

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 2019 State-of-Technology Cases

Energy Systems Division

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by

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1 INTRODUCTION

The Department of Energy's (DOE's) 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* is a TEA that 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: (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 in the 2019 SOT [Tan et al. 2019]); (2) renewable gasoline (RG) and diesel (RD) blendstocks via ex situ catalytic fast pyrolysis of woody lignocellulosic biomass; (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; (5) renewable diesel via HTL of a blend of algae and woody biomass; and (6) renewable diesel via combined algae processing (CAP). This technical report focuses on the environmental performance of these six biofuel production pathways in their 2019 SOT cases. The results of these renewable hydrocarbon fuel pathways in these SCSA analyses update those for the respective 2018 SOT cases (Cai et al., 2018a). 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 2019 SOTs on the sustainability performance of these renewable transportation fuels, and they reflect updates to Argonne National Laboratory's Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET®) model, which was released in October 2019 (Wang et al., 2019). 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 that are used in the SCSA of HOG via IDL, RG and RD from CFP, and renewable fuels from biochemical conversion. In this analysis, we consider the upstream impacts of producing each energy and chemical input to the supply chain.

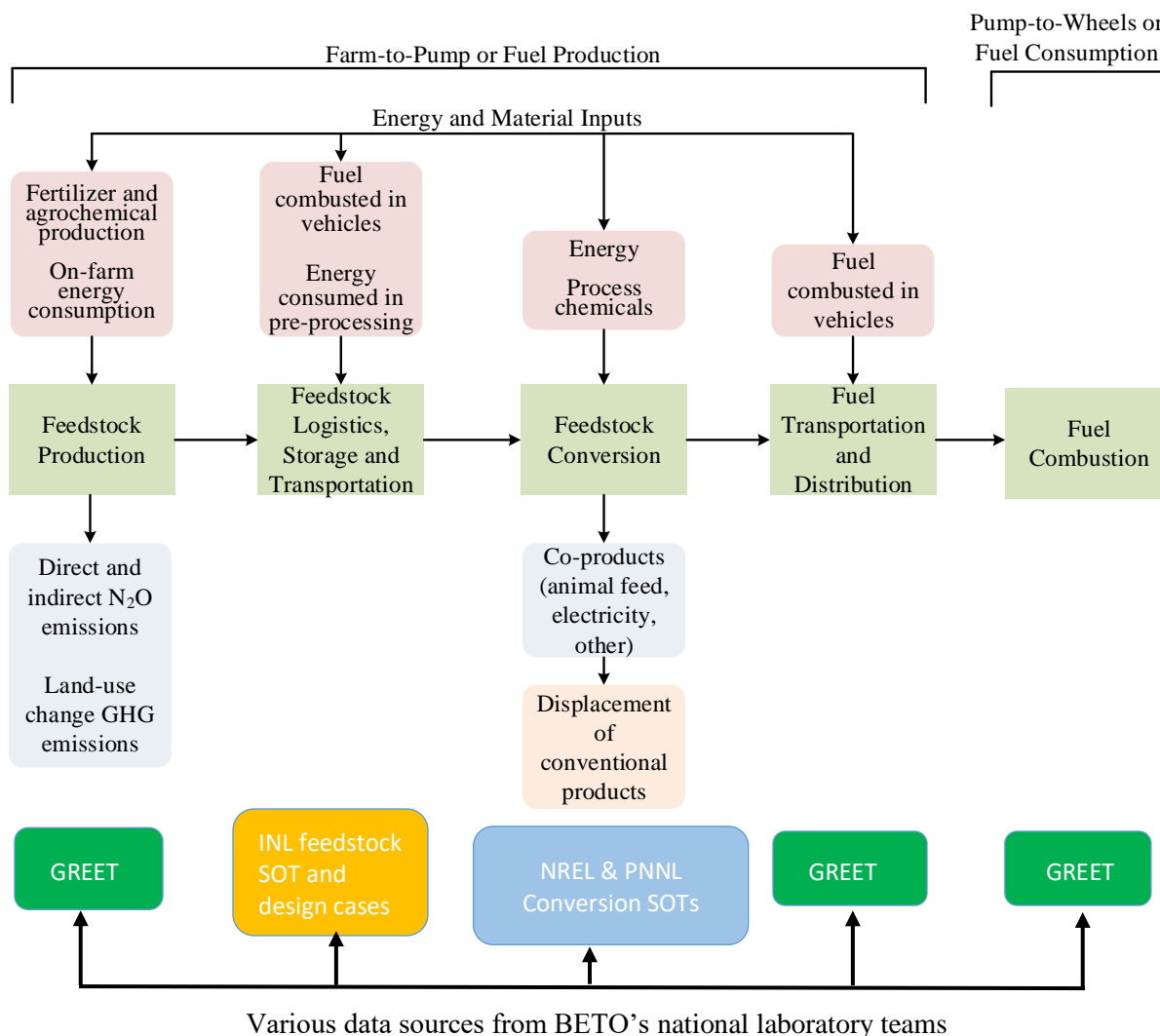


FIGURE 1 General Stages Considered and Data Sources Used in the Supply Chain Sustainability Analyses for HOG via IDL, RG and RD from CFP, and Renewable Fuels from Biochemical Conversion

2 METHODS AND DATA

Argonne National Laboratory's GREET model was used to generate the SCSA results for the 2019 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.

2.1 Material and Energy Requirement of Feedstock Production and Logistics

2.1.1 Herbaceous and Woody Biomass Production and Logistics

For the 2019 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 (Roni et al. 2020; Hartley et al., 2020). The National Renewable Energy Laboratory (NREL) modeled an algal feedstock (Davis and Laurens, 2020) 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., 2017).

The herbaceous feedstock blend comprises 67% two-pass corn stover, 33% three-pass corn stover in the 2019 SOT case. These optimized blending strategies reflect biomass availabilities based on the 2016 Billion Ton Study (U.S. Department of Energy, 2016) and the amount of feedstock required to be delivered to the biorefinery reactor throat (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 2019 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., 2017).

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 1-3.

