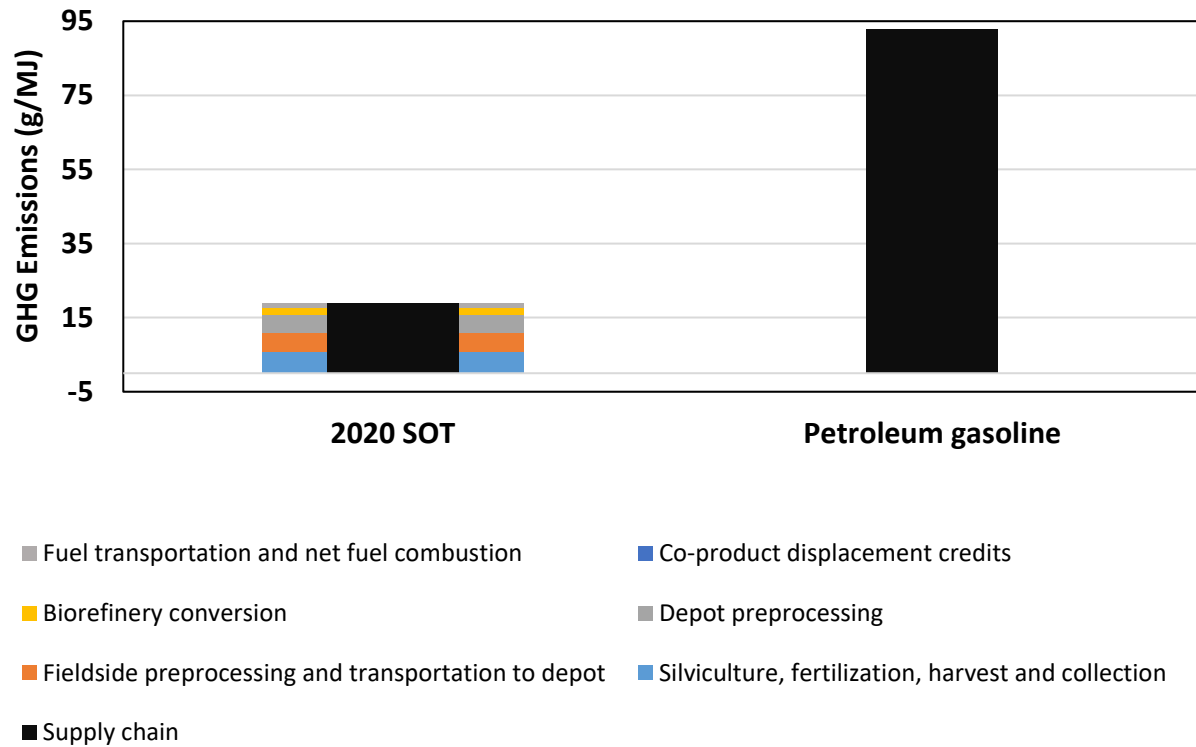


Figure 10 Supply Chain GHG Emissions (g CO₂e/MJ), High Octane Gasoline via IDL

At the biorefinery level with the minimal amount of co-produced electricity, essentially the biorefinery-level emission reduction comes entirely from HOG, as shown in Figure 11. About 475 kg CO₂e of GHG emission reduction could be achieved per ton of feedstock blend converted to HOG fuel via the IDL pathway.

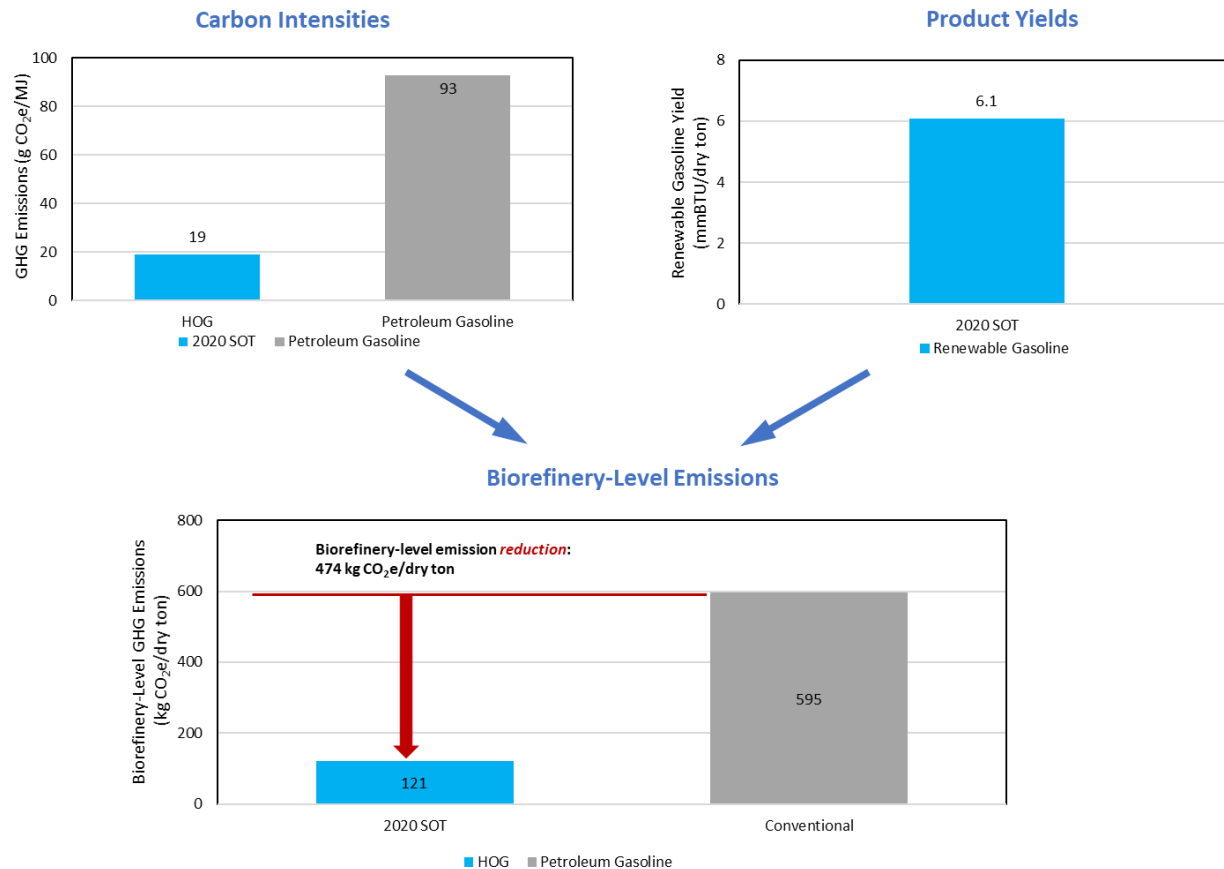


Figure 11 Biorefinery-Level Greenhouse Gas Emissions and Reductions, the 2020 SOT Case of the IDL Pathway

3.1.2 Supply Chain Water Consumption

The supply chain water consumption of HOG produced via IDL is about 4.7 gal/gasoline gallon equivalent (GGE) in the 2020 SOT case, compared to about 3.2 gal/GGE for petroleum gasoline blendstock (Wang et al. 2020).

Figure 12 shows the supply chain water consumption of HOG via IDL in gal/GGE with the displacement method. The largest contributor to the supply chain water consumption is the IDL process (i.e., biorefinery), accounting for about 71%. The water is consumed for process cooling and boiler feed water makeup. Another step contributing to the supply chain water consumption is the relatively energy-intensive depot preprocessing, accounting for about 17%, owing to water consumption associated with the production of process energy (electricity) required for the preprocessing.

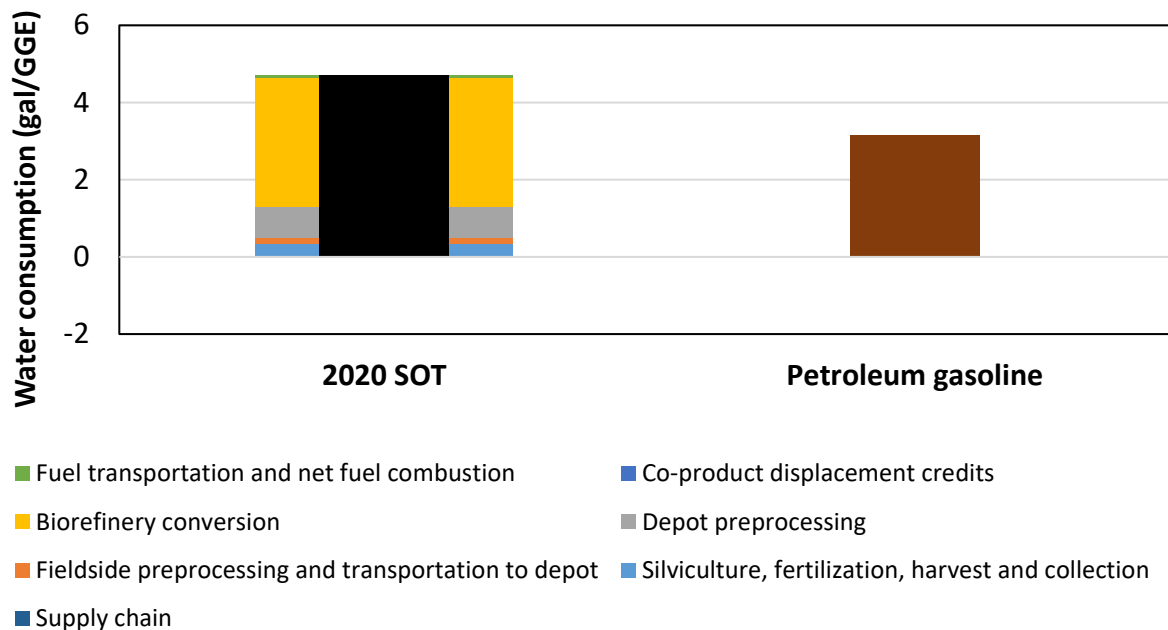


Figure 12 Supply Chain Water Consumption (gal/GGE) of High Octane Gasoline via IDL, Compared to 3.2 gal/GGE for Petroleum Gasoline

The direct water consumption during the conversion process increases from 2.8 gal/GGE in the 2019 SOT case to 3.3 gal/GGE in the 2019 SOT case, which is a 17% increase in direct water consumption.

3.1.3 Supply Chain NO_x Emissions

The supply chain NO_x emissions of HOG produced via IDL is about 0.22 g/MJ in the 2020 SOT case, compared to about 0.05 g/MJ for petroleum gasoline blendstock (Wang et al. 2020).

Figure 13 shows that NO_x emissions are mostly attributable to the IDL process, fieldside preprocessing, and biomass transportation. Similar to the other cases, combusting intermediate bio-char and fuel gas in boilers inside biorefinery for process heat purposes is the dominant cause for the conversion NO_x emissions, accounting for about half of the total supply chain emissions, while diesel fuel combustion by a chipper is responsible for the emissions at the field preprocessing stage. Fuel transportation by diesel truck and fuel combustion contributes about 0.03 g/MJ of the total supply chain emissions. Given the energy self-sufficient design of the IDL process, which heavily relies on the combustion of intermediate bio-char and fuel gas to meet process heat demand, NO_x emission control of this combustion source presents the greatest opportunity to mitigate the supply chain NO_x emissions of the HOG via IDL pathway.

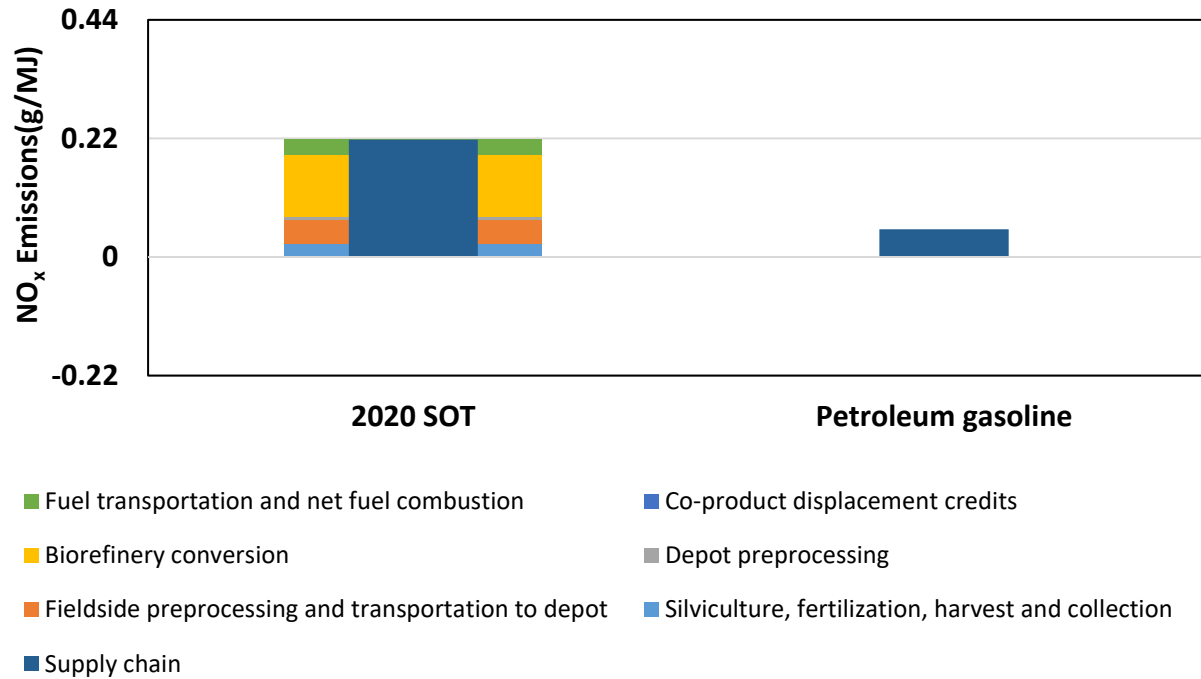


Figure 13 Supply Chain NO_x Emissions (g/MJ), High Octane Gasoline via IDL, Compared to 0.05 g/MJ for Petroleum Gasoline

3.1.4 Summary of Sustainability Metrics

Table 18 summarizes supply chain sustainability metrics in different functional units evaluated for the 2020 SOT case of HOG via IDL.

Table 18 Supply Chain Sustainability Metrics for High Octane Gasoline via IDL

	2020 SOT	Petroleum Gasoline
	Biofuel yield	
Million Btu/dry ton	6.1	
	Fossil energy consumption	
MJ/MJ	0.21 (-83%)	1.23
	Net energy balance	
MJ/MJ	0.79	
	GHG emissions	
g CO ₂ e/MJ	19 (-80%)	93
g CO ₂ e/GGE	2,309	11,357
	Water consumption	
gal/MJ	0.038	0.026
gal/GGE	4.7	3.2
	Total NO_x emissions	
g NO _x /MJ	0.22	0.052
g NO _x /GGE	26.7	6.3
	Urban NO_x emissions	
g NO _x /MJ	0.019	0.023
g NO _x /GGE	2.3	2.8

Note: The values in parentheses are the percentage of difference compared to the petroleum diesel pathway. Reduction is represented with negative values.

In addition to GHG emissions, water consumption, and total NO_x emissions as described above, Table 18 lists the supply chain fossil energy consumption and the net energy balance (NEB) as two energy-related metrics. Fossil energy consumption of HOG via IDL shows a significant reduction of 83% in the 2020 SOT case, compared with that of petroleum gasoline, owing mostly to energy self-sufficient IDL processes and the use of excess process heat from the IDL processes for feedstock depot preprocessing, which reduce the need for external energy. NEB is defined as the balance of biofuel energy output minus the supply chain fossil energy consumption used to produce the biofuel. NEB represents the net fossil energy savings from using biofuels to displace fossil fuels. A net energy balance of 0.79 MJ/MJ of HOG produced is estimated for the 2020 SOT case, showing significant fossil energy saving benefits for HOG via IDL.

As air pollutant emissions (including NO_x emissions) are known to pose potential human health impacts, we define the emissions that occur in municipal statistical areas (MSAs) where more people could be exposed to the emissions as urban emissions, as differentiated from the total supply chain NO_x emissions regardless of where they occur. HOG via IDL shows about 17% reduction potential in urban NO_x emissions in the 2020 SOT case, compared with those of petroleum gasoline, because biorefinery and depot preprocessing emissions, the primary emission sources of HOG, are assumed to occur in rural, non-MSA areas where the biorefinery likely would be built.

3.2 Ex Situ Catalytic Fast Pyrolysis

The feedstock of SCSA of the CFP pathway consists of 50% logging residues and 50% clean pine for the 2020 SOT case.

3.2.1 Supply Chain Greenhouse Gas Emissions

For the CFP pathway, total GHG emissions from the woody feedstock production and logistics in the 2020 SOT case were estimated at 205.9 kg CO₂e/dry ton. A decrease in GHG emission intensities from the 2019 SOT case (253.9 kg CO₂e/dry ton) to the 2020 SOT case reflects an improvement in energy efficiency of feedstock logistics operations to make the woody feedstock blend (50% clean pine and 50% logging residues) ready for CFP conversion.

On the other hand, the GHG emission intensity of renewable fuel production in the CFP biorefinery is 1.4 g CO₂e/MJ, when the displacement credit of the co-products (surplus electricity, acetone, and 2-butanone) is excluded. Most of the process CO₂ emissions at the biorefinery are biogenic CO₂ emissions. They are from the combustion of pyrolysis char, of which 100% of the carbon comes from the biomass feedstock and from hydrogen production from biogenic off-gases. A small amount of fossil-derived GHG emissions at the biorefinery include emissions from H₂ production from minimal supplemental fossil natural gas included for steam reforming and upstream emissions associated with production of catalysts used in the conversion. The energy self-sufficient design of the CFP conversion process contributes to the low emission intensity at the biorefinery. However, significant GHG emissions occur during co-processing at the petroleum refinery because of the assumption of non-renewable, natural gas derived hydrogen use, thus increasing the GHG emissions from the overall conversion process.

Figure 14 shows the supply chain GHG emissions for RG and RD via CFP in the 2020 SOT case compared to petroleum gasoline. Production, logistics, and preprocessing of the feedstock blend to make it conversion-ready accounts for 26.7 g CO₂e/MJ. The petroleum refinery co-hydrotreating, the major change in the 2020 SOT case, contributes 29.0 g CO₂e/MJ, owing to consumption of a significant amount of fuel natural gas and electricity, as shown in Table 9. Acetone and 2-butanone, which account for about 14.9% by mass of the total product slate except for surplus electricity, generates a displacement credit of 19.1 g CO₂e/MJ. In addition, surplus electricity contributes to another displacement credit of 18.5 g CO₂e/MJ.

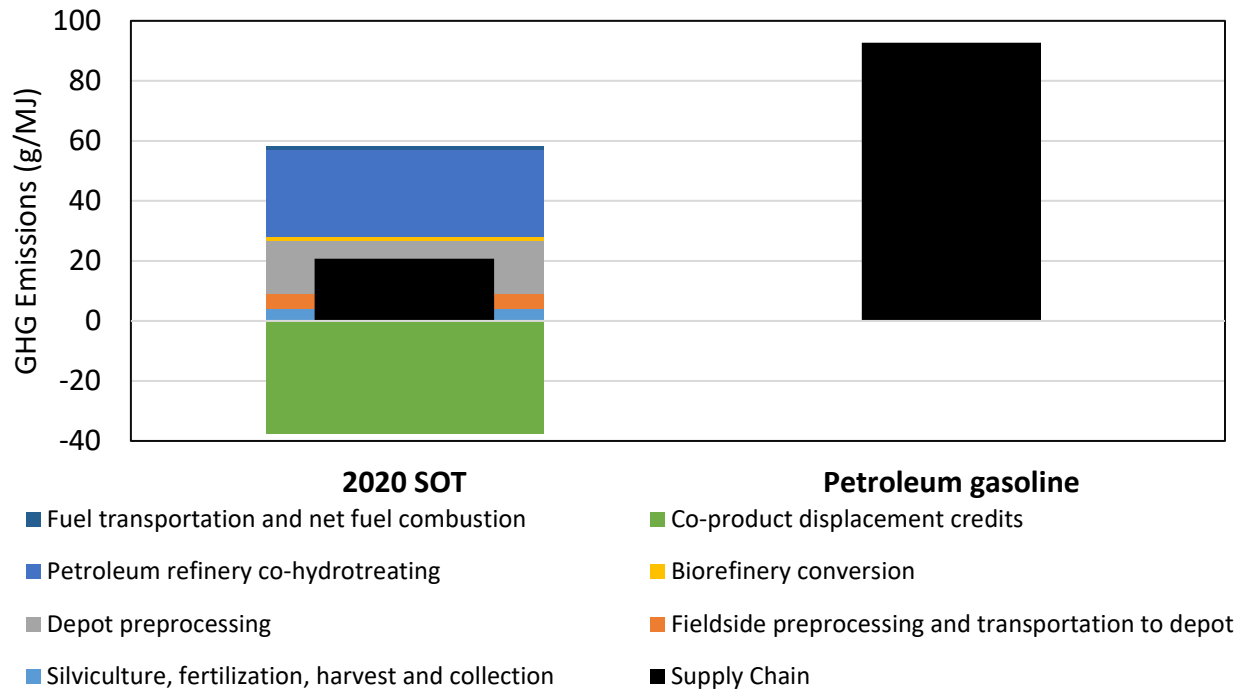


Figure 14 Supply Chain GHG Emissions (g CO₂e/MJ), Renewable Gasoline/Renewable Diesel via CFP

The supply chain GHG emission intensities of RG and RD are estimated at 20.7 g CO₂e/MJ in the 2020 SOT case. Compared with petroleum-derived gasoline, RG and RD via CFP offer a significant supply chain GHG emission reduction of 78% in the 2020 SOT case.

At the biorefinery level, about 531 kg CO₂e/ton of biomass converted to RG/RD fuels via CFP would be expected (see Figure 15). Most of the biorefinery-level GHG emission reduction comes from the RG/RD fuels displacing petroleum gasoline and diesel fuels. In future work, we will examine process-level details to estimate product-specific carbon intensities for RG/RD and the co-products, and will quantify contributions of the fuel products and non-fuel co-products to the biorefinery-level GHG emission reduction.

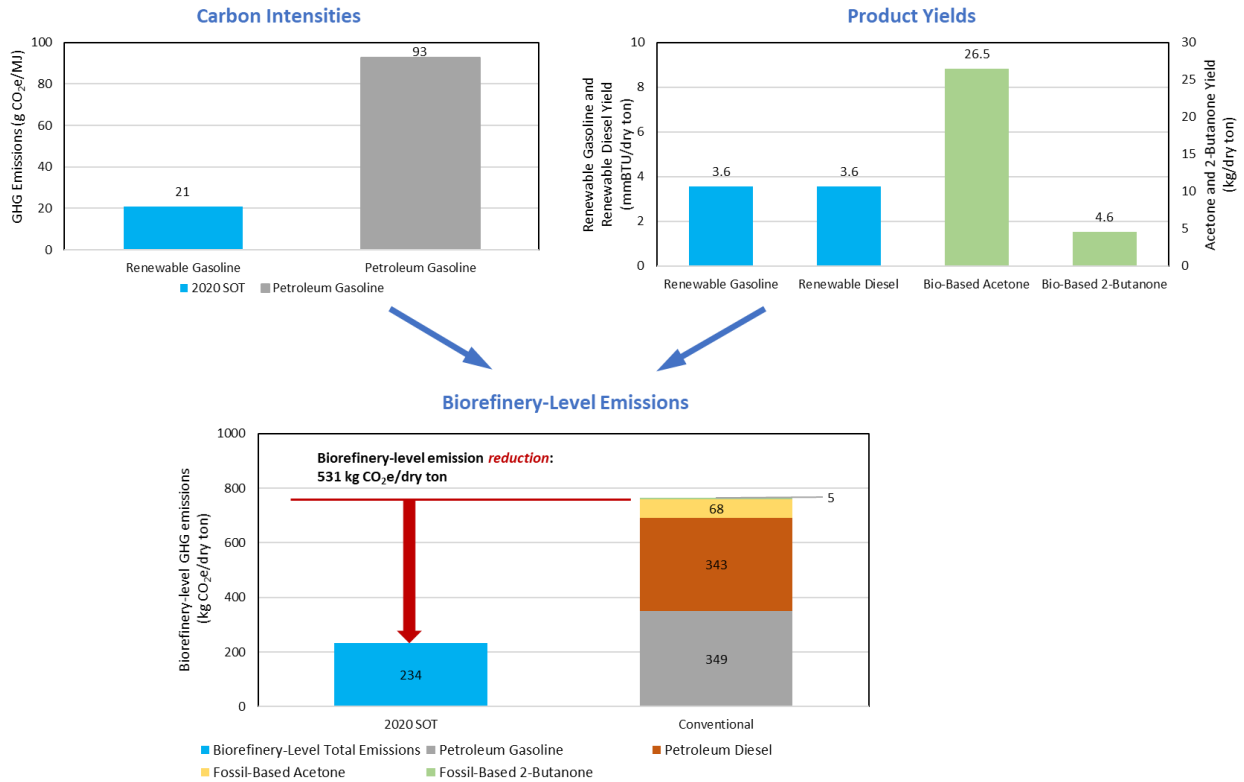


Figure 15 Biorefinery-Level Greenhouse Gas Emissions and Reductions, the 2020 SOT Case of the Ex Situ CFP Pathway

3.2.2 Supply Chain Water Consumption

The supply chain water consumption of RG and RD produced via CFP is about -1.79 gal/GGE in the 2020 SOT case, compared with about 3.2 gal/GGE for petroleum gasoline blendstock (Wang et al. 2020).

Figure 16 shows the supply chain water consumption of RG via CFP in gal/GGE. The petroleum refinery co-hydrotreating, biomass preprocessing, and biomass conversion at the CFP biorefinery are major contributors to the supply chain water consumption. Meanwhile, displacement credit of the co-products, especially 2-butanone, more than offsets the direct water consumption, resulting in a net negative supply chain water consumption for the renewable fuels.

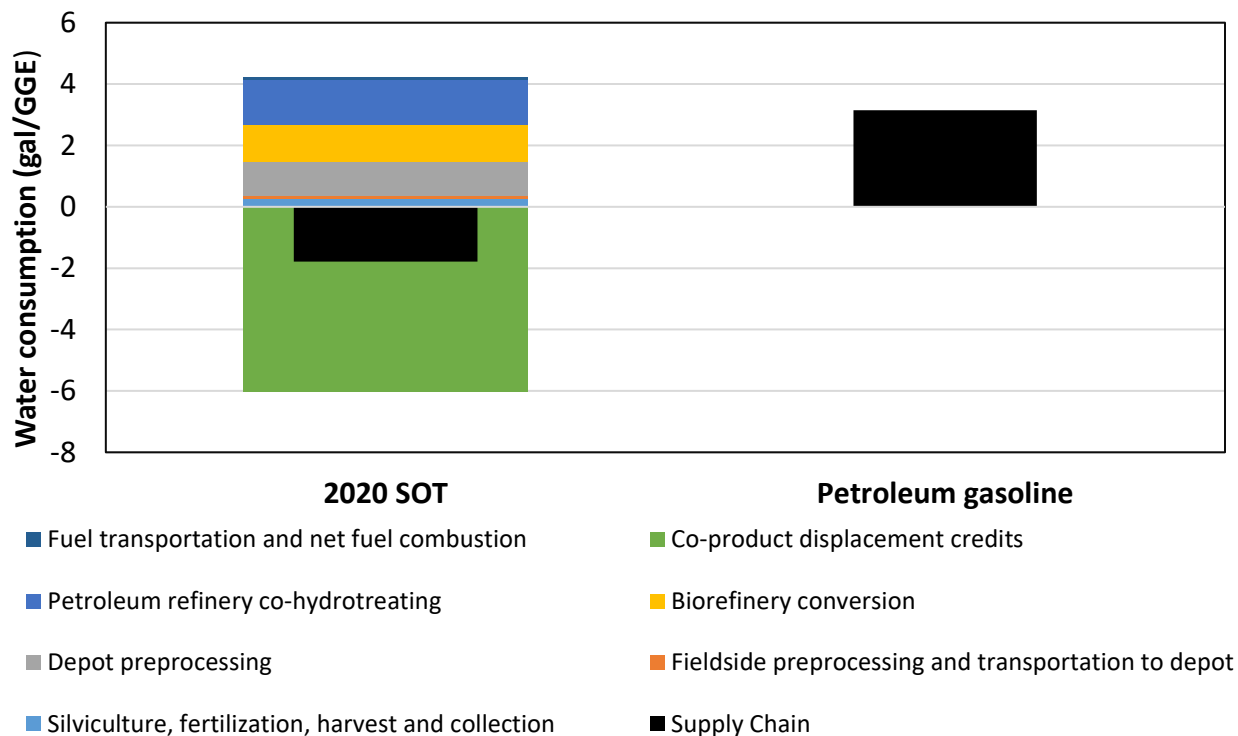


Figure 16 Supply Chain Water Consumption (gal/GGE), Renewable Gasoline/Renewable Diesel via CFP, Compared to 3.2 gal/GGE for Petroleum Gasoline

The direct water consumption during the CFP conversion process is reduced from 1.7 gal/GGE in the 2019 SOT case to 1.1 gal/GGE (excluding the co-processing water consumption) in the 2020 SOT case, which is a 32% reduction in direct water consumption.

3.2.3 Supply Chain NO_x Emissions

The supply chain NO_x emissions of RG and RD via CFP are about 0.27 g/MJ in the 2020 SOT case, compared with about 0.052 g/MJ for petroleum gasoline blendstock (Wang et al. 2020).

According to Figure 17, NO_x emissions in the 2020 SOT case are mostly attributable to energy-intensive depot preprocessing, accounting for about 46% of the total emissions.

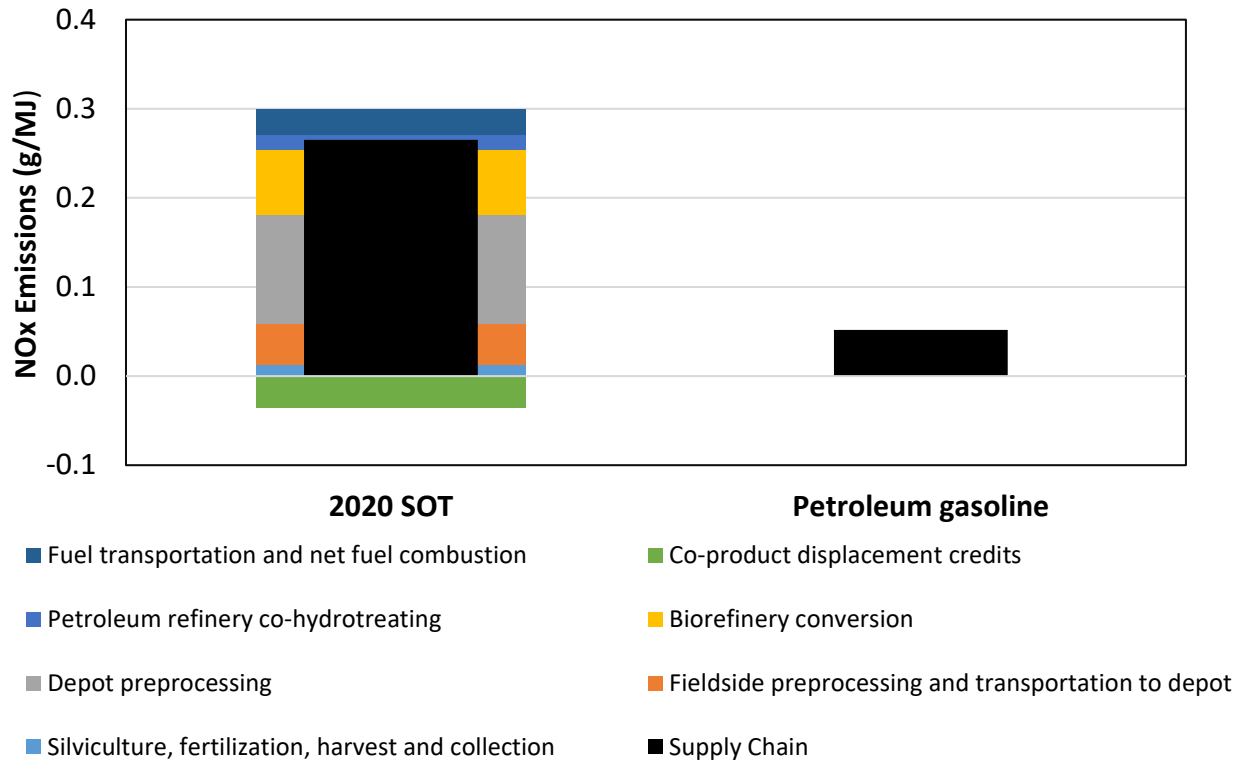


Figure 17 Supply Chain NO_x Emissions (g/MJ), Renewable Gasoline/Renewable Diesel via CFP, Compared to 0.05 g/MJ for Petroleum Gasoline

3.2.4 Summary of Sustainability Metrics

Table 19 summarizes the supply chain sustainability metrics, including fossil energy consumption, net energy balance, greenhouse gas emissions, water consumption, and NO_x emissions of RG and RD from CFP for the 2020 SOT case.

