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Supply Chain Sustainability Analysis of Renewable Hydrocarbon Fuels via Hydrothermal Liquefaction, Combined Algal Processing, and Biochemical Conversion: Update of the 2022 State-of-Technology Cases

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Energy Systems and Infrastructure Analysis Division

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Supply Chain Sustainability Analysis of Renewable Hydrocarbon Fuels via Hydrothermal Liquefaction, Combined Algal Processing, and Biochemical Conversion: Update of the 2022 State-of-Technology Cases

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. 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 informs R&D priorities by identifying areas in need of improvement, tracks sustainability impact of R&D, 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 over 20 years. It enables BETO to identify energy consumption, environmental, and sustainability issues that may be associated with biofuel production. Approaches to mitigating 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 2022 SOTs: (1) renewable hydrocarbon fuels via hydrothermal liquefaction (HTL) of wet sludge from a wastewater treatment plant (Snowden-Swan et al. 2022); (2) renewable hydrocarbon fuels via biochemical conversion of herbaceous lignocellulosic biomass (Davis and Bartling 2023; Lin et al. 2020); (3) renewable hydrocarbon fuels via HTL of an algae/woody biomass blend (Zhu et al. 2023); and (4) renewable hydrocarbon fuels via combined algae processing (CAP) (Klein and Davis 2023, Wiatrowski and Davis 2023). Table 1 summarizes the feedstock options, conversion technologies, and finished products of the four 2022 SOT pathways. Note that the biochemical conversion and CAP pathways also produce renewable aviation fuel (SAF), which is fractionated into the RD and naphtha streams. In the future, these pathways will be configured to focus on maximizing SAF output. For simplicity and comparison with petroleum diesel, all LCI and LCA metrics for the biochemical conversion, HTL, and CAP pathways are reported on a renewable diesel (RD) basis, using an energy-based allocation method that allocates the sustainability impacts of naphtha-, SAF- and diesel-range hydrocarbon fuel products based on their energy contents.

Table 1 2022 SOT pathways for SCSAs

Pathway	Feedstock	Conversion	Finished Products
Renewable hydrocarbon fuels via HTL	Wastewater treatment plant sludge	HTL	RD, SAF and naphtha
Renewable hydrocarbon fuels via biochemical conversion	Corn stover	Biochemical conversion	RD and naphtha
Renewable hydrocarbon fuels via HTL	Algae and woody biomass	HTL	RD, SAF and naphtha
Renewable hydrocarbon fuels via CAP	Algae	CAP	RD and naphtha

This report focuses on the environmental performance of these biofuel production pathways in their 2022 SOT cases. The results of these renewable hydrocarbon fuel pathways in these SCSA analyses update those for the respective 2021 SOT case (Cai et al. 2021). 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 2022 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 2022 (Wang et al. 2022). These GREET updates include the production of natural gas, electricity, and petroleum-based fuels that can influence biofuels' supply chain greenhouse gas (GHG) (CO_2, CH_4, and N_2O) 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 renewable hydrocarbon fuels from biochemical, algae HTL, and algae CAP. In this analysis, we consider the upstream impacts of producing each energy and chemical input to the supply chain.

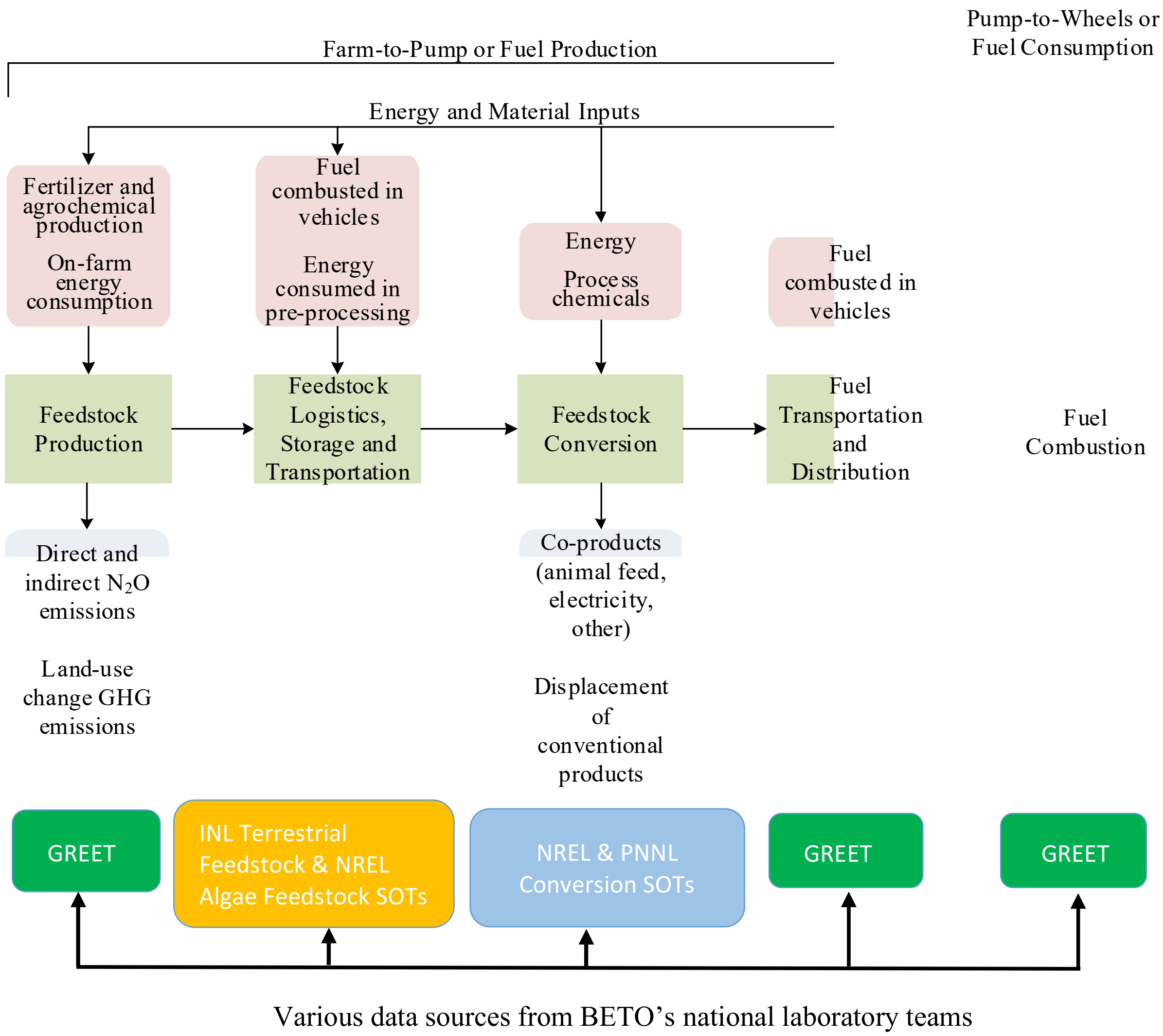


Figure 1 General Stages Considered and Data Sources Used in the Supply Chain Sustainability Analyses for Renewable Hydrocarbon Fuels from Biochemical Conversion, HTL, and CAP

2 METHODS AND DATA

Argonne National Laboratory's GREET model was used to generate the SCSA results for the 2022 SOT cases of the four 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 (PM_{10}) 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.

For biofuel pathways with a significant amount of co-products, e.g., the biochemical conversion pathway and the CAP pathway, we will apply different co-product handling methods including the biorefinery-level method as described in Cai et al. (2021) to address the co-product effects.

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.

2.1 Material and Energy Requirement of Feedstock Production and Logistics

2.1.1 Feedstock Production and Logistics for 2022 SOT Pathways

For the herbaceous feedstock, the 2022 SOT used air classification to clean up the 3-pass corn stover down to a 6% ash content. For the woody feedstock, the 2022 SOT of the algae/woody biomass HTL pathway uses the same feedstock production, logistics considered in the 2020 SOT.

The National Renewable Energy Laboratory (NREL) modeled an algal feedstock (Klein and Davis 2023) used for the algae CAP and HTL pathways. Pacific Northwest National Laboratory (PNNL) modeled wet sludge from wastewater treatment plants as feedstock for the sludge HTL pathway (Snowden-Swan et al. 2022).

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% and a dry matter content that primarily consists of carbon, oxygen, and ash, with a small amount of hydrogen, nitrogen, and sulfur (Snowden-Swan et al. 2022).

2.1.2 Algae Biomass Cultivation

Algae cultivation for CAP and HTL conversion is modeled from the algae farm design report (Klein and Davis 2023; Davis et al. 2016), which assumes sourcing of CO_2 through the capture of flue gas from nearby power plant point sources. 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 assumed to be located 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 DISCOVR experimental cultivation trials at the ASU AzCATI test-bed site (located in Arizona) since the 2017 SOT.

In the 2022 SOT case as consistent with prior SOTs (Klein and Davis 2023), high purity CO_2 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 electricity demand of 0.63 mega-joules (MJ) per kilogram of CO_2 is assumed for CO_2 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* (Klein and Davis 2023). Figure 2 shows a general block-flow diagram of the process. Further details of the process design are given in the report (Klein and Davis 2023). In these SCSAs, saline scenarios with minimally lined ponds are considered for the downstream conversion of algal biomass to fuels and co-products.

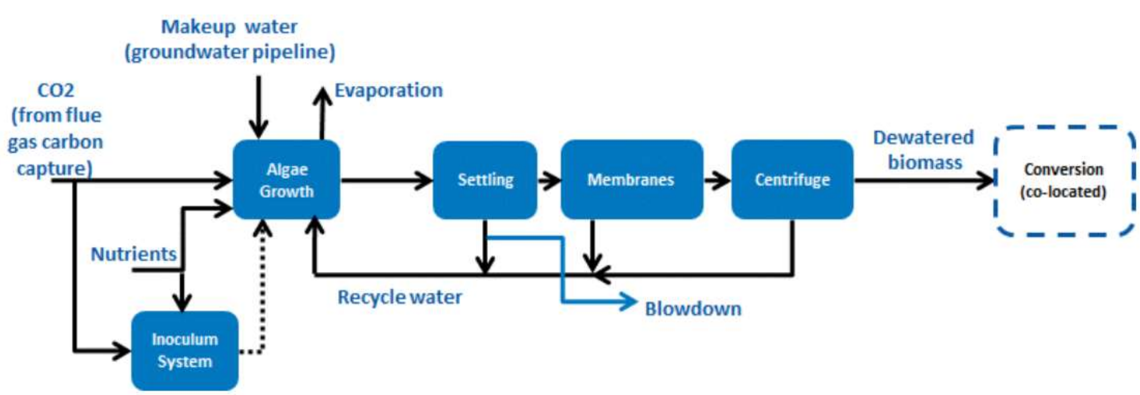


Figure 2 Process Flow Diagram of the Open Pond Algae Farm Model

Table 2 summarizes material and energy inputs and outputs of the 2022 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).

Table 2 Algal Biomass Production and Resource Requirement (Annual Averages, Hourly Rates Reflect Average Daily Rates Divided by a 24-Hour Day)

	2022 SOT
	Algae for CAP and HTL
Products, kg/hr	
Algal biomass (AFDW)	15,364
Algal biomass (total including ash)	15,741
Make-up resource requirement, kg/hr	
CO_2	34,112
Ammonia	309
Diammonium phosphate	149
Total process water input (saline water)	511,527
Electricity demand, kW	9,047
Algae lost in blowdown	2

2.2 Material, Energy, and Water Requirements of Conversion Processes

2.2.1 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. 2022). 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 water resource recovery facility (WRRF). The configuration includes an HTL plant co-located with a WRRF 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 3.

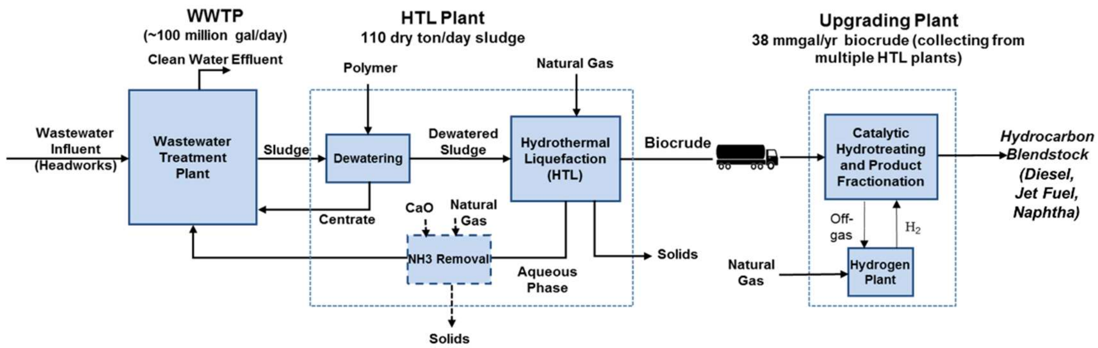


Figure 3 A Simplified Process Flow Diagram of the WRRF/HTL Plant and Centralized Biocrude Upgrading Plant Design

The operations at the HTL plant to produce biocrude in the 2022 SOT case remain the same. The primary updates of the biocrude upgrading operations are the fractionation and deep hydrodenitrogenation (HDN) of a jet fuel cut for production of SAF. Note that 2022 SOT is based on initial R&D on the jet cut from this process (Cronin et al. 2022). Further work is needed to validate that SAF can be produced from this pathway. Table 3 summarizes major inputs and outputs of the HTL process for all the cases investigated. Table 4 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 3 Energy and Material Balances (per lb of Biocrude Produced) at the HTL Plant

	Unit	With Ammonia Removal	Without Ammonia Removal
Material and Energy Inputs			
Dewatered sludge	dry lb	2.6	2.6
Natural gas	Btu	1,292	1,095
Electricity	Btu	309	294
Dewatering polymer	lb	0.012	0.012
Quicklime (CaO)	lb	0.113	0
Cooling water makeup	gal	0.0066	0.0066
Material and Energy Outputs			
Solids from HTL Aqueous Treatment	lb	0.24	0

Table 4 Material and Energy Balances, per MMBtu of Fuel Produced at the Upgrading Plant

	Unit	2022 SOT Case
Material and Energy Inputs		
Biocrude	lb	70.2
Natural gas	Btu	77,910
Electricity	Btu	12,164
Cooling tower chemical	g	0.1
Boiler chemical	g	0.2
Hydrotreating catalyst (CoMo/γ-Al_2O_3)	g	24.4
Hydrotreating catalyst (NiMo/γ-Al_2O_3)	g	3.9
Hydrocracking catalyst	g	0.1
Hydrogen plant catalyst (Ni)	g	0.3
Hydrodenitrogenation Catalyst	g	1.0
Cooling water makeup	gal	4.2
Boiler feedwater makeup	gal	2.3

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), SAF (co-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 3 and 4 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.

2.2.2 Biochemical Conversion

As in previous SOT cases, the biochemical conversion pathway to produce renewable hydrocarbon fuels (spanning the naphtha, SAF, and diesel range) includes two approaches that utilize carboxylic acids and 2,3-butanediol (BDO) as fermentation intermediates in the 2022 SOT. In the SCSAs, we focused on the conversion scenario of both fermentation pathways that co-produce a significant amount of chemical co-product 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 4 is a high-level PFD of the biochemical conversion design with lignin-derived chemical co-production. The process remains largely the same as that reflected in the 2021 SCSA (Cai et al. 2021). In summary, 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 subsequent conversion steps to produce a co-product. A key update in the 2021 SOT, maintained in the 2022 SOT, reflected a switch from adipic acid as the selected coproduct (derived from lignin fermentation to muconic acid), to β-ketoadipate (BKA, a closely-related product which may be directly fermented from lignin monomers and ultimately destined for the same end-product market as adipic acid). 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). The 2022 SOT maintains the use of a more optimal two-stage deacetylation step first incorporated in the 2020 SOT, 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 and Bartling (2023) provides more details on the process design, performance targets, and TEA results.

Given the significant amount of co-produced BKA bioproduct and its significant impact on the sustainability results, we took three co-product handling methods (a purpose-driven, process-level allocation method, the displacement method, and the biorefinery-level analysis) to address the 2022 SOT 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.

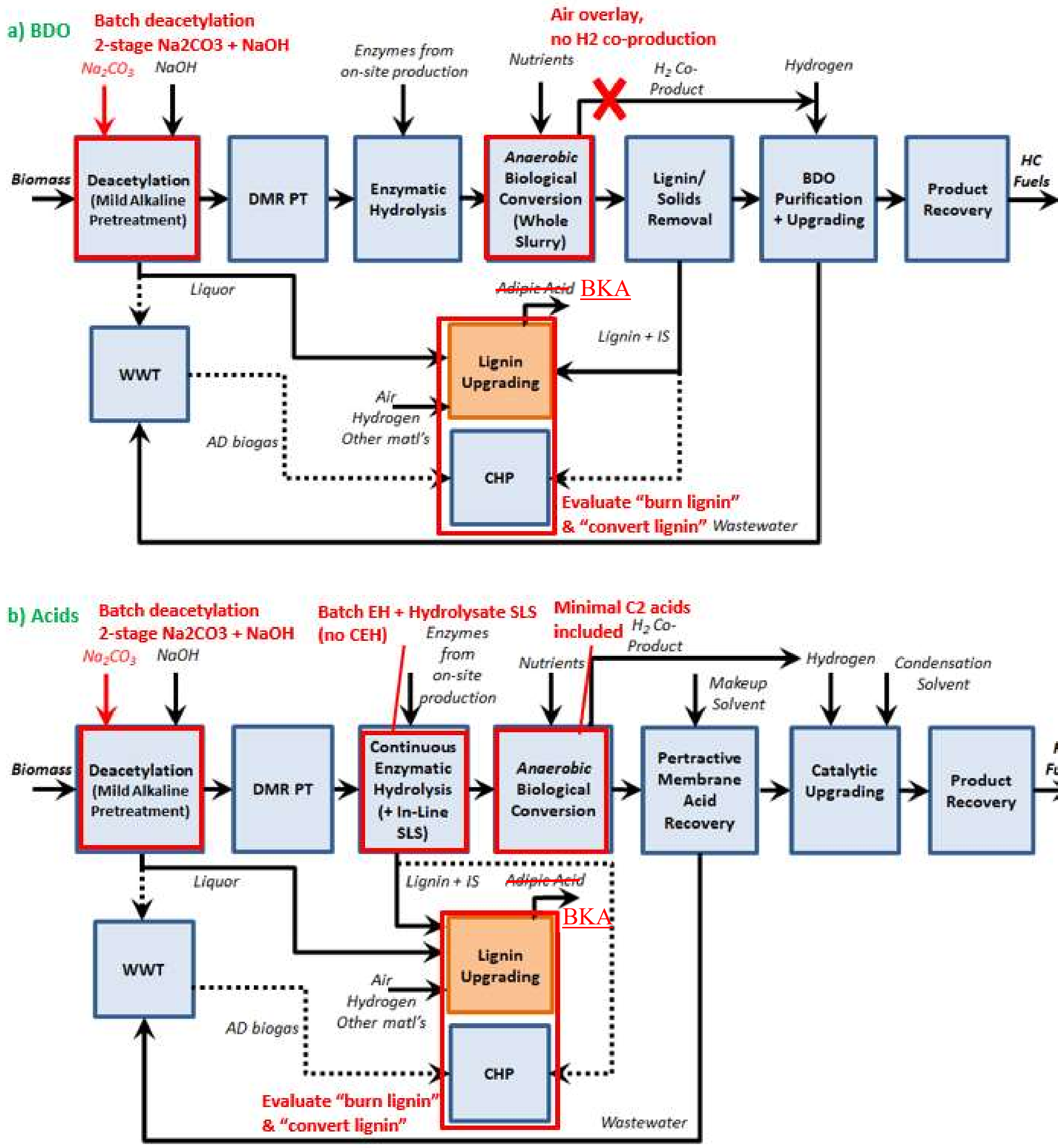


Figure 4 Process Flow Diagram of the Biochemical Conversion Design Case with Two Lignin Strategies: (1) Burn Lignin and (2) Convert Lignin to Co-Product. Modifications from the 2030 targets as reflected in the current 2022 SOT case are denoted in red (Davis and Bartling 2023)

With the purpose-driven, process-level allocation method, the inputs commonly shared by producing both the fuel and non-fuel products were further 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 BKA are assumed to be \$2.5/GGE and \$0.85/lb, respectively.