A series of logistics operations were used to harvest, collect and preprocess corn stover in the 2019 SOT case. The use of supplementary fertilizer to maintain the soil fertility, to compensate for the nutrients lost when corn stover is removed, is considered. Diesel is consumed for harvesting, collection, and transportation of corn stover. Corn stover handling at the depot consumes primarily electricity and also 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 2019 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 of 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 delimbers and loaders, for transportation by truck, and for storage by loaders, while electricity is consumed for receiving and handling of the biomass by conveyors, and for depot preprocessing by debarkers, grinders, dryers, conveyors, and dust collection operation.

The 2019 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 of 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 delimbers and loaders, for transportation by truck, and for storage by loaders, while electricity is consumed for receiving and handling of 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 of 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 2019 SOT Cases for the Biochemical Conversion Pathway (Roni et al., 2020; Canter et al., 2016)

	2019 SOT	
	3-Pass Corn Stover (33%)	2-Pass Corn Stover (67%)
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
- CaCO ₃		
- Herbicides		
Harvest and collection	89,040	108,560
- Diesel	100%	100%
Storage	10,920	10,920
- Electricity	100%	100%
Preprocessing	326,350	326,350
- Electricity	100%	100%
Handling	7,720	7,720
- Diesel	89.5%	89.5%
- Electricity	10.5%	10.5%
Blending	440	440
- Electricity	100%	100%

^a Farming energy consumption and the fertilizer use 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 2019 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 & 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	348,230	160,960	1,918,590	1,379,880
- Natural gas	0%	0%	64%	88%
- Electricity	100%	100%	36%	12%

^a The silviculture energy consumption and the fertilizer use 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, 2019 SOT Case (Roni et al., 2020)

			Truck Payload (Dry Tons)	Transportation Distance (Miles)	Transportation Moisture Content
2019 SOT	From fieldside to depot	3-Pass corn stover	17.7	43.7	25%
		2-Pass corn stover	17.7	36.4	25%
	From depot to biorefinery	3-Pass corn stover	20.9	61.5	11.4%
		2-Pass corn stover	20.9	79.4	11.4%

^{NN} Not needed

TABLE 4 Woody Biomass Transportation Parameters for Transportation from the Landing to the Biorefinery, 2019 SOT Case (Hartley et al., 2020)

	Truck Payload (Dry Tons)	Transportation Distance (Miles)	Transportation Moisture Content
Logging residue ^a	17.7	104.0	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 and meet the throughput requirement, 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 ton to the biorefinery for conversion.