Table 19 Supply Chain Sustainability Metrics for Renewable Gasoline/Renewable Diesel via CFP

	2020 SOT	Petroleum Gasoline
		Biofuel yield^a
Million Btu/dry ton	7.3	
		Fossil energy consumption
MJ/MJ	0.31 (-75%)	1.23
		Net energy balance
MJ/MJ	0.69	
		GHG emissions
g CO ₂ e/MJ	21 (-78%)	93
g CO ₂ e/GGE	2,538	11,360
		Water consumption
gal/MJ	-0.015	0.027
gal/GGE	-1.8	3.2
		Total NO_x emissions
g NO _x /MJ	0.27	0.052
g NO _x /GGE	32.5	6.3
		Urban NO_x emissions
g NO _x /MJ	0.018	0.023
g NO _x /GGE	2.21	2.8

Note: The values in parentheses are the percentage of difference compared to the petroleum diesel pathway. Reduction is represented with negative values.

^a Including both renewable gasoline and renewable diesel.

The NEB of RG and RD from CFP is 0.69 MJ/MJ in the 2020 SOT case, indicating a fossil energy saving potential of 69% for the RG and RD fuel produced, in the 2020 SOT case.

The CFP pathway in the 2020 SOT case shows about 20% reduction potential in urban NO_x emissions, compared with those of petroleum gasoline, since the biorefinery and depot preprocessing emissions (the primary emission sources of RG) are assumed to occur in rural, non-MSA areas where the biorefinery likely would be built.

3.3 Sludge Hydrothermal Liquefaction

The SCSA of the 2020 SOT case of the sludge hydrothermal liquefaction pathway incorporated two treatment scenarios for the conversion of sludge to biocrude via the HTL process: scenario 1 with ammonia removal from the HTL aqueous phase, and scenario 2 without ammonia removal from the HTL aqueous phase.

3.3.1 Supply Chain Greenhouse Gas Emissions

Figure 18 represents the supply chain GHG emissions and their key contributing supply chain processes in g CO₂e/MJ of RD produced from sludge via the HTL and upgrading processes. The GHG emissions reduction of the 2020 SOT case is compared with a life-cycle carbon intensity of 91 g CO₂e/MJ for petroleum diesel. The supply chain GHG emissions for the 2020 SOT case are lower than those for petroleum diesel, especially in the scenarios without NH₃ removal. In the scenario with NH₃ removal, RD GHG emissions represent a 53% reduction compared with petroleum diesel. When NH₃ is not removed from the HTL aqueous, RD GHG emissions represent a 71% reduction in the 2020 SOT case compared with petroleum diesel. Higher GHG emissions reductions when NH₃ is not removed are achieved by avoiding quicklime (CaO) use and reducing the use of the natural gas associated with the NH₃ stripping process.

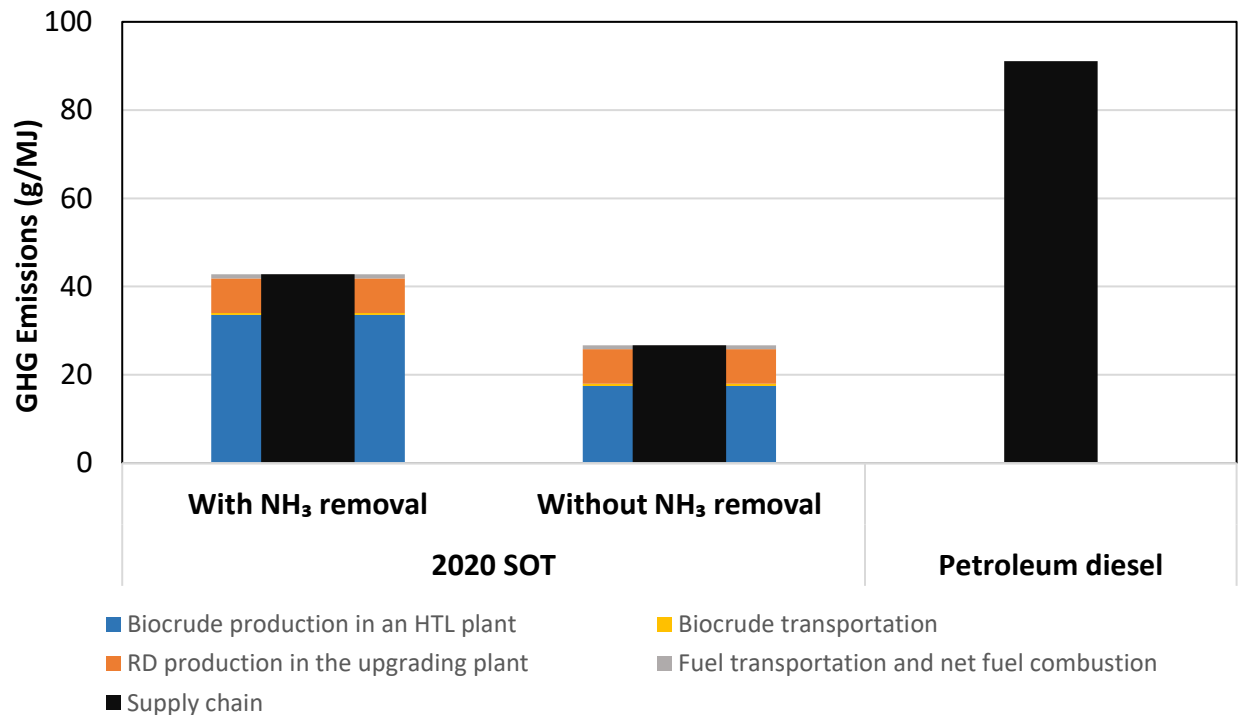


Figure 18 Supply Chain GHG Emissions (g CO₂e/MJ) of Renewable Diesel via Sludge HTL, Compared to 91 g CO₂e/MJ for Petroleum Diesel

The major contributor to the supply chain GHG emissions are the emissions during biocrude production in the HTL plant, accounting for about 78% of the total emissions with NH₃ removal, and for about 65% of the total emissions without NH₃ removal. When the HTL aqueous NH₃ is not removed, the supply chain GHG emission intensities are lowered by about 16 g CO₂e/MJ in the 2020 SOT case.

At the biorefinery level, without a biochemical co-product the biorefinery-level emission reduction comes entirely from the fuels (Figure 19). Approximately 559 kg to 745 kg CO₂e of GHG emission reduction could be achieved per ton of wastewater sludge converted to renewable diesel via the HTL pathway, depending on whether ammonia removal is considered.

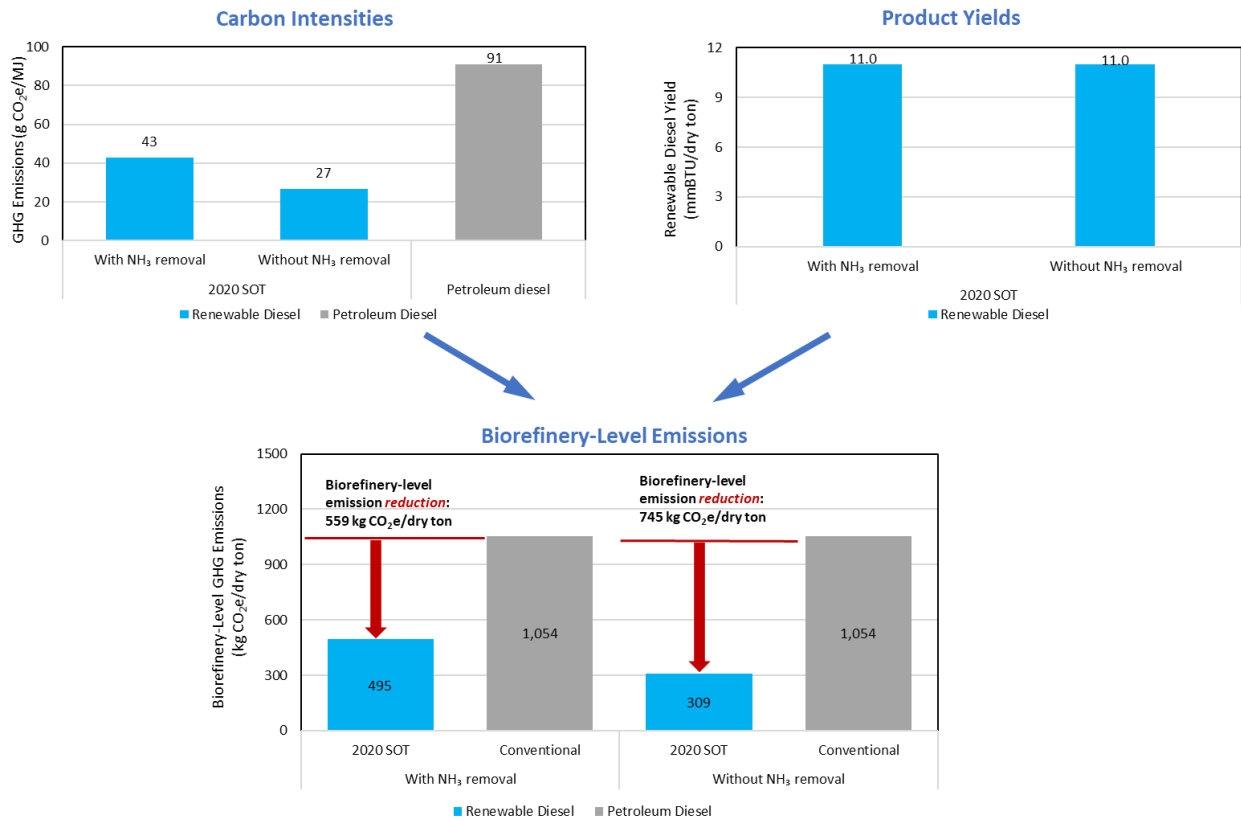


Figure 19 Biorefinery-Level Greenhouse Gas Emissions and Reductions, the 2020 SOT Case of the Wastewater Sludge HTL Pathway, with and without Ammonia Removal

3.3.2 Supply Chain Water Consumption

Figure 20 shows supply chain water consumption producing one GGE of RD from sludge via the HTL and upgrading processes. The 2020 SOT “with NH₃ removal” scenario consumes 4.4 gal/GGE, compared to 2.7 gal/GGE for petroleum diesel. When ammonia stripping is not part of the process design, water use during the conversion of sludge to biocrude is reduced to 3.1 gal/GGE, owing to the avoidance of embedded water consumption of CaO.

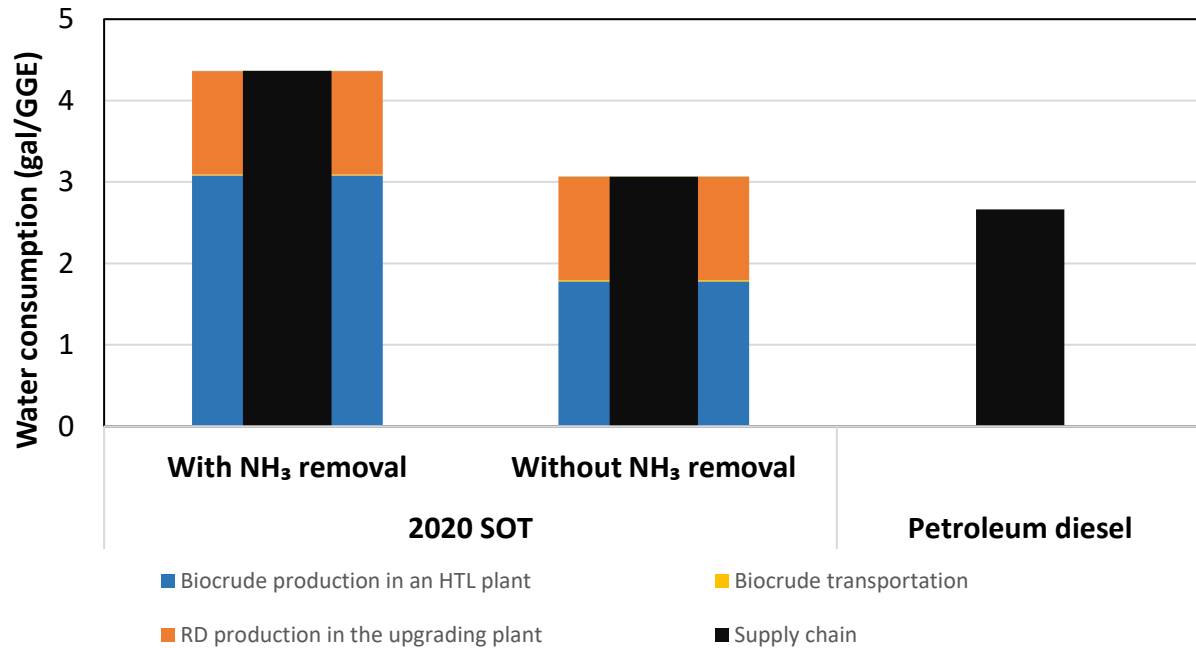


Figure 20 Supply Chain Water Consumption (gal/GGE) of Renewable Diesel via Sludge HTL, Compared to 2.7 gal/GGE for Petroleum Diesel

The direct water consumption during the conversion process remains the same in the 2020 SOT case as in the 2019 SOT case, which is 1.0 gal/GGE.

3.3.3 Supply Chain NO_x Emissions

Figure 21 shows that, in the 2020 SOT case, total supply chain NO_x emissions measure about 0.065 and 0.056 g/MJ with and without NH₃ removal, respectively. Fuel combustion represents the main contributor of NO_x emissions, which is assumed to equal that of petroleum diesel combustion, as modeled in GREET. The second-largest contributor is NO_x emissions associated with energy consumption during biocrude production.

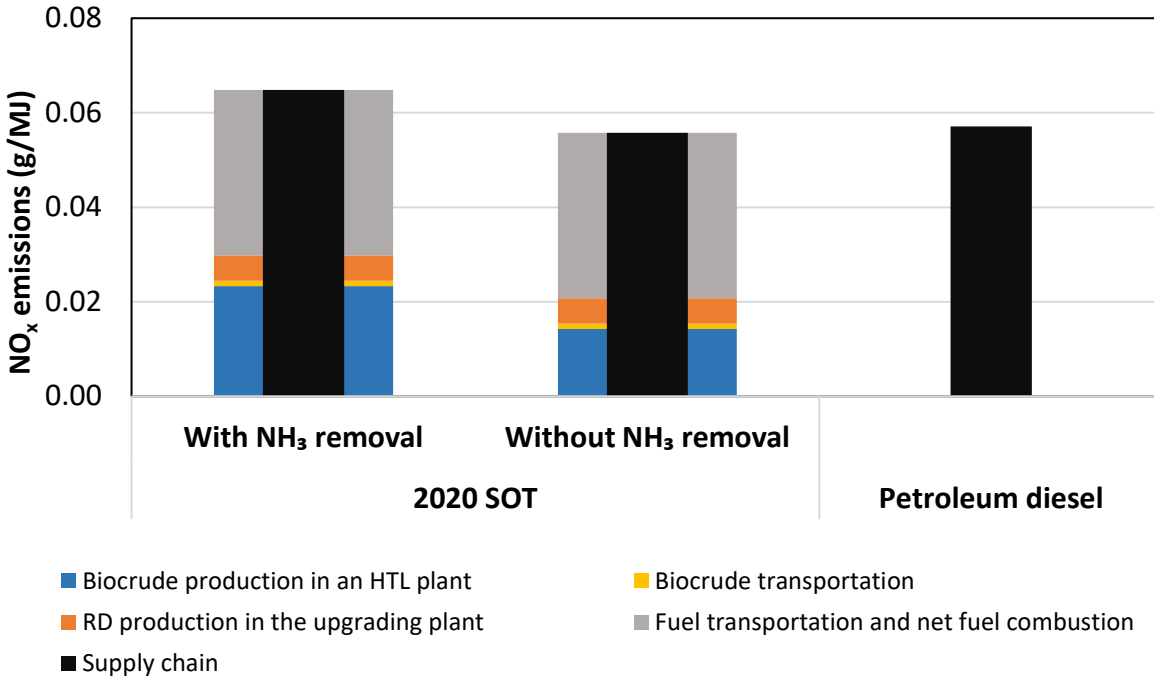


Figure 21 Supply Chain NO_x Emissions (g/MJ) of Renewable Diesel via HTL, Compared to 0.06 g/MJ for Petroleum Diesel

3.3.4 Summary of Sustainability Metrics

Table 20 summarizes the SCSA sustainability metrics evaluated for the 2020 SOT case of RD production from wet sludge via the HTL and upgrading processes. The 2020 SOT case involves little fossil energy use, which is primarily associated with the use of natural gas and electricity during the HTL and upgrading processes. The supply chain fossil energy consumption of the 2020 SOT cases is 0.44 and 0.36 MJ per MJ of RD, with and without NH₃ removal, respectively. The NEB of RD is 0.56 MJ/MJ (with NH₃ removal) and 0.64 MJ/MJ (without NH₃ removal) for the 2020 SOT case of the sludge HTL pathway.

In the 2020 SOT case, the sludge HTL pathway shows minimal urban NO_x emission reduction potential, compared with that of petroleum diesel.

Table 20 Supply Chain Sustainability Metrics for Renewable Diesel via Sludge HTL

	2020 SOT		Petroleum Diesel
	With NH ₃ removal	Without NH ₃ removal	
Biofuel yield			
Million Btu/dry ton	11.0	11.0	
Fossil energy consumption			
MJ/MJ	0.44	0.36	1.2
Net energy balance			
MJ/MJ	0.56	0.64	
GHG emissions			
g CO ₂ e/MJ	43 (-53%)	27 (-71%)	91
g CO ₂ e/ GGE	5,239	3,270	11,157
Water consumption			
L/MJ	0.13	0.09	0.1
gal/GGE	4.4	3.1	2.7
Total NO_x emissions			
g NO _x /MJ	0.065	0.056	0.06
g NO _x /GGE	7.9	6.8	7.0
Urban NO_x emissions			
g NO _x /MJ	0.037	0.027	0.03
g NO _x /GGE	4.6	3.3	3.3

Note: The values in parentheses are the percentage of difference compared to the petroleum diesel pathway. Reduction is represented with negative values.

3.4 Biochemical Conversion

The SCSA of the biochemical pathway incorporated the 2020 SOT case of herbaceous feedstock blends with the 2020 SOT case of the biochemical conversion pathways via acids and BDO intermediates.

We use three co-product handling methods to derive supply chain GHG emission results of the biochemical conversion pathway when the lignin is upgraded to AA:

- 1) Purpose-driven, process-level allocation method
- 2) Displacement method
- 3) Biorefinery-level analysis

The process-level allocation method separates process-level energy and material requirements between biofuel production and co-product production, and generates product-specific results for the biofuel and non-fuel co-product, respectively. The displacement method results for the biofuel combine effects of both the fuel and non-fuel co-product, and thus need to be interpreted with caution (Cai et al. 2018). The biorefinery-level results include emission reduction benefits of both the fuel product and the non-fuel co-product, thus presenting a complete picture of the biorefinery's emission performance.

3.4.1 Supply Chain Greenhouse Gas Emissions

Figure 22 displays the supply chain GHG emissions and their key contributing supply chain processes, in g CO₂e/MJ of RD, in the 2020 SOT case and 2030 target case, compared with a life-cycle carbon intensity of 91 g CO₂e/MJ for petroleum diesel. The table presents results for two conversion process designs that 1) burn the lignin to generate heat and power for use by the conversion process or 2) convert and upgrade the lignin to AA. Where lignin is upgraded to AA, we apply both mass- and market-value-based process-level allocation methods to allocate inputs that are common to both the fuel and AA products. Feedstock preprocessing accounts for 7%-10% of the emissions in the 2020 SOT case when lignin is upgraded to AA, and 7%-9% in the 2030 target case, due to electricity and diesel usage for meeting feedstock quality targets for conversion. In both process designs, the conversion step is the major GHG emission source of the entire supply chain.

Where lignin is upgraded to AA, large quantities of process chemicals are consumed at the DMR pretreatment step. These chemicals are responsible for a significant amount of GHG emissions. The recovered sodium sulfate salt from WWTP translates to a displacement emission credit of about 5-6 g CO₂e/MJ (via acids) and 4-5 g CO₂e/MJ (via BDO routes) after the process-level allocation. GHG emission intensity of the fuel in the lignin upgrading to the AA case is somewhat higher than that in the burning lignin case for both scenarios because additional NG and electricity are required when lignin is not burned to provide process energy for the biorefinery. The overall net GHG emission intensities of the fuel in the lignin conversion to AA designs may offer little to no emission reduction benefit in the 2020 SOT case. Under the same purpose-driven, process-level allocation methods, the 2030 target cases show significant reductions in emissions owing to improved renewable diesel yield, expressed in ranges:

- Via acids scenario: 94% (mass) to 157% (market value)
- BDO scenario: 80% (mass-based allocation) to 142% (market value-based allocation)

As a result, the 2030 target cases could reduce GHG emissions by 36%-48% for the via acids route and by 31%-43% for the via BDO route, relative to those of petroleum diesel.

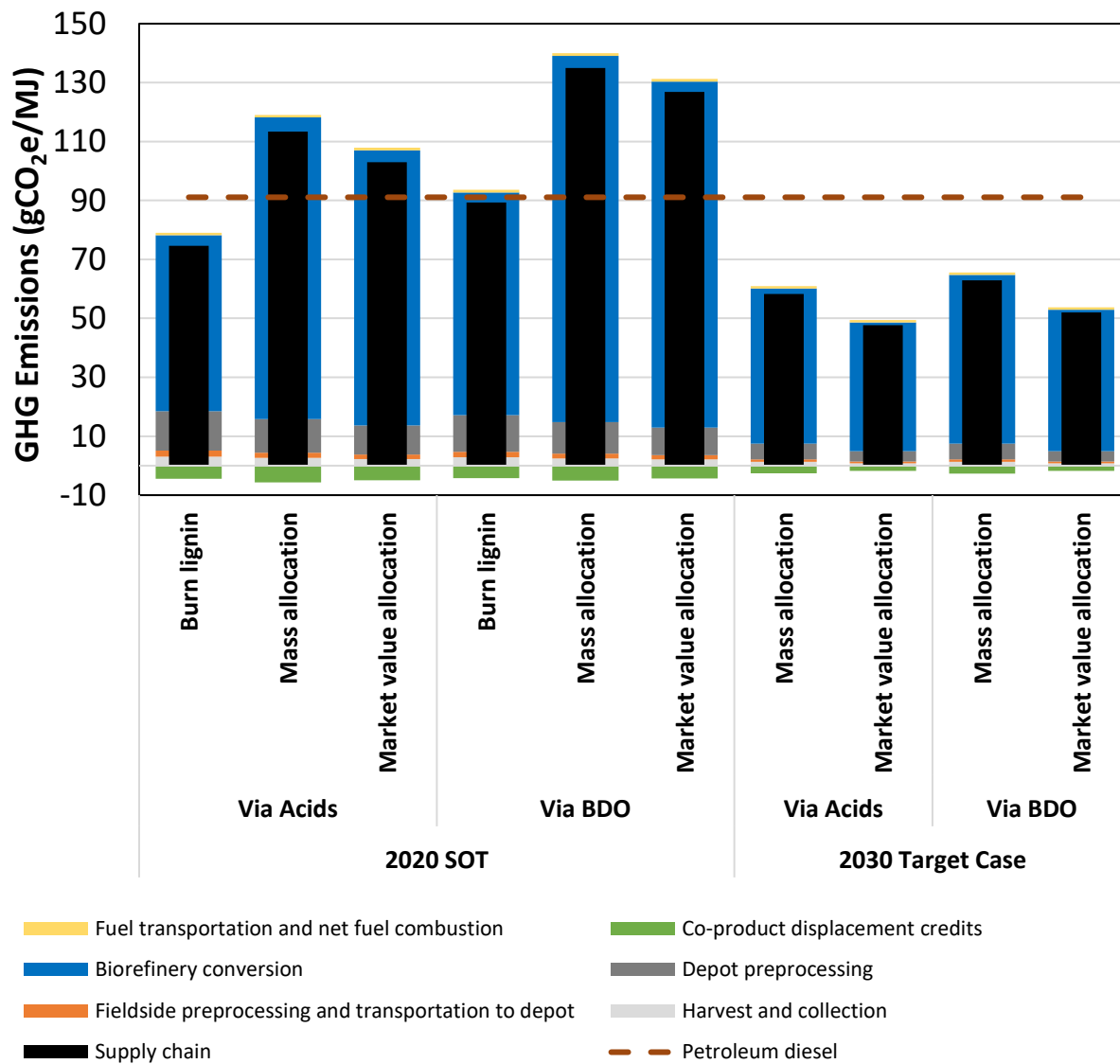


Figure 22 Supply Chain GHG Emissions of Renewable Diesel via Biochemical Conversion, Using the Process-Level Allocation Method to Address Effects of AA

Under the displacement method, all the chemical use and associated emissions are attributed to the hydrocarbon fuels. Meanwhile, the renewable diesel fuels also get all the credits from the AA co-product displacing conventional fossil-based AA. In addition, bio-based AA generates GHG emission credits by sequestering biogenic carbon given that its carbon is derived from herbaceous biomass. AA production has a significant impact on GHG emissions in the 2030 target case because of a significant increase in AA yield, generating -261 to -279 g CO₂e/MJ GHG emission credits from both displacing conventional AA (-222 to -238 g CO₂e/MJ) and biogenic carbon sequestration (-39 to -41 g CO₂e/MJ). As a result, supply chain GHG emission intensities of renewable diesel are -148 g CO₂e/MJ in both the acids and BDO intermediate pathways, as shown in Figure 23.

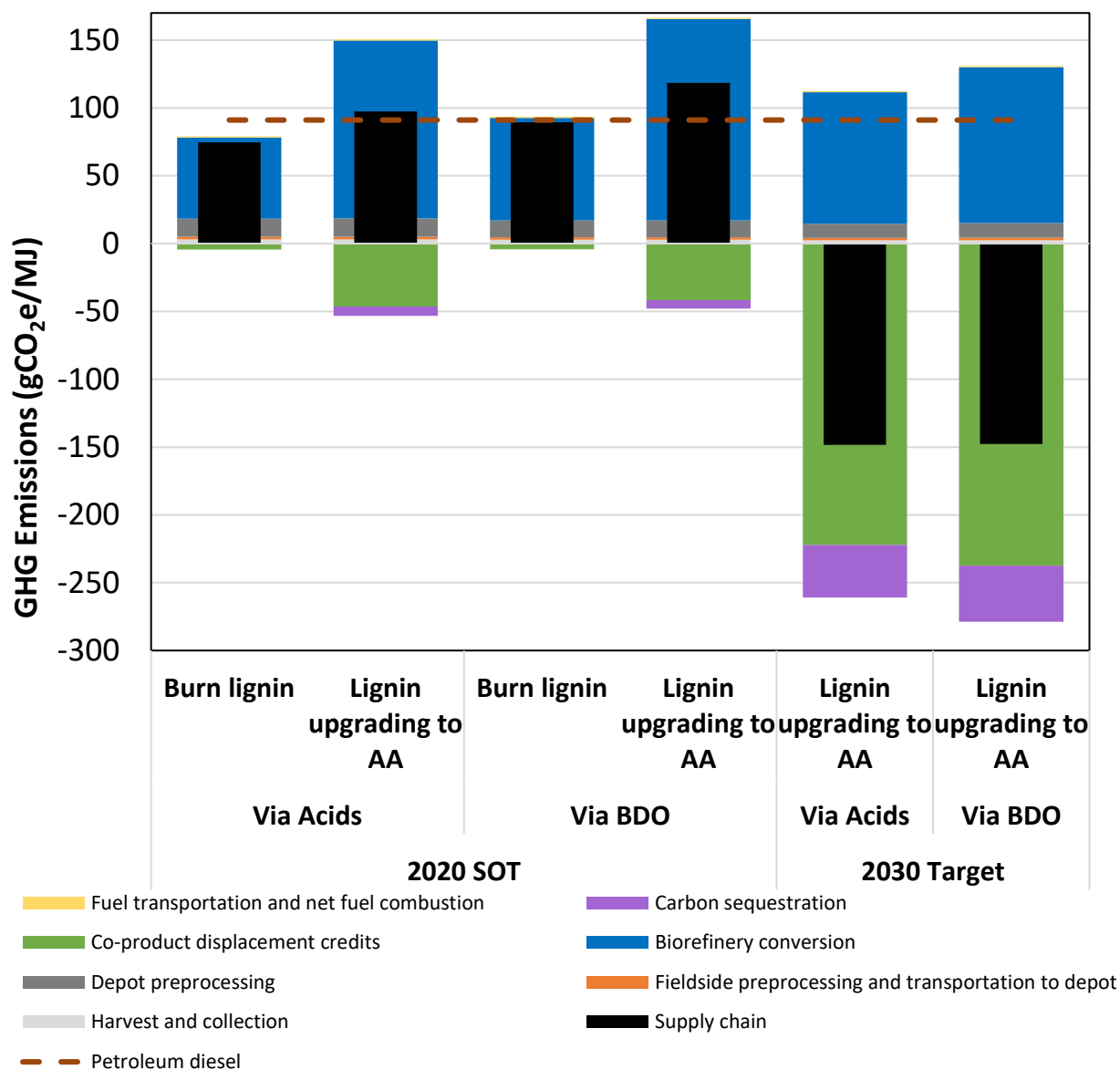
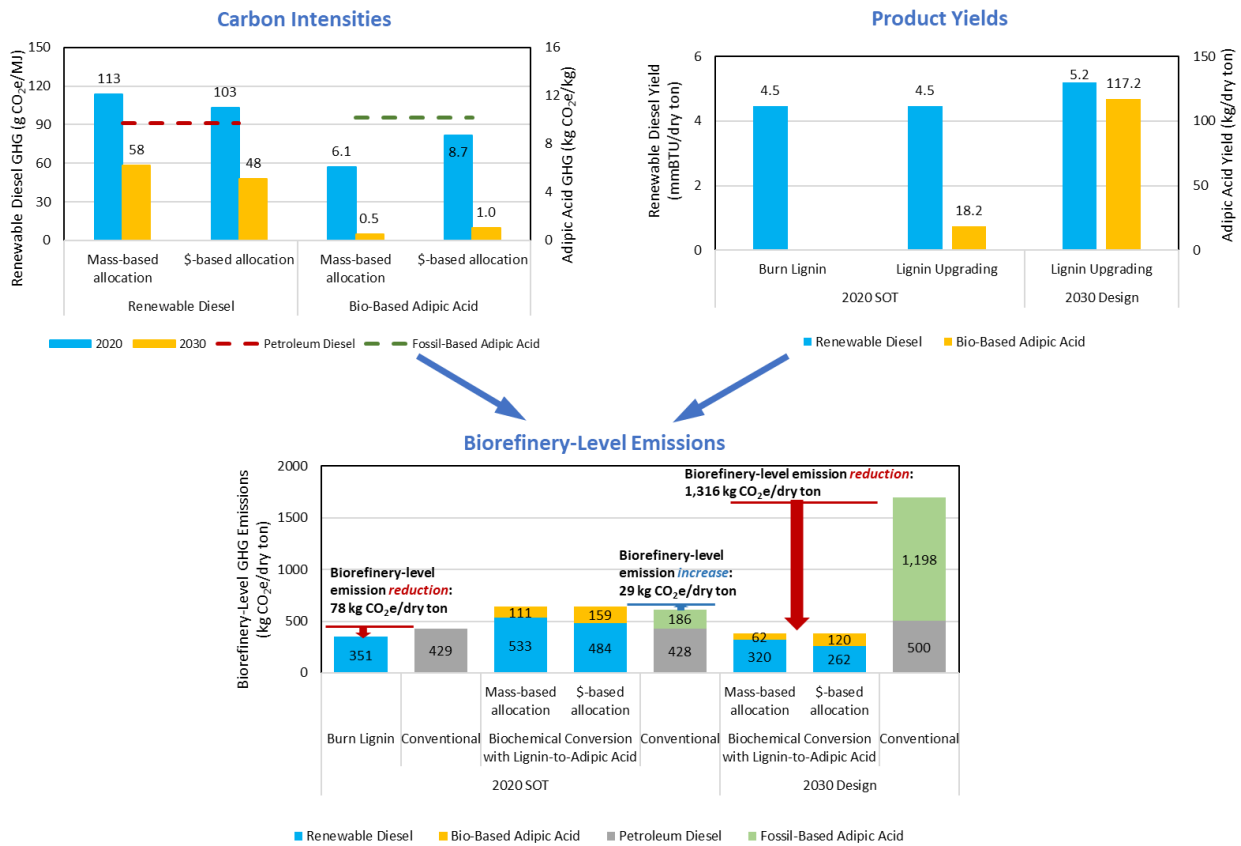


Figure 23 Supply Chain GHG Emissions of Renewable Diesel via Biochemical Conversion, Using the Displacement Method to Address Effects of AA

The biorefinery-level emissions of the biochemical conversion pathway vary among process designs, given variation in yields of the fuels and AA co-product and in total biorefinery emissions. The burning lignin design in the 2020 SOT case could achieve about 78 kg CO₂e of GHG emission reduction per dry ton of herbaceous feedstock blend converted to renewable diesel, owing to the somewhat lower carbon intensity of renewable diesel fuel compared to that of petroleum diesel.