Tables 5 presents the overall energy and material balances of the biochemical conversion pathway for both intermediate designs in the 2022 SOT case.

Table 5 Energy and Material Balances of the Biochemical Conversion Pathway for Both the Acids and BDO Intermediate Designs, 2022 SOT Case. Yellow inputs contribute to fuel production only, green inputs contribute to chemical production only, and blue inputs and outputs are shared by both the fuel and chemical products.

	Via Acids		Via BDO		
	2022 SOT (Burn Lignin)	**2022 SOT (Convert Lignin – BKA)**	**2022 SOT (Burn Lignin)**	**2022 SOT (Convert Lignin – BKA)**	
Products	**Production Rate**				
Hydrocarbon fuel	10,231	10,212	11,942	11,948	kg/hr
	427	426	501	502	MMBtu/hr
Co-Products					
Beta ketoadipate	0	2,674	0	2,645	kg/hr
Recovered sodium sulfate salt from WWT	12,446	17,430	12,642	16,550	kg/hr
Resource Consumption	**Flow Rate (kg/hr)**				
Biomass feedstock (20% moisture)	104,167	104,167	104,167	104,167	
Sulfuric acid, 93%	11,124	13,380	11,124	12,472	
Caustic (as pure)	2,750	5,292	2,750	4,550	
BKA train		2,542		1,800	
Both		2,750		2,750	
Sodium carbonate	7,500	7,500	7,500	7,500	
Ammonia	1,242	2,209	1,059	1,960	
Fuel train		64		64	
BKA train		17		17	
Both		2,128		1,879	
Glucose	1,336	1,336	1,336	1,336	
Corn steep liquor	1,276	1,276	929	929	
Corn oil	7	7	7	7	
Host nutrients	37	37	37	37	
Sulfur dioxide	9	9	9	9	

Table 5 (Cont.)

	Via Acids		Via BDO		
	2021 SOT (Burn Lignin)	**2021 SOT (Convert Lignin – Base)**	**2021 SOT (Burn Lignin)**	**2021 SOT (Convert Lignin – Base)**	
Diammonium phosphate	177	177	104	104	
Flocculant	418	418	433	433	
Toluene solvent makeup	90	90	0	0	
Hydrogen	0	0	945	948	
Boiler chemicals	0	0	0	1	
FGD lime	119	191	116	174	
WWT polymer	35	0	31	0	
Cooling tower chemicals	3	1	1	1	
Makeup water	325,149	254,541	112,059	144,834	
Natural gas for boiler	0	400	0	6,800	
Natural gas for hot oil system	39	39	0	0	MMBtu/hr
Grid electricity (net import)	8,697	58,127	29,515	44,353	kW
Fuel train		22,886		19,571	
BKA train		4,350		4,308	
Both		30,891		20,474	

About 97% of the toluene solvent makeup for the acids case ends up in the boiler and is combusted. The CO_2 emissions of toluene combustion are fully accounted for, and the emissions are considered fossil CO_2 emissions because toluene is made from fossil feedstock. CO_2 released upon acid neutralization of sodium carbonate (maintained in the 2022 SOT as part of the deacetylation step noted above) is also accounted for as fossil CO_2 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 5, 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 BKA co-production.

2.2.3 Algae Hydrothermal Liquefaction (HTL)

This SCSA evaluates RD production from algae via HTL processing. Saline algae with forest residue supplement during lower algae productivity seasons (winter, fall, and spring) to match the algae production rate in summer is assumed in the 2022 SOT case. The purpose is to maintain a constant plant capacity in all the seasons. An annual average blend of 64% algae and 36% woody biomass by ash-free dry weight (AFDW) is formulated. Figure 5 displays a simplified PFD for the algae/wood blend feedstock conversion via an HTL and upgrading system. In the modeled commercial-scale plant, algae blended with woody biomass slurry is pumped to the HTL process. In the HTL reactor, condensed phase liquefaction takes place through the effects of time, heat and pressure. The resulting HTL products, including biocrude, solid, aqueous and gas, are separated. The biocrude is upgraded via hydrotreating and hydrocracking to generate diesel, jet fuel and naphtha range fuels. The jet cut is further sent to an HDN unit to reduce nitrogen to trace level to produce a SAF quality product. The HTL aqueous phase is assumed to be recycled directly to the algae farm. The gas stream is used for process heating and hydrogen generation. A hydrogen plant is included for hydrotreating, which is assumed to be co-located with the HTL conversion. Nutrients recovered by acid extraction of the HTL solids are recycled to the farm along with the HTL and the hydrotreating aqueous streams. Flue gas containing carbon dioxide is also assumed to be recycled to the farm to provide carbon elements for algae growth. Detailed process designs for HTL conversion of algae with woody biomass supplement to make renewable hydrocarbon fuels are given in Zhu et al. (2023).

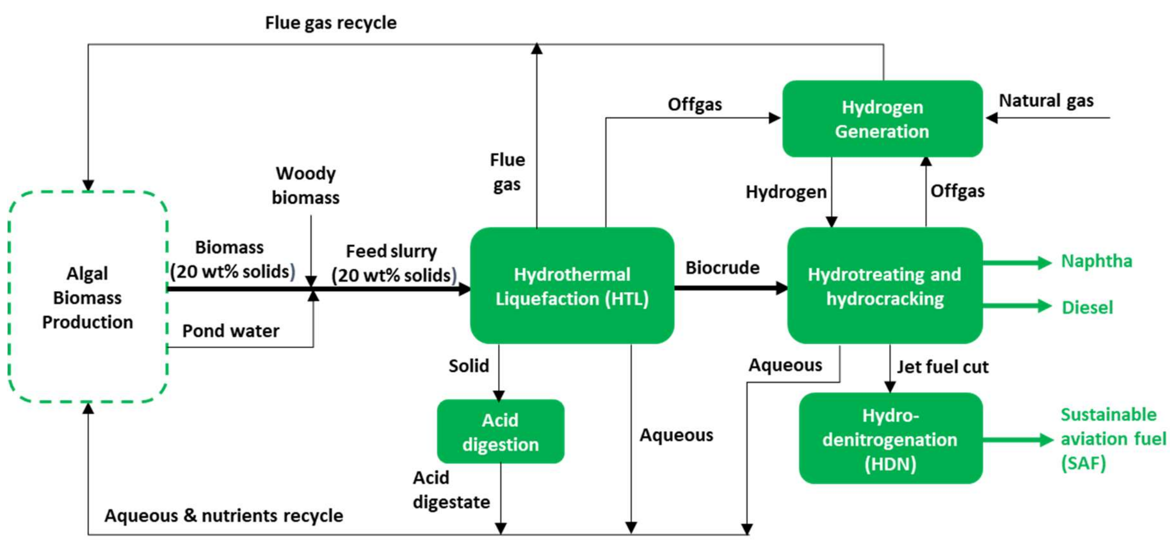


Figure 5 Process Flow Diagram for Hydrothermal Liquefaction of Algae with Woody Biomass Supplement for Renewable Diesel Production in the 2022 SOT.

Table 6 lists the overall material, energy, and water consumption for the modeled HTL conversion process at the plant in the 2022 SOT case.

Table 6 Material, Energy, and Water Consumption for the Modeled HTL Conversion and Upgrading Process, 2021 SOT Case.

	Values	Unit
Fuel Products		
Diesel	3,314	kg/h
	136	MMBtu/h
SAF	1,772	kg/h
	73	MMBtu/h
Naphtha	1,251	kg/h
	50	MMBtu/h
Resource Consumption		
Algae (AFDW basis), annual average	15,987	kg/h
Wood (AFDW basis), annual average	9,053	kg/h
Sulfuric-Acid (96 wt%) makeup	910	kg/h
Hydrotreating (HT) main bed catalyst	1.2	kg/h
HT guard bed catalyst	2.1	kg/h
Hydrodenitrogenation catalyst	0.2	kg/h
Hydrocracking catalyst	0.03	kg/h
Natural gas for H_2 generation	1,331	kg/h
Natural gas for process heating	925	kg/h
Process water makeup	14,716	kg/h
Purchased Electricity	1,854	kW
Nutrient elements recycled to algae farm		
Carbon	7,081	kg/h
Nitrogen	1,614	kg/h
Phosphorus	242	kg/h

2.2.4 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 2023). 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. As in the 2021 SOT, a polyurethane (PU) co-product is 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). Figure 6 shows a block-flow diagram of the CAP conversion process. The 2022 SOT case reflects updates in the SOT algae farm model cultivation performance parameters as well as conversion parameters for the fermentation step in the case of the BDO pathway, with other process parameters maintained consistently with the 2021 SOT.

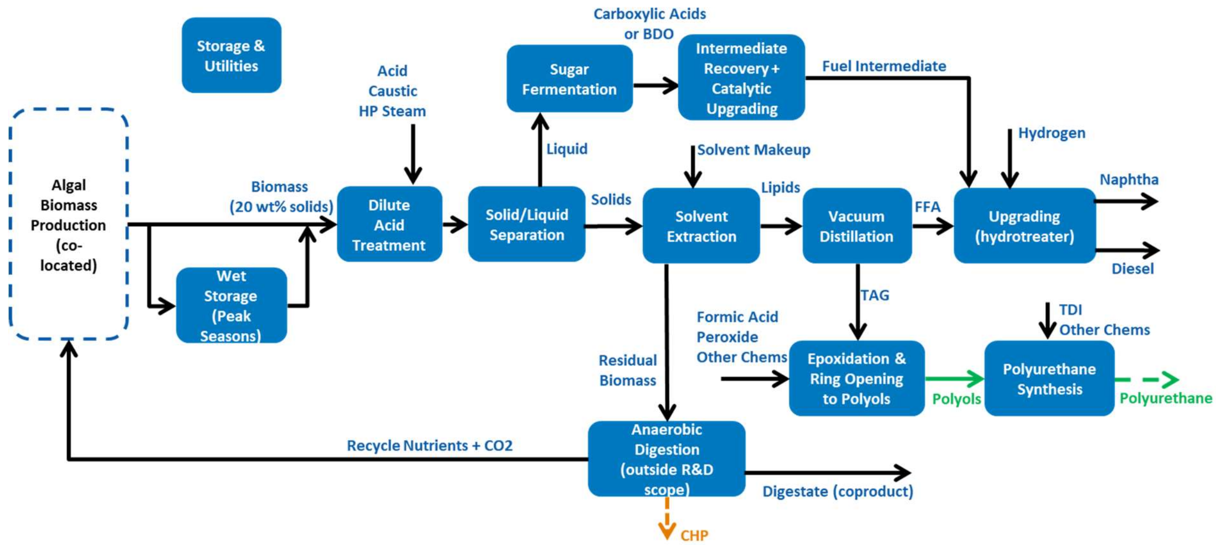


Figure 6 Block-Flow Diagram of the CAP Conversion Process as Reflected in the 2022 SOT

Given the significant amount of PU co-product as maintained in the 2022 SOT case, which accounts for 53% by mass of the total product slate including RD, SAF, naphtha, and PU, we applied the same purpose-driven, process-level allocation method in this SCSA. 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 hydrocarbon fuels and PU are assumed to be $2.5/GGE and $2.04/lb. 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 13% 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 2022 SOT case in addition to the displacement method and biorefinery-level analysis. The environmental impacts, including GHG emissions, water consumption, and NO_x emissions, of conventional, fossil-derived flexible PU foam were model in GREET (Keoleian et al. 2012) and used to account for the displacement credit and biorefinery-level emissions.

Table 7 lists the overall energy and material inputs for the modeled CAP conversion process in the 2022 SOT case, via either acids or BDO intermediate pathways for fuel production.

Table 7 Overall Energy and Material Inputs and Outputs in the Modeled CAP Conversion Processes in the 2022 SOT Case via Acids and BDO as Intermediate Pathways. Yellow inputs contribute to fuel production only, green inputs contribute to chemical production only, and blue inputs and outputs are shared by both the fuel and chemical products.

	Via Acids	Via BDO	
Products		**Production Rate**	
Hydrocarbon Fuel			
Diesel	94	86	MMBtu/hr
Naphtha	37	48	MMBtu/hr
Co-products			
Polyurethane	3,593	3,593	kg/hr
Power exported to grid	5,045	5,846	kW
Resource Consumption		**Flow Rate (kg/hr)**	
Feedstock (AFDW basis)	15,987	15,987	
Pretreatment			
Sulfuric acid (93% pure)	1,420	1,420	
Ammonia	459	459	
Lipid Extraction and Cleanup			
Hexane requirement	84	84	
Ethanol	34	34	
Phosphoric acid (oil cleanup)	46	46	
Silica (oil cleanup)	5	5	
Clay (oil cleanup)	9	9	
Carboxylic Acid / 2,3-BDO Conversion			
Corn steep liquor	721	107	
Diammonium phosphate	75	13	
Hydrogen		89	
Flocculant	64	64	
Dehydration catalyst		0.07	
Oligomerization catalyst		0.13	
Hydrotalcite	1		
Hexane	1		
Final Fuel Upgrading (HDO/HI)			
Hydrogen	107	97	
One-step HDO/HI catalyst (1% Pt/SAPO-11)	0.23	0.25	
Polyurethane Production			
Formic acid	347	347	
H_2O_2	549	549	
Catalysts and other chemicals	9	9	
Nitrogen	52	52	
Toluene diisocyanate	953	953	
Diethanolamine	9	9	
Surfactant	17	17	

Table 7 (Cont.)

	Via Acids	Via BDO
Other Resource Consumption		
Supplemental natural gas (total)	1,977	3,245
Supplemental natural gas (fuel+PU)	944	1,280
Supplemental natural gas (fuel)	120	756
Supplemental natural gas (PU)	914	1,210
Process water (total)	65,643	103,954
Process water (fuel+PU)	47,769	54,374
Process water (fuel)	100	31,814
Process water (PU)	17,774	17,766
Output Streams	**Flow Rate (kg/hr)**	
AD digestate cake (dry basis total flow)	3,479	3,341
AD digestate cake bioavailable N	19	18
AD effluent NH_3	233	228
AD effluent DAP	110	81
Recycle water (excluding N/P nutrients)	104,969	107,210
CO_2 Recycle		
CO_2 (biogenic)	9,090	8,981
CO_2 (fossil)	5,986	9,467

A nutrient-rich effluent produced in the AD process can be recycled to the algae cultivation ponds. For the SCSAs, we assumed that the NH_3 and DAP 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.

3 RESULTS AND DISCUSSION

The feedstock and conversion process model input/output inventories were furnished to the GREET-based Interactive LCA model (Ou et al. 2022) to calculate overall life-cycle metrics of the four renewable fuel pathways.

3.1 Sludge Hydrothermal Liquefaction

The SCSA of the 2022 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.

3.1.1 Supply Chain Greenhouse Gas Emissions

Figure 7 represents the supply chain GHG emissions and their key contributing supply chain processes in g CO_2e/MJ of RD produced from sludge via the HTL and upgrading processes. The GHG emissions reduction of the 2022 SOT case is compared with a life-cycle carbon intensity of 91 g CO_2e/MJ for petroleum diesel. The supply chain GHG emissions for the 2022 SOT case are lower than those for petroleum diesel, especially in the scenarios without NH_3 removal. In the scenario with NH_3 removal, RD GHG emissions represent a 77% reduction compared with petroleum diesel. When NH_3 is not removed from the HTL aqueous, RD GHG emissions represent an 81% reduction in the 2022 SOT case compared with petroleum diesel. Higher GHG emissions reductions when NH_3 is not removed are achieved by avoiding quicklime (CaO) use and reducing the use of the natural gas associated with the NH_3 stripping process. However, the WRRF would need to treat the additional NH_3 if it were not removed at the HTL plant and the potential resulting GHG impacts are outside the system boundaries of this analysis.

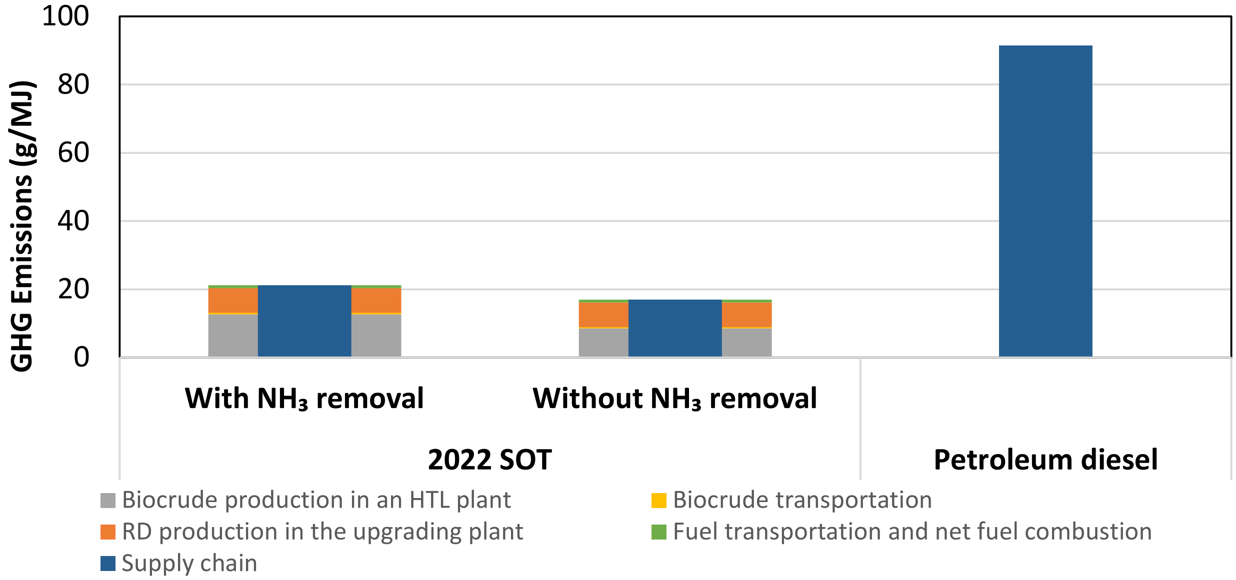


Figure 7 Supply Chain GHG Emissions (g CO_2e/MJ) of Renewable Diesel via Sludge HTL, Compared to 91 g CO_2e/MJ for Petroleum Diesel

The major contributor to the supply chain GHG emissions are the emissions during biocrude production in the HTL plant, accounting for about 60% of the total emissions with NH_3 removal, and for about 50% of the total emissions without NH_3 removal. When the HTL aqueous NH_3 is not removed, the supply chain GHG emission intensities are lowered by about 4 g CO_2e/MJ in the 2022 SOT case.