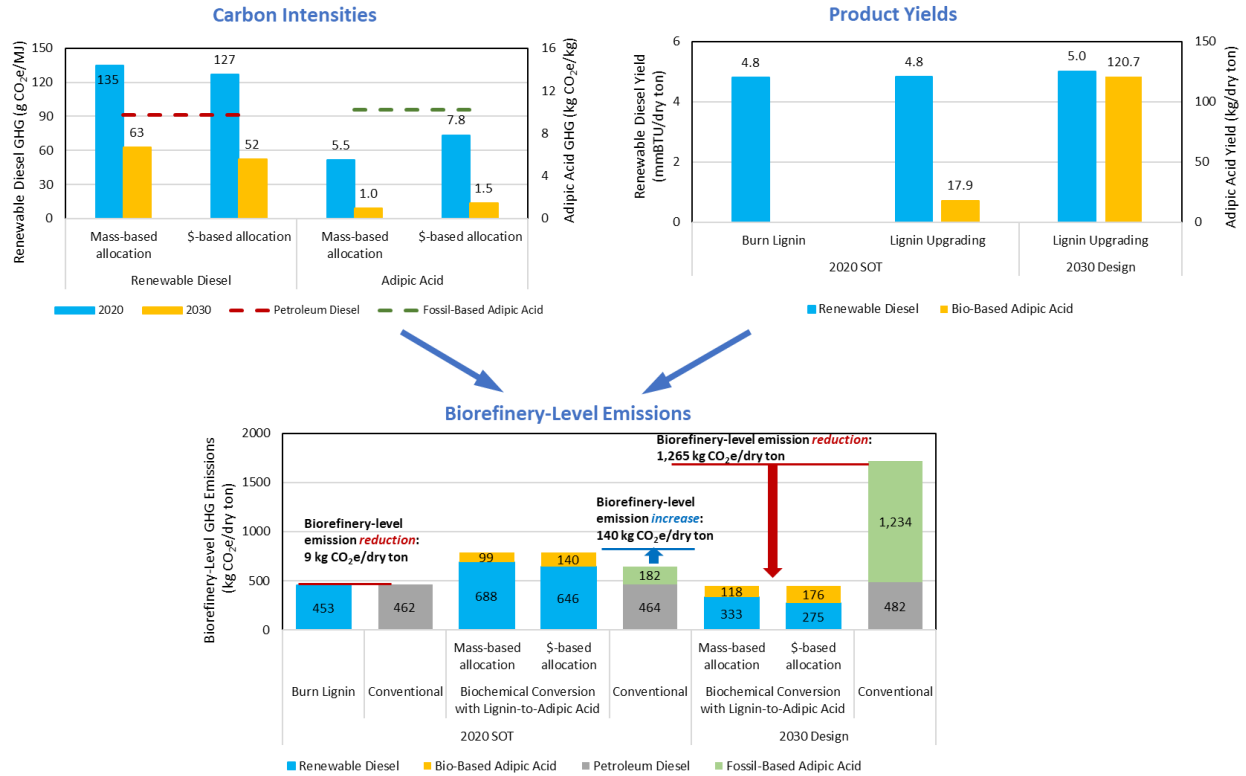
When lignin is converted to the AA co-product in the 2020 SOT case, we estimated an increase in biorefinery-level GHG emissions by about 29 kg CO₂e per dry ton of the feedstock blend converted to fuels and AA, owing to higher carbon intensities of the fuels relative to that of petroleum diesel, which outweighs the emission reduction benefits of the AA co-product relative to its fossil-derived counterpart (Figure 24). In the 2030 target case, with a significant increase in the AA co-product from the 2020 SOT case, significantly lower carbon intensities of the AA co-product relative to this fossil-counterpart, which is partly attributable to a significant biogenic carbon sequestration credit of the lignin-derived AA, and improved carbon intensities of the fuels, a biorefinery-level GHG emission reduction of 1,316 kg CO₂e per dry ton of the feedstock blend converted to fuels and AA could be expected. In this target case, about 12%-18% of the biorefinery-level emission reduction, which varies with the intermediate conversion routes and process-level allocation basis (market value or mass), comes from production of renewable diesel fuels, with the remaining 82%-88% of emission reduction benefits coming from production of the AA co-product.



(a) Via acids

Figure 24 Biorefinery-Level Greenhouse Gas Emissions and Reductions, the 2020 SOT Case and 2030 Target Case of the Biochemical Conversion Pathway for (a) Via Acids and (b) Via BDO Intermediate Routes

Figure 24 (Cont.)



(b) Via BDO

One major modification of the process model in the 2020 SOT case is to move from the 1-stage DMR preprocessing in the 2019 SOT case to a two-stage DMR approach in the current case, using Na₂CO₃ as the base that allows for 70% NaOH reduction. As a result, 58.2 kg of GHG emissions in the via acids intermediate pathway and 59.4 kg of GHG emissions in the via BDO intermediate pathway are avoided per ton of herbaceous biomass converted to fuels and AA (Table 21).

Table 21 GHG Emission Reduction from Changing the Base for a Two-Stage DMR Preprocessing in the 2020 SOT Case, Relative to the 2019 SOT Case

DMR Preprocessing	Inputs of the Base of Choice	Via Acids		Via BDO	
		Consumption (kg/dry ton)	GHG (kg/dry ton)	Consumption (kg/dry ton)	GHG (kg/dry ton)
1-stage (2019 SOT)	Na ₂ CO ₃	0	0	0	0
	NaOH	115.2	243.0	108.0	227.8
	Total	115.2	243.0	108.0	227.8
2-stage (2020 SOT)	Na ₂ CO ₃	72.6	81.5*	72.6	81.5*
	NaOH	49.0	103.3	41.2	86.9
	Total	121.6	184.8	113.8	168.4

*CO₂ emission from use of Na₂CO₃ (0.4 kg CO₂e/kg Na₂CO₃) is included.

3.4.2 Supply Chain Water Consumption

Figure 25 shows that the 2020 SOT case has much higher water consumption than that of petroleum diesel. This higher consumption exists regardless of the lignin utilization strategies, intermediate conversion routes, and co-product handling methods, owing to significant embedded water consumption associated with the process chemical use as well as the makeup water requirements during the biochemical conversion process. The embedded water consumption is driven by cooling demands in the process and by process water requirements and losses attributable to biochemical processing at 20 to 30% (by mass) solids with high water flows throughout the conversion process.

Under the purpose-driven, process-level allocation method, total water consumption at the biorefinery conversion step when embedded water for process chemicals is excluded is 13-15 gal/GGE and 6-7 gal/GGE for the acids and BDO routes, respectively, depending on the basis for allocation in the 2020 SOT case; and 5-7 gal/GGE and 3-4 gal/GGE, respectively, in the 2030 design case. When embedded water for process chemicals is also included, total water consumption at the biorefinery conversion step is 38-41 gal/GGE and 26-27 gal/GGE for the acids and BDO routes, respectively, depending on the basis for allocation in the 2020 SOT case; and 24-28 gal/GGE and 17-20 gal/GGE, respectively, in the 2030 design case. The acids design uses more water than the BDO design because it uses more makeup water and more chemicals with high embedded water consumption, such as corn steep liquor.

Under the displacement method, water consumption is driven by the conversion process (Figure 26). When lignin is upgraded to AA via acids, water consumption by the conversion process is 44 and 49 gal/GGE in the 2020 SOT and 2030 target cases, respectively. When lignin is upgraded to AA via BDO, water consumption by the conversion process is 32 and 35 gal/GGE in the 2020 SOT and 2030 target cases, respectively. The 2030 target case has lower water consumption than the 2020 SOT case for both acids and BDO pathways because of greater displacement credits generated by a significant increase in the AA co-product production in the target case.

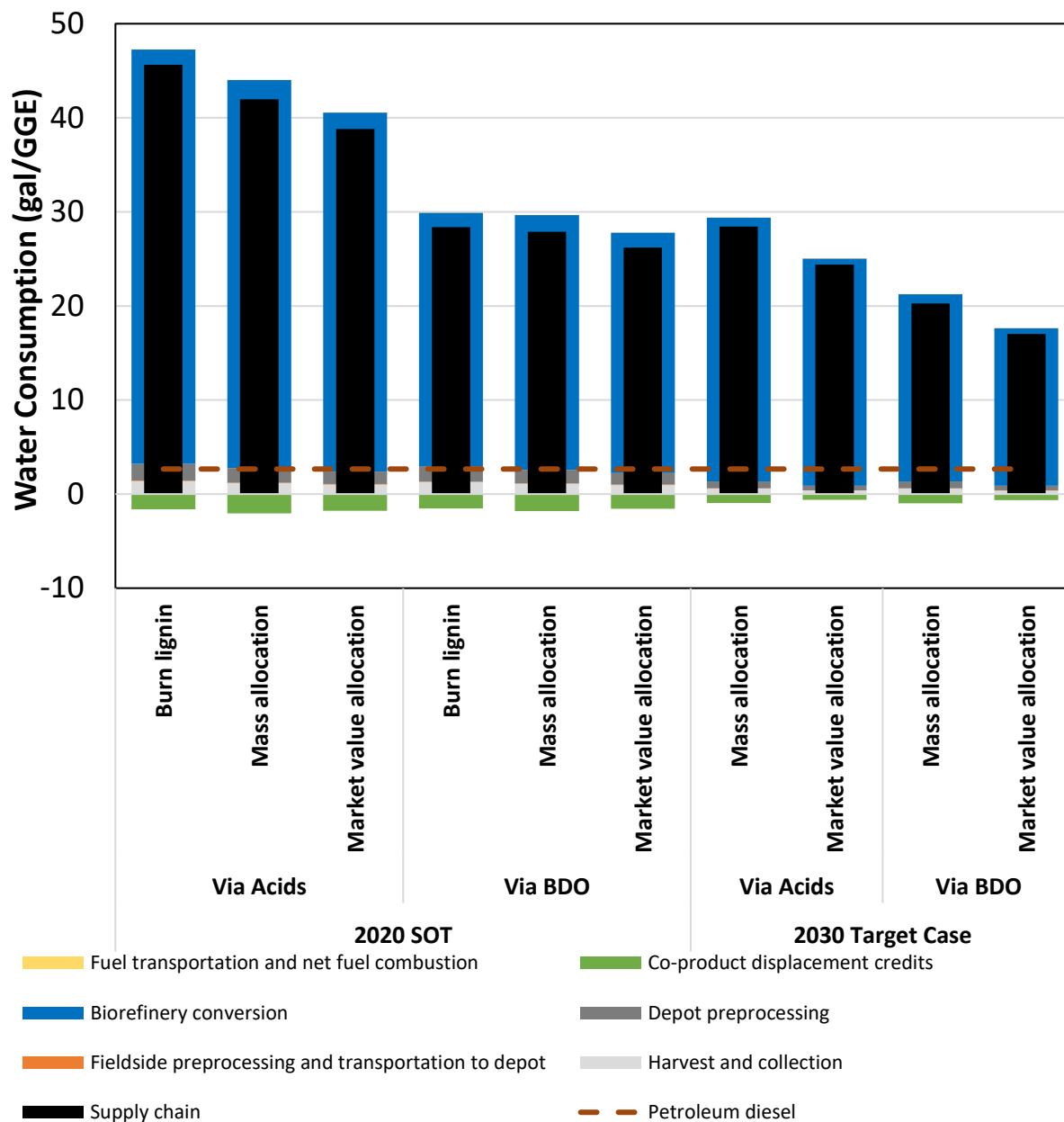


Figure 25 Supply Chain Water Consumption (gal/GGE) of Renewable Diesel via Biochemical Conversion, Using the Process-Level Allocation Method to Address Effects of AA, Compared to 2.7 gal/GGE for Petroleum Diesel

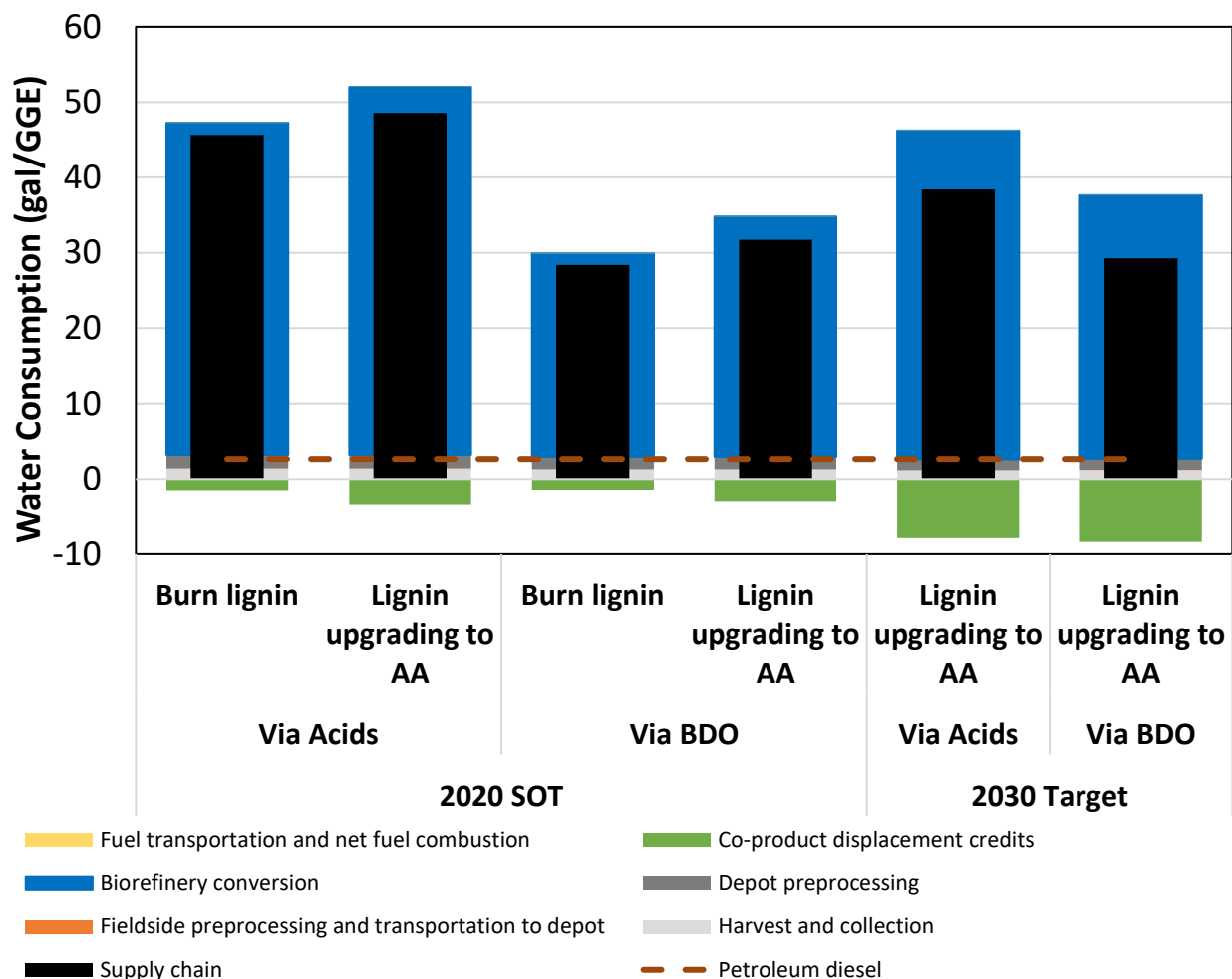


Figure 26 Supply Chain Water Consumption (gal/GGE) of Renewable Diesel via Biochemical Conversion, Using the Displacement Method to Address Effects of AA

The direct water consumption during the conversion process for the via acids pathway is reduced from 20.0 gal/GGE in the 2019 SOT case to 17.9 gal/GGE in the 2020 SOT case, which is a 10% reduction in direct water consumption, and is reduced from 9.2 gal/GGE in the 2019 SOT case to 7.8 gal/GGE in the 2020 SOT case for the via BDO pathway, which is a 15% reduction in direct water consumption.

We summarized the biorefinery-level results for water consumption in Tables 27 and 28 for the biochemical conversion pathway.

3.4.3 Supply Chain NO_x Emissions

Under the process-level allocation method, Figure 27 shows that total NO_x emissions are higher than those of petroleum diesel in the 2020 SOT case and 2030 target case, regardless of the intermediate pathway and the basis for process-level allocation. Biorefinery conversion is the

largest contributor to the NO_x emissions, followed by fuel combustion by vehicles, energy consumption during preprocessing, and harvest/collection of feedstocks using diesel-driven equipment such as harvesters and tractors.

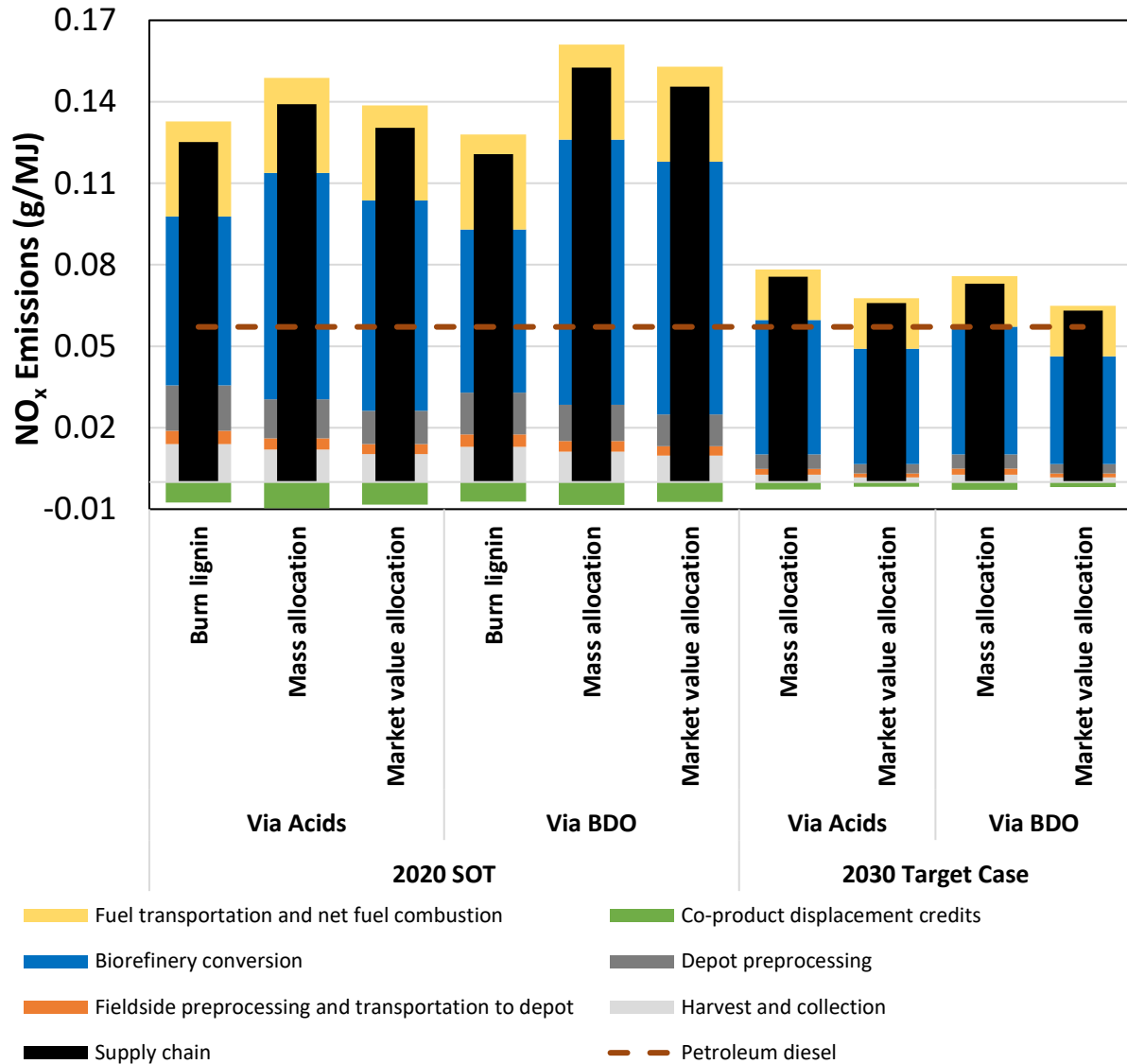


Figure 27 Supply Chain NO_x Emissions (g/MJ) of Renewable Diesel via Biochemical Conversion Using the Process-Level Allocation Method, Relative to 0.06 g/MJ for Petroleum Diesel

Under the displacement method, in the 2020 SOT case the biochemical pathways have higher NO_x emissions than petroleum diesel when lignin is burned for energy, but lower NO_x emissions when lignin is upgraded to AA. In the 2030 target case, the AA co-product generates a significant displacement credit, driving NO_x emissions down to negative values in both the acids and BDO pathways (Figure 28).

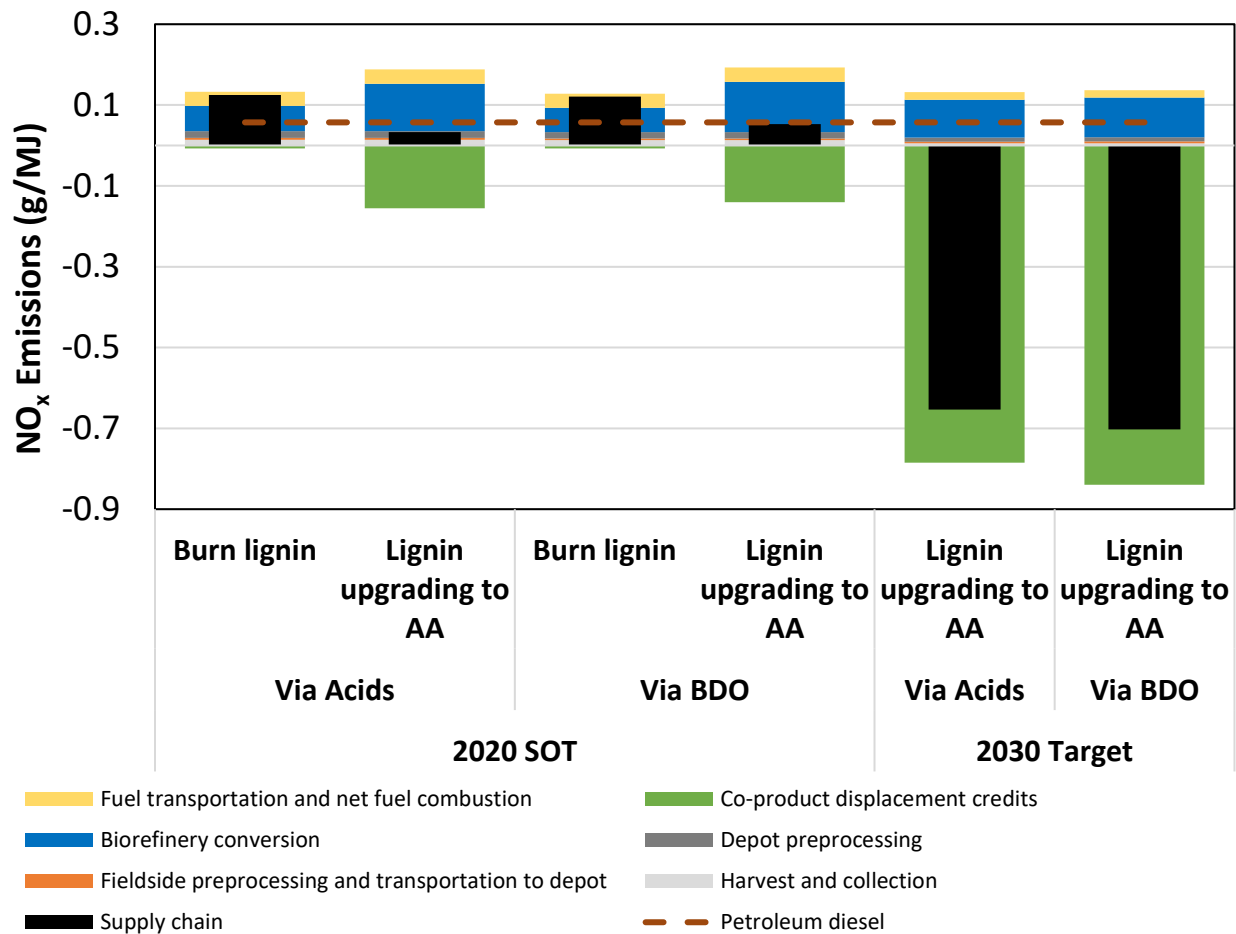


Figure 28 Supply Chain NO_x Emissions (g/MJ) of Renewable Diesel via Biochemical Conversion, Using the Displacement Method to Address Effects of AA

We summarize biorefinery-level results for NO_x emissions in Tables 27 and 28 for the biochemical conversion pathway.

3.4.4 Summary of Sustainability Metrics

Tables 22 and 23 summarize supply chain sustainability metrics, including fossil energy consumption, NEB, GHG emissions, water consumption, and NO_x emissions of renewable diesel from these biochemical conversion designs, using the process-level allocation method. GHG emissions estimated by market-value-based allocation are lower than those estimated by mass-based allocation because renewable diesel has a lower market value than the AA product on a per-kg basis. Thus, a smaller portion of the emission burdens are allocated to renewable diesel by market value than by mass. These sustainability metrics are substantially improved in the 2030 target case due to increased fuel yield and reduced energy and chemicals usage.

Table 22 Supply Chain Sustainability Metrics for Renewable Diesel via Biochemical Pathway, 2020 SOT Case

	Scenario 1: Via Acids			Scenario 2: Via BDO			
	Lignin upgrading to adipic acid			Lignin upgrading to adipic acid			Petroleum Diesel
	Burning lignin	Mass-based allocation	Market-value-based allocation	Burning lignin	Mass-based allocation	Market-value-based allocation	
	Biofuel yield						
mmBtu/dry ton	4.5	5.2	6.0	4.8	5.6	6.4	
	Co-product yield						
Sodium sulfate, Kg/mmBtu of biofuel	25.1	32.0	27.6	23.9	28.1	24.5	
	Fossil energy consumption						
MJ/MJ	0.8	1.3	1.2	0.9	1.2	1.1	1.2
	Net energy balance						
MJ/MJ	0.2	-0.3	-0.2	0.1	-0.2	-0.1	
	GHG emissions^a						
g CO ₂ e/MJ	75 (-18%)	113 (24%)	103 (13%)	89 (-2%)	135 (48%)	127 (39%)	91
g CO ₂ e/ GGE	9,136	13,884	12,616	10,941	16,534	15,539	11,157
	Water consumption						
L/MJ	1.4	1.3	1.2	0.9	0.9	0.8	0.1
gal/GGE	45.6	42.0	38.8	28.4	27.9	26.2	2.7
	Total NO_x emissions						
g NO _x /MJ	0.1	0.1	0.1	0.1	0.2	0.1	0.06
g NO _x /GGE	15.3	17.0	16.0	14.8	18.7	17.8	7.0
	Urban NO_x emissions						
g NO _x /MJ	0.03	0.04	0.04	0.03	0.04	0.03	0.03
g NO _x /GGE	3.8	4.5	4.4	4.0	4.4	4.3	3.3

^a The values in parentheses are the percentage of difference compared to the petroleum diesel pathway. Reduction is represented with negative values.

Table 23 Supply Chain Sustainability Metrics for Renewable Diesel via Biochemical Pathway, 2030 Design Case

	Scenario 1: Via Acids		Scenario 2: Via BDO		Petroleum Diesel
	Mass-based allocation	Market-value-based allocation	Mass-based allocation	Market-value-based allocation	
Biofuel yield					
mmBtu/dry ton	10.1	15.4	10.1	15.5	
Co-product yield					
Sodium sulfate, Kg/mmBtu of biofuel	15.0	9.8	15.3	9.9	
Fossil energy consumption					
MJ/MJ	0.7	0.6	0.7	0.5	1.2
Net energy balance					
MJ/MJ	0.3	0.4	0.3	0.5	
GHG emissions^a					
g CO ₂ e/MJ	58 (-36%)	48 (-48%)	63 (-31%)	52 (-43%)	91
g CO ₂ e/ GGE	7,140	5,844	7,700	6,371	11,157
Water consumption					
L/MJ	0.9	0.8	0.6	0.5	0.1
gal/GGE	28.4	24.4	20.3	17.0	2.7
Total NO_x emissions					
g NO _x /MJ	0.08	0.07	0.07	0.06	0.06
g NO _x /GGE	9.3	8.1	8.9	7.7	7.0
Urban NO_x emissions					
g NO _x /MJ	0.02	0.02	0.02	0.02	0.03
g NO _x /GGE	2.6	2.4	2.5	2.3	3.3

^a The values in parentheses are the percentage of difference compared to the petroleum diesel pathway. Reduction is represented with negative values.

Tables 24 and 25 summarize the supply chain sustainability metrics of AA produced from the acid and BDO pathways in 2020 SOT case and 2030 target cases, respectively, under the purpose-driven, process-level allocation method. Under this method, lignin-derived AA could achieve reductions in GHG emissions by about 41%-46% (mass-based allocation) and 14%-23% (market value-based allocation), relative to conventional natural gas (NG)-based AA in the 2020 SOT case. Lignin-derived AA could achieve much greater GHG emission reduction: by about 90%-95% (mass-based allocation) and 86%-90% (market value-based allocation) in the 2030 target case, relative to NG-based AA, owing to significant improvement in AA production yield and material/energy efficiency from the 2020 SOT case to the 2030 target case.

Table 24 Supply Chain Sustainability Metrics for Adipic Acid via Biochemical Pathway, 2020 SOT Case

	Scenario 1: Via Acids		Scenario 2: Via BDO		Conventional AA
	Mass-based allocation	Market-value-based allocation	Mass-based allocation	Market-value-based allocation	
	AA yield				
ton/dry ton	0.14	0.077	0.15	0.081	
	Fossil energy consumption				
MJ/kg	101.9	134.8	86.7	115.3	129.0
	GHG emissions^a				
g CO ₂ e/kg	6,072 (-41%)	8,743 (-14%)	5,528 (-46%)	7,846 (-23%)	10,216
	Water consumption				
L/kg	61.3	86.6	42.7	57.4	8.7
	Total NO_x emissions				
g NO _x /kg	9.7	12.0	8.6	10.7	37.2

^a The values in parentheses are the percentage of difference compared to the petroleum diesel pathway. Reduction is represented with negative values.

Table 25 Supply Chain Sustainability Metrics for Adipic Acid via Biochemical Pathway, 2030 Target Case

	Scenario 1: Via Acids		Scenario 2: Via BDO		Conventional AA
	Mass-based allocation	Market-value-based allocation	Mass-based allocation	Market-value-based allocation	
	AA yield				
ton/dry ton	0.27	0.20	0.27	0.20	
	Fossil energy consumption				
MJ/kg	33.0	40.2	35.6	42.5	129.0
	GHG emissions				
g CO ₂ e/kg	532 (-95%)	1,028 (-90%)	981 (-90%)	1,457 (-86%)	10,216
	Water consumption				
L/kg	23.1	29.0	20.9	25.4	8.7
	Total NO_x emissions				
g NO _x /kg	3.0	3.5	3.2	3.6	37.2

Note: The values in parentheses are the percentage of difference compared to the petroleum diesel pathway. Reduction is represented with negative values.

Table 26 summarizes the supply chain sustainability metrics, including fossil energy consumption, NEB, GHG emissions, water consumption, and NO_x emissions of renewable diesel from these biochemical conversion designs, using the displacement method.

Table 26 Supply Chain Sustainability Metrics for Renewable Diesel via Biochemical Pathway in the 2020 SOT Case and 2030 Target Case, Using the Displacement Method

	2020 SOT				2030 Target		
	Scenario 1: Via Acids		Scenario 2: Via BDO		Scenario 1: Via Acids	Scenario 2: Via BDO	Petroleum Diesel
	Burning lignin	Lignin upgrading to adipic acid	Burning lignin	Lignin upgrading to adipic acid	Lignin upgrading to adipic acid	Lignin upgrading to adipic acid	
Biofuel yield							
mmBtu/dry ton	4.5	4.5	4.8	4.8	5.2	5.0	
Co-product yield							
Adipic acid, kg/mmBtu of biofuel	0	4.1	0	3.7	22.5	24.1	
Sodium sulfate, kg/mmBtu of biofuel	25.1	37.5	23.9	32.4	29.0	30.7	
Fossil energy consumption							
MJ/MJ	0.8	1.2	0.9	1.0	-1.3	-1.5	1.2
Net energy balance							
MJ/MJ	0.2	-0.2	0.1	0.0	2.3	2.5	
GHG emissions							
g CO ₂ e/MJ	75 (-18%)	97 (7%)	89 (-2%)	119 (30%)	-148 (-263%)	-148 (-262%)	91
g CO ₂ e/ GGE	9,136	11,917	10,941	14,521	-18,174	-18,101	11,157
Water consumption							
L/MJ	1.4	1.5	0.9	1.0	1.2	0.9	0.1
gal/GGE	45.6	48.6	28.4	31.7	38.4	29.3	2.7
Total NO_x emissions							
g NO _x /MJ	0.13	0.03	0.12	0.05	-0.65	-0.70	0.06
g NO _x /GGE	15.3	4.0	14.8	6.4	-80.0	-86.0	7.0
Urban NO_x emissions							
g NO _x /MJ	0.03	0.04	0.03	0.04	0.02	0.02	0.03
g NO _x /GGE	3.8	4.9	4.0	4.6	2.8	2.8	3.3

Tables 27 and 28 summarize biorefinery-level sustainability metrics for the biochemical pathway. For fossil energy consumption, GHG emissions, water consumption, and NO_x emissions, we present supply chain direct impacts per ton of biomass converted to both RD and AA co-product, the total displacement credit from RD, the total displacement credit from lignin-derived AA, and the net, combined impacts from both RD and AA.

Biorefinery-level GHG emissions of RD and lignin-derived AA in the 2020 SOT case are comparable to those of the conventional diesel and AA production pathways, but the 2030 target case achieves a considerable reduction in biorefinery-level GHG emissions. In the 2030 target case, both RD and AA reduce biorefinery-level GHG emissions compared to their conventional counterparts. The biorefinery-level GHG emission reduction comes primarily from AA production, which accounts for 82%-88% of the overall biorefinery-level GHG emission reduction.

Table 27 Biorefinery-Level Sustainability Metrics of the Biochemical Pathway, 2020 SOT Case

	Scenario 1: Via Acids			Scenario 2: Via BDO			
	Lignin upgrading to adipic acid			Lignin upgrading to adipic acid			
	Burn lignin	Mass-based allocation	Market-value-based allocation	Burn lignin	Mass-based allocation	Market-value-based allocation	
Products							
Renew diesel	4.5	4.5		4.8	4.8		mmBtu/dry ton biomass
Adipic acid	-	0.02		-	0.02		ton/dry ton biomass
Fossil energy consumption							
Direct consumption by RD production	3,802	6,097	5,497	4,646	5,913	5,403	MJ/dry ton biomass
Credits from RD production	-5,651	-5,641	-5,641	-6,092	-6,113	-6,113	MJ/dry ton biomass
<i>Net consumption by RD production</i>	<i>-1,850</i>	<i>456 (-1218%)</i>	<i>-144 (384%)</i>	<i>-1,446</i>	<i>-200 (21%)</i>	<i>-710 (74%)</i>	MJ/dry ton biomass
Direct consumption by AA production	-	1,856	2,456	-	1,549	2,059	MJ/dry ton biomass
Credits from AA production	-	-2,350	-2,350	-	-2,304	-2,304	MJ/dry ton biomass
<i>Net consumption by AA production</i>	<i>-</i>	<i>-494 (1318%)</i>	<i>106 (-284%)</i>	<i>-</i>	<i>-755 (79%)</i>	<i>-245 (26%)</i>	MJ/dry ton biomass
Net total consumption	-1,850	-37	-	-1,446	-955	-	MJ/dry ton biomass
GHG emissions							
Direct emissions from RD production	351	533	484	453	688	646	kg/dry ton biomass
Credits from RD production	-429	-428	-428	-462	-464	-464	kg/dry ton biomass

Table 27 (Cont.)

	Scenario 1: Via Acids			Scenario 2: Via BDO			
	Lignin upgrading to adipic acid			Lignin upgrading to adipic acid			
	Burn lignin	Mass-based allocation	Market-value-based allocation	Burn lignin	Mass-based allocation	Market-value-based allocation	
<i>Net emissions from RD production</i>	-78	105 (359%)	56 (192%)	-9	224 (160%)	182 (130%)	kg/dry ton biomass
Direct emissions from AA production	-	111	159	-	99	140	kg/dry ton biomass
Credits from AA production	-	-186	-186	-	-182	-182	kg/dry ton biomass
<i>Net emissions from AA production</i>	-	-75 (-259%)	-27 (-92%)	-	-84 (-60%)	-42 (-30%)	kg/dry ton biomass
Net total emissions	-78		29	-9		140	kg/dry ton biomass
Water consumption							
Direct consumption by RD production	1,755	1,611	1,489	1,176	1,159	1,090	gal/dry ton biomass
Credits from RD production	-102	-102	-102	-110	-111	-111	gal/dry ton biomass
<i>Net consumption by RD production</i>	1,653	1,509 (86%)	1,387 (79%)	1,065	1,048 (86%)	979 (81%)	gal/dry ton biomass
Direct consumption by AA production	-	295	417	-	206	276	gal/dry ton biomass
Credits from AA production	-	-42	-42	-	-42	-42	gal/dry ton biomass
<i>Net consumption by AA production</i>	-	253 (14%)	375 (21%)	-	164 (14%)	234 (19%)	gal/dry ton biomass
Net total consumption	1,653		1,762	1,065		1,212	gal/dry ton biomass
Total NO_x emissions							
Direct emissions from RD production	589	654	613	613	777	742	g/dry ton biomass
Credits from RD production	-269	-268	-268	-290	-291	-291	g/dry ton biomass
<i>Net emissions from RD production</i>	320	386 (-336%)	344 (-300%)	323	486 (-2129%)	451 (-1972%)	g/dry ton biomass
Direct emissions from AA production	-	177	218	-	154	190	g/dry ton biomass
Credits from AA production	-	-677	-677	-	-664	-664	g/dry ton biomass
<i>Net emissions from AA production</i>	-	-500 (436%)	-459 (400%)	-	-509 (2229%)	-473 (2072%)	g/dry ton biomass
Net total emissions	320		-115	323		-23	g/dry ton biomass

Note: Positive net totals indicate net increases compared to conventional products. Negative net totals indicate net reductions compared to conventional products. The values in parentheses are contributions to the net totals by RD and co-product in percentage.

Table 28 Biorefinery-Level Sustainability Metrics of the Biochemical Pathway, 2030 Target Case

	Scenario 1: Via Acids		Scenario 2: Via BDO		
	Lignin upgrading to adipic acid		Lignin upgrading to adipic acid		
	Mass-based allocation	Market-value-based allocation	Mass-based allocation	Market-value-based allocation	
Products					
Renew diesel		5.2		5.0	mmBtu/dry ton biomass
Adipic acid		0.13		0.13	ton/dry ton biomass
Fossil energy consumption					
Direct consumption by RD production	3,865	3,023	3,498	2,668	MJ/dry ton biomass
Credits from RD production	-6,593	-6,593	-6,353	-6,353	MJ/dry ton biomass
<i>Net consumption by RD production</i>	<i>-2,728 (20%)</i>	<i>-3,570 (26%)</i>	<i>-2,854 (20%)</i>	<i>-3,684 (26%)</i>	MJ/dry ton biomass
Direct consumption by AA production	3,870	4,712	4,296	5,126	MJ/dry ton biomass
Credits from AA production	-15,124	-15,124	-15,576	-15,576	MJ/dry ton biomass
<i>Net consumption by AA production</i>	<i>-11,254 (80%)</i>	<i>-10,412 (74%)</i>	<i>-11,280 (80%)</i>	<i>-10,450 (74%)</i>	MJ/dry ton biomass
Net Total		-13,981		-14,134	MJ/dry ton biomass
GHG emissions					
Direct emissions from RD production	320	262	333	275	kg/dry ton biomass
Credits from RD production	-500	-500	-482	-482	kg/dry ton biomass
<i>Net emissions from RD production</i>	<i>-180 (14%)</i>	<i>-238 (18%)</i>	<i>-149 (12%)</i>	<i>-207 (16%)</i>	kg/dry ton biomass
Direct emissions from AA production	62	120	118	176	kg/dry ton biomass
Credits from AA production	-1,198	-1,198	-1,234	-1,234	kg/dry ton biomass
<i>Net emissions from AA production</i>	<i>-1,135 (86%)</i>	<i>-1,077 (82%)</i>	<i>-1,115 (88%)</i>	<i>-1,058 (84%)</i>	kg/dry ton biomass
Net total		-1,316		-1,265	kg/dry ton biomass
Water consumption					
Direct consumption by RD production	1,276	1,095	876	735	gal/dry ton biomass
Credits from RD production	-119	-119	-115	-115	gal/dry ton biomass
<i>Net consumption by RD production</i>	<i>1,156 (72%)</i>	<i>975 (61%)</i>	<i>761 (66%)</i>	<i>620 (54%)</i>	gal/dry ton biomass
Direct consumption by AA production	717	898	668	809	gal/dry ton biomass
Credits from AA production	-270	-270	-278	-278	gal/dry ton biomass

Table 28 (Cont.)

	Scenario 1: Via Acids		Scenario 2: Via BDO		
	Lignin upgrading to adipic acid		Lignin upgrading to adipic acid		
	Mass-based allocation	Market-value-based allocation	Mass-based allocation	Market-value-based allocation	
<i>Net consumption by AA production</i>	447 (28%)	628 (39%)	390 (34%)	530 (46%)	gal/dry ton biomass
Net total		1,603		1,150	gal/dry ton biomass
Total NO_x emissions					
Direct emissions from RD production	415	362	386	334	g/dry ton biomass
Credits from RD production	-314	-314	-302	-302	g/dry ton biomass
<i>Net emissions from RD production</i>	101 (-3%)	48 (-1%)	84 (-2%)	32 (-1%)	g/dry ton biomass
Direct emissions from AA production	353	406	383	435	g/dry ton biomass
Credits from AA production	-4,356	-4,356	-4,487	-4,487	g/dry ton biomass
<i>Net emissions from AA production</i>	-4,004 (103%)	-3,951 (101%)	-4,104 (102%)	-4,051 (101%)	g/dry ton biomass
Net total		-3,902		-4,020	g/dry ton biomass

Note: Positive net totals indicate net increases compared to conventional products. Negative net totals indicate net reductions compared to conventional products. The values in parentheses are contributions to the net totals by RD and co-product in percentage.

3.5 Algae/Corn Stover Hydrothermal Liquefaction

The SCSA of the algae/corn stover blend HTL pathway incorporated the saline algae biomass cultivation data from the testbeds in the 2020 algae cultivation SOT case, the corn stover feedstock inputs from the 2020 SOT, and the 2020 algae HTL SOT case. The 2030 projection case for saline algae cultivation is used in the 2030 projection case of the pathway.

The chemicals and energy inputs in the algae HTL pathway, as shown in Table 14, are allocated to the RD and LA products following the underlying physical relationship between material inputs and RD/LA production. As a result, the purpose-driven process-level allocation is applied to the HTL NG consumption and Na₂CO₃ usage only.

3.5.1 Supply Chain Greenhouse Gas Emissions

Figure 29 shows the supply chain GHG emissions and their key contributing supply chain processes, in g CO₂e/MJ, of RD in the 2020 SOT and 2030 projection cases, compared to a life-cycle carbon intensity of 91 g CO₂e/MJ for petroleum diesel. RD reduces GHG emissions by

40% and 48% in the 2020 SOT case, and by 44% and 53% in the 2030 projection case, with mass- and market value-based process-level allocation approaches, respectively. The HTL conversion processes, which consume grid electricity, natural gas for hydrogen production, and chemicals and catalysts for biocrude production and upgrading, contribute to about 42.3 and 35.4 g CO₂e/MJ in the 2020 SOT case, and 37.0 and 28.3 g CO₂e/MJ in the 2030 projection case, based on mass- and market value-based allocation, respectively. Use of Na₂CO₃ contributes about 12.1 g CO₂e/MJ in the 2020 SOT case and 11.1 g CO₂e/MJ in the 2030 projection case with mass-based process-level allocation; and about 8.4 g CO₂e/MJ in the 2020 SOT case and 7.2 g CO₂e/MJ in the 2030 projection case with market value-based process-level allocation, including the emissions from its manufacturing and the CO₂ emissions during the use phase, with the latter being the major source of GHG emissions. The hydrogen production via steam methane reforming of natural gas is responsible for about 14.2 and 7.0 g CO₂e/MJ in the 2020 SOT and 2030 projection cases, respectively. Electricity is consumed for algae cultivation and dewatering, presenting another source of GHG emissions. No external CO₂ is required for algae cultivation in the 2020 SOT case as the CO₂ recycled from the HTL conversion is sufficient to meet the carbon demand for algae growth. However, 0.34 kg of makeup CO₂ per kg of algae (as AFDW), together with recycled CO₂ from the HTL conversion, is needed in the 2030 projection case.

In the 2020 SOT and 2030 projection cases, co-fed corn stover has a small emission impact, accounting for about 2.4 and 1.5 g CO₂e/MJ, respectively. Increasing the saline algae share in the feedstock blend adds about 0.9 g CO₂e/MJ in the 2030 SOT.

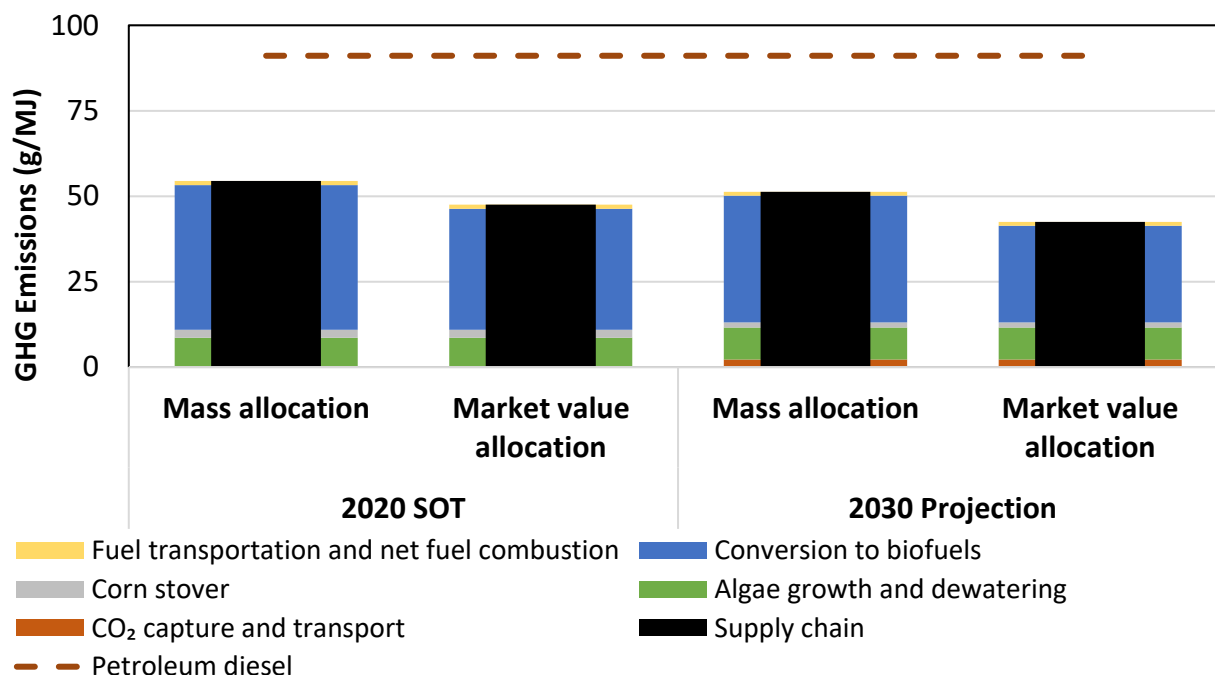


Figure 29 Supply Chain GHG Emissions (g CO₂e/MJ) of Renewable Diesel via Algae/Corn Stover HTL, Using the Process-Level Allocation Method

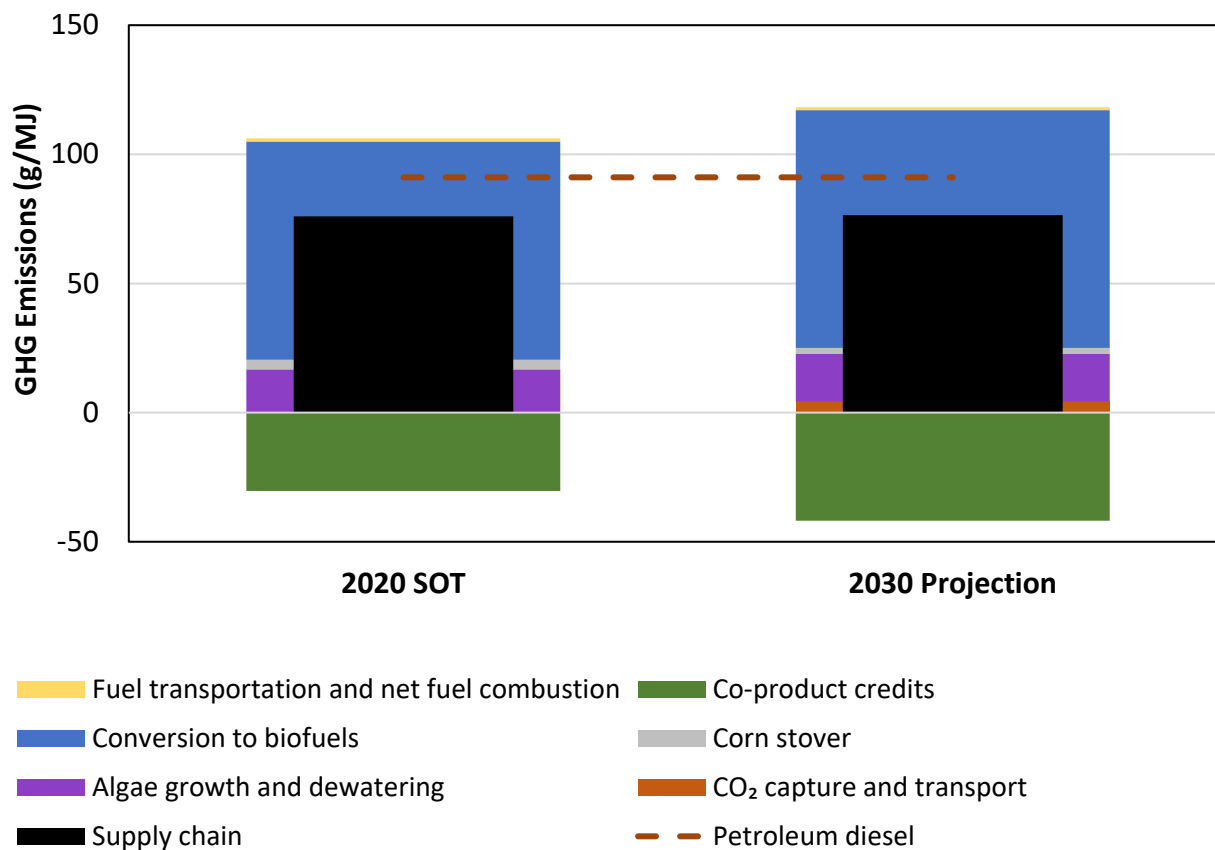


Figure 30 Supply Chain GHG Emissions (g CO₂e/MJ) of Renewable Diesel via Algae/Corn Stover HTL, Using the Displacement Method

With the displacement method, all the chemical use and the resulting emissions are attributed to the renewable diesel fuels. Meanwhile, the renewable diesel fuels get all the credits from the LA co-product displacing conventional corn-based LA (Adom and Dunn, 2016). The LA co-product generates -30 and -42 g CO₂e/MJ in the 2020 SOT and 2030 projection cases, respectively. The 2030 case has higher GHG emissions than the conversion process due to increased NG use. As a result, both the 2020 and 2030 cases have GHG emissions of around 74 g CO₂e/MJ.

A biorefinery-level GHG emission reduction could be expected for the algae/corn stover HTL pathway (Figure 31). The emission reduction varies from about 150 kg CO₂e per dry ton of the feedstock blend converted to fuels and LA in the 2020 SOT case, to about 142 kg CO₂e per dry ton of the feedstock blend converted in the 2030 projection case. All emission reduction benefits come from production of the renewable diesel fuels. The LA co-product, on the other hand, would increase biorefinery-level emissions, owing to its higher carbon intensities from the integrated biorefinery conversion than those of the incumbent counterpart assumed to be produced from corn stover (Adom and Dunn, 2016).

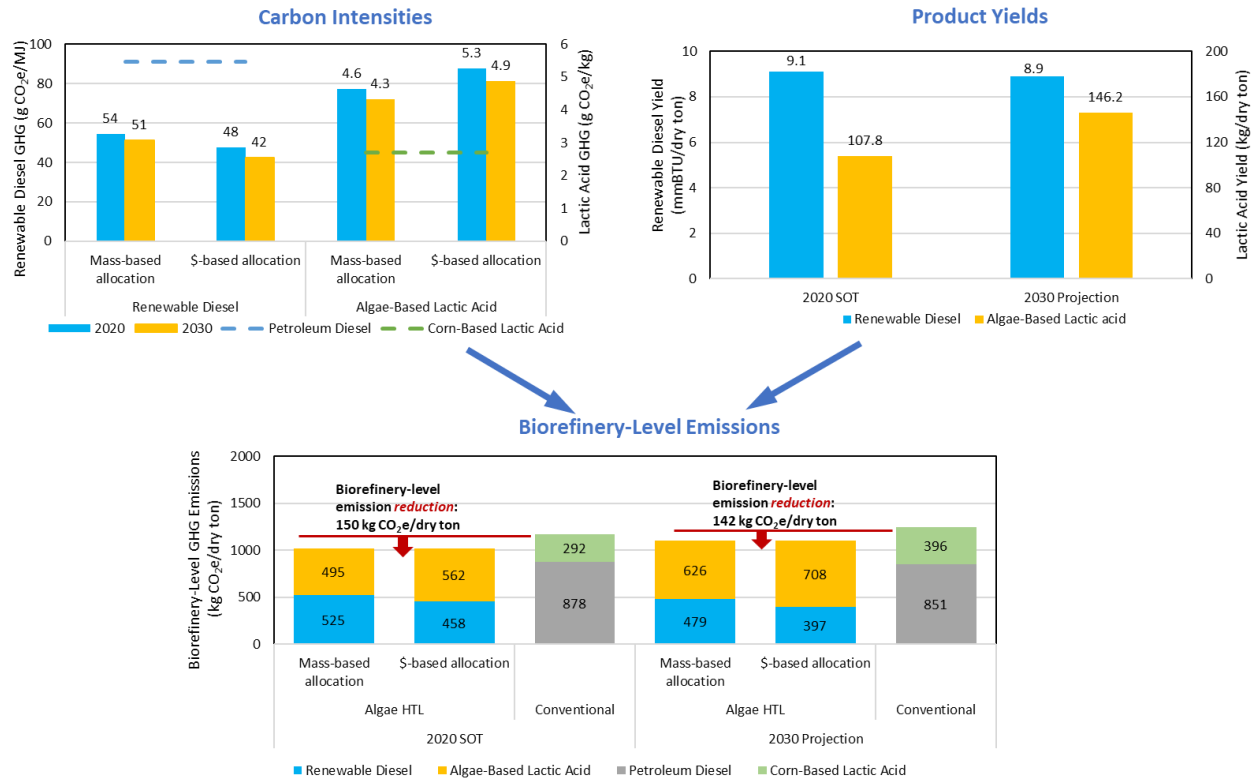


Figure 31 Biorefinery-Level Greenhouse Gas Emissions and Reductions, the 2020 SOT Case and 2030 Projection Case of the Algae/Corn Stover HTL Pathway

3.5.2 Supply Chain Water Consumption

In the 2020 SOT and 2030 projection cases, water consumption associated with natural gas consumption for hydrogen production and with chemical and catalyst use during the HTL processes is the major contributor to supply chain water consumption (Figure 32). Water consumption associated with energy consumption for algae dewatering is another major driver of water consumption. Saline water evaporation in the pond or lost in blowdown during cultivation of saline algae strains does not contribute to water consumption because we consider only fresh water consumption in this analysis.

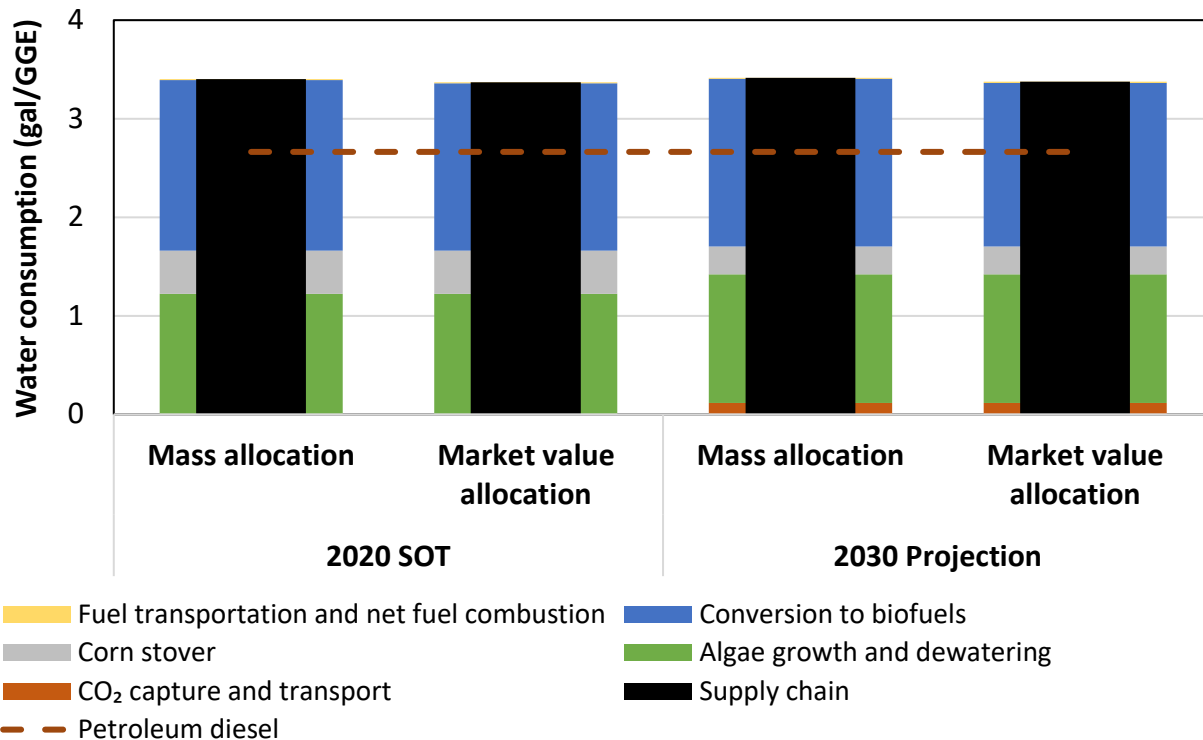


Figure 32 Supply Chain Water Consumption (gal/GGE) of Renewable Diesel via Algae/Corn Stover HTL Using the Process-Level Allocation Method, Compared to 2.7 gal/GGE for Petroleum Diesel

Under the displacement method, water consumption associated with natural gas consumption for renewable fuel production and with chemical and catalyst use during the HTL processes is the major contributor to supply chain water consumption (Figure 33). Water consumption associated with energy consumption for algae dewatering is another major driver of water consumption. Saline water evaporation in the pond or lost in blowdown during cultivation of saline algae strains does not contribute to water consumption because we consider only fresh water consumption in this analysis. Meanwhile, the LA co-product generates significant displacement credits and drives the supply chain water consumption to negative values because the production of conventional corn-based LA consumes a significant amount of water, owing to significant irrigation water consumption to grow corn as the feedstock (Lampert et al. 2016).