As in the 2021 SOT case, we considered the potential impacts of lime sludge that is formed during the ammonia stripping process to treat the HTL aqueous waste. Lime sludge is rich in $CaCO_3$. We assume that this solid waste is transported to a landfill by truck. The carbon in the lime sludge originates from the wastewater sludge and thus we assume that it is biogenic carbon. We assume that 49.2% of the biogenic carbon in the lime sludge upon soil amendment or landfill ends up as biogenic CO_2 emissions (0.216 g CO_2/g $CaCO_3$) (Cai, Wang, and Han 2014), while the remaining will be sequestered and result in a biogenic carbon sequestration credit of -0.224 g CO_2/g $CaCO_3$, which translates to about -1.4 g CO_2e/MJ of RD.

At the biorefinery level, without a biochemical co-product the biorefinery-level emission reduction comes entirely from the fuels (Figure 8). Approximately 827 kg to 877 kg CO_2e of GHG emission reduction could be achieved per ton of biosolids in wastewater sludge converted to renewable diesel via the HTL pathway, depending on whether ammonia removal is considered.

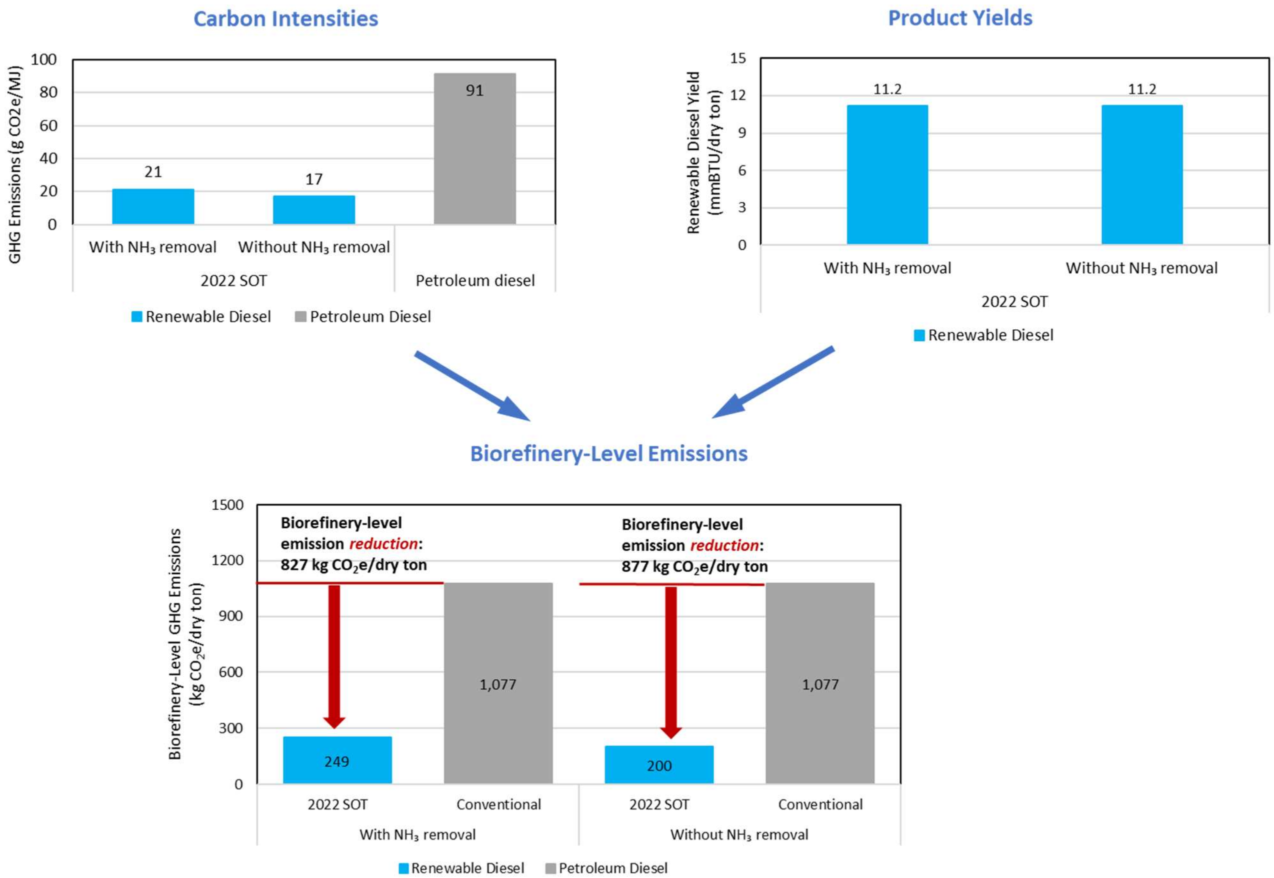


Figure 8 Biorefinery-Level Greenhouse Gas Emissions and Reductions, the 2022 SOT Case of the Wastewater Sludge HTL Pathway, with and without Ammonia Removal

3.1.2 Supply Chain Water Consumption

Figure 9 shows supply chain water consumption producing one GGE of RD from sludge via the HTL and upgrading processes. The 2022 SOT "with NH_3 removal" scenario consumes 2.2 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 1.6 gal/GGE, owing to the avoidance of embedded water consumption of CaO and reduction in electricity and natural gas consumption.

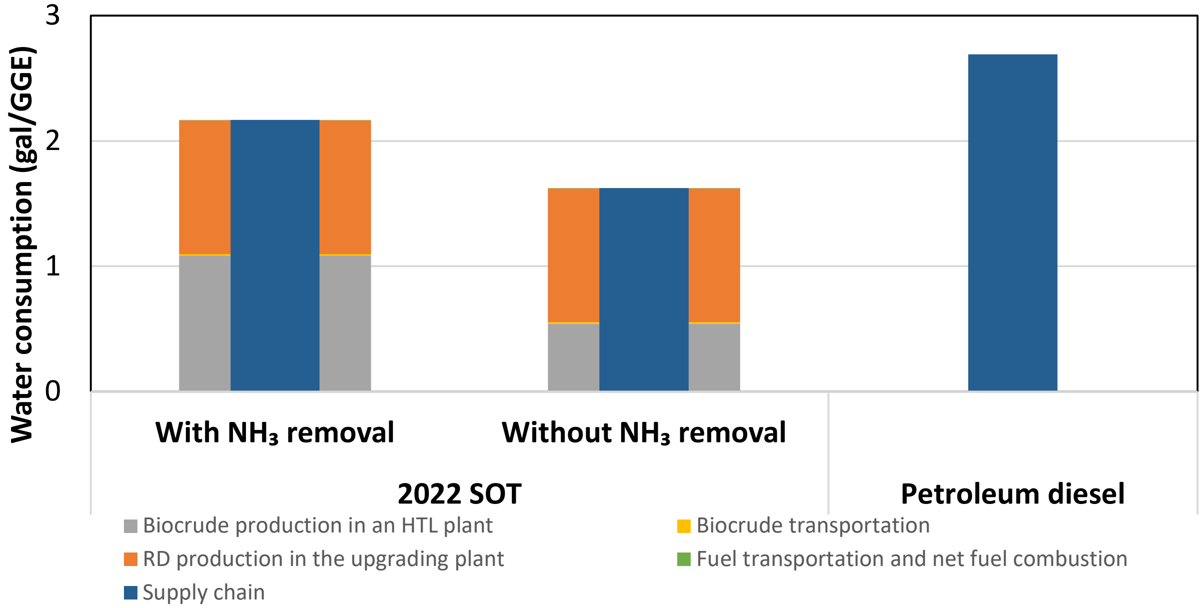


Figure 9 Supply Chain Water Consumption (gal/GGE) of Renewable Diesel via Sludge HTL, Compared to 2.7 gal/GGE for Petroleum Diesel

The direct water consumption during the conversion process in the 2022 SOT case is 0.8 gal/GGE in the 2022 SOT case, which is lower than the direct water consumption of 1.0 gal/GGE in the 2021 SOT case. The lower direct water consumption in the 2022 SOT case is mainly due to reduced cooling water makeup and boiler feedwater makeup.

3.1.3 Supply Chain NO_x Emissions

Figure 10 shows that, in the 2022 SOT case, total supply chain NO_x emissions measure about 0.041 and 0.039 g/MJ with and without NH_3 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.

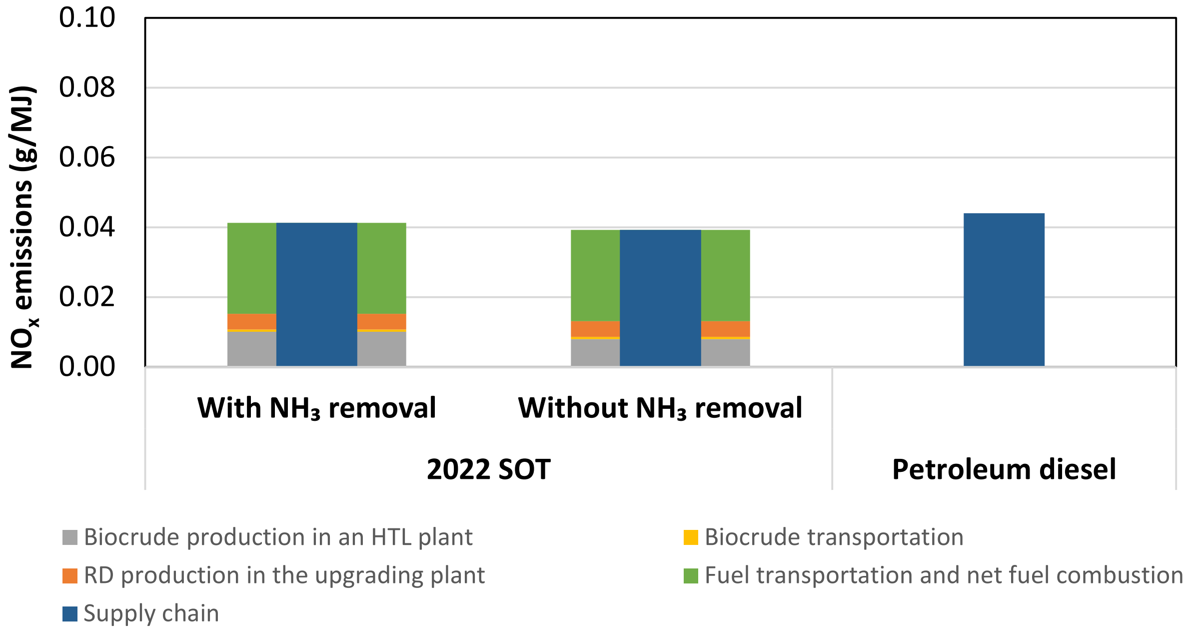


Figure 10 Supply Chain NO_x Emissions (g/MJ) of Renewable Diesel via HTL, Compared to 0.04 g/MJ for Petroleum Diesel

3.1.4 Summary of Sustainability Metrics

Table 8 summarizes the SCSA sustainability metrics evaluated for the 2022 SOT case of RD production from wet sludge via the HTL and upgrading processes. In addition to GHG emissions, water consumption, and total NO_x emissions as described above, Table 8 lists the supply chain fossil energy consumption and the net energy balance (NEB) as two energy-related metrics. The supply chain fossil energy consumption of the 2022 SOT cases is 0.28 and 0.24 MJ per MJ of RD, with and without NH_3 removal, respectively, which is attributable to natural gas and electricity consumption in the HTL and upgrading processes. 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. The NEB of RD is 0.72 MJ/MJ (with NH_3 removal) and 0.76 MJ/MJ (without NH_3 removal) for the 2022 SOT case of the sludge HTL pathway.

In the 2022 SOT case, the sludge HTL pathway shows a reduction in urban NO_x emissions by about 6% compared with that of petroleum diesel, regardless of whether ammonia removal is considered. It is noted that the supply chain NO_x and urban NO_x emissions of petroleum diesel decrease from 0.06 g/CO_2e and 0.03 g/CO_2e to 0.04 g/CO_2e and 0.02 g/CO_2e, respectively, due to an update of the NO_x emission factor for fuel combustion by vehicles in the GREET model.

Table 8 Supply Chain Sustainability Metrics for Renewable Diesel via Sludge HTL

	2022 SOT		
	With NH_3 removal	Without NH_3 removal	Petroleum Diesel
	Biofuel yield		
Million Btu/dry ton	11.2	11.2	
	Fossil energy consumption		
MJ/MJ	0.28	0.24	1.2
	Net energy balance		
MJ/MJ	0.72	0.76	
	GHG emissions		
g CO_2e/MJ	21 (*-77%)*	17 (*-81%)*	91
g CO_2e/ GGE	2,591	2,077	11,197
	Water consumption		
L/MJ	0.07	0.05	0.08
gal/GGE	2.2	1.6	2.7
	Total NO_x emissions		
g NO_x/MJ	0.041	0.039	0.044
g NO_x/GGE	5.1	4.8	5.4
	Urban NO_x emissions		
g NO_x/MJ	0.020	0.020	0.021
g NO_x/GGE	2.4	2.4	2.6

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

3.2 Biochemical Conversion

The SCSA of the biochemical pathway incorporated the 2022 SOT case of herbaceous feedstock with the 2022 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 BKA:

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 in comparison to the same amounts of the same products produced through conventional means from fossil feedstocks, thus presenting a complete picture of the biorefinery's emission performance.

3.2.1 Supply Chain Greenhouse Gas Emissions

Figure 11 displays the supply chain GHG emissions and their key contributing supply chain processes, in g CO_2e/MJ of RD, in the 2022 SOT case, compared with a life-cycle carbon intensity of 91 g CO_2e/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 BKA. When lignin is upgraded to BKA, we apply both mass- and market-value-based process-level allocation methods to allocate inputs that are common to both the fuel and BKA products. Feedstock preprocessing accounts for 7% – 10% of the emissions in the 2022 SOT case when lignin is upgraded to BKA 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.

For either lignin end-use scenario, 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 -4 – -6 g CO_2e/MJ in both routes after the process-level allocation. GHG emission intensity of the fuel in the lignin upgrading to the BKA 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 BKA designs may offer little to no emission reduction benefit in the 2022 SOT case relative to burning lignin for heat and power. However, it is anticipated that this will improve substantially moving to future 2030 performance targets through higher fuel and co-product yields without increasing the process energy and chemical demands by the same magnitudes.

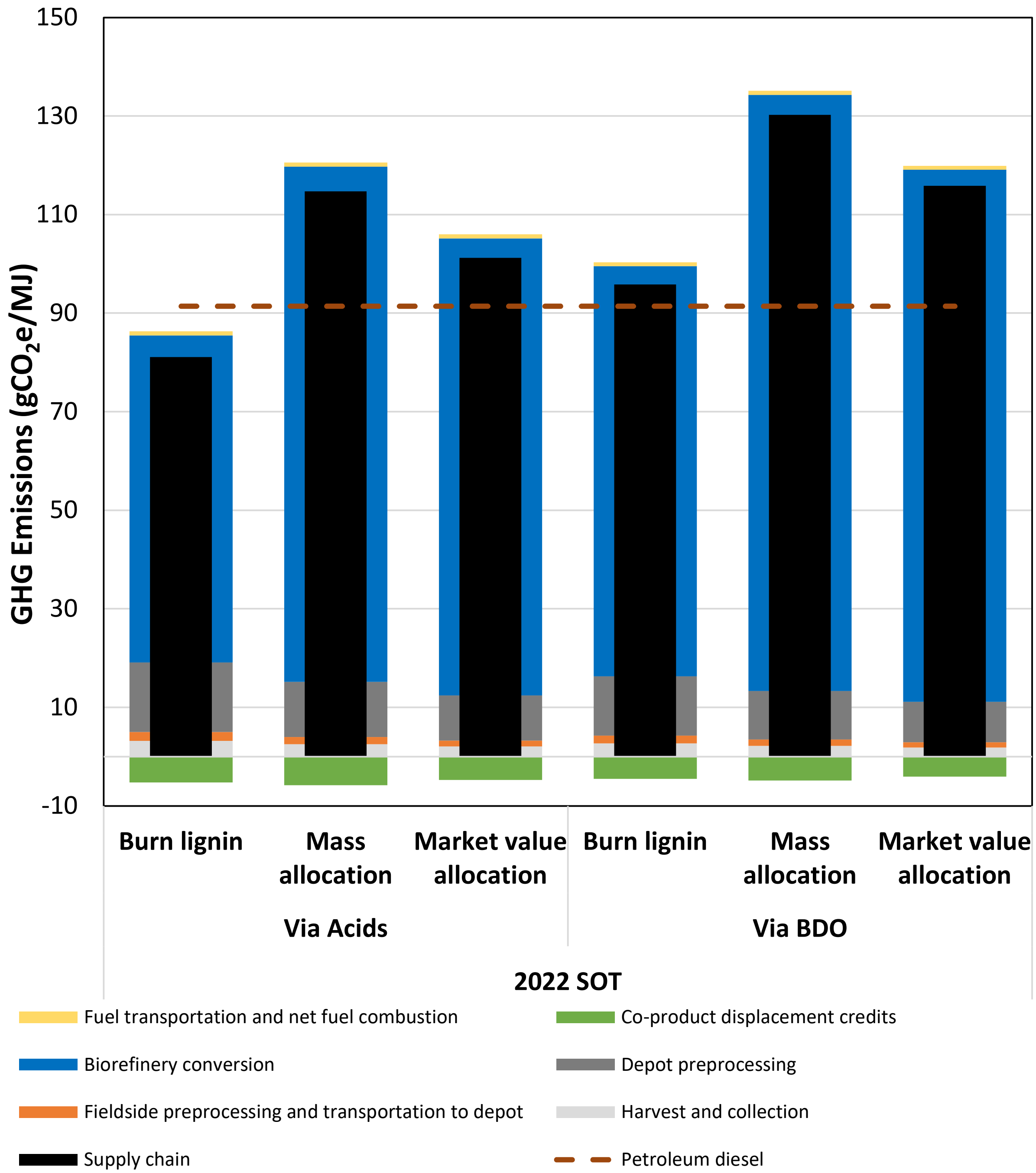


Figure 11 Supply Chain GHG Emissions of Renewable Diesel via Biochemical Conversion, Using the Process-Level Allocation Method to Address Effects of BKA Co-Production

It should be noted that the supply chain GHG emissions of the 2022 SOT cases are generally higher than the 2021 SOT cases, especially when lignin is combusted. For instance, the supply chain GHG emissions are 8 – 10 g CO_2e/MJ higher in the 2022 SOT cases when lignin is combusted. The increase in the GHG emissions of the 2022 SOT cases is mainly attributable to three reasons. First, the annual update of the GREET model causes increased carbon intensities of NG, electricity, and chemicals, which drives up the life cycle GHG emissions of the 2022 SOT cases. The update in GREET 2022 is responsible for an increase of 4 g CO_2e/MJ in the supply chain GHG emissions when lignin is combusted. Second, feedstock preprocessing in the 2022 SOT case consumes more electricity for comminution of corn stover tissues with rotary shear and densification of rotary sheared tissues to meet feedstock quality and throughput targets for conversion, causing an increase of 2 – 3 g CO_2e/MJ in the supply chain GHG emissions. Third, the modification of the conversion step in the 2022 SOT cases causes an increase of 3 – 5 g CO_2e/MJ in the GHG emissions relative to the 2021 SOT cases (Cai et al. 2022). Even though biofuel yield at the biorefinery is slightly improved in the 2022 SOT cases, the consumption of electricity, caustic, and sodium carbonate at the biorefinery increases more substantially and eclipses the slightly improved fuel yield. As a result, the supply chain GHG emissions of the 2022 SOT cases are higher than those of the 2021 SOT cases.

A relatively small increase in the supply chain GHG emissions from the 2021 SOT cases to the 2022 SOT is observed when lignin is upgraded to BKA. Even though the yields of hydrocarbon fuels and BKA both increase in the 2022 SOT case, the increase in the yield of BKA is more significant. As a result, less environmental burden is allocated to the hydrocarbon fuels when using the purpose-driven, process-level allocation method, thus mitigating the increase in GHG emissions caused by the same reasons as the burning lignin design mentioned above.

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 lignin-derived BKA co-product displacing conventional fossil-based AA (as both BKA and AA are intended for the same end-product market). In addition, bio-based BKA generates GHG emission credits by sequestering biogenic carbon given that its carbon is derived from herbaceous biomass. BKA production generates -62 to -74 g CO_2e/MJ GHG emission credits from both displacing conventional AA (-53 to -64 g CO_2e/MJ) and biogenic carbon sequestration (-8 to -10 g CO_2e/MJ). As a result, supply chain GHG emission intensities of renewable diesel are 86 and 106 g CO_2e/MJ in the acids and BDO intermediate pathways, respectively, as shown in Figure 12.

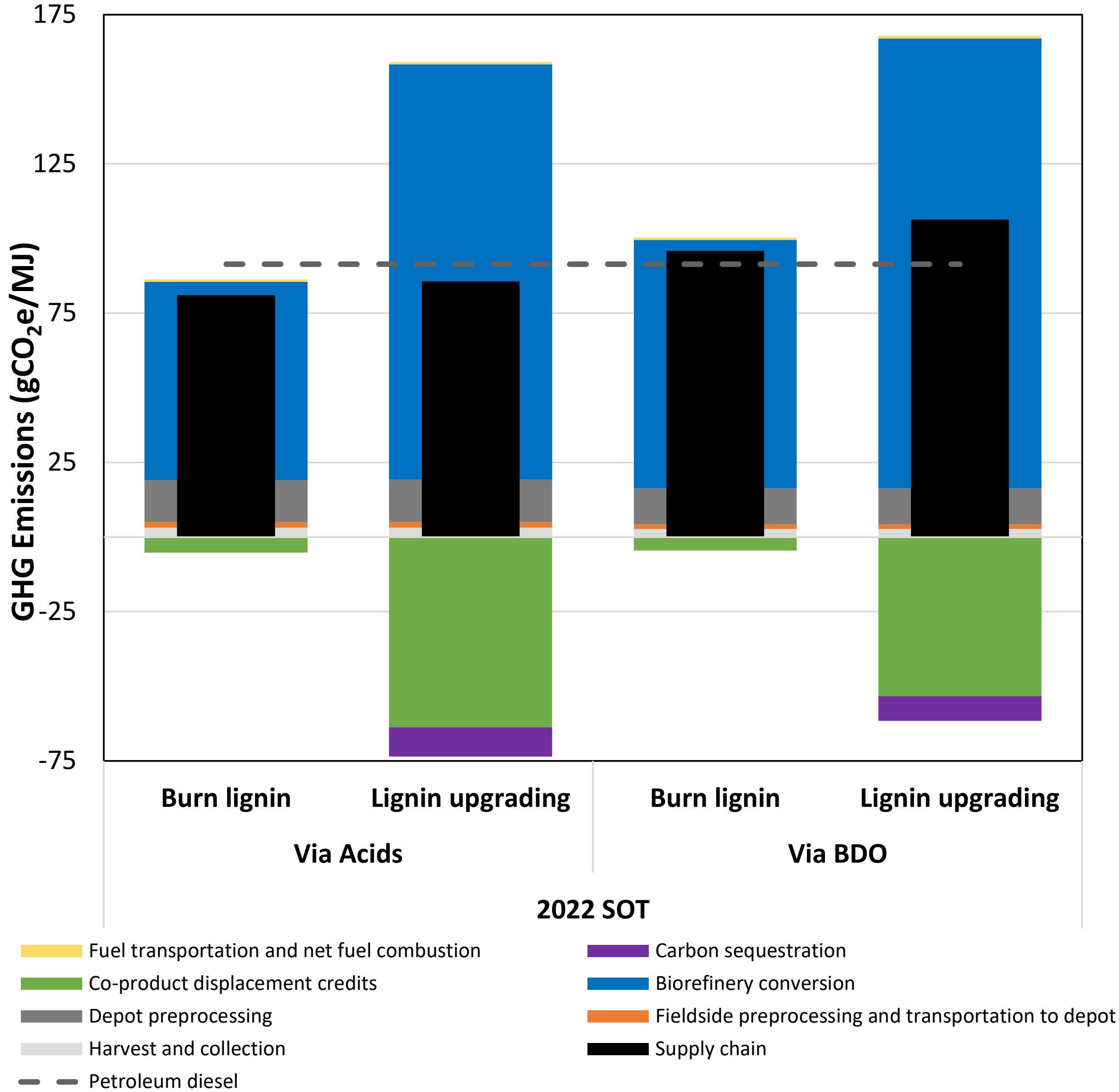
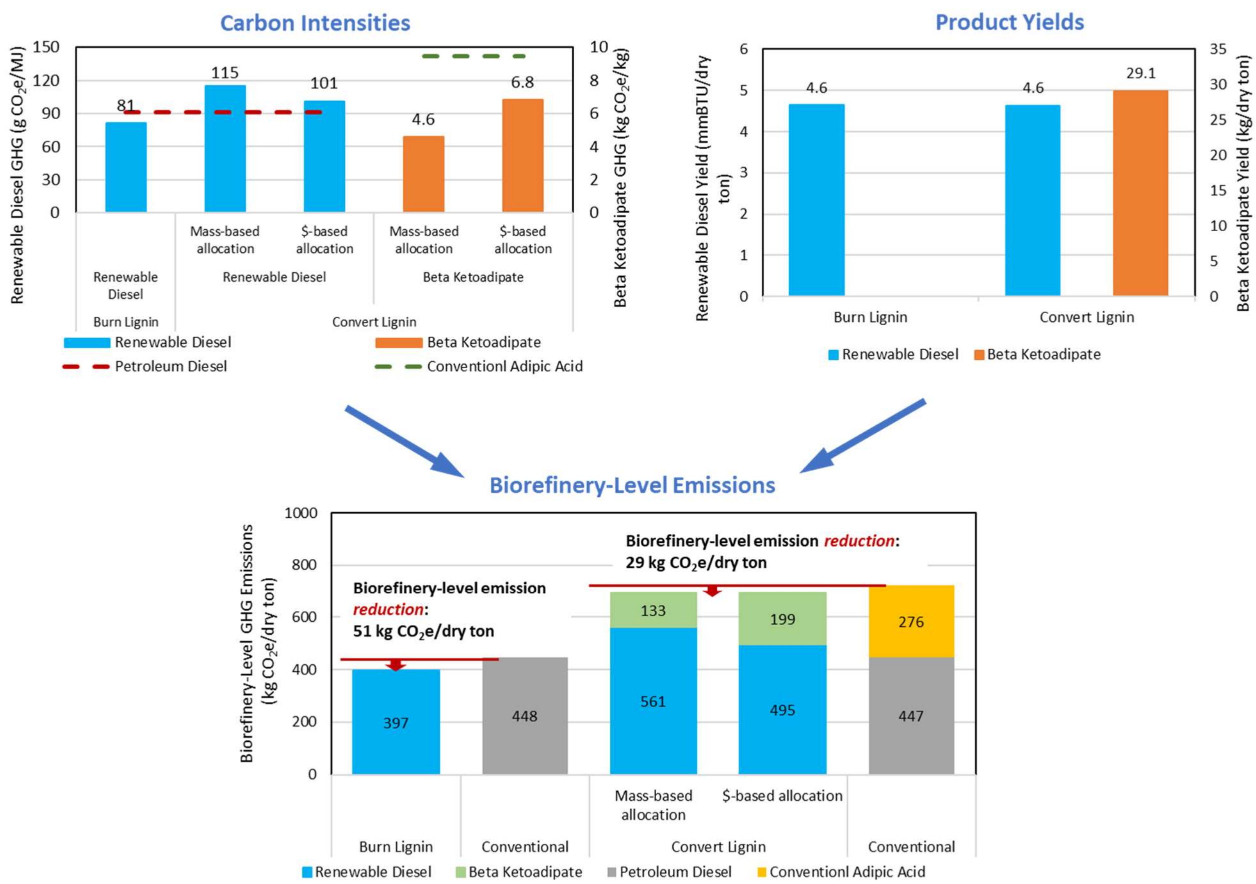


Figure 12 Supply Chain GHG Emissions of Renewable Diesel via Biochemical Conversion, Using the Displacement Method to Address Effects of BKA Co-Production

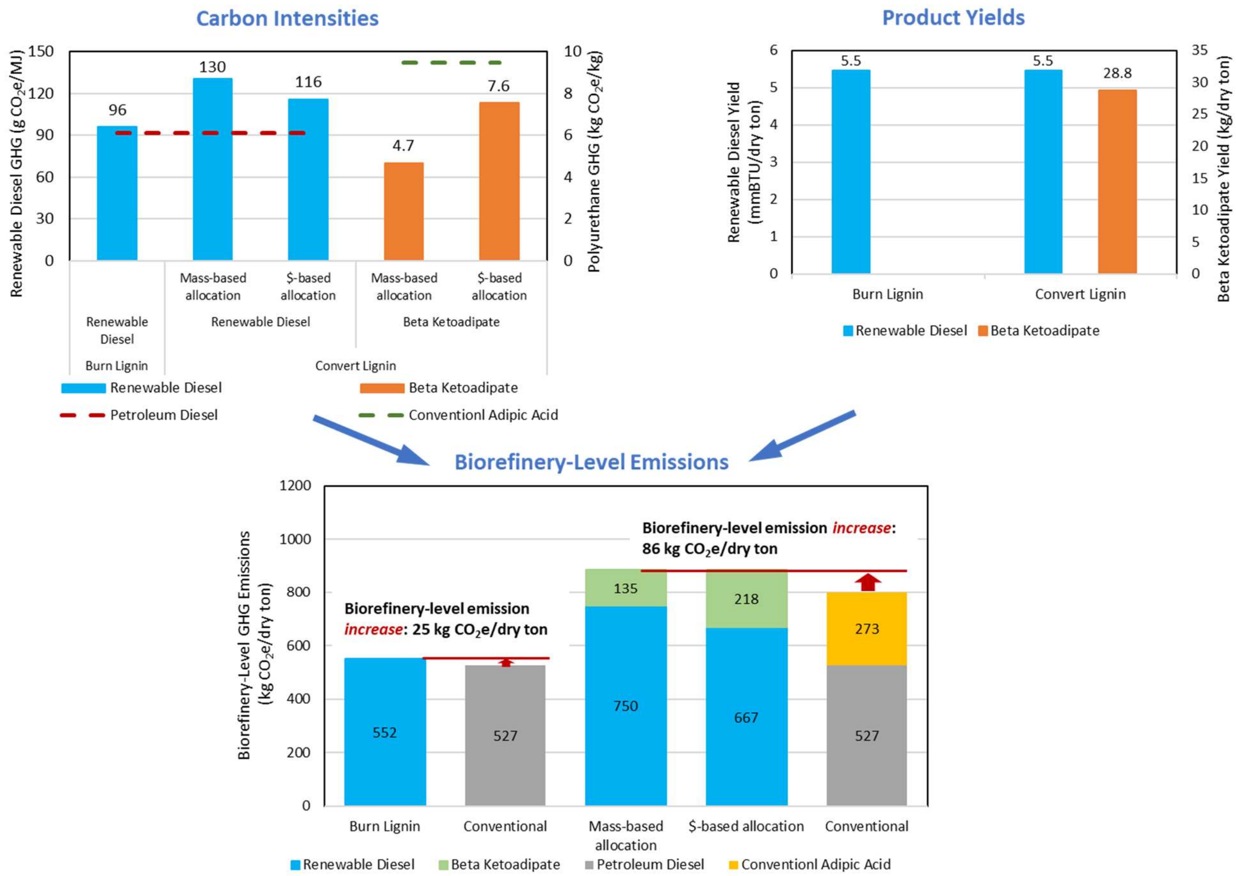
The biorefinery-level emissions of the biochemical conversion pathway vary among process designs, given variation in yields of the fuels and BKA co-product and in total biorefinery emissions. The burning lignin design in the 2022 SOT case achieved about a 51 kg CO_2e of GHG emission reduction per dry ton of herbaceous feedstock converted to renewable diesel with the via acids intermediate route, and caused a 25 kg CO_2e of GHG emission increase per dry ton of herbaceous feedstock converted to renewable diesel with the via BDO intermediate route.

When lignin is converted to the BKA co-product in the 2022 SOT case, we estimated a reduction in biorefinery-level GHG emissions by about 29 kg CO_2e per dry ton of the feedstock blend converted to fuels and BKA for the via acids intermediate route, and an increase in biorefinery-level GHG emissions by about 86 kg CO_2e per dry ton of the feedstock blend converted to fuels and BKA for the via BDO intermediate route (Figure 13).



(a) Via acids

Figure 13 Biorefinery-Level Greenhouse Gas Emissions and Reductions, for the 2022 SOT Case of the Biochemical Conversion Pathway for (a) Via Acids and (b) Via BDO Intermediate Routes



(b) Via BDO

Figure 13 (Cont.)

3.2.2 Supply Chain Water Consumption

Figure 14 shows that the 2022 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 12 – 15 gal/GGE and 6 – 7 gal/GGE for the acids and BDO routes, respectively, depending on the basis for allocation in the 2022 SOT case. When embedded water for process chemicals is also included, total water consumption at the biorefinery conversion step is 36 – 40 gal/GGE and 24 – 26 gal/GGE for the acids and BDO routes, respectively, depending on the basis for allocation. 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 15). When lignin is upgarded to BKA via acids, water consumption by the conversion process is 49 gal/GGE. When lignin is upgraded to BKA via BDO, water consumption by the conversion process is 31 gal/GGE.

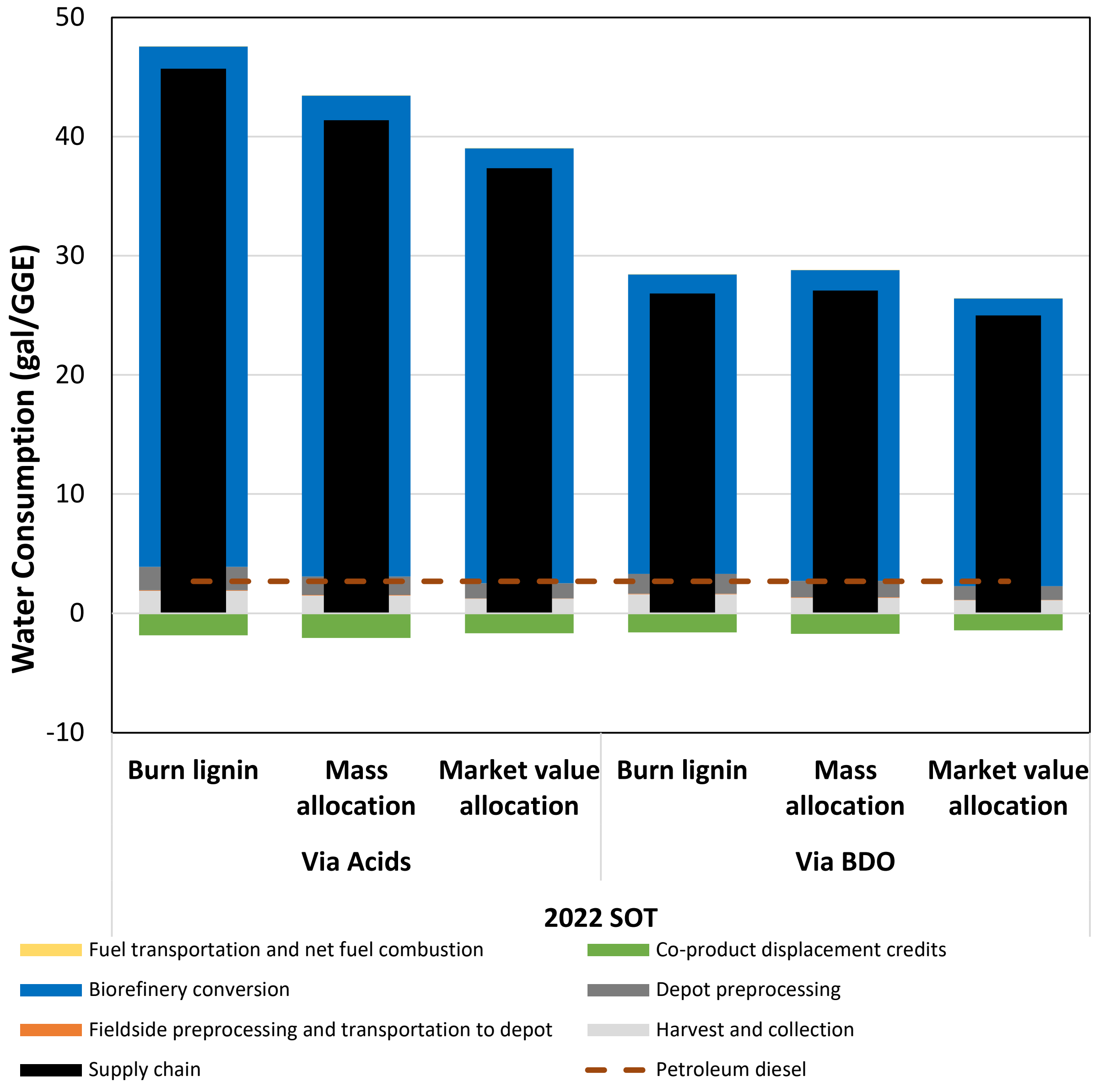


Figure 14 Supply Chain Water Consumption (gal/GGE) of Renewable Diesel via Biochemical Conversion, Using the Process-Level Allocation Method to Address Effects of BKA Co-Production, Compared to 2.7 gal/GGE for Petroleum Diesel