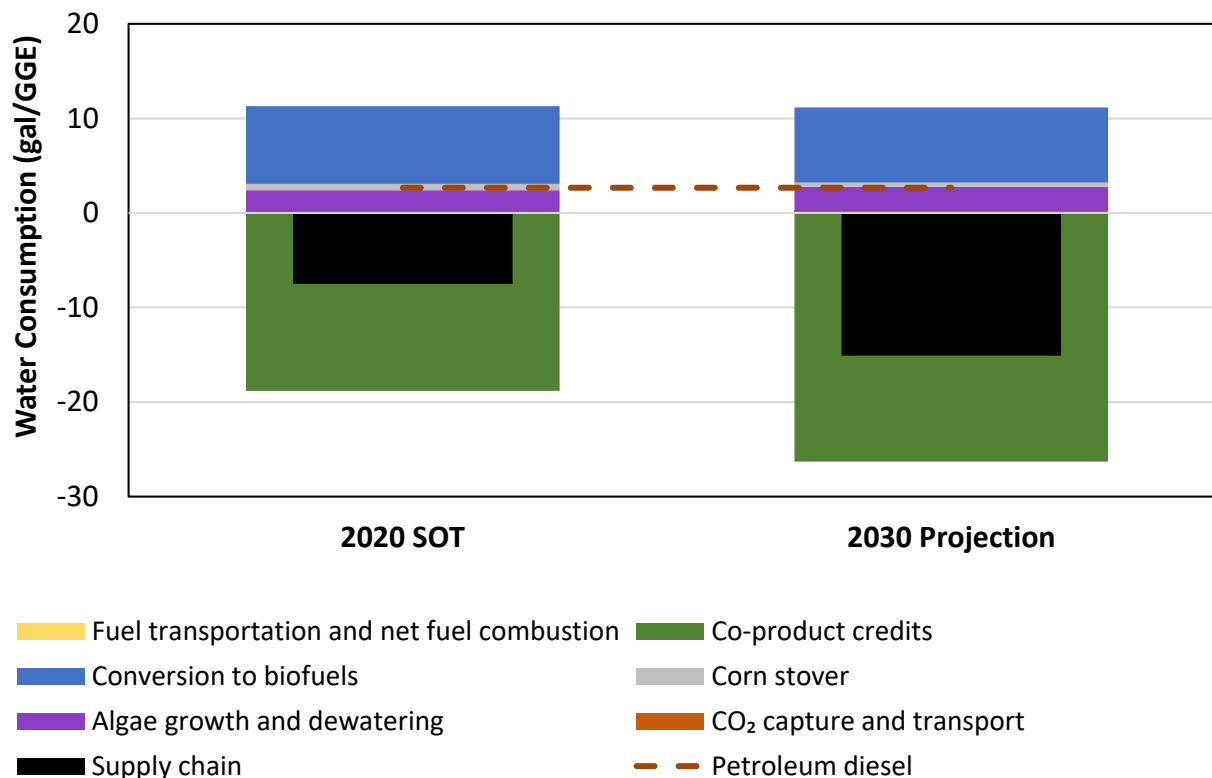


Figure 33 Supply Chain Water Consumption (gal/GGE) of Renewable Diesel via Algae/Corn Stover HTL Using the Displacement Method, Compared to 2.7 gal/GGE for Petroleum Diesel

The direct water consumption during the conversion process is reduced from 1.4 gal/GGE in the 2019 SOT case to 0.8 gal/GGE in the 2020 SOT case, which is a 43% decrease in direct water consumption.

3.5.3 Supply Chain NO_x Emissions

Under the mass- and market value-based allocation methods, total NO_x emissions are about 26%-34% and 2%-8% higher in the 2020 SOT but 1%-12% lower in the 2030 projection case, respectively, than those of petroleum diesel depending on the basis for the process-level allocation method. The HTL conversion process is the largest emission source, accounting for about 31%-36% and 37%-44% of the total emissions in the 2020 SOT and 2030 projection cases, respectively, due to energy and catalyst consumption (Figure 34). RD fuel combustion is another major source of NO_x emissions, assuming that the fuel has the same tailpipe NO_x emission factor as petroleum diesel. Co-fed corn stover has only a small NO_x emission impact.

Under the displacement method (see Figure 35), the 2020 SOT has higher supply chain NO_x emissions than petroleum diesel, while the 2030 case projects supply chain NO_x emissions somewhat comparable to those of petroleum diesel. Embedded emissions from manufacturing the process chemicals and catalysts required for the HTL conversion are the major source of NO_x

emissions. NO_x associated with energy consumption for algae cultivation and dewatering and NO_x emissions during vehicle operation are other major drivers of NO_x emissions. The LA co-product generates considerable NO_x emission credits from avoiding emissions from production of conventional corn-based LA.

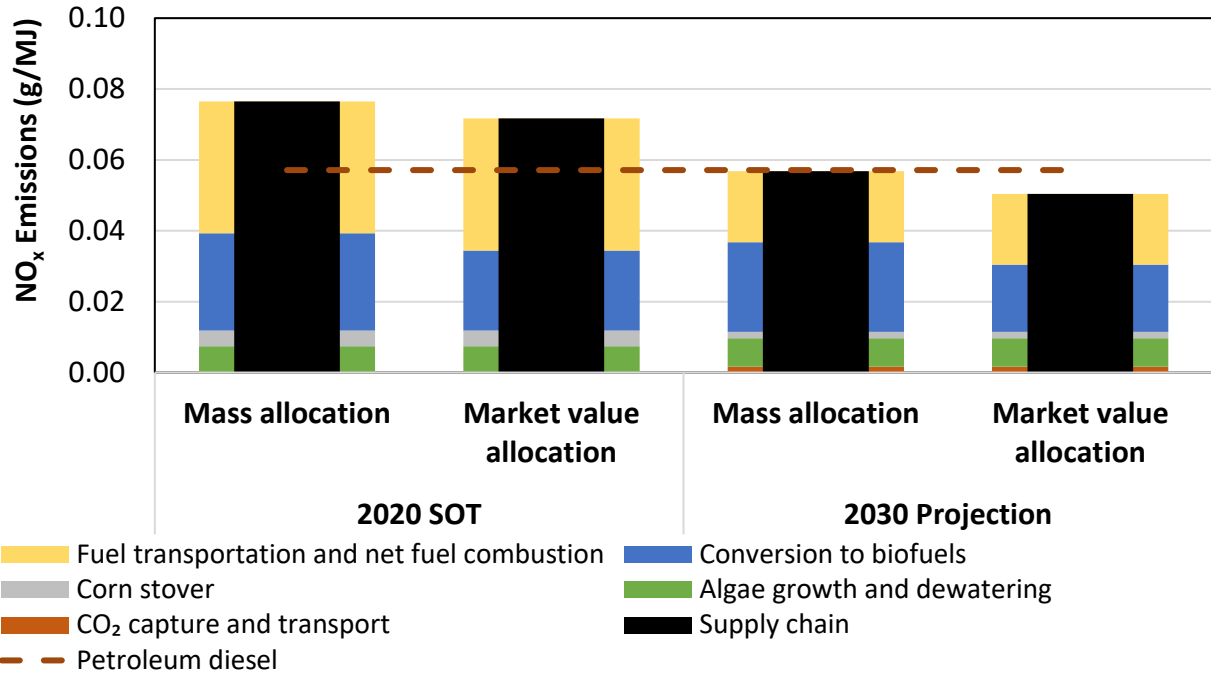


Figure 34 Supply Chain NO_x Emissions (g/MJ) of Renewable Diesel via Algae/Corn Stover HTL Using the Process-Level Allocation Method, Compared to 0.06 g/MJ for Petroleum Diesel

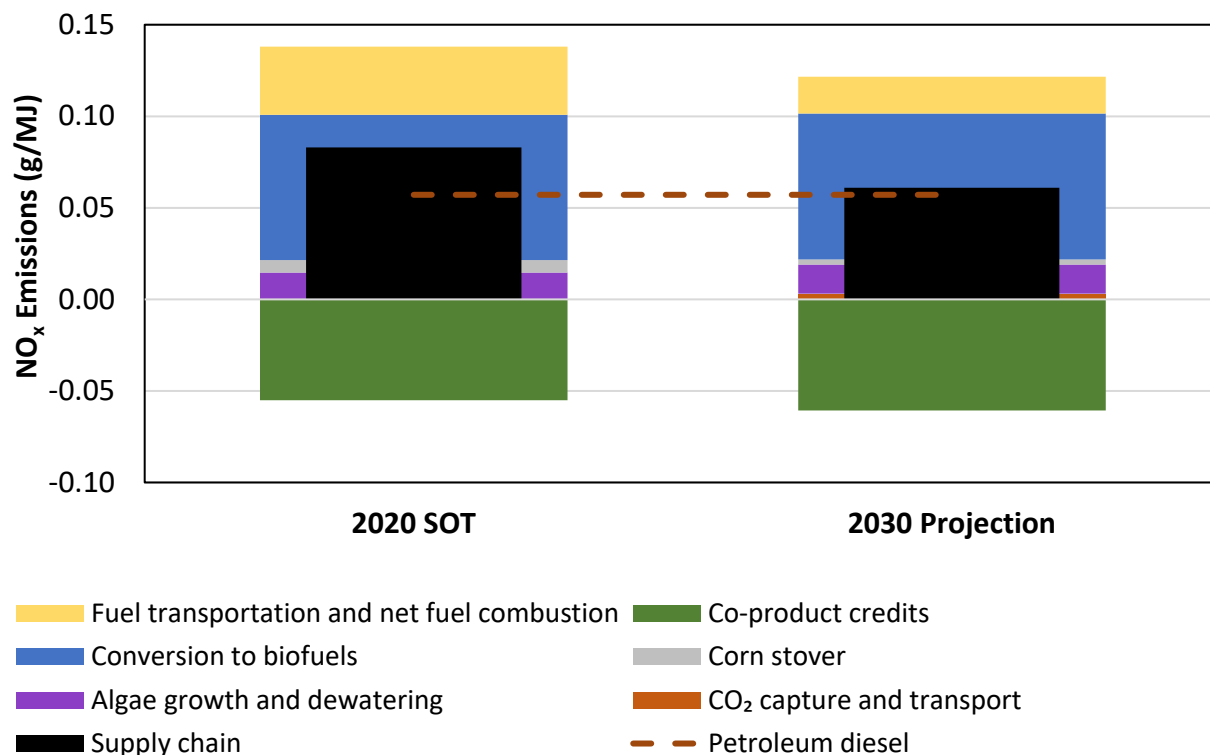


Figure 35 Supply Chain NO_x Emissions (g/MJ) of Renewable Diesel via Algae/Corn Stover HTL Using the Displacement Method, Compared to 0.06 g/MJ for Petroleum Diesel
3.5.4 Summary of Sustainability Metrics

Table 29 summarizes supply chain sustainability metrics, including fossil energy consumption, NEB, GHG emissions, water consumption, and NO_x emissions, of RD from co-feeding algae with corn stover via HTL in the 2020 SOT and 2030 projection cases. Fossil energy consumption is 42% and 48% lower compared to that of petroleum diesel based on mass- and market value-based process-level allocation methods, respectively, resulting in an NEB of about 0.3 MJ/MJ in the 2020 SOT case. In the 2030 projection case, fossil energy consumption is 46% and 54% lower compared to that of petroleum diesel based on mass- and market value-based process-level allocation methods, respectively.

Table 29 Supply Chain Sustainability Metrics for Renewable Diesel via Algae/Corn Stover HTL

	2020 SOT		2030 Projection		Petroleum Diesel
	Mass-based allocation	Market-value-based allocation	Mass-based allocation	Market-value-based allocation	
Biofuel yield					
mmBtu/dry ton	16.1	16.1	16.1	16.1	

Fossil energy consumption					
MJ/MJ	0.7 (-42%)	0.6 (-48%)	0.6 (-46%)	0.5 (-54%)	1.2
Net energy balance					
MJ/MJ	0.3	0.4	0.4	0.5	
GHG emissions					
g CO ₂ e/MJ	54 (-40%)	48 (-48%)	51 (-44%)	42 (-53%)	91
g CO ₂ e/ GGE	6,672	5,818	6,277	5,204	11,157
Water consumption					
L/MJ	0.11	0.10	0.11	0.10	0.08
gal/GGE	3.4	3.4	3.4	3.4	2.7
Total NO_x emissions					
g NO _x /MJ	0.08	0.07	0.06	0.05	0.06
g NO _x /GGE	9.4	8.8	7.0	6.2	7.0
Urban NO_x emissions					
g NO _x /MJ	0.03	0.03	0.02	0.02	0.03
g NO _x /GGE	3.5	3.4	2.1	2.1	3.3

Note: The values in parentheses are the percentage of difference compared to the petroleum diesel pathway. Reduction is represented with negative values.

Despite somewhat higher total supply chain NO_x emissions in the 2020 SOT case than those of petroleum diesel, the algae/corn stover HTL pathway has urban NO_x emissions comparable to those of petroleum diesel, assuming that the algae farm, corn stover logistics, and HTL and upgrading plant that are important emission sources of RD operate in rural, non-MSA areas.

Table 30 summarizes the sustainability metrics of LA produced from co-feeding algae with corn stover via HTL in the 2020 SOT and 2030 projection cases. Fossil energy and GHG emissions increase considerably relative to corn-based LA (the conventional pathway to produce LA) due to greater NG requirements for hydrogen production and heat supply to produce LA in the 2020 SOT and 2030 projection cases than that of corn-based LA production. However, water consumption and total NO_x emissions are reduced compared to corn-based LA, given higher water consumption and NO_x emissions from corn farming.

Table 30 Supply Chain Sustainability Metrics for Lactic Acid via Algae/Corn Stover HTL

	2020 SOT		2030 Projection		Corn-based LA
	Mass-based allocation	Market-value-based allocation	Mass-based allocation	Market-value-based allocation	
LA yield					
ton/dry ton	0.3	0.3	0.4	0.4	
Fossil energy consumption					
MJ/kg	61.7	68.1	58.3	64.6	38.7
GHG emissions					
g CO ₂ e/kg	4,592 (70%)	5,216 (93%)	4,281 (58%)	4,841 (79%)	2,709
Water consumption					
L/kg	21.7	21.8	15.4	15.4	52.1
Total NO_x emissions					
g NO _x /kg	4.5	4.9	4.1	4.5	4.9

Note: The values in parentheses are the percentage of difference compared to the petroleum diesel pathway. Reduction is represented with negative values.

Table 31 summarizes the supply chain sustainability metrics, including fossil energy consumption, NEB, GHG emissions, water consumption, and NO_x emissions of renewable diesel from the algae/corn stover HTL pathway, under the displacement method.

Table 31 Supply Chain Sustainability Metrics for Renewable Diesel via Algae/Corn Stover Pathway in the 2020 SOT Case and 2030 Projection Case, Using the Displacement Method

	2020 SOT	2030 Projection	Petroleum Diesel
Biofuel yield			
mmBtu/dry ton	9.1	8.9	
Fossil energy consumption			
MJ/MJ	1.0 (-20%)	1.0 (-20%)	1.2
Net energy balance			
MJ/MJ	0.0	0.0	
GHG emissions			
g CO ₂ e/MJ	76 (-17%)	76 (-16%)	91
g CO ₂ e/ GGE	9,300	9,360	11,157
Water consumption			
L/MJ	-0.23	-0.47	0.08
gal/GGE	-7.5	-15.1	2.7
Total NO_x emissions			
g NO _x /MJ	0.08	0.06	0.06
g NO _x /GGE	10.2	7.5	7.0
Urban NO_x emissions			
g NO _x /MJ	0.03	0.02	0.03
g NO _x /GGE	3.8	2.6	3.3

Table 32 summarizes the biorefinery-level sustainability metrics compared to conventional production of the petroleum diesel and LA, which are displaced by products from the 2020 SOT and 2030 projection cases. Fossil energy use, GHG emissions, and water consumption are reduced by co-production of renewable diesel and LA via algae/corn stover HTL. RD produced from algae HTL helps reduce the biorefinery-level emissions because it causes lower GHG emissions than petroleum diesel. Meanwhile, the LA co-product has a higher carbon intensity than conventional corn-based LA, negatively affecting biorefinery-level GHG emissions. NO_x emissions slightly increase in the 2020 SOT case but decrease in the 2030 projection case compared to conventional RD and LA production.

Table 32 Biorefinery-Level Sustainability Metrics of Algae/Corn Stover HTL

	2020 SOT		2030 Projection		
	Mass-based allocation	Market value-based allocation	Mass-based allocation	Market value-based allocation	
Products					
Renew diesel		9.1		8.9	mmBtu/dry ton biomass
Lactic acid		0.12		0.16	ton/dry ton biomass
Fossil energy consumption					
Direct consumption by RD production	6,693	5,998	6,027	5,106	MJ/dry ton biomass
Credits from RD production	-11,571	-11,571	-11,212	-11,212	MJ/dry ton biomass
<i>Net consumption by RD production</i>	-4,878 (203%)	-5,572 (232%)	-5,185 (224%)	-6,106 (264%)	MJ/dry ton biomass
Direct consumption by LA production	6,648	7,342	8,524	9,445	MJ/dry ton biomass
Credits from LA production	-4,167	-4,167	-5,654	-5,654	MJ/dry ton biomass
<i>Net consumption by LA production</i>	2,480 (-103%)	3,175 (-132%)	2,871 (-124%)	3,791 (-164%)	MJ/dry ton biomass
Net Total	-2,397	-2,397	-2,314	-2,314	MJ/dry ton biomass
GHG emissions					
Direct emissions from RD production	525	458	479	397	kg/dry ton biomass
Credits from RD production	-878	-878	-851	-851	kg/dry ton biomass
<i>Net emissions from RD production</i>	-353 (235%)	-420 (280%)	-372 (261%)	-454 (319%)	kg/dry ton biomass
Direct emissions from LA production	495	562	626	708	kg/dry ton biomass
Credits from LA production	-292	-292	-396	-396	kg/dry ton biomass
<i>Net emissions from LA production</i>	203 (-135%)	270 (-180%)	230 (-161%)	312 (-219%)	kg/dry ton biomass
Net total	-150	-150	-142	-142	kg/dry ton biomass
Water consumption					
Direct consumption by RD production	268	265	261	257	gal/dry ton biomass
Credits from RD production	-210	-210	-203	-203	gal/dry ton biomass
<i>Net consumption by RD production</i>	58 (-7%)	56 (-7%)	57 (-4%)	54 (-4%)	gal/dry ton biomass
Direct consumption by LA production	618	621	593	596	gal/dry ton biomass
Credits from LA production	-1,482	-1,482	-2,011	-2,011	gal/dry ton biomass
<i>Net consumption by LA production</i>	-864 (107%)	-862 (107%)	-1,418 (104%)	-1,415 (104%)	gal/dry ton biomass
Net total	-806	-806	-1,360	-1,360	gal/dry ton biomass
Total NO_x emissions					
Direct emissions from RD production	738	691	530	471	g/dry ton biomass
Credits from RD production	-551	-551	-534	-534	g/dry ton biomass
<i>Net emissions from RD production</i>	187 (137%)	141 (103%)	-3 (3%)	-63 (53%)	g/dry ton biomass
Direct emissions from LA production	480	527	605	665	g/dry ton biomass
Credits from LA production	-531	-531	-720	-720	g/dry ton biomass
<i>Net emissions from LA production</i>	-51 (-37%)	-4 (-3%)	-115 (97%)	-55 (47%)	g/dry ton biomass
Net total	137	137	-118	-118	g/dry ton biomass

Note: Positive net totals indicate net increases compared to conventional products. Negative net totals indicate net reductions compared to conventional products. The values in parentheses are contributions to the net totals by RD and co-product in percentage.

3.6 Combined Algae Processing

The SCSA of the CAP pathway incorporates the 2020 SOT case for algae biomass cultivation with unlined ponds using saline algae strains as well as the 2020 SOT case for CAP conversion for both the acids and BDO pathway designs. The purpose-driven, process-level allocation method is applied to address the effect of the PU co-product.

3.6.1 Supply Chain Greenhouse Gas Emissions

Figure 36 shows the supply chain GHG emissions and their key contributing supply chain processes, in g CO₂e/MJ, of RD in the 2020 SOT case and 2025 and 2030 projection cases, using the mass- and market value-based, process-level allocation method, relative to a life-cycle carbon intensity of 91 g CO₂e/MJ for petroleum diesel. GHG emissions of RD in the 2020 SOT cases are about 36% and 20% lower for the acids and BDO pathways, respectively, than those of petroleum diesel with mass-based process-level allocation. The market value-based process-allocation method achieves reductions in GHG emissions of 63% and 47%, respectively, for the acids and BDO pathways, relative to petroleum diesel.

Manufacturing of chemicals and catalysts for use in the CAP conversion processes is the primary emission source in the 2020 SOT case. Energy consumption for algae growth and dewatering and for CO₂ capture and transportation to the algae farm are also notable emission sources. Recycling nutrients from the AD effluent reduces the demand for makeup nutrients for algae cultivation and thus contributes to reducing the emission impacts for the algae production phase. Similar to the Biochemical Conversion pathway discussed earlier, the GHG emissions profiles for the algae CAP pathway are expected to improve substantially in future 2030 projection cases. Relative to petroleum diesel, GHG emissions of RD in the 2025 projection case are 41%-65% lower for the acids pathway, and 25%-47% lower for the BDO pathway, depending on the allocation basis (mass- or market value) used for the process-level allocation method. RD from the acids and BDO pathways in the 2030 projection case achieves similar GHG emission reductions compared to those in the 2025 projection case. The co-product credits shown in Figure 36 are from surplus electricity displacing U.S. average grid mix. The displacement method is used for surplus electricity because it accounts for only 15%-18% by energy relative to fuel in the 2020 SOT case and 18% to 20% in the 2025 and 2030 projection cases, which is much smaller than 116% for PU by mass relative to fuel in the 2020 SOT case and 94%-109% in the 2025 and 2030 projection cases. The market value-based allocation results lead to lower emissions than those with the mass-based allocation methods because the market value of renewable diesel (\$2.5/GGE, or \$0.39/lbs) is lower than that of PU (\$2.04/lbs) on a mass basis.

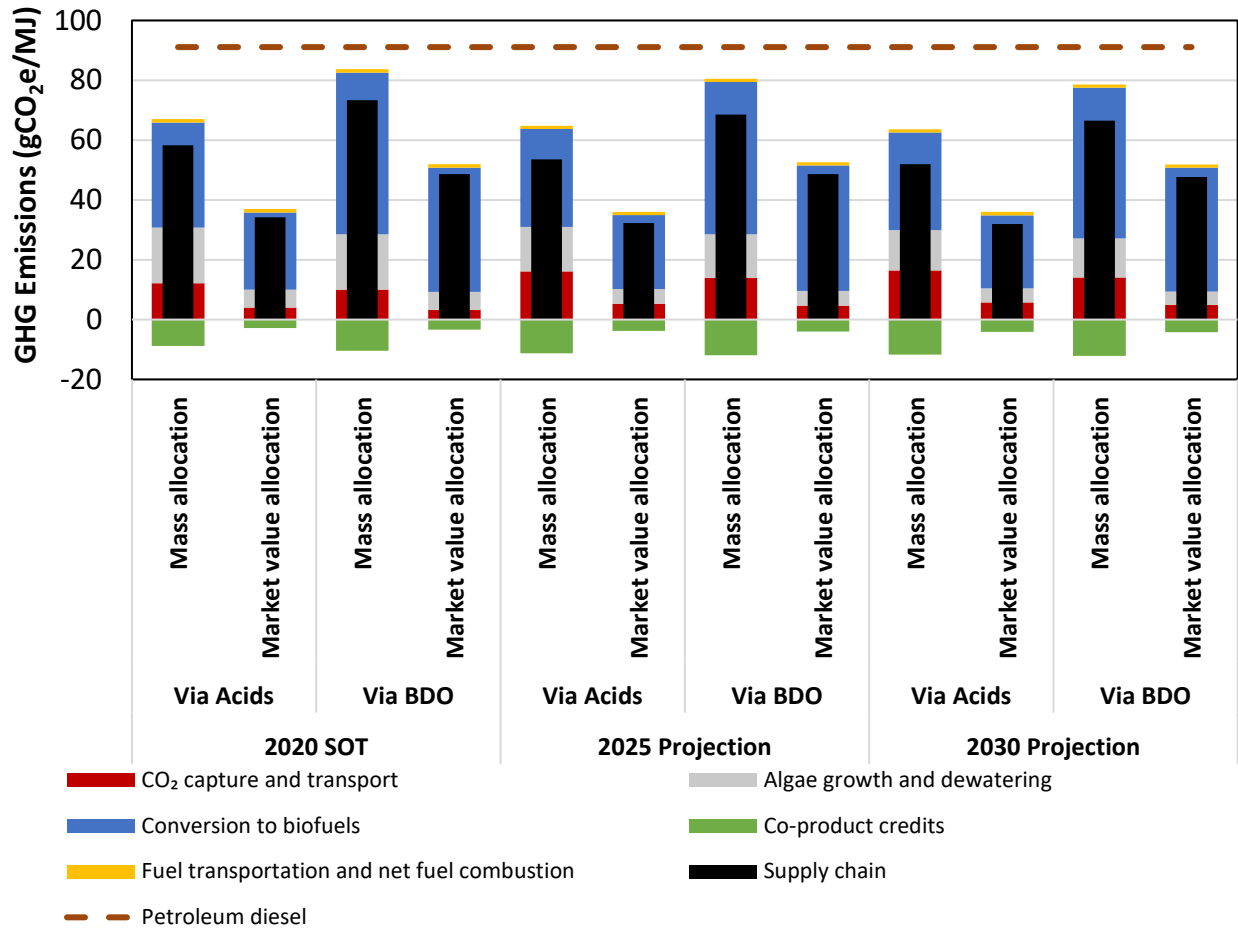


Figure 36 Supply Chain GHG Emissions of Renewable Diesel via CAP Using the Process-Level Allocation Method, Compared to 91 g CO₂e/MJ for Petroleum Diesel

Under the displacement method, all chemical use and associated emissions are attributed to the hydrocarbon fuels. Meanwhile, the renewable diesel fuels get all the credits from the PU co-product displacing conventional fossil-based PU. In addition, bio-based PU generates GHG emission credits by sequestration of biogenic carbon, given that it contains biogenic carbon derived from algal biomass (the overall carbon content of the PU is 66%, 73% of which is biogenic per process modeling). The production of PU has a significant impact on the GHG emissions in the 2020 SOT and projection cases because of a significant PU yield, generating more than -100 g CO₂e/MJ displacement credits by displacing conventional PU (-116 – -120 g CO₂e/MJ in the 2020 SOT case, -113 – -115 g CO₂e/MJ in the 2025 projection case, and -102 – -105 g CO₂e/MJ in the 2030 projection case) and biogenic carbon sequestration (-47 g CO₂e/MJ in the 2020 SOT case, -43 – -44 g CO₂e/MJ in the 2025 projection case, and -38 – -39 g CO₂e/MJ in the 2030 projection case). The PU displacement emission credits per MJ of renewable fuels are smaller in the 2025 and 2030 projection cases than those in the 2020 SOT case because the yield of the renewable fuels is improved in the projection cases but the yield of the PU co-product is not improved. As a result, the renewable diesel produced from algae CAP

has low supply chain GHG emissions in all cases, ranging from 3 to 9 g CO₂e/MJ in the acids pathway and 24 to 31 g CO₂e/MJ in the BDO pathway (Figure 37). The BDO pathway has higher GHG emissions than the acids pathway because it consumes more hydrogen and natural gas in the conversion process.

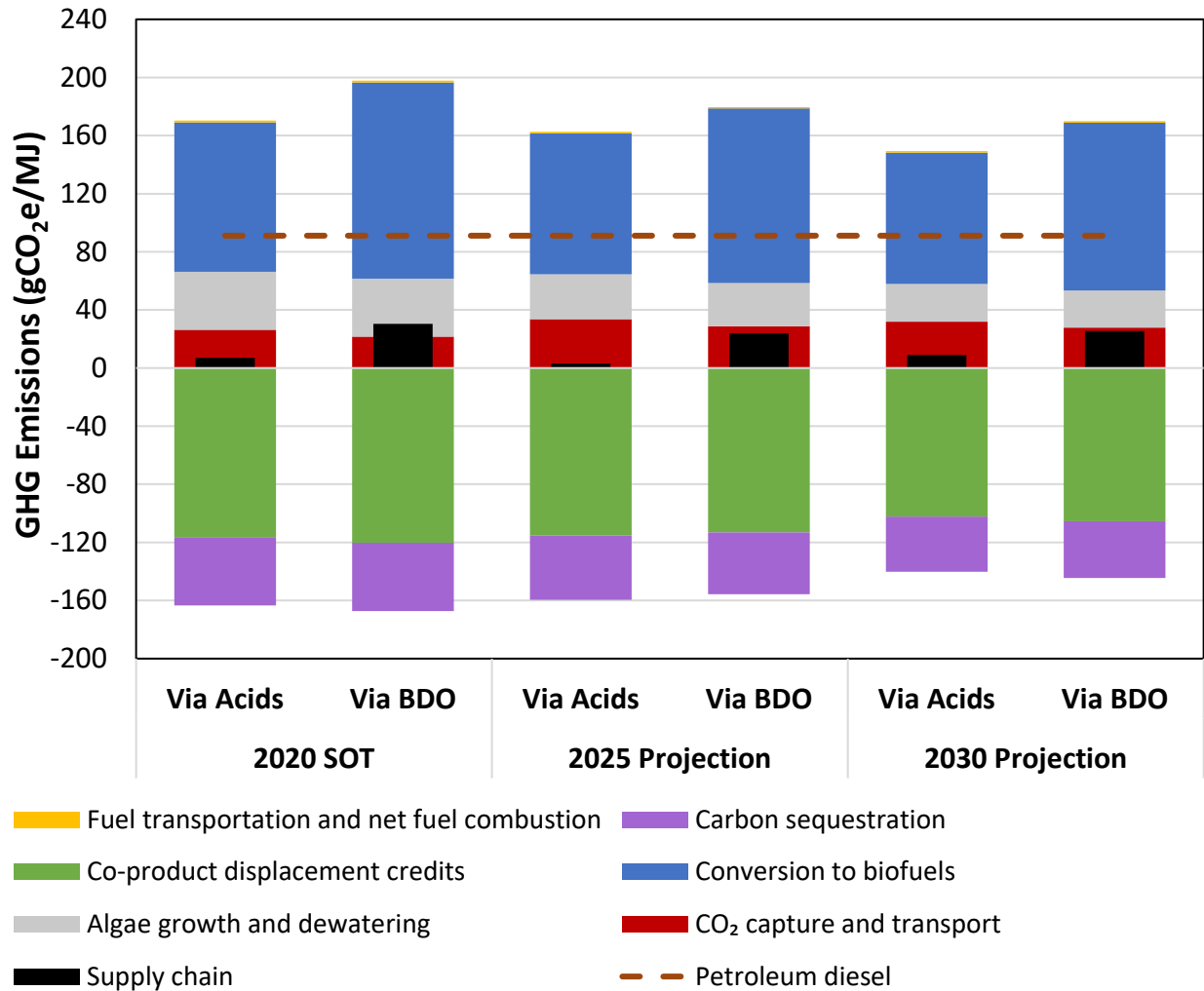
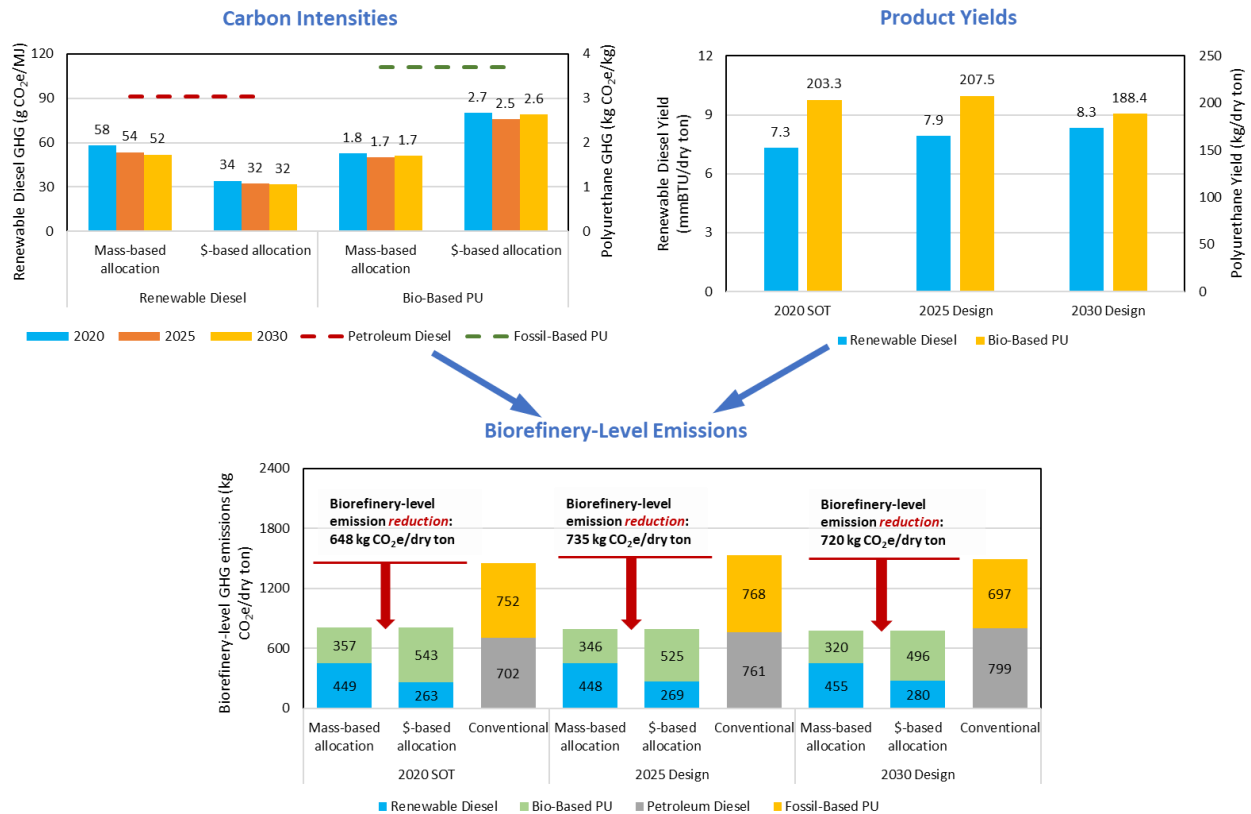


Figure 37 Supply Chain GHG Emissions of Renewable Diesel via CAP, Using the Displacement Method to Address Effects of PU

A biorefinery-level GHG emission reduction could be expected for the algae CAP conversion pathway. With the via acids intermediate route, the biorefinery-level emission reduction varies from about 648 kg CO₂e per dry ton of algae converted to fuels and PU in the 2020 SOT case, to about 720 – 735 kg CO₂e per dry ton algae converted in the 2025 and 2030 projection cases. The increase in biorefinery-level emission reduction from the 2020 SOT case to the projection cases is driven by improvement in the fuel yields and decreases in fuel carbon intensities. On the other hand, neither the carbon intensities nor the PU co-product yields change much from the 2020 SOT case to the projection cases. As a result, from 48% to 72% of the

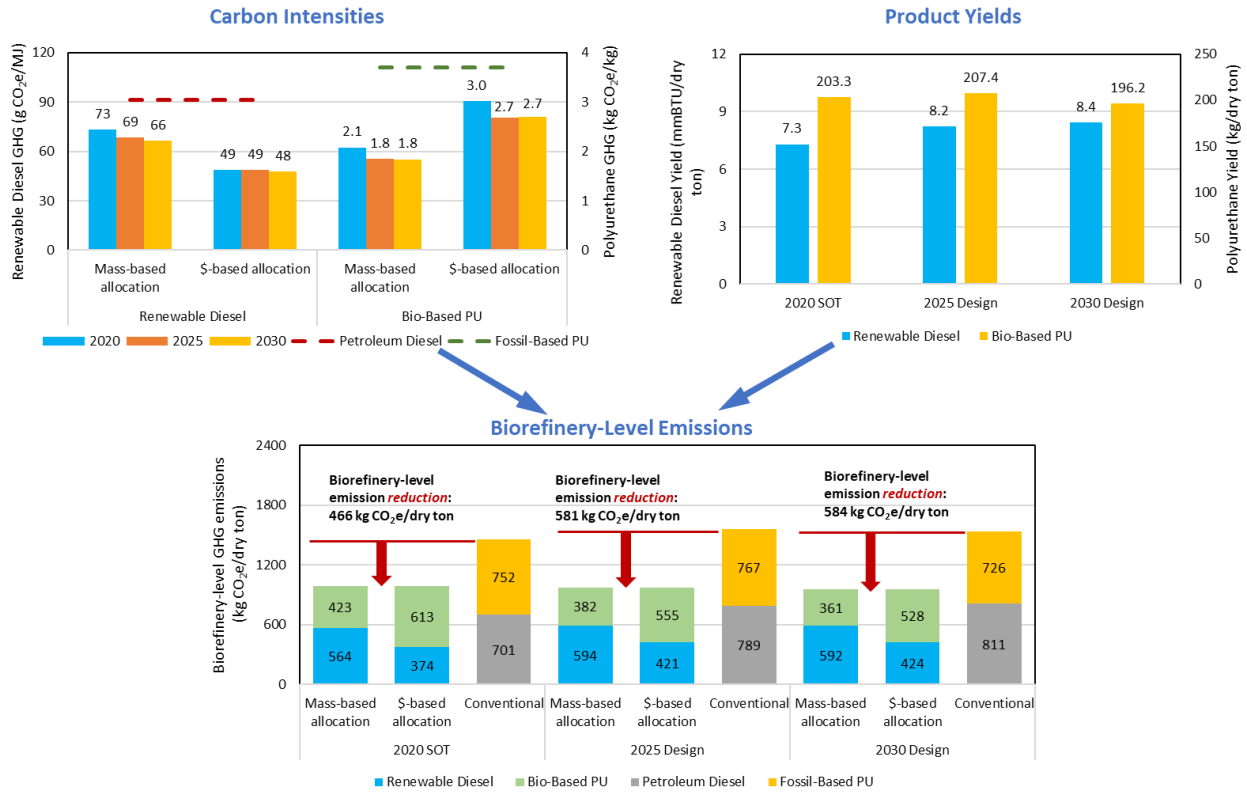
biorefinery-level GHG emission reduction in the 2030 projection case (which varies with process-level allocation basis, either market value or mass) would come from the production of renewable diesel fuels. With the via BDO intermediate route, the biorefinery-level emission reduction varies from about 466 kg CO₂e per dry ton of algae converted to fuels and PU in the 2020 SOT case, to about 581 – 584 kg CO₂e per dry ton algae converted in the 2025 and 2030 projection cases (Figure 38). In this case, 37% to 66% of the biorefinery-level GHG emission reduction in the 2030 projection case (which varies with process-level allocation basis, either market value or mass) would come from the production of renewable diesel fuels.



(a) Via acids

Figure 38 Biorefinery-Level Greenhouse Gas Emissions and Reductions, the 2020 SOT Case and 2025 and 2030 Projection Cases of the Biochemical Conversion Pathway for (a) Via Acids and (b) Via BDO Intermediate Routes

Figure 38 (Cont.)



(b) Via BDO

3.6.2 Supply Chain Water Consumption

Figure 39 shows that the 2020 SOT case has higher water consumption than that of petroleum diesel, owing to significant water consumption associated with the process chemical and catalyst use as well as the makeup water requirements for the CAP conversion process. Direct makeup water consumption within the biorefinery process is 2-5 and 10-14 gal/GGE for the acids and BDO pathways, respectively, depending on the basis (mass or market value) for the process-level allocation (excluding water consumption embedded in chemical usage). Total water consumption within the biorefinery is 24-28 gal/GGE and 14-18 gal/GGE for the acids and BDO pathways, respectively, when water consumption embedded in chemical usage is included. The total water consumption of the acids pathway is high because it uses 7 times more corn steep liquor, which is water intensive to make, than the BDO pathway. Water consumption associated with electricity consumption for algae cultivation and dewatering is another major driver. According to algae cultivation models, saline makeup water inputs are required for algae cultivation but do not contribute to freshwater consumption for either the CAP or algae HTL pathways. Water consumption in the 2025 and 2030 projection cases is comparable to that in the 2020 SOT case.

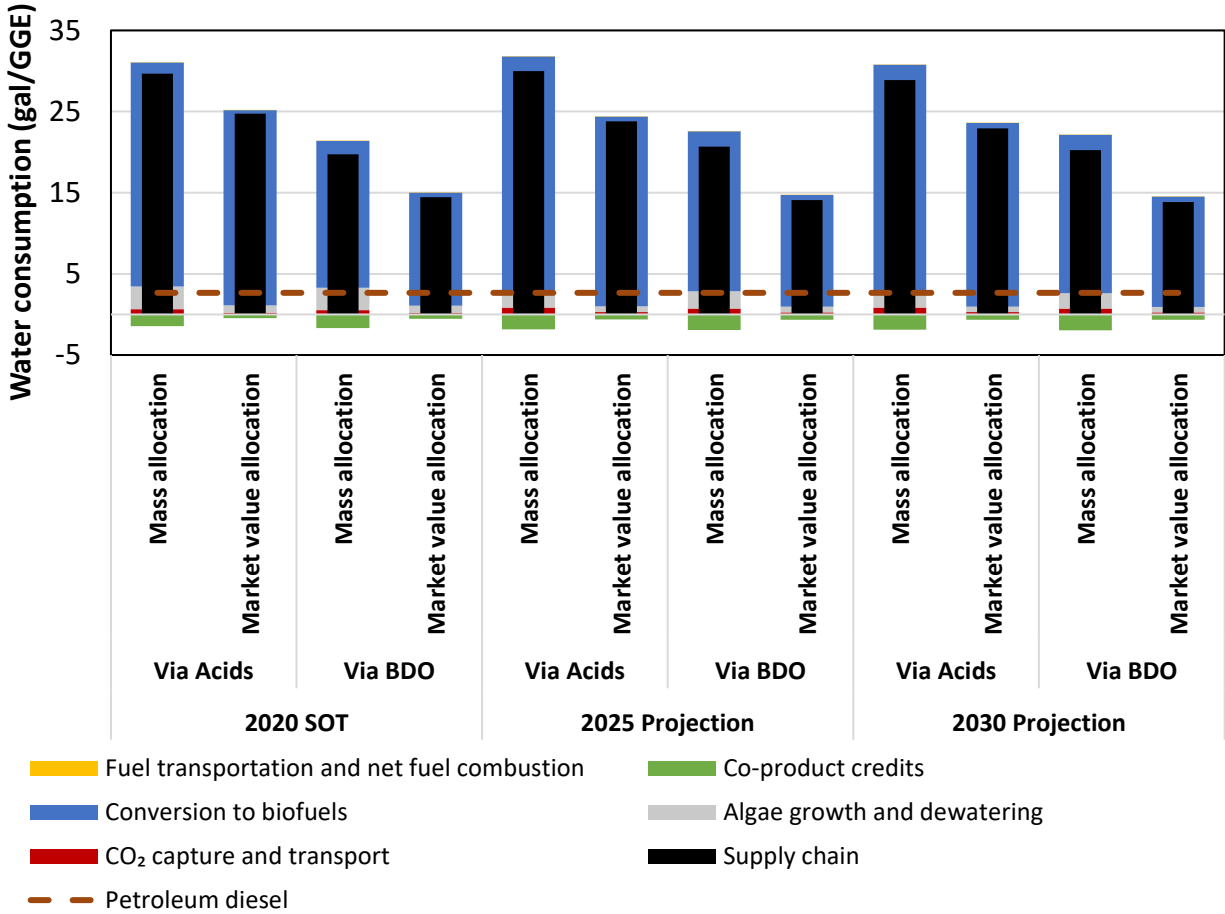


Figure 39 Supply Chain Water Consumption (gal/GGE) of Renewable Diesel via CAP Using the Process-Level Allocation Method, Compared to 2.7 gal/GGE for Petroleum Diesel

Under the displacement method, direct makeup water consumption and water consumption associated with chemical use during conversion are the major contributors to supply chain water consumption (Figure 40). Water consumption associated with energy consumption for algae cultivation and dewatering is another major driver of water consumption. Saline water evaporation in the pond or lost in blowdown during cultivation of saline algae strains does not contribute to water consumption because we consider only fresh water consumption in this analysis. The PU co-product also generates considerable displacement credits by displacing conventional fossil-based PU.

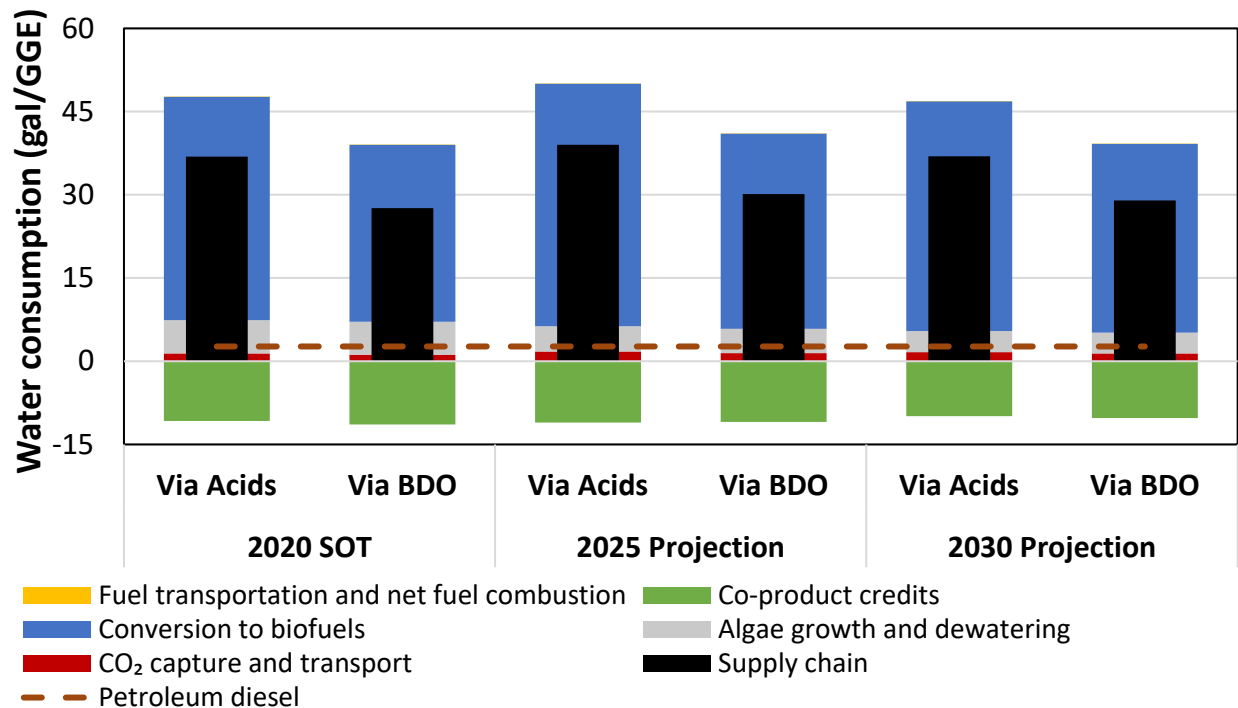


Figure 40 Supply Chain Water Consumption (gal/GGE) of Renewable Diesel via CAP Using the Displacement Method, Compared to 2.7 gal/GGE for Petroleum Diesel

The direct water consumption during the conversion process increases from 10.2 gal/GGE in the 2019 SOT case to 15.4 gal/GGE in the 2020 SOT case for the via acids pathway, which is a 50% increase in direct water consumption, and increases from 13.7 gal/GGE in the 2019 SOT case to 24.6 gal/GGE in the 2020 SOT case for the via BDO pathway, which is a 79% increase in direct water consumption.

3.6.3 Supply Chain NO_x Emissions

Total NO_x emissions from the 2020 SOT cases are 21% to 54% and 20% to 56% higher than petroleum diesel for the acids and BDO pathway designs, respectively, depending on the basis (mass or market value) used for the process-level allocation (Figure 41). Embedded emissions from manufacturing the process chemicals and catalysts required for the CAP conversion are the major emission source. In the 2025 and 2030 projection cases, total NO_x emissions are further reduced to comparable to (with the mass-based process-level allocation) or lower than (with the market value-based process allocation) those of petroleum diesel, primarily due to reduced usage of chemicals and catalysts for the CAP conversion.

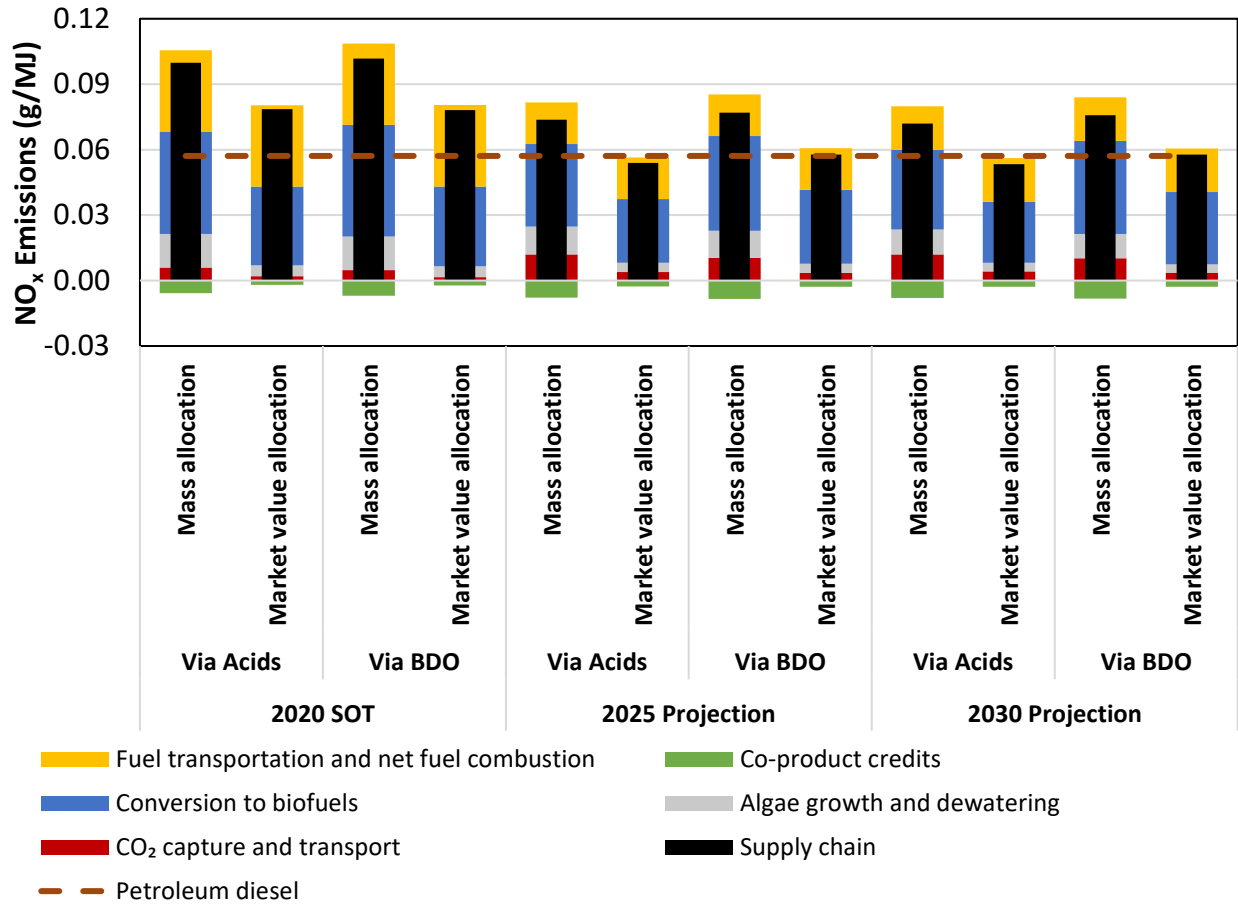


Figure 41 Supply Chain NO_x Emissions (g/MJ), Renewable Diesel via CAP Using the Process-Level Allocation Method, Compared to 0.06 g/MJ for Petroleum Diesel

Under the displacement method (Figure 42), embedded NO_x emissions from manufacturing the process chemicals and catalysts required for the CAP conversion are the major source of NO_x emissions. Other major drivers include NO_x associated with energy consumption for algae cultivation and dewatering and NO_x emissions during vehicle operation. The PU co-product also generates considerable NO_x displacement emission credits from avoiding emissions from production of conventional fossil-based PU.

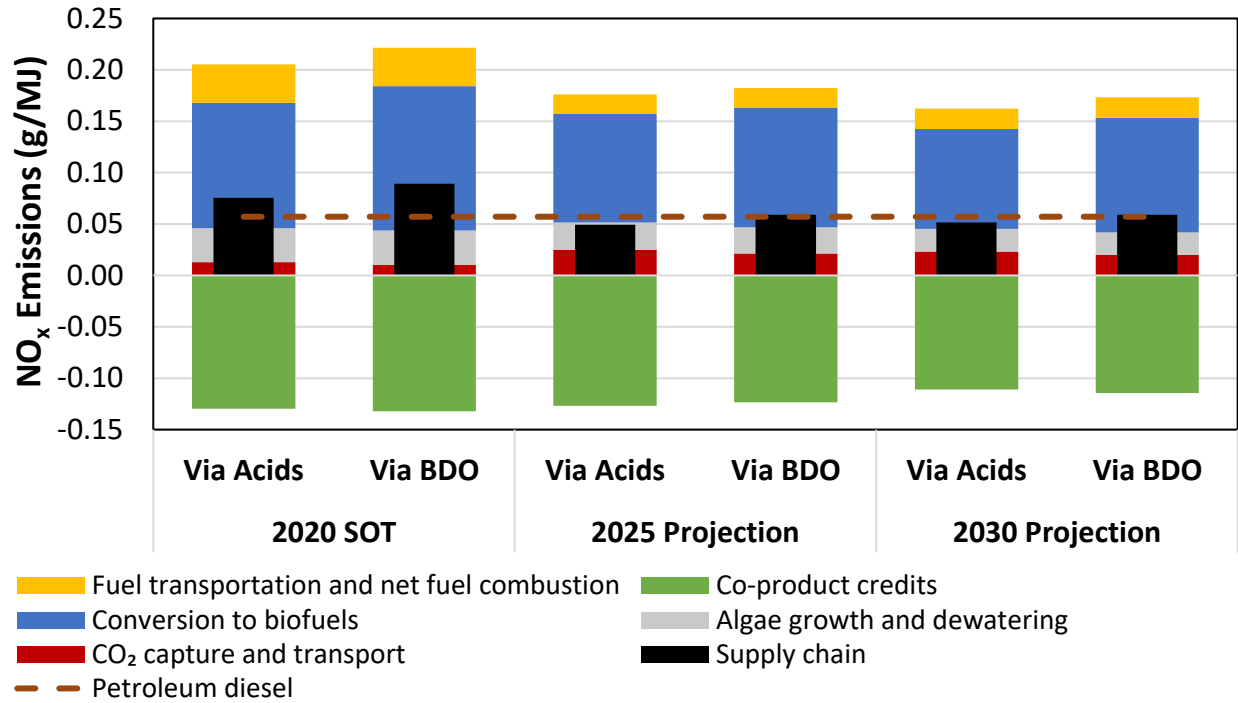


Figure 42 Supply Chain NO_x Emissions (g/MJ), Renewable Diesel via CAP Using the Displacement Method, Compared to 0.06 g/MJ for Petroleum Diesel

3.6.4 Summary of Sustainability Metrics

Tables 33 to 35 summarize supply chain sustainability metrics, including fossil energy consumption, NEB, GHG emissions, water consumption, and NO_x emissions of RD from the CAP conversion designs in the 2020 SOT and future scenarios. Note that these results also consider the displacement credits of recycled nutrients, such as ammonia and diammonium phosphate from anaerobic digester effluent during the CAP conversion processes, which reduces makeup requirements of such nutrients in the algae cultivation phase. The basis on which the process-level allocation is performed has a great impact on the results because the PU co-product has much higher market value than the renewable diesel on a per-kg basis. Improvements are made in the projection cases due to improved yield and reduced energy and chemicals usage from the 2020 SOT case to the 2025/2030 future cases.

Table 33 Supply Chain Sustainability Metrics for Renewable Diesel via CAP, 2020 SOT Case

Scenario 1: Via Acids		Scenario 2: Via BDO		Petroleum Diesel
Mass-based allocation	Market-value-based allocation	Mass-based allocation	Market-value-based allocation	

		Biofuel yield			
mmBtu/dry ton	15.8	48.3	15.8	48.3	
		Co-product yield			
Power exported to grid, kWh/mmBtu of biofuel	20.1	6.6	24.0	7.8	
		Fossil energy consumption			
MJ/MJ	0.8	0.4	1.1	0.7	1.2
		Net energy balance			
MJ/MJ	0.2	0.6	-0.1	0.3	
		GHG emissions			
g CO ₂ e/MJ	58 (-36%)	34 (-63%)	73 (-20%)	49 (-47%)	91
g CO ₂ e/ GGE	7,134	4,183	8,980	5,951	11,157
		Water consumption			
L/MJ	0.92	0.76	0.61	0.45	0.08
gal/GGE	29.7	24.7	19.7	14.4	2.7
		Total NO_x emissions			
g NO _x /MJ	0.10	0.08	0.10	0.08	0.06
g NO _x /GGE	12.2	9.6	12.5	9.6	7.0
		Urban NO_x emissions			
g NO _x /MJ	0.03	0.03	0.03	0.03	0.03
g NO _x /GGE	3.6	3.3	3.6	3.4	3.3

Note: The values in parentheses are the percentage of difference compared to the petroleum diesel pathway. Reduction is represented with negative values.

Table 34 Supply Chain Sustainability Metrics for Renewable Diesel via CAP, 2025 Projection Case

	Scenario 1: Via Acids		Scenario 2: Via BDO		Petroleum Diesel
	Mass-based allocation	Market-value-based allocation	Mass-based allocation	Market-value-based allocation	
Biofuel yield					
mmBtu/dry ton	16.5	49.8	16.9	50.1	
Co-product yield					
Power exported to grid, kWh/mmBtu of biofuel	26.4	8.8	27.9	9.4	
Fossil energy consumption					
MJ/MJ	0.7	0.4	1.0	0.7	1.2
Net energy balance					
MJ/MJ	0.3	0.6	0.0	0.3	
GHG emissions					
g CO ₂ e/MJ	54 (-41%)	32 (-65%)	69 (-25%)	49 (-47%)	91
g CO ₂ e/ GGE	6,560	3,948	8,395	5,950	11,157
Water consumption					
L/MJ	0.93	0.74	0.64	0.44	0.08
gal/GGE	30.0	23.8	20.7	14.1	2.7
Total NO_x emissions					
g NO _x /MJ	0.07	0.05	0.08	0.06	0.06
g NO _x /GGE	9.0	6.6	9.4	7.1	7.0
Urban NO_x emissions					
g NO _x /MJ	0.02	0.02	0.02	0.02	0.03
g NO _x /GGE	2.3	1.8	2.3	1.9	3.3

Note: The values in parentheses are the percentage of difference compared to the petroleum diesel pathway. Reduction is represented with negative values.

Table 35 Supply Chain Sustainability Metrics for Renewable Diesel via CAP, 2030 Projection Case

	Scenario 1: Via Acids		Scenario 2: Via BDO		Petroleum Diesel
	Mass-based allocation	Market-value-based allocation	Mass-based allocation	Market-value-based allocation	
Biofuel yield					
mmBtu/dry ton	16.1	46.3	16.6	48.0	
Co-product yield					
Power exported to grid, kWh/mmBtu of biofuel	28	10	28.6	9.9	
Fossil energy consumption					
MJ/MJ	0.7	0.4	1.0	0.7	1.2
Net energy balance					
MJ/MJ	0.3	0.6	0.0	0.3	
GHG emissions					
g CO ₂ e/MJ	52 (-43%)	32 (-65%)	66 (-27%)	48 (-48%)	91
g CO ₂ e/ GGE	6,360	3,910	8,143	5,839	11,157
Water consumption					
L/MJ	0.89	0.71	0.63	0.43	0.08
gal/GGE	28.9	22.9	20.2	13.8	2.7
Total NO_x emissions					
g NO _x /MJ	0.07	0.05	0.08	0.06	0.06
g NO _x /GGE	8.8	6.5	9.3	7.1	7.0
Urban NO_x emissions					
g NO _x /MJ	0.02	0.02	0.02	0.02	0.03
g NO _x /GGE	2.3	1.9	2.3	2.0	3.3

Note: The values in parentheses are the percentage of difference compared to the petroleum diesel pathway. Reduction is represented with negative values.

Tables 36 to 38 summarize the sustainability metrics for PU produced via CAP. In this analysis, we have updated our LCA results of conventional rigid foam PU (produced from methylene diphenylene diisocyanate and polyether polyol) with detailed LCI of the PU production processes (Franklin Associates, 2011; Keoleian et al. 2012). Algae-based PU has 19% to 52% lower GHG emissions than conventional PU in the 2020 SOT case because it contains biogenic carbon, which comes from algae and generates a biogenic carbon sequestration credit. Algae-based PU has higher GHG emissions when market value-based, process-level allocation is used because more emission burdens are allocated to PU production, given its higher market value than that of the fuel on a mass basis.

Table 36 Supply Chain Sustainability Metrics for PU via CAP, 2020 SOT Case

	Scenario 1: Via Acids		Scenario 2: Via BDO		Conventional PU
	Mass-based allocation	Market-value-based allocation	Mass-based allocation	Market-value-based allocation	
PU yield					
ton/dry ton	0.42	0.26	0.42	0.26	
Fossil energy consumption					
MJ/kg	52.2	65.1	58.2	71.9	56.0
GHG emissions					
g CO ₂ e/kg	1,758 (-52%)	2,672 (-28%)	2,080 (-44%)	3,016 (-19%)	3,700
Water consumption					
L/kg	17.5	23.3	18.3	24.4	9.0
Total NO_x emissions					
g NO _x /kg	3.5	4.3	4.0	4.9	4.4

Note: The values in parentheses are the percentage of difference compared to the petroleum diesel pathway. Reduction is represented with negative values.

Table 37 Supply Chain Sustainability Metrics for PU via CAP, 2025 Projection Case

	Scenario 1: Via Acids		Scenario 2: Via BDO		Conventional PU
	Mass-based allocation	Market-value-based allocation	Mass-based allocation	Market-value-based allocation	
PU yield					
ton/dry ton	0.44	0.27	0.45	0.27	
Fossil energy consumption					
MJ/kg	50.6	62.4	54.1	65.8	56.0
GHG emissions					
g CO ₂ e/kg	1,669 (-55%)	2,528 (-32%)	1,843 (-50%)	2,676 (-28%)	3,700
Water consumption					
L/kg	20.2	28.0	21.2	29.7	9.0
Total NO_x emissions					
g NO _x /kg	3.5	4.3	3.7	4.5	4.4

Note: The values in parentheses are the percentage of difference compared to the petroleum diesel pathway. Reduction is represented with negative values.

Table 38 Supply Chain Sustainability Metrics for PU via CAP, 2030 Projection Case

	Scenario 1: Via Acids		Scenario 2: Via BDO		Conventional PU
	Mass-based allocation	Market-value-based allocation	Mass-based allocation	Market-value-based allocation	
PU yield					
ton/dry ton	0.43	0.25	0.44	0.26	
Fossil energy consumption					
MJ/kg	51.3	64.0	54.1	66.1	56.0
GHG emissions					
g CO ₂ e/kg	1,700 (-54%)	2,632 (-29%)	1,839 (-50%)	2,692 (-27%)	3,700
Water consumption					
L/kg	20.6	29.2	21.3	30.2	9.0
Total NO_x emissions					
g NO _x /kg	3.5	4.4	3.7	4.5	4.4

Note: The values in parentheses are the percentage of difference compared to the petroleum diesel pathway. Reduction is represented with negative values.

Table 39 summarizes supply chain sustainability metrics, using the displacement method.