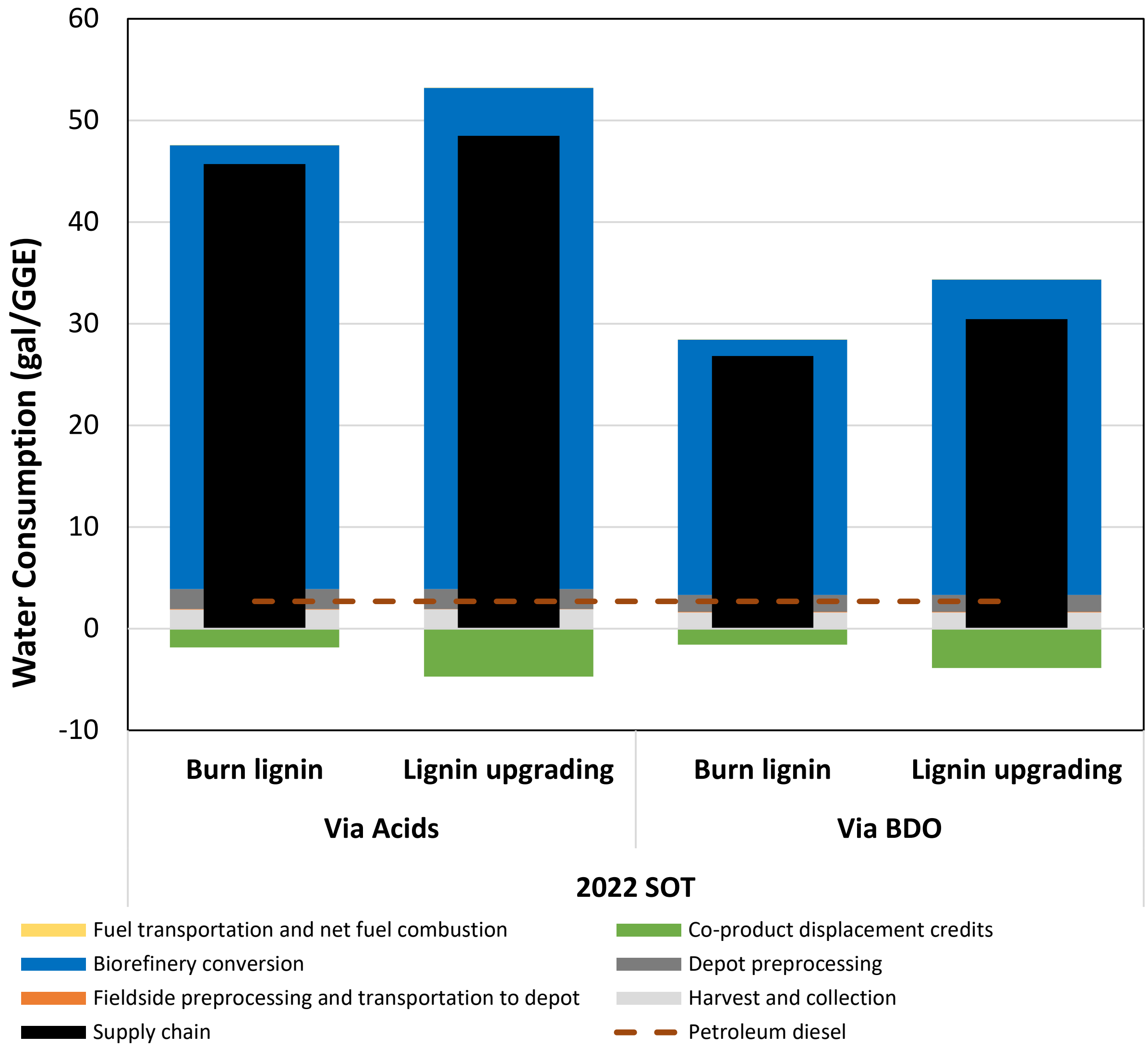


Figure 15 Supply Chain Water Consumption (gal/GGE) of Renewable Diesel via Biochemical Conversion, Using the Displacement Method to Address Effects of BKA Co-Production

The direct water consumption during the conversion process decreases from 19.7 gal/GGE in the 2021 SOT case to 18.3 gal/GGE in the 2022 SOT case for the via acids pathway, which is a 7% decrease in direct water consumption, and decreases from 10.1 gal/GGE in the 2021 SOT case to 8.9 gal/GGE in the 2022 SOT case for the via BDO pathway, which is a 12% decrease in direct water consumption.

We summarized the biorefinery-level results for water consumption in Table 12 for the biochemical conversion pathway.

3.2.3 Supply Chain NO_x Emissions

Under the process-level allocation method, Figure 16 shows that total NO_x emissions are higher than those of petroleum diesel in the 2022 SOT 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.

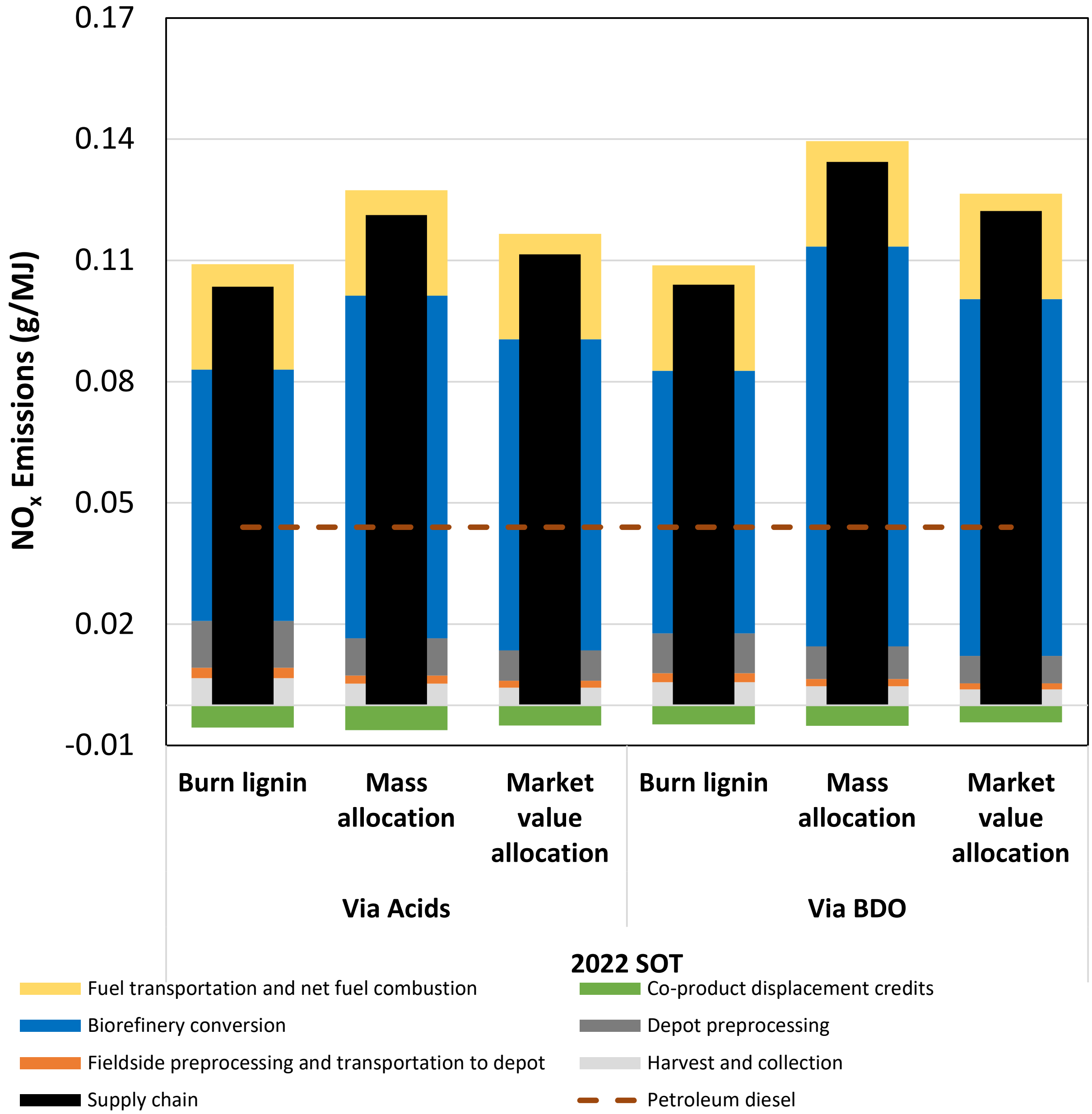


Figure 16 Supply Chain NO_x Emissions (g/MJ) of Renewable Diesel via Biochemical Conversion Using the Process-Level Allocation Method, Relative to 0.04 g/MJ for Petroleum Diesel

Under the displacement method, in the 2022 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 BKA (Figure 17).

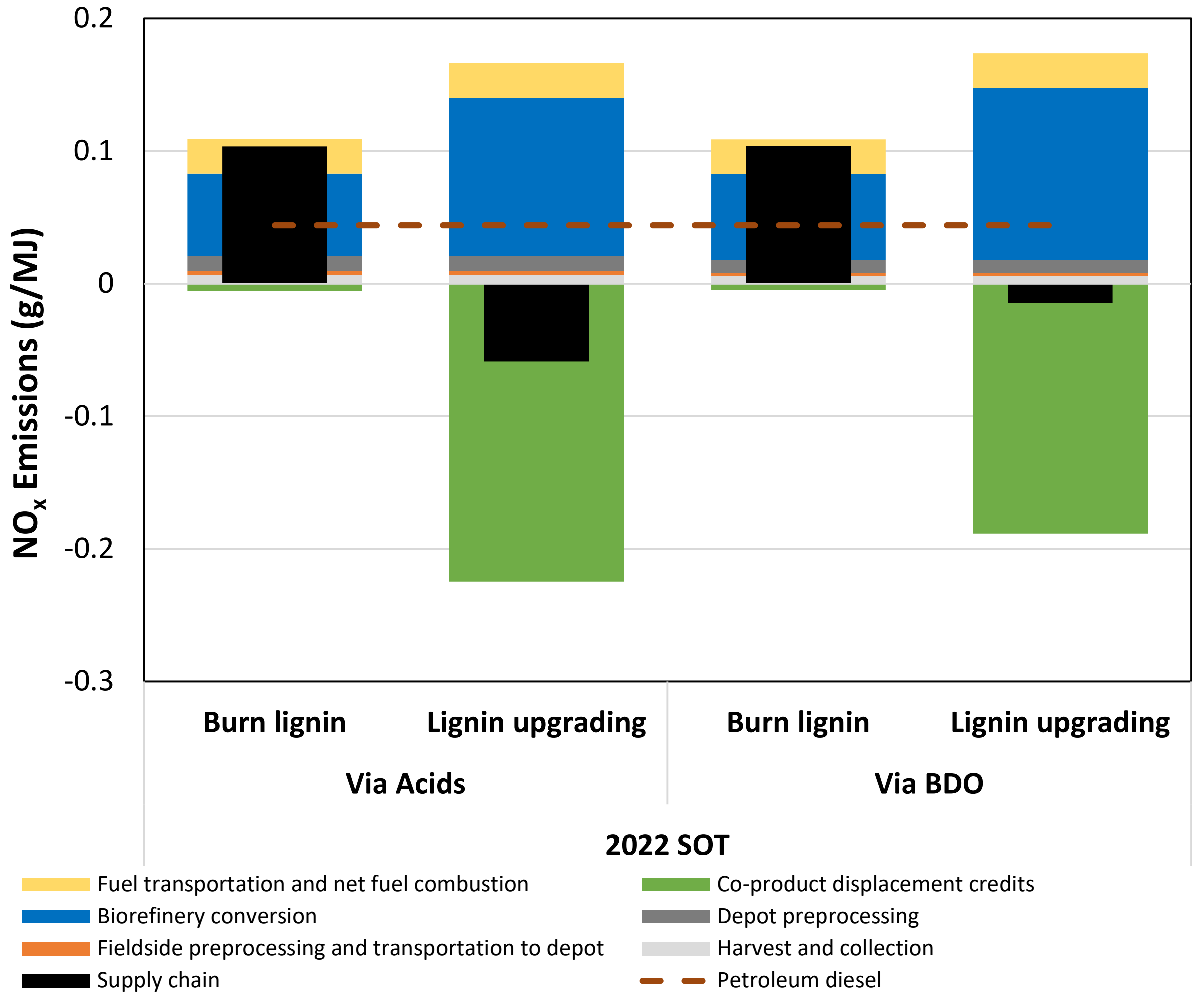


Figure 17 Supply Chain NOx Emissions (g/MJ) of Renewable Diesel via Biochemical Conversion, Using the Displacement Method to Address Effects of BKA

3.2.4 Summary of Sustainability Metrics

Table 9 summarizes 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 BKA 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.

Table 9 Supply Chain Sustainability Metrics for Renewable Diesel via Biochemical Pathway, 2022 SOT Case

	Scenario 1: Via Acids			Scenario 2: Via BDO			
		Lignin upgrading to beta ketoadipate			Lignin upgrading to beta ketoadipate		
	Burning lignin	Mass-based allocation	Market-value-based allocation	Burning lignin	Mass-based allocation	Market-value-based allocation	Petroleum Diesel
Biofuel yield							
mmBtu/dry ton	4.6	5.8	7.2	5.5	6.7	8.0	
Co-product yield							
Sodium sulfate, Kg/mmBtu of biofuel	29.2	32.4	26.5	25.2	27.0	22.6	
Fossil energy consumption							
MJ/MJ	1.0	1.4	1.2	1.0	1.5	1.3	1.2
Net energy balance							
MJ/MJ	0.0	-0.4	-0.2	0.0	-0.5	-0.3	
GHG emissions[a]							
g CO_2e/MJ	81 (-11%)	115 (26%)	101 (11%)	96 (5%)	130 (42%)	116 (27%)	91
g CO_2e/ GGE	9,929	14,053	12,399	11,734	15,954	14,191	11,197
Water consumption							
L/MJ	1.4	1.3	1.2	0.8	0.8	0.8	0.1
gal/GGE	45.7	41.4	37.3	26.8	27.1	25.0	2.7
Total NO_x emissions							
g NO_x/MJ	0.10	0.12	0.11	0.10	0.13	0.12	0.04
g NO_x/GGE	12.7	14.8	13.7	12.7	16.5	15.0	5.4
Urban NO_x emissions							
g NO_x/MJ	0.03	0.03	0.03	0.03	0.03	0.03	0.02
g NO_x/GGE	3.2	4.0	3.8	3.5	3.7	3.6	2.6

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

Tables 10 summarizes the supply chain sustainability metrics of BKA, which displaces conventional AA that are mainly used to produce nylon, produced from the acid and BDO pathways in 2022 SOT case under the purpose-driven, process-level allocation method. Under this method, lignin-derived BKA could achieve reductions in GHG emissions by about 51% – 52% (mass-based allocation) and 20% – 28% (market value-based allocation), relative to conventional natural gas (NG)-based AA in the 2022 SOT case.

Table 10 Supply Chain Sustainability Metrics for Beta Ketoadipate via Biochemical Pathway, 2022 SOT Case

	Scenario 1: Via Acids		Scenario 2: Via BDO		
	Mass-based allocation	Market-value-based allocation	Mass-based allocation	Market-value-based allocation	Conventional AA
			BKA yield		
ton/dry ton	0.15	0.091	0.18	0.10	
			Fossil energy consumption		
MJ/kg	80.2	108.0	85.7	124.8	103.4
			GHG emissions[a]		
g CO_2e/kg	4,576 (-52%)	6,845 (-28%)	4,681 (-51%)	7,562 (-20%)	9,475
			Water consumption		
L/kg	48.0	69.0	32.0	44.9	11.1
			Total NO_x emissions		
g NO_x/kg	6.2	7.9	6.6	9.0	36.5

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

Table 11 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 11 Supply Chain Sustainability Metrics for Renewable Diesel via Biochemical Pathway in the 2022 SOT Case, Using the Displacement Method

	Scenario 1: Via Acids		Scenario 2: Via BDO		
	Burning lignin	Lignin upgrading to BKA	Burning lignin	Lignin upgrading to BKA	Petroleum Diesel
			Biofuel yield		
mmBtu/dry ton	4.6	4.6	5.5	5.5	
			Co-product yield		
BKA, kg/mmBtu of biofuel	0	6.3	0	5.3	
Sodium sulfate, kg/mmBtu of biofuel	29.2	40.9	25.2	33.0	
			Fossil energy consumption		
MJ/MJ	1.0	1.3	1.0	1.5	1.2
			Net energy balance		
MJ/MJ	0.0	-0.3	0.0	-0.5	
			GHG emissions		
g CO_2e/MJ	81 (-11%)	86 (-6%)	96 (5%)	106 (16%)	91
g CO_2e/ GGE	9,929	10,482	11,734	13,019	11,197
			Water consumption		
L/MJ	1.4	1.5	0.8	0.9	0.1
gal/GGE	45.7	48.5	26.8	30.5	2.7
			Total NO_x emissions		
g NO_x/MJ	0.10	-0.06	0.10	-0.01	0.04
g NO_x/GGE	12.7	-7.2	12.7	-1.8	5.4
			Urban NO_x emissions		
g NO_x/MJ	0.03	0.04	0.03	0.03	0.02
g NO_x/GGE	3.2	4.3	3.5	3.9	2.6

Tables 12 summarizes 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 BKA co-product, the total displacement credit from RD, the total displacement credit from lignin-derived BKA, and the net, combined impacts from both RD and BKA.

Table 12 Biorefinery-Level Sustainability Metrics of the Biochemical Pathway, 2022 SOT Case

	Scenario 1: Via Acids			Scenario 2: Via BDO			
		Lignin upgrading to BKA			Lignin upgrading to BKA		
	Burn lignin	Mass-based allocation	Market-value-based allocation	Burn lignin	Mass-based allocation	Market-value-based allocation	
Products							
Renewable diesel	4.6	4.6		5.5	5.5		mmBtu/dry ton biomass
BKA	-	0.03		-	0.03		ton/dry ton biomass
Fossil energy consumption							
Direct consumption by RD production	4,725	6,888	6,079	5,685	8,901	7,775	MJ/dry ton biomass
Credits from RD production	-5,783	-5,772	-5,772	-6,797	-6,798	-6,798	MJ/dry ton biomass
Net consumption by RD production	*-1,057*	*1,116 (253%)*	*307 (70%)*	*-1,112*	*2,102 (132%)*	*976 (61%)*	MJ/dry ton biomass
Direct consumption by BKA production	-	2,334	3,142	-	2,468	3,594	MJ/dry ton biomass
Credits from BKA production	-	-3,008	-3,008	-	-2,976	-2,976	MJ/dry ton biomass
Net consumption by BKA production	-	*-674 (-153%)*	*134 (30%)*	-	*-508 (-32%)*	*618 (39%)*	MJ/dry ton biomass
Net total consumption	-1,057	442		-1,112	1,594		MJ/dry ton biomass
GHG emissions							
Direct emissions from RD production	397	561	495	552	750	667	kg/dry ton biomass
Credits from RD production	-448	-447	-447	-527	-527	-527	kg/dry ton biomass
Net emissions from RD production	*-51*	*114 (-399%)*	*48 (-168%)*	*25*	*224 (261%)*	*141 (164%)*	kg/dry ton biomass
Direct emissions from BKA production	-	133	199	-	135	218	kg/dry ton biomass
Credits from BKA production	-	-276	-276	-	-273	-273	kg/dry ton biomass

Table 12 (Cont.)