Table 39 Supply Chain Sustainability Metrics for Renewable Diesel via CAP Pathways in the 2020 SOT Case and 2025/2030 Projection Cases, Using the Displacement Method

	2020 SOT		2025		2030		Petroleum Diesel
	Scenario 1: Via Acids	Scenario 2: Via BDO	Scenario 1: Via Acids	Scenario 2: Via BDO	Scenario 1: Via Acids	Scenario 2: Via BDO	
	Biofuel yield						
mmBtu/dry ton	7.3	7.3	7.9	8.2	8.3	8.4	
	Co-product yield						
Polyurethane, kg/mmBtu of biofuel	27.8	27.9	26.2	25.3	22.7	23.3	
Power exported to grid, kWh/mmBtu of biofuel	43.4	51.8	55.0	57.2	53.6	56.3	
	Fossil energy consumption						
MJ/MJ	0.7	1.1	0.6	1.0	0.6	0.9	1.2
	Net energy balance						
MJ/MJ	0.3	-0.1	0.4	0.0	0.4	0.1	
	GHG emissions						
g CO ₂ e/MJ	7 (-92%)	31 (-67%)	3 (-97%)	24 (-74%)	9 (-90%)	25 (-72%)	91
g CO ₂ e/ GGE	861	3,737	381	2,947	1,099	3,118	11,157
	Water consumption						
L/MJ	1.14	0.85	1.21	0.93	1.14	0.90	0.08
gal/GGE	36.9	27.6	39.0	30.1	37.0	29.0	2.7
	Total NO_x emissions						
g NO _x /MJ	0.08	0.09	0.05	0.06	0.05	0.06	0.06
g NO _x /GGE	9.3	10.9	6.0	7.2	6.3	7.2	7.0
	Urban NO_x emissions						
g NO _x /MJ	0.03	0.03	0.02	0.02	0.02	0.02	0.03
g NO _x /GGE	3.7	3.8	2.6	2.5	2.6	2.5	3.3

Tables 40 to 42 summarize biorefinery-level sustainability metrics for the algae CAP pathway. The CAP biorefinery achieves reductions in fossil energy consumption and GHG emissions, but consumed more water due to makeup water requirements and the use of chemicals like corn steep liquor, which requires a large amount of water for its production. RD produced from CAP has lower GHG emissions than petroleum diesel in all the cases despite the basis for the process-level allocation method. PU production from CAP also contributes to the biorefinery GHG emissions reduction when compared to conventional PU production because of the sequestration of its biogenic carbon. In the 2020 SOT case, biorefinery NO_x emissions saw a slight increase relative to the conventional diesel and PU production. However, in the 2025 and 2030 projection cases, biorefinery-level NO_x emissions are reduced to comparable to those of the conventional diesel and PU production.

Table 40 Biorefinery-Level Sustainability Metrics of Algae CAP, 2020 SOT Case

	Scenario 1: Via Acids		Scenario 2: Via BDO		
	Mass-based allocation	Market-value-based allocation	Mass-based allocation	Market-value-based allocation	
Products					
Renew diesel		7.3		7.3	mmBtu/dry ton biomass
PU		0.2		0.2	ton/dry ton biomass
Fossil energy consumption					
Direct consumption by RD production	5,962	3,354	8,393	5,612	MJ/dry ton biomass
Credits from RD production	-9,254	-9,254	-9,239	-9,239	MJ/dry ton biomass
<i>Net consumption by RD production</i>	-3,292 (81%)	-5,900 (145%)	-846 (209%)	-3,627 (897%)	MJ/dry ton biomass
Direct consumption by PU production	10,620	13,227	11,832	14,613	MJ/dry ton biomass
Credits from PU production	-11,390	-11,390	-11,390	-11,390	MJ/dry ton biomass
<i>Net consumption by PU production</i>	-770 (19%)	1,837 (-45%)	442 (-109%)	3,223 (-797%)	MJ/dry ton biomass
Net Total		-4,062		-404	MJ/dry ton biomass
GHG emissions					
Direct emissions from RD production	449	263	564	374	kg/dry ton biomass
Credits from RD production	-702	-702	-701	-701	kg/dry ton biomass
<i>Net emissions from RD production</i>	-253 (39%)	-439 (68%)	-137 (29%)	-327 (70%)	kg/dry ton biomass
Direct emissions from PU production	357	543	423	613	kg/dry ton biomass
Credits from PU production	-752	-752	-752	-752	kg/dry ton biomass
<i>Net emissions from PU production</i>	-395 (61%)	-209 (32%)	-330 (71%)	-139 (30%)	kg/dry ton biomass
Net Total		-648		-466	
Water consumption					
Direct consumption by RD production	1,867	1,556	1,239	908	gal/dry ton biomass
Credits from RD production	-168	-168	-167	-167	gal/dry ton biomass
<i>Net consumption by RD production</i>	1,699 (79%)	1,389 (64%)	1,072 (68%)	741 (47%)	gal/dry ton biomass
Direct consumption by PU production	942	1,252	982	1,313	gal/dry ton biomass
Credits from PU production	-485	-485	-485	-485	gal/dry ton biomass
<i>Net consumption by PU production</i>	457 (21%)	767 (36%)	497 (32%)	828 (53%)	gal/dry ton biomass
Net Total		2,156		1,569	gal/dry ton biomass
Total NO_x emissions					
Direct emissions from RD production	770	605	783	602	g/dry ton biomass
Credits from RD production	-440	-440	-440	-440	g/dry ton biomass
<i>Net emissions from RD production</i>	329 (231%)	165 (116%)	343 (139%)	162 (65%)	g/dry ton biomass
Direct emissions from PU production	716	881	808	989	g/dry ton biomass
Credits from PU production	-903	-903	-903	-903	g/dry ton biomass
<i>Net emissions from PU production</i>	-187 (-131%)	-23 (-16%)	-95 (-39%)	86 (35%)	g/dry ton biomass
Net Total		142		248	g/dry ton biomass

Note: Positive net totals indicate net increases compared to conventional products. Negative net totals indicate net reductions compared to conventional products. The values in parentheses are contributions to the net totals by RD and co-product in percentage.

Table 41 Biorefinery-Level Sustainability Metrics of Algae CAP, 2025 Projection Case

	Scenario 1: Via Acids		Scenario 2: Via BDO		
	Mass-based allocation	Market-value-based allocation	Mass-based allocation	Market-value-based allocation	
Products					
Renew diesel		7.9		8.2	mmBtu/dry ton biomass
PU		0.2		0.2	ton/dry ton biomass
Fossil energy consumption					
Direct consumption by RD production	5,894	3,454	8,748	6,320	MJ/dry ton biomass
Credits from RD production	-10,030	-10,030	-10,395	-10,395	MJ/dry ton biomass
<i>Net consumption by RD production</i>	<i>-4,136</i>	<i>-6,575</i>	<i>-1,647</i>	<i>-4,075</i>	MJ/dry ton biomass
	(79%)	(125%)	(80%)	(199%)	
Direct consumption by PU production	10,511	12,950	11,216	13,645	MJ/dry ton biomass
Credits from PU production	-11,626	-11,626	-11,618	-11,618	MJ/dry ton biomass
<i>Net consumption by PU production</i>	<i>-1,115</i>	<i>1,324 (-</i>	<i>-402 (20%)</i>	<i>2,026 (-</i>	MJ/dry ton biomass
	<i>(21%)</i>	<i>25%)</i>		<i>99%)</i>	
Net Total		-5,251		-2,049	MJ/dry ton biomass
GHG emissions					
Direct emissions from RD production	448	269	594	421	kg/dry ton biomass
Credits from RD production	-761	-761	-789	-789	kg/dry ton biomass
<i>Net emissions from RD production</i>	<i>-314 (43%)</i>	<i>-492 (67%)</i>	<i>-195 (34%)</i>	<i>-368 (63%)</i>	kg/dry ton biomass
Direct emissions from PU production	346	525	382	555	kg/dry ton biomass
Credits from PU production	-768	-768	-767	-767	kg/dry ton biomass
<i>Net emissions from PU production</i>	<i>-422 (57%)</i>	<i>-243 (33%)</i>	<i>-385 (66%)</i>	<i>-212 (37%)</i>	kg/dry ton biomass
Net Total		-735		-581	
Water consumption					
Direct consumption by RD production	2,047	1,625	1,462	997	gal/dry ton biomass
Credits from RD production	-182	-182	-188	-188	gal/dry ton biomass
<i>Net consumption by RD production</i>	<i>1,865</i>	<i>1,443</i>	<i>1,274</i>	<i>808 (42%)</i>	gal/dry ton biomass
	(75%)	(58%)	(66%)		
Direct consumption by PU production	1,110	1,533	1,162	1,627	gal/dry ton biomass
Credits from PU production	-495	-495	-495	-495	gal/dry ton biomass
<i>Net consumption by PU production</i>	<i>615 (25%)</i>	<i>1,038</i>	<i>668 (34%)</i>	<i>1,133</i>	gal/dry ton biomass
		(42%)		(58%)	
Net Total		2,481		1,941	gal/dry ton biomass
Total NO_x emissions					
Direct emissions from RD production	616	450	667	501	g/dry ton biomass
Credits from RD production	-477	-477	-495	-495	g/dry ton biomass
<i>Net emissions from RD production</i>	<i>139 (-</i>	<i>-27 (42%)</i>	<i>172</i>	<i>6 (38%)</i>	g/dry ton biomass
	<i>214%)</i>		<i>(1124%)</i>		
Direct emissions from PU production	718	884	764	931	g/dry ton biomass
Credits from PU production	-922	-922	-921	-921	g/dry ton biomass
<i>Net emissions from PU production</i>	<i>-204</i>	<i>-38 (58%)</i>	<i>-157 (-</i>	<i>10 (62%)</i>	g/dry ton biomass
	<i>(314%)</i>		<i>1024%)</i>		
Net Total		-65		15	g/dry ton biomass

Note: Positive net totals indicate net increases compared to conventional products. Negative net totals indicate net reductions compared to conventional products. The values in parentheses are contributions to the net totals by RD and co-product in percentage.

Table 42 Biorefinery-Level Sustainability Metrics of Algae CAP, 2030 Projection Case

	Scenario 1: Via Acids		Scenario 2: Via BDO		
	Mass-based allocation	Market-value-based allocation	Mass-based allocation	Market-value-based allocation	
Products					
Renew diesel		8.3		8.4	mmBtu/dry ton biomass
PU		0.2		0.2	ton/dry ton biomass
Fossil energy consumption					
Direct consumption by RD production	5,998	3,600	8,720	6,367	MJ/dry ton biomass
Credits from RD production	-10,527	-10,527	-10,682	-10,682	MJ/dry ton biomass
<i>Net consumption by RD production</i>	<i>-4,529</i>	<i>-6,927</i>	<i>-1,962</i>	<i>-4,315</i>	MJ/dry ton biomass
	<i>(83%)</i>	<i>(128%)</i>	<i>(84%)</i>	<i>(185%)</i>	
Direct consumption by PU production	9,655	12,053	10,622	12,974	MJ/dry ton biomass
Credits from PU production	-10,553	-10,553	-10,991	-10,991	MJ/dry ton biomass
<i>Net consumption by PU production</i>	<i>-898 (17%)</i>	<i>1,500 (-28%)</i>	<i>-369 (16%)</i>	<i>1,983 (-85%)</i>	MJ/dry ton biomass
Net Total		-5,427		-2,332	MJ/dry ton biomass
GHG emissions					
Direct emissions from RD production	455	280	592	424	kg/dry ton biomass
Credits from RD production	-799	-799	-811	-811	kg/dry ton biomass
<i>Net emissions from RD production</i>	<i>-344 (48%)</i>	<i>-519 (72%)</i>	<i>-219 (37%)</i>	<i>-386 (66%)</i>	kg/dry ton biomass
Direct emissions from PU production	320	496	361	528	kg/dry ton biomass
Credits from PU production	-697	-697	-726	-726	kg/dry ton biomass
<i>Net emissions from PU production</i>	<i>-377 (52%)</i>	<i>-201 (28%)</i>	<i>-365 (63%)</i>	<i>-198 (34%)</i>	kg/dry ton biomass
Net Total		-720		-584	
Water consumption					
Direct consumption by RD production	2,070	1,643	1,470	1,007	gal/dry ton biomass
Credits from RD production	-191	-191	-194	-194	gal/dry ton biomass
<i>Net consumption by RD production</i>	<i>1,879</i>	<i>1,453</i>	<i>1,276</i>	<i>813 (43%)</i>	gal/dry ton biomass
	<i>(76%)</i>	<i>(59%)</i>	<i>(67%)</i>		
Direct consumption by PU production	1,027	1,454	1,103	1,566	gal/dry ton biomass
Credits from PU production	-449	-449	-468	-468	gal/dry ton biomass
<i>Net consumption by PU production</i>	<i>578 (24%)</i>	<i>1,005 (41%)</i>	<i>635 (33%)</i>	<i>1,099 (57%)</i>	gal/dry ton biomass
Net Total		2,457		1,912	gal/dry ton biomass
Total NO_x emission					
Direct emissions from RD production	631	468	674	513	g/dry ton biomass
Credits from RD production	-501	-501	-508	-508	g/dry ton biomass
<i>Net emissions from RD production</i>	<i>130 (-263%)</i>	<i>-33 (67%)</i>	<i>166 (993%)</i>	<i>5 (29%)</i>	g/dry ton biomass
Direct emissions from PU production	658	821	722	883	g/dry ton biomass
Credits from PU production	-837	-837	-871	-871	g/dry ton biomass
<i>Net emissions from PU production</i>	<i>-179 (363%)</i>	<i>-16 (33%)</i>	<i>-149 (-893%)</i>	<i>12 (71%)</i>	g/dry ton biomass
Net Total		-49		17	g/dry ton biomass

Note: Positive net totals indicate net increases compared to conventional products. Negative net totals indicate net reductions compared to conventional products. The values in parentheses are contributions to the net totals by RD and co-product in percentage.

4 CONCLUSIONS

SCSAs of the 2020 SOT cases of six renewable diesel and renewable gasoline pathways are conducted, together with target/projection cases of the biochemical conversion, algae CAP, and algae/corn stover HTL pathways with significant outputs of co-products. For pathways with significant co-product effects, we applied three co-product handling methods to address the co-product effects: a process-level allocation method, a displacement method, and a biorefinery-level analysis. Detailed SCSA results of the 2020 SOT case continue to track sustainability performance as ongoing research and development efforts aim to improve the technology readiness level and economic viability of these biofuel production pathways.

Producing HOG via IDL from logging residues in the 2020 SOT case yields a fuel that is 84% less GHG-intensive throughout its supply chain than conventional gasoline. GHG emissions from the biomass field preprocessing and depot preprocessing were the largest contributors to supply chain GHG emissions among the biomass logistics steps, while the energy-independent IDL process itself is a minor emission source. Research and development efforts to further reduce supply chain GHG emissions could focus on reduced consumption of process energy for biomass preprocessing and improvement of conversion yield. Although relatively water-efficient, the IDL process is the most water-intensive step in the supply chain and has the largest potential for further water consumption reduction for the pathway. The IDL process that combusts intermediate bio-char and fuel gas to meet process heat demand is the primary NO_x emission source, and thus NO_x emission control of this combustion source presents the greatest opportunity to mitigate supply chain NO_x emissions of the HOG via IDL pathway. HOG via IDL shows significant reduction potential in fossil energy consumption, as indicated by its NEB values of 0.80 MJ/MJ in the 2020 SOT case, owing mostly to energy self-sufficient IDL processes.

SCSAs for RG and RD production from a blend of clean pine and logging residues via ex situ catalytic fast pyrolysis indicate that these fuels offer GHG emission reductions compared to conventional gasoline. We estimated a 73% reduction in GHG emissions for the 2020 SOT case. Among the different supply chain stages, petroleum refinery co-hydrotreating and biomass depot preprocessing were the largest contributors to supply chain GHG emissions. Co-products, which account for about 15% of the total product slate by mass, generate significant GHG emission credits with the displacement method and are important for achieving GHG emissions reduction. The impact of catalyst production and consumption on supply chain GHG emissions is small. Due to the significant contribution of biomass preprocessing to supply chain GHG emissions, increasing the energy efficiency of biomass preprocessing technologies or tapping alternative low-carbon energy sources that might be available would notably decrease the GHG emissions of these fuels. The NEB of RG and RD from CFP is about 0.67 MJ/MJ in the 2020 SOT case.

Producing RD via sludge HTL in the 2020 SOT case offers 53% and 71% GHG emission reductions with and without NH₃ removal, respectively. Supply chain water consumption is 4.4 gal/GGE and 3.1 gal/GGE with and without NH₃ removal, respectively—both slightly higher than that of petroleum diesel. Fuel combustion and HTL for biocrude production are the primary contributors to NO_x emissions. With improvement in HTL energy efficiency, the design case has

a slightly lower NO_x emission intensity than that of petroleum diesel. The sludge HTL pathway has a NEB of 0.56 MJ/MJ (with NH₃ removal) and 0.64 MJ/MJ (without NH₃ removal) in the 2020 SOT case.

SCSA results vary significantly with different co-product handling methods. With the process-level allocation method, the supply chain energy and material requirement to produce the renewable fuels and non-fuel co-products are separated based on the design purposes and the relative ratios by mass or market value between the fuel and co-products. The displacement method considers impacts from both the fuel and non-fuel co-products, but attributes these overall impacts to the fuel product only. As a result, the SCSA results of the fuel product may be distorted by a significant displacement credit from the co-products. A biorefinery-level analysis, on the other hand, aims to provide a full picture of the sustainability impacts brought about by both the fuel and non-fuel co-products and sheds light on the overall sustainability of the biorefinery in comparison to incumbent technologies and products.

For the biochemical conversion pathway producing AA as a co-product from lignin upgrading, taking the supply chain GHG emissions as an example, the conversion step is the primary GHG emission source in the 2020 SOT case, owing to large quantities of process chemicals and energy required for pretreatment operations. With the process-level allocation method, the supply chain GHG emissions are 24% to 48% higher for the 2020 SOT acids and BDO intermediate pathways, respectively, than those of the petroleum diesel. In the lignin upgrading to AA case, supply chain GHG emissions are 7% to 30% higher for the 2020 SOT acids and BDO intermediate pathways, respectively, than those of the petroleum diesel, when the co-product AA is handled with the displacement method. When a greater amount of AA co-product is produced in the 2030 target case, supply chain GHG emissions are about -148 g CO₂e/MJ, owing primarily to a significant co-product displacement credit as well as a biogenic carbon sequestration credit from the lignin-derived AA, to some lesser extent. At a biorefinery level, about 1.39 ton to 1.45 ton of GHG emissions could be reduced per ton of biomass feedstock converted to both the fuel and AA products in the 2030 target case, relative to their conventional counterparts. The biorefinery-level GHG emission reduction primarily comes from the AA co-product, which accounts for 82% to 88% of the overall biorefinery-level GHG emission reduction.

When the process-level allocation method is applied, RD biofuel produced from co-feeding algae and corn stover to the HTL processes offers a 40% to 48% reduction in GHG emissions in the 2020 case compared with those of petroleum diesel. The 2030 projection case shows only a slight improvement in supply chain GHG emissions, given modest little changes in fuel yields. Research and development efforts to further reduce supply chain GHG emissions could focus on reducing emissions associated with hydrogen production, increasing algal biomass productivity, and reducing energy consumption for algal biomass cultivation and dewatering and HTL conversion, as these are the primary emission sources in both the 2020 SOT and 2030 projection cases. Embedded water consumption associated with natural gas consumption for hydrogen production and energy consumption for algae cultivation and dewatering are the major contributors to supply chain water consumption in the 2020 SOT case. Increasing algal biomass productivity and improve HTL conversion efficiency would be key to mitigating water consumption as well as NO_x emissions. With the displacement method, the

GHG emission intensity of the fuel is only about 16% to 17% lower than that of petroleum diesel. The algae/corn stover-derived LA co-product does not provide displacement emission credit because the incumbent LA production with corn has lower GHG emission intensity. At a biorefinery-level, 0.16 to 0.17 tons of GHG emission reduction per ton of biomass converted to fuel and LA products would be expected, with all of the emission reduction attributable to the fuel production.

When the process-level allocation method is applied, the algae CAP pathway has 20% to 36% (mass-based allocation) and 47% to 63% (market value-based allocation) lower GHG emission intensities in the 2020 SOT case, compared to petroleum diesel. Water consumption remains higher for the CAP pathway even when saline algae species are reflected, because of significant embedded water consumption associated with the process chemical and catalyst use for fuel production operations, as well as water consumption associated with electricity demands for algae cultivation and dewatering. Reducing process chemical and energy requirements and improving algae biomass productivity and algal fuel yield would be key to mitigating the sustainability impacts including GHG emissions, water consumption, and NO_x emissions. With the displacement method, the GHG emission intensity of the fuel is about 67% to 92%, 74% to 97%, and 72% to 90% lower in the 2020 SOT, 2025 projection, and 2030 project cases, respectively, than that of petroleum diesel. At a biorefinery-level, 0.51 to 0.71 tons of GHG emission reduction per ton of biomass converted to fuel and PU products would be expected.

Finally, biomass-derived chemical co-products in integrated biorefineries tend to offer significant carbon reduction potential, compared to conventional counterparts that use fossil feedstocks to produce. It is an important contribution to the overall biorefinery-level carbon reduction potential and should be considered together with potential carbon emission reduction potentials of biofuels.

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APPENDIX

Table A1 Energy and Material Balances Associated with Fuel Production, Using the Process-Level Allocation Method, of the Biochemical Conversion Pathway for Both the Acids and BDO Intermediate Designs, in the 2020 SOT Case

	Acids Pathway			BDO Pathway			Unit
	Burning lignin	Lignin upgrading to adipic acid		Burning lignin	Lignin upgrading to adipic acid		
		Mass-based allocation	\$-based allocation		Mass-based allocation	\$-based allocation	
Products							
Hydrocarbon fuel	4.5	5.2	6.0	4.8	5.6	6.4	mmBtu/dry ton
Co-products							
Recovered sodium sulfate salt from wastewater treatment plant	25.1	32.0	27.6	23.9	28.1	24.5	kg/mmBtu
Resource Consumption							
Biomass feedstock	0.22	0.19	0.17	0.21	0.18	0.16	dry ton/mmBtu
Sulfuric acid	20.9	0.0	0.0	19.4	0	0	kg/mmBtu
Caustic	4.9	4.2	3.6	4.5	3.9	3.4	kg/mmBtu
Ammonia	3.1	4.7	4.0	2.6	4.1	3.6	kg/mmBtu
Glucose	3.2	3.2	3.2	3.0	3.0	3.0	kg/mmBtu
Corn steep liquor	3.0	3.0	3.0	2.1	2.1	2.1	kg/mmBtu
Corn oil	0.018	0.018	0.018	0.016	0.016	0.016	kg/mmBtu
Host nutrients	0.089	0.089	0.089	0.083	0.082	0.082	kg/mmBtu
Sulfur dioxide	0.022	0.022	0.022	0.020	0.020	0.020	kg/mmBtu
Diammonium phosphate	0.41	0.41	0.41	0.23	0.23	0.23	kg/mmBtu
Flocculant	0.99	1.0	1.0	0.99	0.98	1.0	kg/mmBtu
Toluene solvent makeup	0.22	0.22	0.22	0	0	0.0	kg/mmBtu
Hydrogen	0	0	0	1.92	1.90	1.9	kg/mmBtu
Boiler chemicals	0.0006	0.0007	0.0006	0.0006	0.0011	0.0010	kg/mmBtu
FGD lime	0.27	0.40	0.35	0.25	0.35	0.31	kg/mmBtu
Sodium Carbonate	16.3	13.9	12.0	15.1	13.0	11.4	kg/mmBtu
Wastewater plant polymer	0.091	0.000	0.000	0.076	0.000	0.000	kg/mmBtu
Cooling tower chemicals	0.006	0.004	0.003	0.004	0.003	0.003	kg/mmBtu
Makeup water	213.2	132.0	114.0	80.5	57.9	50.6	Gal/mmBtu

Natural gas for boiler	0	0	0	0	0.44	0.44	mmBtu/mmBtu
Natural gas for hot oil system	0.10	0.10	0.10	0	0	0	mmBtu/mmBtu
Grid electricity (net import)	17.1	111.9	102.7	40.5	81.7	75.4	kWh/mmBtu

Table A2 Energy and Material Balances Associated with Fuel Production, Using the Process-Level Allocation Method, of the Biochemical Conversion Pathway for Both the Acids and BDO Intermediate Designs, in the 2030 Target Case

	Acids Pathway		BDO Pathway		
	Lignin upgrading to adipic acid		Lignin upgrading to adipic acid		
	Mass-based allocation	\$-based allocation	Mass-based allocation	\$-based allocation	
Products					
Hydrocarbon fuel	10.1	15.4	10.1	15.5	mmBtu/dry ton
Co-products					
Recovered sodium sulfate salt from wastewater treatment plant	15.0	9.8	15.3	9.9	kg/mmBtu
Resource Consumption					
Biomass feedstock	0.10	0.06	0.10	0.06	dry ton/mmBtu
Sulfuric acid	0	0	0	0	kg/mmBtu
Caustic	6.3	4.1	6.3	4.1	kg/mmBtu
Ammonia	1.4	1.0	1.3	0.9	kg/mmBtu
Glucose	2.8	2.8	2.9	2.9	kg/mmBtu
Corn steep liquor	2.9	2.9	1.5	1.5	kg/mmBtu
Corn oil	0.015	0.015	0.016	0.016	kg/mmBtu
Host nutrients	0.077	0.077	0.080	0.080	kg/mmBtu
Sulfur dioxide	0.019	0.019	0.020	0.020	kg/mmBtu
Diammonium phosphate	0.40	0.40	0.15	0.15	kg/mmBtu
Toluene solvent makeup	0.19	0.19	0	0	kg/mmBtu
Hydrogen	0.00	0.00	0.89	0.9	kg/mmBtu
Boiler chemicals	0.0002	0.0001	0.0002	0.0001	kg/mmBtu
FGD lime	0.10	0.07	0.11	0.07	kg/mmBtu
Cooling tower chemicals	0.004	0.002	0.002	0.001	kg/mmBtu
Makeup water	59.8	39.2	38.1	24.7	Gal/mmBtu
Natural gas for boiler	0	0	0.13	0.13	MMBtu/mmBtu
Natural gas for hot oil system	0.08	0.08	0	0	MMBtu/mmBtu
Grid electricity (net import)	53.8	46.0	45.9	37.5	kWh/mmBtu

Table A3 Energy and Material Balances Associated with Biochemical (Adipic Acid) Production, Using the Process-Level Allocation Method, of the Biochemical Conversion Pathway for Both the Acids and BDO Intermediate Designs, in the 2020 SOT Case

	Acids		BDO		
	Mass-based allocation	Market value -based allocation	Mass-based allocation	Market value -based allocation	
Products					
Adipic acid	125.1	69.4	132.8	73.4	kg AA/dry ton
Co-products					
Recovered sodium sulfate salt from wastewater treatment plant	1.3	2.4	1.2	2.1	kg/kg AA
Resource Consumption					
Biomass feedstock	7.3	13.1	6.8	12.4	kg/kg AA
Sulfuric acid	6.9	6.9	6.5	6.5	kg/kg AA
Caustic	1.7	1.8	1.3	1.4	kg/kg AA
Sodium Carbonate	0.6	1.0	0.5	1.0	kg/kg AA
Ammonia	0.2	0.3	0.2	0.3	kg/kg AA
Diammonium phosphate	0.06	0.06	0.06	0.06	kg/kg AA
Hydrogen	0	0	0.09	0.09	kg/kg AA
Ethanol	0.008	0.008	0.008	0.008	kg/kg AA
Boiler chemicals	0.00003	0.00005	0.00005	0.00008	kg/kg AA
FGD lime	0.02	0.03	0.01	0.03	kg/kg AA
Cooling tower chemicals	0.0001	0.0003	0.0001	0.0002	kg/kg AA
Makeup water	5.5	9.9	2.4	4.4	gal/kg AA
Grid electricity (net import)	4.8	7.1	4.0	5.7	kWh/kg AA

Table A4 Energy and Material Balances Associated with Biochemical (Adipic Acid) Production, Using the Process-Level Allocation Method, of the Biochemical Conversion Pathway for Both the Acids and BDO Intermediate Designs, in the 2030 Target Case

	Acids		BDO		
	Mass-based allocation	Market value-based allocation	Mass-based allocation	Market value-based allocation	
Products					
Adipic acid	242.1	177.1	240.8	178.4	kg AA/dry ton
Co-products					
Recovered sodium sulfate salt from wastewater treatment plant	0.6	0.9	0.6	0.9	kg/kg AA
Resource Consumption					
Biomass feedstock	3.7	5.1	3.8	5.1	kg/kg AA
Sulfuric acid	0.9	0.9	0.9	0.9	kg/kg AA

Caustic	0.5	0.6	0.5	0.6	kg/kg AA
Corn steep liquor	0.007	0.007	0.009	0.009	kg/kg AA
Ammonia	0.06	0.08	0.06	0.07	kg/kg AA
Diammonium phosphate	0.05	0.05	0.05	0.05	kg/kg AA
Hydrogen	0	0	0.04	0.04	kg/kg AA
Ethanol	0.003	0.003	0.003	0.003	kg/kg AA
Boiler chemicals	0.00001	0.00001	0.00001	0.00001	kg/kg AA
FGD lime	0.004	0.006	0.005	0.006	kg/kg AA
Cooling tower chemicals	0.0002	0.0002	0.00009	0.0001	kg/kg AA
Makeup water	2.5	3.4	1.6	2.2	gal/kg AA
Grid electricity (net import)	1.7	2.0	1.8	2.2	kWh/kg AA

Table A5 Energy and Material Balances Burdened to Fuel Production Only With the Displacement Method, Biochemical Conversion Pathway for Both the Acids and BDO Intermediate Designs, in the 2020 SOT Case

	Acids Pathway		BDO Pathway		
	Burning lignin	Lignin upgrading to adipic acid	Burning lignin	Lignin upgrading to adipic acid	
Products					
Hydrocarbon fuel	4.5	4.5	4.8	4.8	mmBtu/dry ton
Co-products					
Adipic acid	0	4.1	0	3.7	kg/mmBtu
Recovered sodium sulfate salt from wastewater treatment plant	25.1	37.5	23.9	32.4	kg/mmBtu
Resource Consumption					
Biomass feedstock	0.22	0.22	0.21	0.21	dry ton/mmBtu
Sulfuric acid	20.9	28.4	19.4	24.2	kg/mmBtu
Caustic	4.9	11.0	4.5	8.5	kg/mmBtu
Ammonia	3.1	5.5	2.6	4.8	kg/mmBtu
Glucose	3.2	3.2	3.0	3.0	kg/mmBtu
Corn steep liquor	3.0	3.0	2.1	2.1	kg/mmBtu
Corn oil	0.018	0.018	0.016	0.016	kg/mmBtu
Host nutrients	0.089	0.089	0.083	0.082	kg/mmBtu
Sulfur dioxide	0.022	0.022	0.020	0.020	kg/mmBtu
Diammonium phosphate	0.41	0.67	0.23	0.47	kg/mmBtu
Flocculant	0.99	1.00	0.99	0.98	kg/mmBtu
Toluene solvent makeup	0.22	0.22	0	0	kg/mmBtu
Ethanol	0	0.032	0	0.029	kg/mmBtu
Hydrogen	0	0	1.92	2.23	kg/mmBtu
Boiler chemicals	0.0006	0.0008	0.0006	0.0013	kg/mmBtu
FGD lime	0.27	0.47	0.25	0.41	kg/mmBtu
Sodium Carbonate	16.3	16.3	15.1	15.0	kg/mmBtu

Wastewater plant polymer	0.091	0.000	0.076	0.000	kg/mmBtu
Cooling tower chemicals	0.006	0.004	0.004	0.003	kg/mmBtu
Makeup water	213.2	154.6	80.5	66.9	gal/mmBtu
Natural gas for boiler	0	0	0	0.44	mmBtu/mmBtu
Natural gas for hot oil system	0.10	0.10	0	0	mmBtu/mmBtu
Grid electricity (net import)	17.1	131.6	40.5	96.4	kWh/mmBtu
Waste streams (ash)	10.5	10.8	9.7	9.9	kg/mmBtu