	Scenario 1: Via Acids			Scenario 2: Via BDO			
		Lignin upgrading to BKA			Lignin upgrading to BKA		
	Burn lignin	Mass-based allocation	Market-value-based allocation	Burn lignin	Mass-based allocation	Market-value-based allocation	
Net emissions from BKA production	-	*-143 (499%)*	*-77 (268%)*	-	*-138 (-161%)*	*-55 (-64%)*	kg/dry ton biomass
Net total emissions	-51	-29		25	86		kg/dry ton biomass
Water consumption							
Direct consumption by RD production	1,828	1,652	1,491	1,262	1,273	1,175	gal/dry ton biomass
Credits from RD production	-108	-107	-107	-127	-127	-127	gal/dry ton biomass
Net consumption by RD production	*1,720*	*1,545 (84%)*	*1,383 (76%)*	*1,135*	*1,147 (88%)*	*1,048 (80%)*	gal/dry ton biomass
Direct consumption by BKA production	-	369	531	-	243	342	gal/dry ton biomass
Credits from BKA production	-	-85	-85	-	-84	-84	gal/dry ton biomass
Net consumption by BKA production	-	*284 (16%)*	*445 (24%)*	-	*159 (12%)*	*257 (20%)*	gal/dry ton biomass
Net total consumption	1,720	1,829		1,135	1,306		gal/dry ton biomass
Total NO_x emissions							
Direct emissions from RD production	507	593	545	599	774	704	g/dry ton biomass
Credits from RD production	-216	-215	-215	-254	-254	-254	g/dry ton biomass
Net emissions from RD production	*291*	*377 (-75%)*	*330 (-66%)*	*345*	*520 (-153%)*	*450 (-133%)*	g/dry ton biomass
Direct emissions from BKA production	-	182	229	-	190	260	g/dry ton biomass
Credits from BKA production	-	-1,061	-1,061	-	-1,050	-1,050	g/dry ton biomass
Net emissions from BKA production	-	*-879 (175%)*	*-832 (166%)*	-	*-859 (253%)*	*-789 (233%)*	g/dry ton biomass
Net total emissions	291	-502		345	-339		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.

3.3 Algae Hydrothermal Liquefaction

The SCSA of the algae with woody biomass supplement HTL pathway incorporated algae biomass cultivation with minimally lined ponds using saline algae strains in the 2022 SOT case, the woody biomass feedstock inputs from the 2020 SOT, and the 2022 SOT case.

3.3.1 Supply Chain Greenhouse Gas Emissions

Figure 18 shows the supply chain GHG emissions and their key contributing supply chain processes, in g CO_2e/MJ, of RD in the 2022 compared to a life-cycle carbon intensity of 91 g CO_2e/MJ for petroleum diesel. RD reduces GHG emissions by 51%. 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 30.4 g CO_2e/MJ, of which hydrogen production via steam methane reforming of natural gas is responsible for about 15.9 g CO_2e/MJ. Algae growth contribute 21.9 g CO_2e/MJ. Delivery of CO_2 for algae growth contribute 6.5 g CO_2e/MJ after accounting for the CO_2 recycled from the HTL biorefinery.

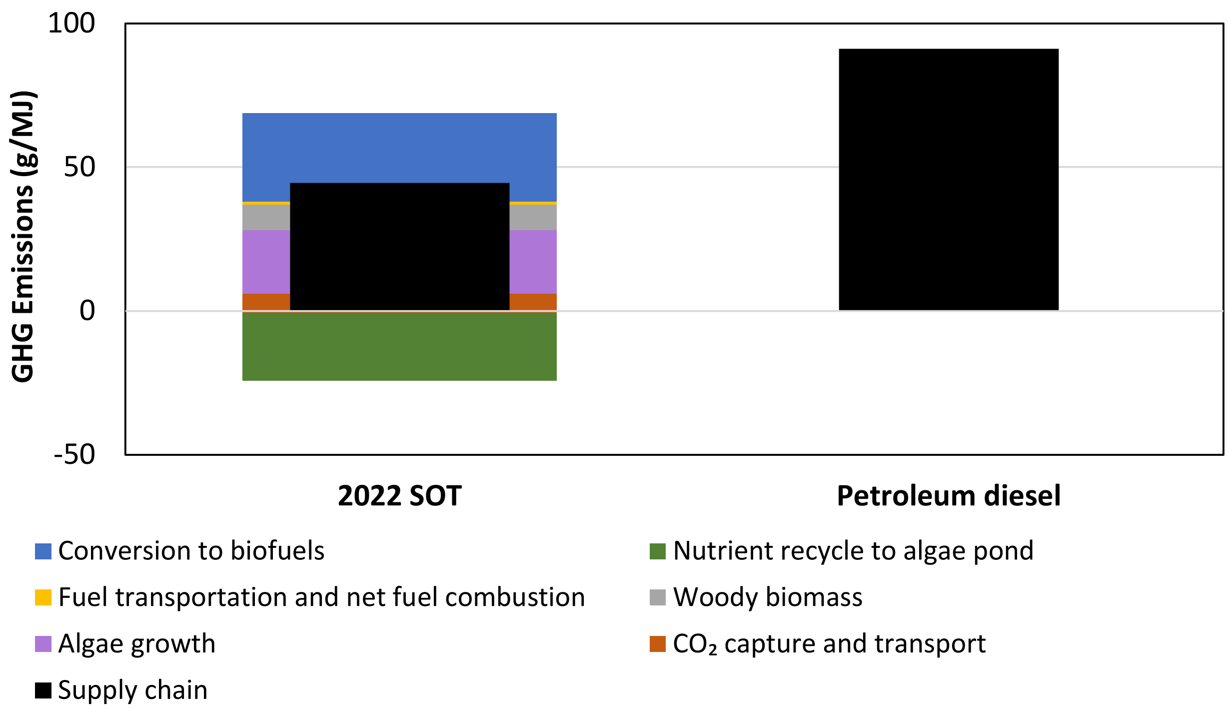


Figure 18 Supply Chain GHG Emissions (g CO_2e/MJ) of Renewable Diesel via Algae HTL

A biorefinery-level GHG emission reduction could be expected for the WWTP algae HTL pathway (Figure 19). An emission reduction of about 465 kg CO_2e per dry ton of algae/wood blend feedstock converted to fuels can be achieved in the 2022 SOT case.

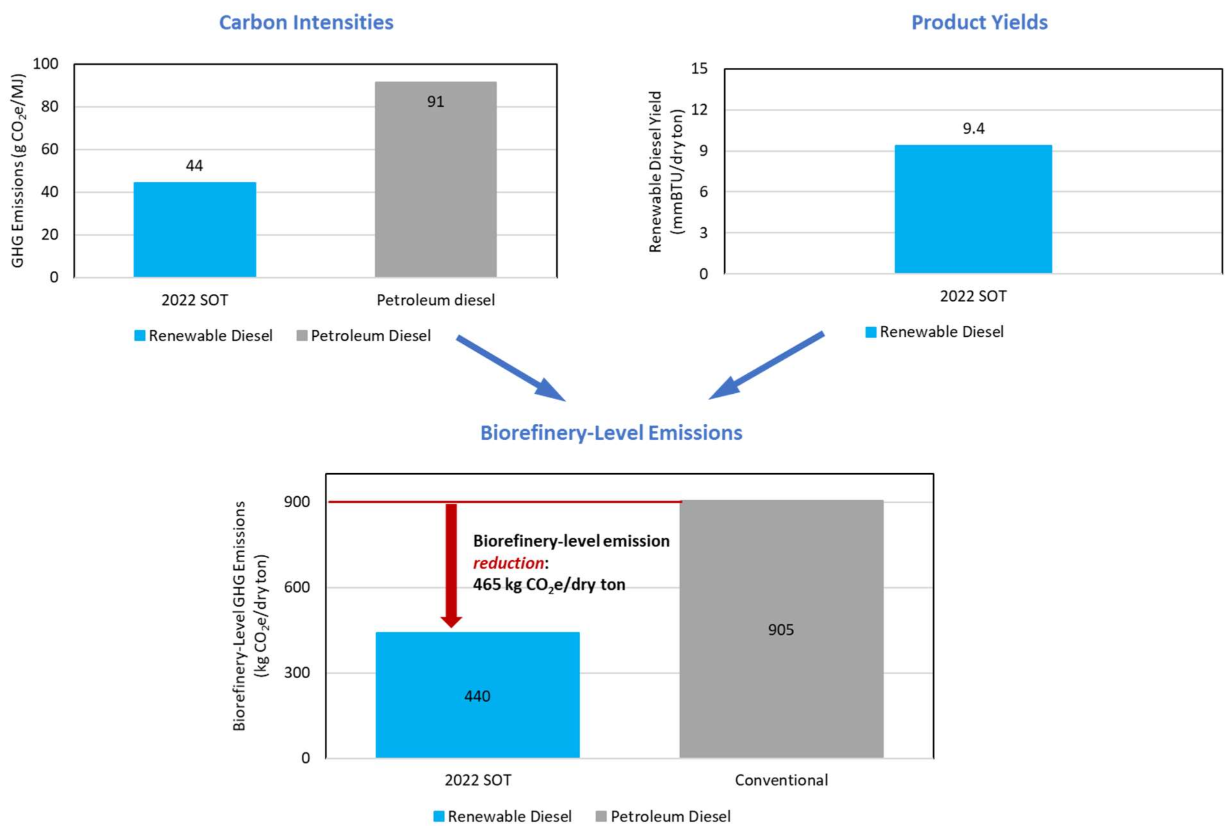


Figure 19 Biorefinery-Level Greenhouse Gas Emissions and Reductions, the 2022 SOT Case of the Algae HTL Pathway

3.3.2 Supply Chain Water Consumption

In the 2022 SOT case, water consumption associated with natural gas consumption for and process heating and hydrogen production and with chemical and catalyst use during the HTL processes is the major contributor to supply chain water consumption (Figure 20). Overall, the 2022 SOT case has 32% lower supply chain water consumption than petroleum diesel.

The direct water consumption during the conversion process decreases substantially from 7.5 gal/GGE in the 2021 SOT case to 1.7 gal/GGE due to the overhaul of the design of the conversion process, which is a 77% decrease in direct water consumption.

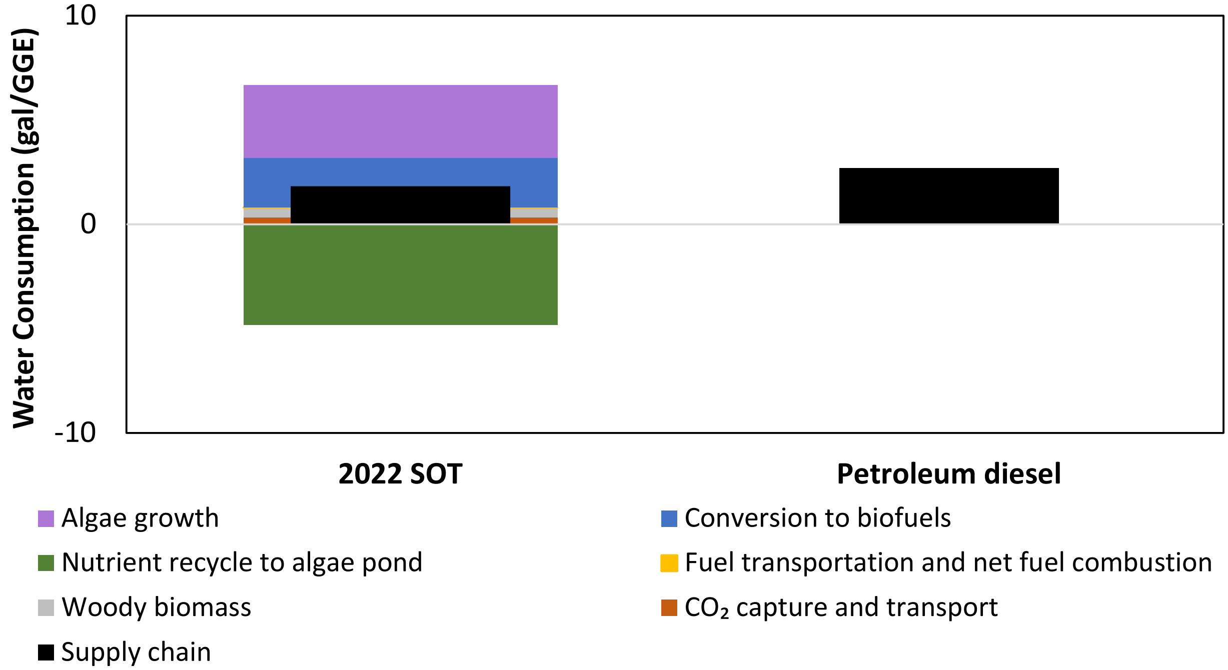


Figure 20 Supply Chain Water Consumption (gal/GGE) of Renewable Diesel via Algae HTL, Compared to 2.7 gal/GGE for Petroleum Diesel

3.3.3 Supply Chain NO_x Emissions

The total NO_x emissions are about 106% higher than those of petroleum diesel in the 2022 SOT (Figure 21). Preprocess of the woody biomass is the largest contributor to the NO_x emissions due to its high natural gas usage, followed by fuel combustion and biomass conversion to biofuels via HTL.

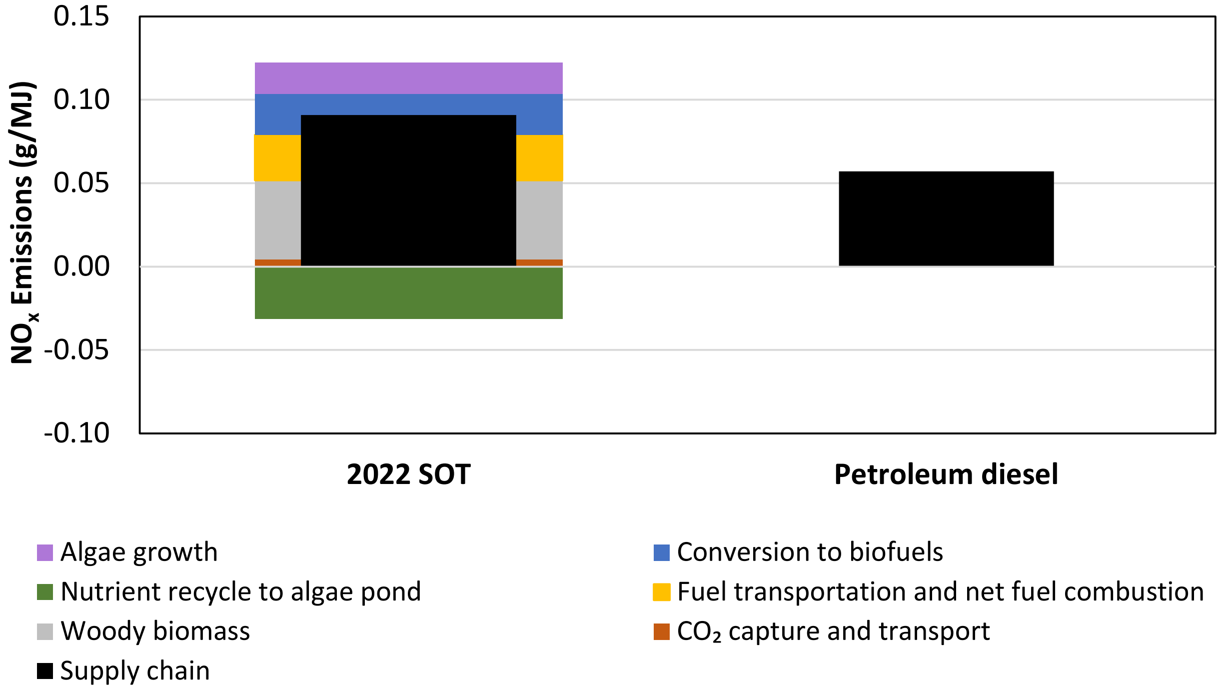


Figure 21 Supply Chain NO_x Emissions (g/MJ) of Renewable Diesel via Algae HTL, Compared to 0.04 g/MJ for Petroleum Diesel

3.3.4 Summary of Sustainability Metrics

Table 13 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 HTL pathway.

Table 13 Supply Chain Sustainability Metrics for Renewable Diesel via Algae/Woody HTLHTL Pathway in the 2022 SOT Case

	2022 SOT		Petroleum Diesel
		Biofuel yield	
mmBtu/dry ton	9.4		
		Fossil energy consumption	
MJ/MJ	0.6		1.2
		Net energy balance	
MJ/MJ	0.4		
		GHG emissions	
g CO_2e/MJ	44 (-51%)		91
g CO_2e/ GGE	5,443		11,197
		Water consumption	
L/MJ	0.06		0.08
gal/GGE	1.8		2.7
		Total NO_x emissions	
g NO_x/MJ	0.09		0.04
g NO_x/GGE	11.1		5.4
		Urban NO_x emissions	
g NO_x/MJ	0.02		0.02
g NO_x/GGE	3.0		2.6

3.4 Combined Algae Processing

The SCSA of the CAP pathway incorporates the 2022 SOT case for algae biomass cultivation with minimally lined ponds using saline algae strains as well as the 2022 SOT case for CAP conversion for both the acids and BDO pathway designs. The purpose-driven, process-level allocation method and the displacement method are applied to address the effect of the PU co-product.

3.4.1 Supply Chain Greenhouse Gas Emissions

Figure 22 shows the supply chain GHG emissions and their key contributing supply chain processes, in g CO_2e/MJ, of RD in the 2022 SOT case, using the mass- and market value-based, process-level allocation method, relative to a life-cycle carbon intensity of 91 g CO_2e/MJ for petroleum diesel. GHG emissions of RD in the 2022 SOT cases are about 35% and 23% 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 suggests reductions in GHG emissions by 63% and 51%, respectively, for the acids and BDO pathways, relative to petroleum diesel.

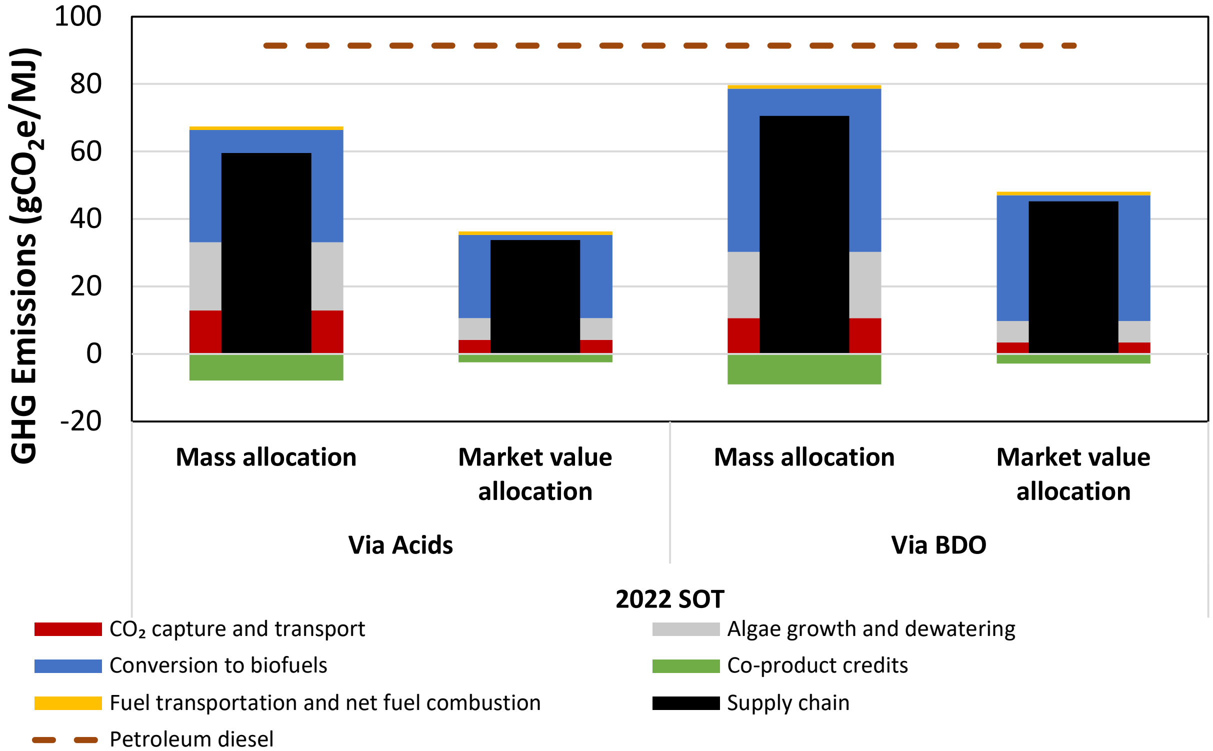


Figure 22 Supply Chain GHG Emissions of Renewable Diesel via CAP Using the Process-Level Allocation Method, Compared to 91 g CO_2e/MJ for Petroleum Diesel

Manufacturing of chemicals and catalysts for use in the CAP conversion processes is the primary emission source in the 2022 SOT case. Energy consumption for algae growth and dewatering and for CO_2 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. The co-product credits shown in Figure 22 are from surplus electricity displacing U.S. average grid mix. The displacement method is used for surplus electricity because it accounts for only 13% – 15% by energy relative to fuel in the 2022 SOT case, which is much smaller than 111% – 113% for PU by mass relative to fuel in the 2022 SOT case. 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/lb) is lower than that of PU ($2.04/lb) on a mass basis.

Under the displacement method, all chemical use and associated emissions are attributed to the hydrocarbon fuels. Meanwhile, the hydrocarbon 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 2022 SOT case because of a significant PU yield, generating more than -80 g CO_2e/MJ displacement credits by displacing conventional PU (-82 – -84 g CO_2e/MJ) and biogenic carbon sequestration (-45 – -46 g CO_2e/MJ). In addition to the credits from algae-derived PU displacing conversion PU, the co-product credits shown in Figure 23 also include the credits from surplus electricity displacing U.S. average grid mix. The BDO pathway has higher GHG emissions than the acids pathway because it consumes more hydrogen and natural gas in the conversion process.

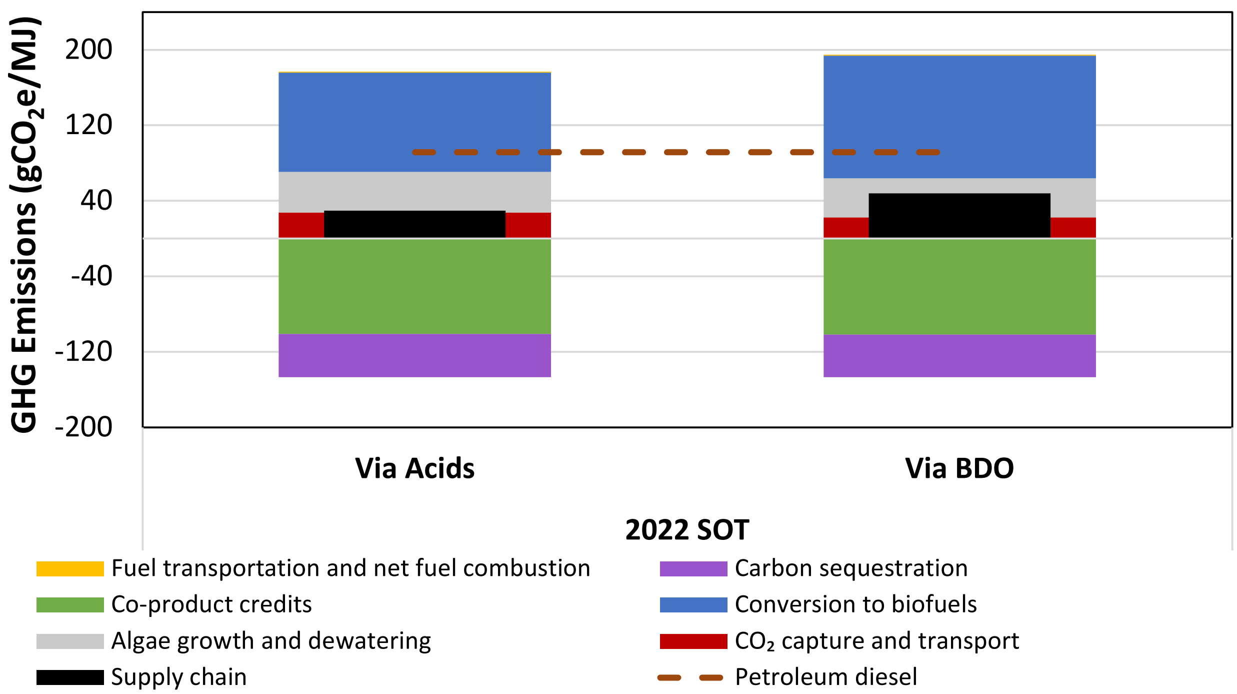
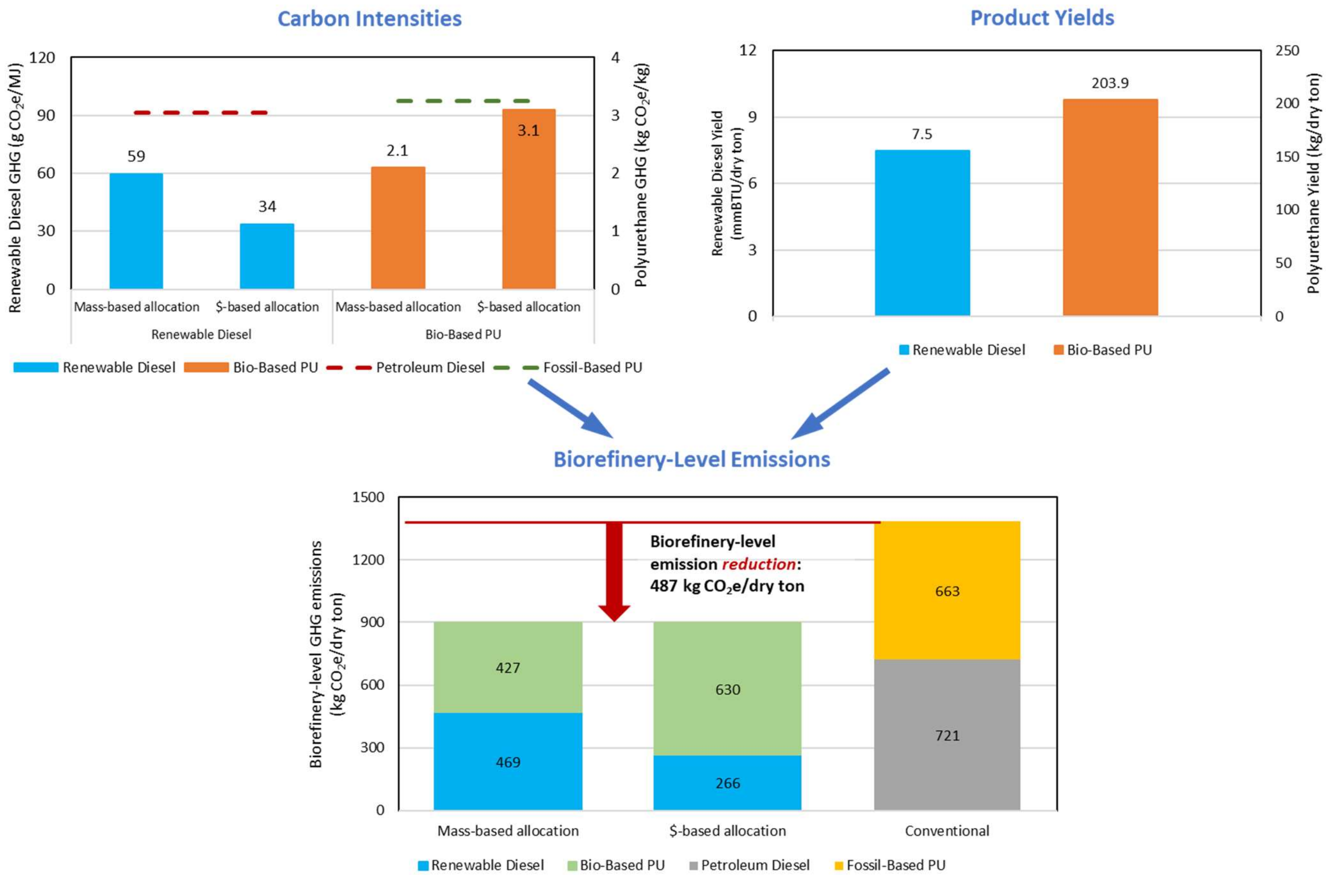


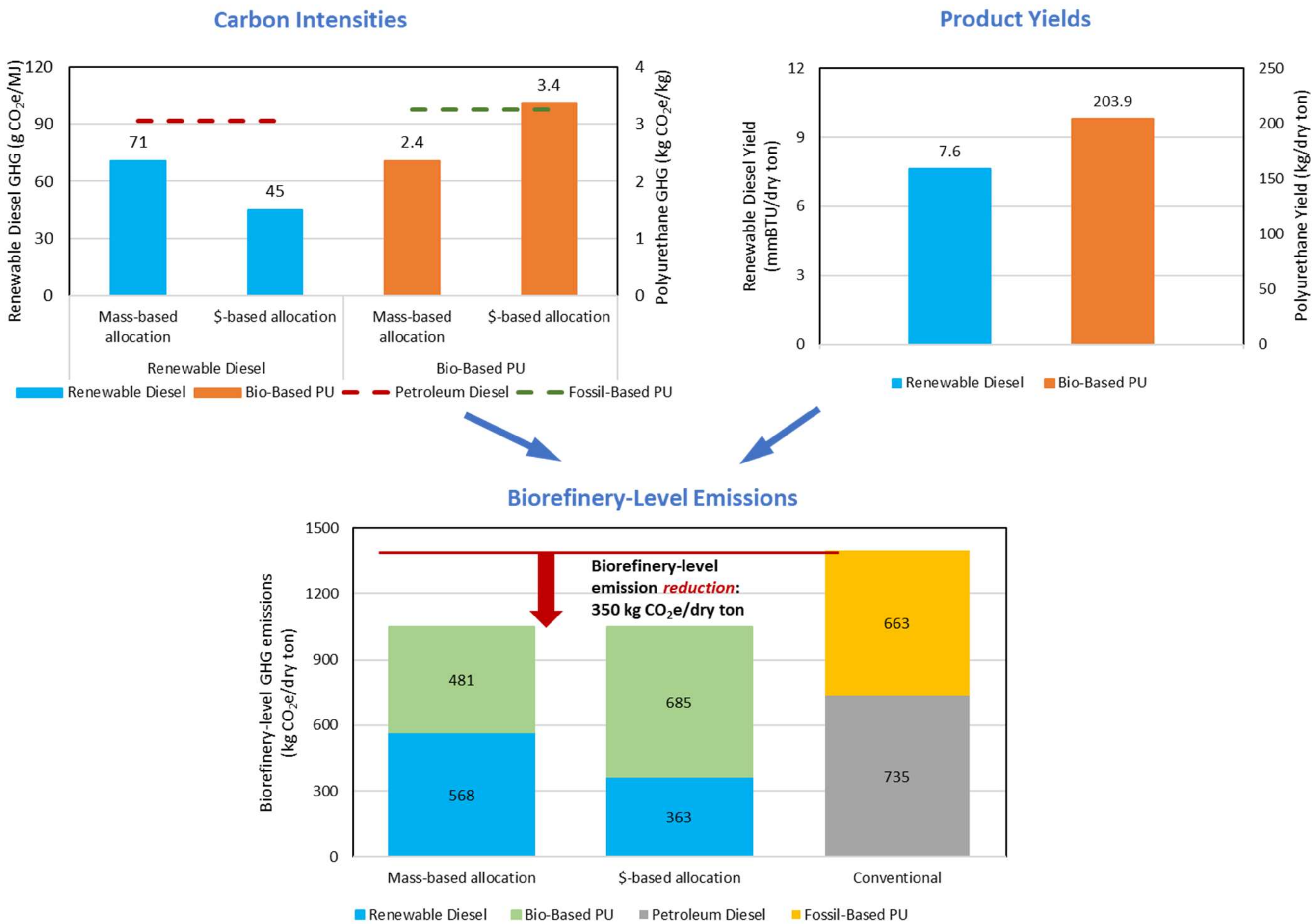
Figure 23 Supply Chain GHG Emissions of Renewable Diesel via CAP, Using the Displacement Method to Address Effects of PU Co-Production

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 is about 487 kg CO_2e per dry ton of algae converted to fuels and PU, as shown in Figure 24. This is slightly worse than the GHG reduction of 505 kg CO_2e per dry ton of algae in the 2021 SOT case (Cai et al. 2022), mainly due to the update of the upstream emissions associated with NG, electricity, and chemicals in GREET 2022. No improvement is made for the via acids intermediate route in the 2022 SOT case in terms of biofuel yield at the biorefinery. With the via BDO intermediate route, the biorefinery-level emission reduction is about 350 kg CO_2e per dry ton of algae converted to fuels and PU, which is slightly better than the GHG reduction of 312 kg CO_2e per dry ton of algae in the 2021 SOT case (Cai et al. 2022). The improvement for the via BDO intermediate route is because the GHG reduction enabled by the increased biofuel yield at the biorefinery outweighs the GHG increase caused by the latest update of the GREET model.



(a) Via acids

Figure 24 Biorefinery-Level Greenhouse Gas Emissions and Reductions, for the 2021 SOT Case of the CAP Conversion Pathway for (a) Via Acids and (b) Via BDO Intermediate Routes



(b) Via BDO

Figure 24 (Cont.)

3.4.2 Supply Chain Water Consumption

Figure 25 shows that the 2022 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 9 – 13 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 – 27 gal/GGE and 13 – 17 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 higher because it uses more corn steep liquor, which is water intensive to make, than the BDO pathway. Water consumption associated with electricity usage 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 the CAP pathway.

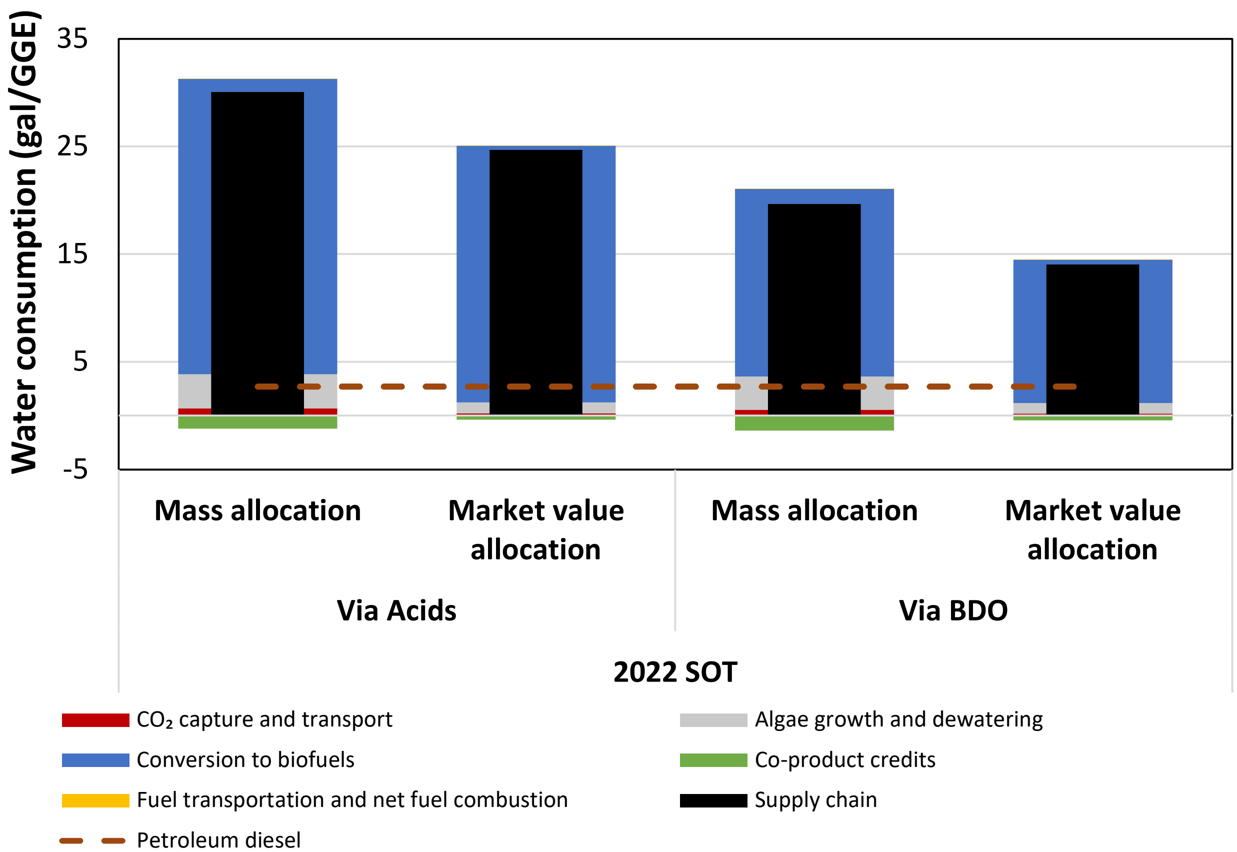


Figure 25 Supply Chain Water Consumption (gal/GGE) of Renewable Diesel via CAP Using the Process-Level Allocation Method, Compared to 2.7 gal/GGE for Petroleum Diesel

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 26). The PU co-product generates a displacement credit by displacing conventional fossil-based PU.