Table A6 Energy and Material Balances Burdened to Fuel Production Only With the Displacement Method, Biochemical Conversion Pathway for Both the Acids and BDO Intermediate Designs, in the 2030 Target Case

	Acids Pathway (Lignin upgrading to adipic acid)	BDO Pathway (Lignin upgrading to adipic acid)
Products		
Hydrocarbon fuel	5.2	5.0 mmBtu/dry ton
Co-products		
Adipic acid	22.5	24 kg/mmBtu
Recovered sodium sulfate salt from wastewater treatment plant	29.0	30.7 kg/mmBtu
Resource Consumption		
Biomass feedstock	0.19	0.20 dry ton/mmBtu
Sulfuric acid	20.5	21.9 kg/mmBtu
Caustic	17.2	18.4 kg/mmBtu
Ammonia	2.8	2.7 kg/mmBtu
Glucose	2.8	2.9 kg/mmBtu
Corn steep liquor	3.1	1.7 kg/mmBtu
Corn oil	0.015	0.016 kg/mmBtu
Host nutrients	0.077	0.080 kg/mmBtu
Sulfur dioxide	0.019	0.020 kg/mmBtu
Diammonium phosphate	1.49	1.36 kg/mmBtu
Toluene solvent makeup	0.19	0 kg/mmBtu
Ethanol	0.077	0.080 kg/mmBtu
Hydrogen	0	1.77 kg/mmBtu
Boiler chemicals	0.0004	0.0004 kg/mmBtu
FGD lime	0.20	0.22 kg/mmBtu
Cooling tower chemicals	0.007	0.005 kg/mmBtu
Makeup water	115.9	76.5 gal/mmBtu
Natural gas for boiler	0	0 mmBtu/mmBtu
Natural gas for hot oil system	0.08	0 mmBtu/mmBtu
Grid electricity (net import)	92.0	90.1 kWh/mmBtu
Waste streams (ash)	8.9	9.3 kg/mmBtu

Table A7 Energy and Material Balances Associated with Fuel Production, Using the Process-Level Allocation Method, of the Algae/Corn Stover HTL Pathway, in the 2020 SOT and 2030 Projection Cases

	2020 SOT		2030 Projection		
	Mass-based allocation	Market-value-based allocation	Mass-based allocation	Market-value-based allocation	
Products					
Diesel	173.3		189.3		mmBtu/hr
Naphtha	92.4		100.9		mmBtu/hr
Resource Consumption					
Feedstock, annual average basis					
Algae (AFDW basis)	29.4	29.4	37.4	37.4	kg/mmBtu
Corn stover (AFDW basis)	27.1	27.1	19.0	19.0	kg/mmBtu
Natural gas for H ₂ production	4.6	4.6	5.3	5.3	kg/mmBtu
Natural gas for utility	3.5	2.5	3.6	2.3	kg/mmBtu
Sulfuric acid (93%)	29.1	29.1	30.0	30.0	kg/mmBtu
Na ₂ CO ₃	16.9	16.9	17.4	17.4	kg/mmBtu
Hydrotreating main bed catalyst	0.005	0.005	0.005	0.005	kg/mmBtu
Hydrotreating guard bed catalyst	0.007	0.007	0.008	0.008	kg/mmBtu
Hydrocracking catalyst	0.00009	0.00009	0.00009	0.00009	kg/mmBtu
Boiler chemicals	0.0001	0.0001	0.0001	0.0001	kg/mmBtu
Cooling tower chemicals	0.0004	0.0004	0.0004	0.0004	kg/mmBtu
Makeup water	23.1	23.1	23.9	23.9	kg/mmBtu
Electricity	11.3	11.3	11.4	11.4	kWh/mmBtu

Table A8 Energy and Material Balances Associated with Biochemical Production (Lactic Acid), Using the Process-Level Allocation Method of the Algae/Corn Stover HTL Pathway, 2020 SOT and 2030 Projection Cases

	2020 SOT		2030 Projection		
	Mass-based allocation	Market value-based allocation	Mass-based allocation	Market value-based allocation	
Products					
Lactic acid (polymer grade, 88 wt%)	3133.0		4790.8		kg/hr
Resource Consumption					
Feedstock, annual average basis					
Algae (AFDW basis)	2.4	2.4	2.2	2.2	kg/kg LA
Corn stover (AFDW basis)	1.2	1.2	0.6	0.6	kg/kg LA
NG for utility	0.1	0.2	0.2	0.3	kg/kg LA
NG for bioprocessing	0.5	0.5	0.5	0.5	kg/kg LA
Sulfuric acid (93%)	2.5	2.5	1.8	1.8	kg/kg LA

Na ₂ CO ₃	0.5	0.8	0.4	0.6	kg/kg LA
Corn steep liquor	0.1	0.1	0.1	0.1	kg/kg LA
NaOH	0.1	0.1	0.0	0.0	kg/kg LA
Ethanol	0.01	0.01	0.01	0.01	kg/kg LA
Ethylene glycol	0.02	0.02	0.02	0.02	kg/kg LA
Reactive distillation catalyst	0.0004	0.0004	0.0004	0.0004	kg/kg LA
Boiler chemicals	0.00002	0.00002	0.00002	0.00002	kg/kg LA
Cooling tower chemicals	0.0003	0.0003	0.0002	0.0002	kg/kg LA
Makeup water	0.2	0.2	0.2	0.2	kg/kg LA
Electricity	1.6	1.6	1.1	1.1	kWh/kg LA

Table A9 Energy and Material Balances Burdened to Fuel Production Only with the Displacement Method, Algae/Corn Stover Pathway, 2020 SOT and 2030 Projection Cases

	2020 SOT	2030 Projection	
Products			
Diesel	173.3	189.3	mmBtu/h
Naphtha	92.4	100.9	mmBtu/h
Co-Product			
Lactic acid	11.8	16.5	kg/mmBtu
Resource Consumption			
Feedstock, annual average basis			
Algae (AFDW basis)	57.6	73.2	kg/mmBtu
Corn stover (AFDW basis)	41.6	29.2	kg/mmBtu
Natural gas for H ₂ production	4.6	2.3	kg/mmBtu
Natural gas for utility	11.0	15.7	kg/mmBtu
Sulfuric acid (93%)	29.1	30.0	kg/mmBtu
Na ₂ CO ₃	16.9	17.4	kg/mmBtu
Hydrotreating main bed catalyst	0.005	0.005	kg/mmBtu
Hydrotreating guard bed catalyst	0.007	0.008	kg/mmBtu
Hydrocracking catalyst	0.00009	0.00009	kg/mmBtu
Corn steep liquor	1.1879	1.1087	kg/mmBtu
Ethanol	0.1122	0.1571	kg/mmBtu
NaOH	0.8	0.7	kg/mmBtu
Ethylene glycol	0.2	0.3	kg/mmBtu
Reactive distillation catalyst	0.005	0.007	kg/mmBtu
Boiler chemicals	0.0004	0.0005	kg/mmBtu
Cooling tower chemicals	0.004	0.004	kg/mmBtu
Makeup water	25.7	26.5	kg/mmBtu
Electricity	29.6	30.0	kWh/mmBtu

Table A10 Allocated Energy and Material Inputs and Outputs for Fuel Production in the Modeled CAP Conversion Processes in the 2020 SOT Case via Acids and BDO as Intermediate Pathways

	Via acids		Via BDO		
	Mass-based allocation	\$-based allocation	Mass-based allocation	\$-based allocation	
Products					
Diesel	11.3	34.7	10.2	31.3	mmBtu/dry ton
Naphtha	4.4	13.6	5.6	17.0	mmBtu/dry ton
Electricity exported to grid	20.1	6.6	24.0	7.8	kWh/mmBtu
Resource Consumption					
Algae (AFDW basis)	57.6	18.8	57.5	18.8	kg/mmBtu
Pretreatment					
Sulfuric acid (93% pure)	5.1	1.7	5.1	1.7	kg/mmBtu
Ammonia	1.7	0.5	1.7	0.5	kg/mmBtu
Lipid Extraction and Cleanup					
Hexane requirement	0.3	0.1	0.3	0.1	kg/mmBtu
Ethanol	0.1	0.0	0.1	0.0	kg/mmBtu
Phosphoric Acid (oil cleanup)	0.2	0.1	0.2	0.1	kg/mmBtu
Silica (oil cleanup)	0.02	0.01	0.02	0.01	kg/mmBtu
Clay (oil cleanup)	0.03	0.01	0.03	0.01	kg/mmBtu
Carboxylic Acid / 2,3-BDO Conversion					
Corn steep liquor	5.6	5.6	0.8	0.8	kg/mmBtu
Diammonium phosphate	0.6	0.6	0.1	0.1	kg/mmBtu
Hydrotalcite	0.0	0.0	0.0	0.0	kg/mmBtu
Flocculant	0.5	0.5	0.5	0.5	kg/mmBtu
Hexane	0.004	0.004	0	0	kg/mmBtu
Ketonization catalyst (ZrO ₂)	0.0002	0.0002	0	0	kg/mmBtu
Condensation catalyst (niobic acid)	0.002	0.002	0	0	kg/mmBtu
Hydrogen	0	0	0.6	0.6	kg/mmBtu
Dehydration catalyst	0	0	0.0005	0.0005	kg/mmBtu
Oligomerization Catalyst	0	0	0.001	0.001	kg/mmBtu
Final Fuel Upgrading (HDO/HI)					
Hydrogen	0.8	0.8	0.7	0.7	kg/mmBtu
One step HDO/HI catalyst (1% Pt/SAPO-11)	0.002	0.002	0.002	0.002	kg/mmBtu
Other Resource Consumption					
Supplemental natural gas	4.6	2.1	11.2	7.6	kg/mmBtu
Process water	168.7	55.5	440.4	310.0	kg/mmBtu
Output Streams					
AD digestate cake bioavailable N	0.07	0.02	0.06	0.02	kg/mmBtu
AD effluent NH ₃	0.8	0.3	0.8	0.3	kg/mmBtu
AD effluent DAP	0.4	0.1	0.3	0.09	kg/mmBtu
CO ₂ recycle	55.5	18.1	68.5	22.4	kg/mmBtu

Table A11 Allocated Energy and Material Inputs and Outputs for Fuel Production in the Modeled CAP Conversion Processes in the 2025 Projection Case via Acids and BDO as Intermediate Pathways

	Via acids		Via BDO		
	Mass-based allocation	\$-based allocation	Mass-based allocation	\$-based allocation	
Products					
Diesel	11.8	35.7	10.7	31.9	mmBtu/dry ton
Naphtha	4.7	14.1	6.1	18.2	mmBtu/dry ton
Electricity exported to grid	26.4	8.8	27.9	9.4	kWh/mmBtu
Resource Consumption					
Algae (AFDW basis)	54.8	18.2	53.8	18.1	kg/mmBtu
Pretreatment					
Sulfuric acid (93% pure)	2.4	0.8	2.3	0.8	kg/mmBtu
Ammonia	0.8	0.3	0.8	0.3	kg/mmBtu
Lipid Extraction and Cleanup					
Hexane requirement	0.3	0.1	0.3	0.1	kg/mmBtu
Ethanol	0.1	0.04	0.1	0.04	kg/mmBtu
Phosphoric Acid (oil cleanup)	0.2	0.1	0.2	0.1	kg/mmBtu
Silica (oil cleanup)	0.02	0.005	0.02	0.005	kg/mmBtu
Clay (oil cleanup)	0.03	0.01	0.03	0.01	kg/mmBtu
Carboxylic Acid / 2,3-BDO Conversion					
Corn steep liquor	5.2	5.2	0.8	0.8	kg/mmBtu
Diammonium phosphate	0.5	0.5	0.1	0.1	kg/mmBtu
Hydrotalcite	0.006	0.006	0	0	kg/mmBtu
Flocculant	0.4	0.4	0.4	0.4	kg/mmBtu
Hexane	0.004	0.004	0	0	kg/mmBtu
Ketonization catalyst (ZrO ₂)	0.0002	0.0002	0	0	kg/mmBtu
Condensation catalyst (niobic acid)	0.002	0.002	0	0	kg/mmBtu
Hydrogen	0	0	0.7	0.7	kg/mmBtu
Dehydration catalyst	0	0	0.0005	0.0005	kg/mmBtu
Oligomerization Catalyst	0	0	0.001	0.001	kg/mmBtu
Final Fuel Upgrading (HDO/HI)					
Hydrogen	0.8	0.8	0.7	0.7	kg/mmBtu
One step HDO/HI catalyst (1% Pt/SAPO-11)	0.002	0.002	0.002	0.002	kg/mmBtu
Other Resource Consumption					
Supplemental natural gas	5.0	2.3	10.8	7.9	kg/mmBtu
Process water	261.7	87.4	497.5	306.5	kg/mmBtu
Output Streams					
AD digestate cake bioavailable N	0.07	0.02	0.06	0.02	kg/mmBtu
AD effluent NH ₃	0.8	0.3	0.8	0.3	kg/mmBtu
AD effluent DAP	0.4	0.1	0.3	0.09	kg/mmBtu

CO₂ recycle 55.3 18.4 64.8 21.8 kg/mmBtu

Table A12 Allocated Energy and Material Inputs and Outputs for Fuel Production in the Modeled CAP Conversion Processes in the 2030 Projection Case via Acids and BDO as Intermediate Pathways

	Via acids		Via BDO		
	Mass-based allocation	\$-based allocation	Mass-based allocation	\$-based allocation	
Products					
Diesel	11.6	33.3	10.6	30.8	mmBtu/dry ton
Naphtha	4.6	13.1	6.0	17.3	mmBtu/dry ton
Electricity exported to grid	27.6	9.6	28.6	9.9	kWh/mmBtu
Resource Consumption					
Algae (AFDW basis)	56.2	19.6	54.6	18.9	kg/mmBtu
Pretreatment					
Sulfuric acid (93% pure)	2.4	0.8	2.4	0.8	kg/mmBtu
Ammonia	0.8	0.3	0.8	0.3	kg/mmBtu
Lipid Extraction and Cleanup					
Hexane requirement	0.3	0.1	0.3	0.1	kg/mmBtu
Ethanol	0.1	0.04	0.1	0.04	kg/mmBtu
Phosphoric Acid (oil cleanup)	0.2	0.1	0.2	0.1	kg/mmBtu
Silica (oil cleanup)	0.02	0.006	0.02	0.005	kg/mmBtu
Clay (oil cleanup)	0.03	0.01	0.03	0.01	kg/mmBtu
Carboxylic Acid / 2,3-BDO Conversion					
Corn steep liquor	5.0	5.0	0.8	0.8	kg/mmBtu
Diammonium phosphate	0.5	0.5	0.1	0.1	kg/mmBtu
Hydrotalcite	0.005	0.005	0	0	kg/mmBtu
Flocculant	0.4	0.4	0.4	0.4	kg/mmBtu
Hexane	0.004	0.004	0	0	kg/mmBtu
Ketonization catalyst (ZrO ₂)	0.0002	0.0002	0	0	kg/mmBtu
Condensation catalyst (niobic acid)	0.002	0.002	0	0	kg/mmBtu
Hydrogen	0	0	0.7	0.7	kg/mmBtu
Dehydration catalyst	0	0	0.0005	0.0005	kg/mmBtu
Oligomerization Catalyst	0	0	0.001	0.001	kg/mmBtu
Final Fuel Upgrading (HDO/HI)					
Hydrogen	0.8	0.8	0.7	0.7	kg/mmBtu
One step HDO/HI catalyst (1% Pt/SAPO-11)	0.002	0.002	0.002	0.002	kg/mmBtu
Other Resource Consumption					
Supplemental natural gas	5.1	2.4	10.7	7.8	kg/mmBtu
Process water	266.0	93.1	494.7	304.6	kg/mmBtu
Output Streams					
AD digestate cake bioavailable N	0.07	0.02	0.06	0.02	kg/mmBtu

AD effluent NH ₃	0.9	0.3	0.8	0.3	kg/mmBtu
AD effluent DAP	0.4	0.1	0.3	0.1	kg/mmBtu
CO ₂ recycle	56.8	19.8	65.8	22.8	kg/mmBtu

Table A13 Allocated Energy and Material Inputs and Outputs for Biochemical (Polyurethane) Production in the Modeled CAP Conversion Processes in the 2020 SOT Case via Acids and BDO as Intermediate Pathways

	Via acids		Via BDO		
	Mass-based allocation	Market value -based allocation	Mass-based allocation	Market value -based allocation	
Products					
Polyurethane		3,432		3,432	kg/hr
Electricity exported to grid	0.8	1.3	1.0	1.6	kWh/kg PU
Resource Consumption					
Algae (AFDW basis)	2.4	3.8	2.4	3.8	kg/kg PU
Pretreatment					
Sulfuric acid (93% pure)	0.2	0.3	0.2	0.3	kg/kg PU
Ammonia	0.07	0.11	0.07	0.11	kg/kg PU
Lipid Extraction and Cleanup					
Hexane requirement	0.01	0.02	0.01	0.02	kg/kg PU
Ethanol	0.005	0.008	0.005	0.008	kg/kg PU
Phosphoric acid (oil cleanup)	0.007	0.011	0.007	0.011	kg/kg PU
Silica (oil cleanup)	0.0007	0.0011	0.0007	0.0011	kg/kg PU
Clay (oil cleanup)	0.001	0.002	0.001	0.002	kg/kg PU
Polyurethane Production					
Formic acid	0.1	0.1	0.1	0.1	kg/kg PU
H ₂ O ₂	0.2	0.2	0.2	0.2	kg/kg PU
Catalysts and other chemicals	0.002	0.002	0.002	0.002	kg/kg PU
Nitrogen	0.01	0.01	0.01	0.01	kg/kg PU
Toluene diisocyanate	0.3	0.3	0.3	0.3	kg/kg PU
Diethanolamine	0.003	0.003	0.003	0.003	kg/kg PU
Surfactant	0.005	0.005	0.005	0.005	kg/kg PU
Other Resource Consumption					
Supplemental natural gas (total)	0.4	0.5	0.6	0.7	kg/kg PU
Process water (total)	11.9	16.0	13.0	17.7	kg/kg PU
Output Streams					
AD Digestate cake bioavailable N	0.003	0.004	0.003	0.004	kg/kg PU
AD effluent NH ₃	0.03	0.05	0.03	0.05	kg/kg PU
AD effluent DAP	0.02	0.03	0.01	0.02	kg/kg PU
CO ₂ recycle	2.3	3.6	2.9	4.5	kg/kg PU

Table A14 Allocated Energy and Material Inputs and Outputs for Biochemical (Polyurethane) Production in the Modeled CAP Conversion Processes in the 2025 Projection Case via Acids and BDO as Intermediate Pathways

	Via acids		Via BDO		
	Mass-based allocation	Market value -based allocation	Mass-based allocation	Market value -based allocation	
Products					
Polyurethane		4,787		4,784	kg/hr
Electricity exported to grid	1.1	1.8	1.2	1.9	kWh/kg PU
Resource Consumption					
Algae (AFDW basis)	2.3	3.7	2.2	3.7	kg/kg PU
Pretreatment					
Sulfuric acid (93% pure)	0.1	0.2	0.1	0.2	kg/kg PU
Ammonia	0.03	0.05	0.03	0.05	kg/kg PU
Lipid Extraction and Cleanup					
Hexane requirement	0.01	0.02	0.01	0.02	kg/kg PU
Ethanol	0.005	0.008	0.005	0.008	kg/kg PU
Phosphoric acid (oil cleanup)	0.007	0.01	0.006	0.01	kg/kg PU
Silica (oil cleanup)	0.0007	0.001	0.0006	0.001	kg/kg PU
Clay (oil cleanup)	0.001	0.002	0.001	0.002	kg/kg PU
Polyurethane Production					
Formic acid	0.1	0.1	0.1	0.1	kg/kg PU
H ₂ O ₂	0.153	0.153	0.153	0.153	kg/kg PU
Catalysts and other chemicals	0.002	0.002	0.002	0.002	kg/kg PU
Nitrogen	0.01	0.01	0.01	0.01	kg/kg PU
Toluene diisocyanate	0.3	0.3	0.3	0.3	kg/kg PU
Diethanolamine	0.003	0.003	0.003	0.003	kg/kg PU
Surfactant	0.005	0.005	0.005	0.005	kg/kg PU
Other Resource Consumption					
Supplemental natural gas (total)	0.4	0.6	0.5	0.7	kg/kg PU
Process water (total)	15.9	22.5	17.0	24.6	kg/kg PU
Output Streams					
AD Digestate cake bioavailable N	0.003	0.004	0.003	0.004	kg/kg PU
AD effluent NH ₃	0.03	0.06	0.03	0.05	kg/kg PU
AD effluent DAP	0.02	0.03	0.01	0.02	kg/kg PU
CO ₂ recycle	2.3	3.7	2.7	4.4	kg/kg PU

Table A15 Allocated Energy and Material Inputs and Outputs for Biochemical (Polyurethane) Production in the Modeled CAP Conversion Processes in the 2030 Projection Case via Acids and BDO as Intermediate Pathways

	Via acids		Via BDO		
	Mass-based allocation	Market value -based allocation	Mass-based allocation	Market value -based allocation	
Products					
Polyurethane		4,345		4,525	kg/hr
Electricity exported to grid	1.1	1.9	1.2	2.0	kWh/kg PU
Resource Consumption					
Algae (AFDW basis)	2.3	4.0	2.3	3.8	kg/kg PU
Pretreatment					
Sulfuric acid (93% pure)	0.1	0.2	0.1	0.2	kg/kg PU
Ammonia	0.03	0.06	0.03	0.05	kg/kg PU
Lipid Extraction and Cleanup					
Hexane requirement	0.01	0.02	0.01	0.02	kg/kg PU
Ethanol	0.005	0.008	0.005	0.008	kg/kg PU
Phosphoric acid (oil cleanup)	0.007	0.01	0.007	0.01	kg/kg PU
Silica (oil cleanup)	0.0007	0.001	0.0007	0.001	kg/kg PU
Clay (oil cleanup)	0.001	0.002	0.001	0.002	kg/kg PU
Polyurethane Production					
Formic acid	0.1	0.1	0.1	0.1	kg/kg PU
H ₂ O ₂	0.153	0.153	0.153	0.153	kg/kg PU
Catalysts and other chemicals	0.002	0.002	0.002	0.002	kg/kg PU
Nitrogen	0.01	0.01	0.01	0.01	kg/kg PU
Toluene diisocyanate	0.3	0.3	0.3	0.3	kg/kg PU
Diethanolamine	0.003	0.003	0.003	0.003	kg/kg PU
Surfactant	0.005	0.005	0.005	0.005	kg/kg PU
Other Resource Consumption					
Supplemental natural gas (total)	0.5	0.6	0.6	0.7	kg/kg PU
Process water (total)	16.6	24.2	17.4	25.6	kg/kg PU
Output Streams					
AD Digestate cake bioavailable N	0.003	0.005	0.003	0.004	kg/kg PU
AD effluent NH ₃	0.04	0.06	0.03	0.06	kg/kg PU
AD effluent DAP	0.02	0.03	0.01	0.02	kg/kg PU
CO ₂ recycle	2.4	4.0	2.7	4.6	kg/kg PU

Table A16 Energy and Material Balances Burdened to Fuel Production Only With the Displacement Method, CAP Conversion Processes in the 2020 SOT Case via Acids and BDO as Intermediate Pathways

	Via acids	Via BDO	
Products			
Diesel	88.6	79.8	mmBtu/hr
Naphtha	34.8	43.4	mmBtu/hr
Polyurethane	3431.9	3431.9	kg/hr
Electricity exported to grid	5356.7	6382.2	kW
Resource Consumption			
Algae (AFDW basis)	124.1	124.3	kg/mmBtu
Pretreatment			
Sulfuric acid (93% pure)	11.1	11.1	kg/mmBtu
Ammonia	3.6	3.6	kg/mmBtu
Lipid Extraction and Cleanup			
Hexane requirement	0.6	0.7	kg/mmBtu
Ethanol	0.3	0.3	kg/mmBtu
Phosphoric acid (oil cleanup)	0.4	0.4	kg/mmBtu
Silica (oil cleanup)	0.04	0.04	kg/mmBtu
Clay (oil cleanup)	0.07	0.07	kg/mmBtu
Carboxylic Acid / 2,3-BDO Conversion			
Corn steep liquor	5.6	0.8	kg/mmBtu
Diammonium phosphate	0.6	0.1	kg/mmBtu
Hydrotalcite	0.005	0	kg/mmBtu
Flocculant	0.5	0.5	kg/mmBtu
Hexane	0.004	0	kg/mmBtu
Ketonization catalyst (ZrO ₂)	0.0002	0	kg/mmBtu
Condensation catalyst (niobic acid)	0.002	0	kg/mmBtu
Hydrogen	0	0.6	kg/mmBtu
Dehydration catalyst	0	0.0005	kg/mmBtu
Oligomerization catalyst	0	0.001	kg/mmBtu
Final Fuel Upgrading (HDO/HI)			
Hydrogen	0.8	0.7	kg/mmBtu
One step HDO/HI Catalyst (1% Pt/SAPO-11)	0.002	0.002	kg/mmBtu
Polyurethane Production			
Formic acid	2.7	2.7	kg/mmBtu
H ₂ O ₂	4.3	4.3	kg/mmBtu
Catalysts and other chemicals	0.07	0.07	kg/mmBtu
Nitrogen	0.4	0.4	kg/mmBtu
Toluene diisocyanate	7.4	7.4	kg/mmBtu
Diethanolamine	0.07	0.07	kg/mmBtu
Surfactant	0.1	0.1	kg/mmBtu

Other Resource Consumption

Supplemental natural gas	16.1	26.8	kg/mmBtu
Process water	500.8	803.5	kg/mmBtu

Output Streams

AD digestate cake bioavailable N	0.14	0.14	kg/mmBtu
AD effluent NH ₃	1.80	1.8	kg/mmBtu
AD effluent DAP	0.85	0.6	kg/mmBtu
CO ₂ recycle	119.6	148.1	kg/mmBtu

Table A17 Energy and Material Balances Burdened to Fuel Production Only With the Displacement Method, CAP Conversion Processes in the 2025 Projection Case via Acids and BDO as Intermediate Pathways

	Via acids	Via BDO	
Products			
Diesel	130.8	120.5	mmBtu/hr
Naphtha	51.9	68.9	mmBtu/hr
Polyurethane	4787.0	4783.7	kg/hr
Electricity exported to grid	10052.8	10839.5	kW
Resource Consumption			
Algae (AFDW basis)	114.5	110.5	kg/mmBtu
Pretreatment			
Sulfuric acid (93% pure)	5.0	4.8	kg/mmBtu
Ammonia	1.6	1.5	kg/mmBtu
Lipid Extraction and Cleanup			
Hexane requirement	0.6	0.6	kg/mmBtu
Ethanol	0.2	0.2	kg/mmBtu
Phosphoric acid (oil cleanup)	0.3	0.3	kg/mmBtu
Silica (oil cleanup)	0.03	0.03	kg/mmBtu
Clay (oil cleanup)	0.07	0.06	kg/mmBtu
Carboxylic Acid / 2,3-BDO Conversion			
Corn steep liquor	5.2	0.8	kg/mmBtu
Diammonium phosphate	0.5	0.1	kg/mmBtu
Hydrotalcite	0.006	0	kg/mmBtu
Flocculant	0.4	0.4	kg/mmBtu
Hexane	0.004	0	kg/mmBtu
Ketonization catalyst (ZrO ₂)	0.0002	0	kg/mmBtu
Condensation catalyst (niobic acid)	0.002	0	kg/mmBtu
Hydrogen	0	0.7	kg/mmBtu
Dehydration catalyst	0	0.0005	kg/mmBtu
Oligomerization catalyst	0	0.001	kg/mmBtu
Final Fuel Upgrading (HDO/HI)			
Hydrogen	0.8	0.7	kg/mmBtu

One step HDO/HI Catalyst (1% Pt/SAPO-11)	0.002	0.002	kg/mmBtu
<i>Polyurethane Production</i>			
Formic acid	2.5	2.4	kg/mmBtu
H ₂ O ₂	4.0	3.9	kg/mmBtu
Catalysts and other chemicals	0.06	0.06	kg/mmBtu
Nitrogen	0.4	0.4	kg/mmBtu
Toluene diisocyanate	7.0	6.7	kg/mmBtu
Diethanolamine	0.07	0.07	kg/mmBtu
Surfactant	0.1	0.1	kg/mmBtu
<i>Other Resource Consumption</i>			
Supplemental natural gas	16.8	24.5	kg/mmBtu
Process water	677.3	927.5	kg/mmBtu
<i>Output Streams</i>			
AD digestate cake bioavailable N	0.1	0.1	kg/mmBtu
AD effluent NH ₃	1.7	1.6	kg/mmBtu
AD effluent DAP	0.8	0.6	kg/mmBtu
CO ₂ recycle	115.4	133.0	kg/mmBtu

Table A18 Energy and Material Balances Burdened to Fuel Production Only With the Displacement Method, CAP Conversion Processes in the 2030 Projection Case via Acids and BDO as Intermediate Pathways

	Via acids	Via BDO	
Products			
Diesel	137.7	124.6	mmBtu/hr
Naphtha	54.1	70.0	mmBtu/hr
Polyurethane	4345.0	4525.3	kg/hr
Electricity exported to grid	10274.8	10962.7	kW
Resource Consumption			
Algae (AFDW basis)	109.1	107.5	kg/mmBtu
<i>Pretreatment</i>			
Sulfuric acid (93% pure)	4.7	4.7	kg/mmBtu
Ammonia	1.5	1.5	kg/mmBtu
<i>Lipid Extraction and Cleanup</i>			
Hexane requirement	0.6	0.6	kg/mmBtu
Ethanol	0.2	0.2	kg/mmBtu
Phosphoric acid (oil cleanup)	0.3	0.3	kg/mmBtu
Silica (oil cleanup)	0.03	0.03	kg/mmBtu
Clay (oil cleanup)	0.06	0.06	kg/mmBtu
<i>Carboxylic Acid / 2,3-BDO Conversion</i>			
Corn steep liquor	5.0	0.8	kg/mmBtu
Diammonium phosphate	0.5	0.1	kg/mmBtu
Hydrotalcite	0.005	0	kg/mmBtu

Flocculant	0.4	0.4	kg/mmBtu
Hexane	0.004	0	kg/mmBtu
Ketonization catalyst (ZrO ₂)	0.0002	0	kg/mmBtu
Condensation catalyst (niobic acid)	0.002	0	kg/mmBtu
Hydrogen	0	0.7	kg/mmBtu
Dehydration catalyst	0	0.0005	kg/mmBtu
Oligomerization catalyst	0	0.001	kg/mmBtu
<i>Final Fuel Upgrading (HDO/HI)</i>			
Hydrogen	0.8	0.7	kg/mmBtu
One step HDO/HI Catalyst (1% Pt/SAPO-11)	0.002	0.002	kg/mmBtu
<i>Polyurethane Production</i>			
Formic acid	2.2	2.2	kg/mmBtu
H ₂ O ₂	3.5	3.6	kg/mmBtu
Catalysts and other chemicals	0.06	0.06	kg/mmBtu
Nitrogen	0.3	0.3	kg/mmBtu
Toluene diisocyanate	6.0	6.2	kg/mmBtu
Diethanolamine	0.06	0.06	kg/mmBtu
Surfactant	0.1	0.1	kg/mmBtu
<i>Other Resource Consumption</i>			
Supplemental natural gas	15.9	23.7	kg/mmBtu
Process water	642.2	900.1	kg/mmBtu
<i>Output Streams</i>			
AD digestate cake bioavailable N	0.1	0.1	kg/mmBtu
AD effluent NH ₃	1.7	1.6	kg/mmBtu
AD effluent DAP	0.8	0.5	kg/mmBtu
CO ₂ recycle	110.2	129.6	kg/mmBtu

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