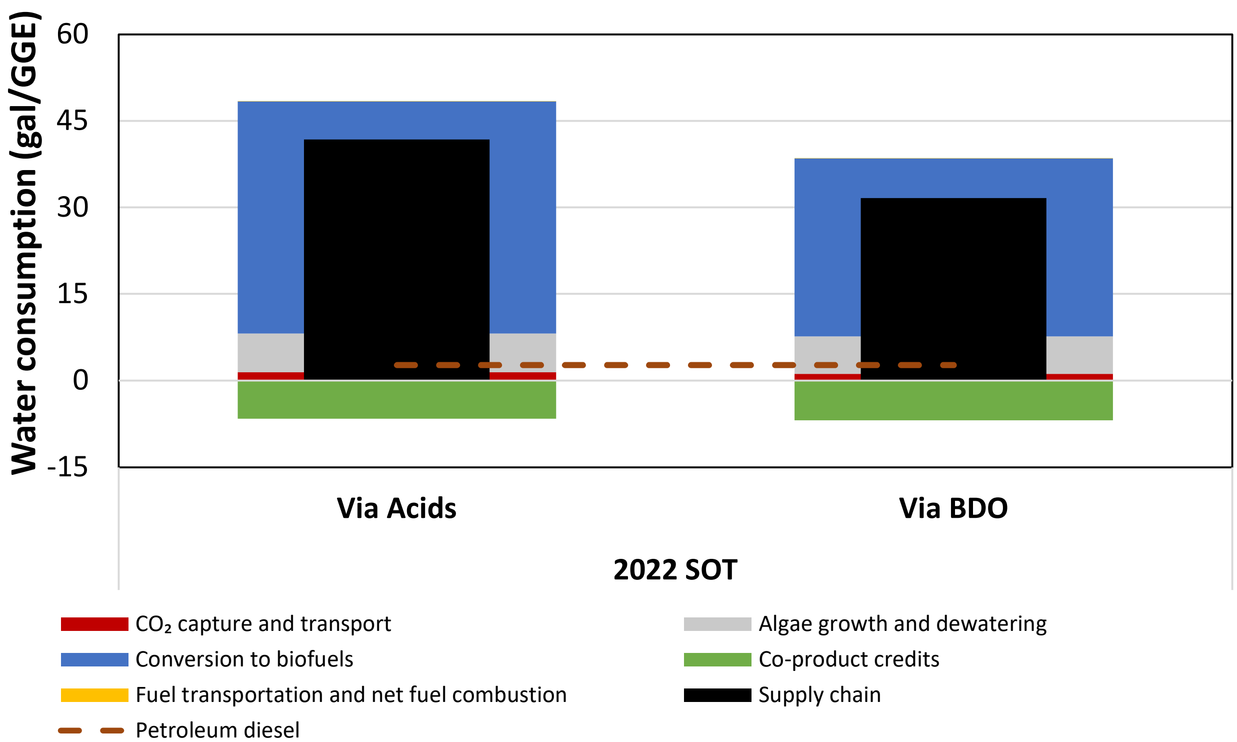


Figure 26 Supply Chain Water Consumption (gal/GGE) of Renewable Diesel via CAP Using the Displacement Method, Compared to 2.7 gal/GGE for Petroleum Diesel

The direct water consumption for the via acids pathway in the 2022 SOT case is 15.3 gal/GGE, which is the same as the 2021 SOT case. The direct water consumption of the via BDO pathway is 23.7 gal/GGE in the 2021 SOT case, which is slightly lower than the 24.6 gal/GGE in the 2021 SOT case.

3.4.3 Supply Chain NO_x Emissions

Total NO_x emissions from the 2022 SOT cases are 54% to 107% and 55% to 109% 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 27). It should be noted that the supply chain NO_x emissions from the 2022 SOT cases are comparable to the 2021 SOT cases, and the increase in the relative change to the petroleum is mainly attributed to the lower NO_x emissions from petroleum diesel in the latest GREET model due to an update of the NOx emission factor for fuel combustion by vehicles. Embedded emissions from manufacturing the process chemicals and catalysts required for the CAP conversion are the major emission source.

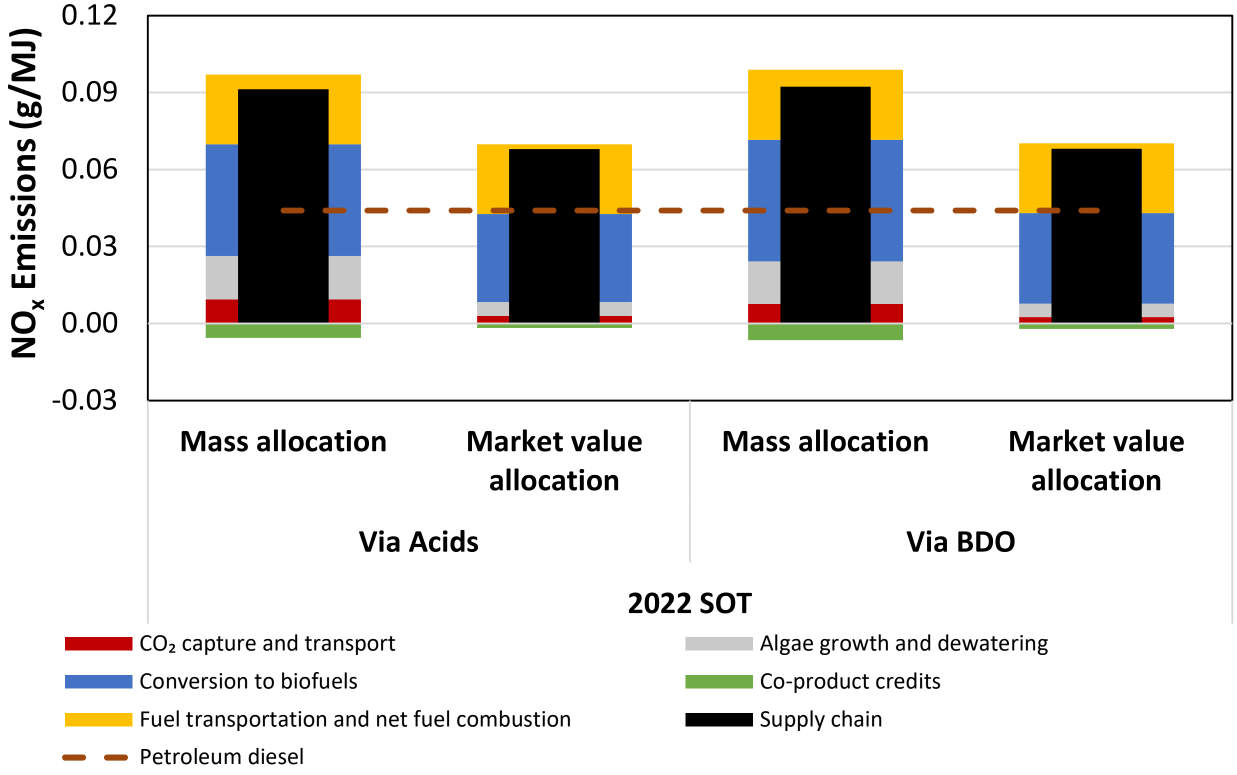


Figure 27 Supply Chain NO_x Emissions (g/MJ), Renewable Diesel via CAP Using the Process-Level Allocation Method, Compared to 0.04 g/MJ for Petroleum Diesel

Under the displacement method (Figure 28), 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 generate a significant NO_x displacement emission credit from avoiding emissions from production of conventional fossil-based PU.

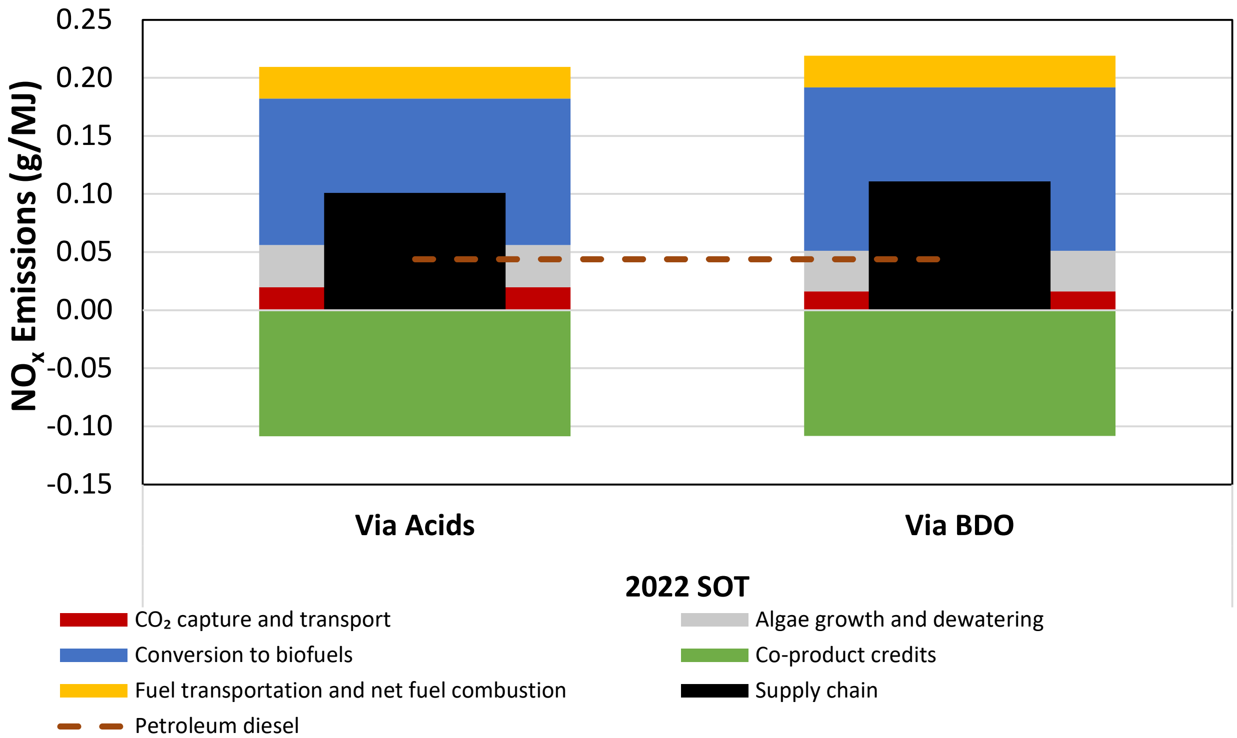


Figure 28 Supply Chain NO_x Emissions (g/MJ), Renewable Diesel via CAP Using the Displacement Method, Compared to 0.04 g/MJ for Petroleum Diesel

3.4.4 Summary of Sustainability Metrics

Table 14 summarizes 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 2022 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.

Table 14 Supply Chain Sustainability Metrics for Renewable Diesel via CAP, 2022 SOT Case

	Scenario 1: Via Acids		Scenario 2: Via BDO		
	Mass-based allocation	Market-value-based allocation	Mass-based allocation	Market-value-based allocation	Petroleum Diesel
			Biofuel yield		
mmBtu/dry ton	15.9	48.6	16.1	48.8	
			Co-product yield		
Power exported to grid, kWh/mmBtu of biofuel	18.0	5.9	20.6	6.8	
			Fossil energy consumption		
MJ/MJ	0.7	0.3	0.9	0.5	1.2
			Net energy balance		
MJ/MJ	0.3	0.7	0.1	0.5	
			GHG emissions		
g CO_2e/MJ	59 (-35%)	34 (-63%)	71 (-23%)	45 (-51%)	91
g CO_2e/ GGE	7,287	4,137	8,645	5,532	11,197
			Water consumption		
L/MJ	0.93	0.76	0.61	0.43	0.08
gal/GGE	30.0	24.7	19.6	14.0	2.7
			Total NO_x emissions		
g NO_x/MJ	0.09	0.07	0.09	0.07	0.04
g NO_x/GGE	11.2	8.3	11.3	8.3	5.4
			Urban NO_x emissions		
g NO_x/MJ	0.03	0.02	0.02	0.02	0.02
g NO_x/GGE	3.1	2.6	3.1	2.6	2.6

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

Table 15 summarizes the sustainability metrics for PU produced via CAP. In this analysis, we have updated our LCA results of conventional flexible foam PU (produced from toluene diisocyanate and polyether polyol) with detailed LCI of the PU production processes (Keoleian et al. 2012). When mass-based, process level allocation method is used, algae-based PU has 36% and 27% lower GHG emissions than conventional PU in the 2022 SOT case for the via acids and BDO pathway, respectively, because it contains biogenic carbon, which comes from algae and generates a biogenic carbon sequestration credit. Algae-based PU has comparable GHG emissions to conventional PU 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 15 Supply Chain Sustainability Metrics for PU via CAP, 2022 SOT Case

	Scenario 1: Via Acids		Scenario 2: Via BDO		
	Mass-based allocation	Market-value-based allocation	Mass-based allocation	Market-value-based allocation	Conventional PU
			PU yield		
ton/dry ton	0.42	0.27	0.43	0.27	
			Fossil energy consumption		
MJ/kg	55.8	69.3	60.7	74.8	70.2
			GHG emissions		
g CO_2e/kg	2,096 (-36%)	3,090 (-5%)	2,358 (-27%)	3,361 (3%)	3,252
			Water consumption		
L/kg	18.7	25.2	19.4	26.2	4.8
			Total NO_x emissions		
g NO_x/kg	4.1	5.0	4.5	5.4	3.7

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

Table 16 summarizes supply chain sustainability metrics, using the displacement method.

Table 16 Supply Chain Sustainability Metrics for Renewable Diesel via CAP Pathways in the 2021 SOT Case, Using the Displacement Method

	Scenario 1: Via Acids	Scenario 2: Via BDO	Petroleum Diesel
		Biofuel yield	
mmBtu/dry ton	7.5	7.6	
		Co-product yield	
Polyurethane, kg/mmBtu of biofuel	27.3	26.7	
Power exported to grid, kWh/mmBtu of biofuel	38.3	43.5	
		Fossil energy consumption	
MJ/MJ	0.3	0.6	1.2
		Net energy balance	
MJ/MJ	0.7	0.4	
		GHG emissions	
g CO_2e/MJ	30 (-68%)	48 (-48%)	91
g CO_2e/ GGE	3,625	5,871	11,197
		Water consumption	
L/MJ	1.29	0.98	0.08
gal/GGE	41.7	31.6	2.7
		Total NO_x emissions	
g NO_x/MJ	0.10	0.11	0.04
g NO_x/GGE	12.4	13.6	5.4
		Urban NO_x emissions	
g NO_x/MJ	0.03	0.03	0.02
g NO_x/GGE	3.6	3.5	2.6

Table 17 summarizes biorefinery-level sustainability metrics for the algae CAP pathway. In the 2022 SOT case, 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. Biorefinery NO_x emissions saw a slight increase relative to the conventional diesel and PU production.

Table 17 Biorefinery-Level Sustainability Metrics of Algae CAP, 2022 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	7.5		7.6		mmBtu/dry ton biomass
PU	0.2		0.2		ton/dry ton biomass
		Fossil energy consumption			
Direct consumption by RD production	5,332	2,581	7,017	4,150	MJ/dry ton biomass
Credits from RD production	-9,303	-9,303	-9,491	-9,491	MJ/dry ton biomass
Net consumption by RD production	*-3,971 (57%)*	*-6,722 (97%)*	*-2,474 (56%)*	*-5,341 (121%)*	MJ/dry ton biomass
Direct consumption by PU production	11,372	14,123	12,386	15,253	MJ/dry ton biomass
Credits from PU production	-14,318	-14,318	-14,318	-14,318	MJ/dry ton biomass
Net consumption by PU production	*-2,946 (43%)*	*-195 (3%)*	*-1,932 (44%)*	*934 (-21%)*	MJ/dry ton biomass
Net Total	-6,917		-4,406		MJ/dry ton biomass
		GHG emissions			
Direct emissions from RD production	469	266	568	363	kg/dry ton biomass
Credits from RD production	-721	-721	-735	-735	kg/dry ton biomass
Net emissions from RD production	*-252 (52%)*	*-454 (93%)*	*-168 (48%)*	*-372 (106%)*	kg/dry ton biomass
Direct emissions from PU production	427	630	481	685	kg/dry ton biomass
Credits from PU production	-663	-663	-663	-663	kg/dry ton biomass
Net emissions from PU production	*-236 (48%)*	*-33 (7%)*	*-182 (52%)*	*22 (-6%)*	kg/dry ton biomass
Net Total	-487		-350		
		Water consumption			
Direct consumption by RD production	1,934	1,588	1,289	921	gal/dry ton biomass
Credits from RD production	-173	-173	-177	-177	gal/dry ton biomass
Net consumption by RD production	*1,760 (70%)*	*1,415 (56%)*	*1,113 (59%)*	*744 (39%)*	gal/dry ton biomass
Direct consumption by PU production	1,010	1,355	1,044	1,412	gal/dry ton biomass
Credits from PU production	-256	-256	-256	-256	gal/dry ton biomass
Net consumption by PU production	*753 (30%)*	*1,099 (44%)*	*787 (41%)*	*1,156 (61%)*	gal/dry ton biomass
Net Total	2,514		1,900		gal/dry ton biomass
		Total NO_x emissions			
Direct emissions from RD production	720	536	742	548	g/dry ton biomass
Credits from RD production	-347	-347	-354	-354	g/dry ton biomass
Net emissions from RD production	*372 (83%)*	*189 (42%)*	*388 (72%)*	*193 (36%)*	g/dry ton biomass
Direct emissions from PU production	835	1,019	909	1,103	g/dry ton biomass
Credits from PU production	-759	-759	-759	-759	g/dry ton biomass
Net emissions from PU production	*76 (17%)*	*259 (58%)*	*149 (28%)*	*344 (64%)*	g/dry ton biomass
Net Total	448		537		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 2022 SOT cases of four renewable diesel, SAF, and renewable gasoline pathways are conducted. 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 2022 SOT cases 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 RD via sludge HTL in the 2022 SOT case offers 77% and 81% GHG emission reductions with and without NH_3 removal from the HTL aqueous, respectively. Supply chain water consumption is 2.2 gal/GGE and 1.6 gal/GGE with and without NH_3 removal, respectively. Fuel combustion and HTL for biocrude production are the primary contributors to NO_x emissions. The sludge HTL pathway in the 2022 SOT case has a slightly lower NO_x emission intensity than that of petroleum diesel. The NEB of this pathway in the 2022 SOT case is 0.72 MJ/MJ if NH_3 is removed from the HTL aqueous and 0.76 MJ/MJ if NH_3 removal is not considered.

SCSA results vary significantly with different co-product handling methods for those pathways that include significant non-fuel co-products. 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 BKA 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 2022 SOT case, owing to large quantities of process chemicals and energy required for pretreatment operations. In the lignin upgrading to BKA case and with the process-level allocation method, the supply chain GHG emissions are 11% – 26% and 27% – 42% higher for the 2022 SOT acids and BDO intermediate pathways, respectively, than those of the petroleum diesel. On the other hand, supply chain GHG emissions are 11% lower and 5% higher for the 2022 SOT acids and BDO intermediate pathways, respectively, than those of the petroleum diesel, when the co-product BKA is handled with the displacement method, assuming conventional NG-derived AA is displaced. In either case, the supply chain GHG emissions are projected to improve substantially relative to these SOT benchmarks based on future 2030 performance goals (Cai et al. 2021).

RD biofuel produced from HTL of algae with supplemental woody biomass offers a 51% reduction in GHG emissions in the 2022 SOT case compared with those of petroleum diesel. GHG emissions from biomass conversion to biofuels were the largest contributors to supply chain GHG emissions, followed by GHG emissions associated with the energy and nutrients consumption for algae growth. HTL of the algae/woody biomass blend achieves a 32% reduction in supply chain water consumption relative to petroleum diesel. Algae cultivation and biomass conversion to biofuels are the largest contributor to water consumption. Woody biomass harvest/collection and preprocessing is the primary NO_x emission source due to the energy consumption during woody biomass collection and preprocessing.

When the process-level allocation method is applied, the algae CAP pathway has 23% to 35% (mass-based allocation) and 51% to 63% (market value-based allocation) lower GHG emission intensities in the 2022 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 48% to 68% lower in the 2022 SOT case than that of petroleum diesel. At a biorefinery-level, 350 to 487 kg 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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