TABLE 5 Dry Matter Losses (in % by Mass) of Herbaceous and Woody Biomass, 2019 SOT Case (Hartley et al., 2020; Roni et al., 2020)

		Depot Storage	Depot Preprocessing	Landing Preprocessing	Preprocessing
Herbaceous biomass	Corn stover	12%	2%		
Woody biomass	Logging residue			5%	10%
	Clean pine			5%	13%

2.1.2 Algae Biomass Cultivation

Algae cultivation for HTL and CAP conversion is modeled from the algae farm design report (Davis and Laurens, 2020), 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 and harmonization models (ANL 2012). This is overlaid with algal biomass productivity data which has reflected experimental cultivation trials at the ASU AzCATI test-bed site since the 2017 SOT.

In the 2019 SOT case (Davis and Laurens, 2020), 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 Laurens, 2020). Figure 2 shows a general block-flow diagram of the process. Further details of the process design are given in the report (Davis and Laurens, 2020). In these SCSAs, saline scenarios with minimally lined ponds are considered for the downstream conversion of algal biomass to fuels and co-products.

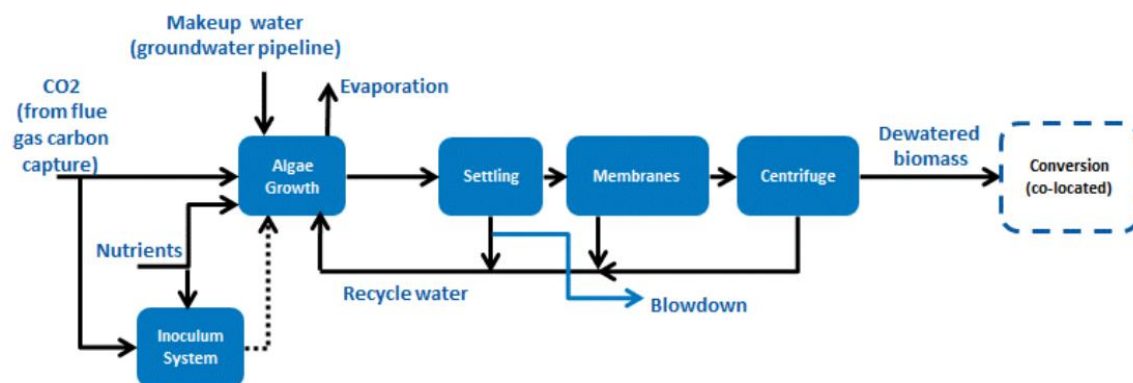


FIGURE 2 Process Flow Diagram of the Open Pond Algae Farm Model

Table 6 summarizes material and energy inputs and outputs of the 2019 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 6 Algal Biomass Production and Resource Requirement (annual averages, hourly rates below reflect average daily rates divided by a 24-hour day).

	2019 SOT
Products, kg/hr	
Algal biomass (AFDW)	13,246
Algal biomass (total including ash)	13,576
Resource Consumption, kg/hr	
CO ₂	29,441
Ammonia	265
Diammonium phosphate	128
Total process water input (saline water)	537,257
Electricity demand, kW	7,566
Algae lost in blowdown	5

2.2 Material, Energy, and Water Requirements of Conversion Progress

2.2.1 Indirect Liquefaction (IDL)

The 2019 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 51.6 gallons, or 5.7 MMBtu per dry U.S. short ton of feedstock, with an amount of 5.6 gallons, or 0.6 MMBtu of mixed butanes per dry ton, as well as a small amount of surplus electricity as co-products (Tan et al., 2019), which is assumed to be displacing petroleum gasoline and exported to the grid, respectively. Figure 3 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 2019 SOT case (Tan et al., 2019). 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 2.7 g/MMBTU of HOG).

2.2.2 Ex Situ Catalytic Fast Pyrolysis (CFP)

Ex situ CFP converts woody biomass to infrastructure-compatible liquid hydrocarbon fuels. The 2019 SOT case for the ex situ CFP processes 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., 2018). 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 52% RG and 48% RD by energy. The total RG and RD yields at the biorefinery are 6.9MMBtu per dry U.S. short ton of biomass (50% clean pine and 50% logging residues by mass). Surplus electricity is produced as a co-product (Dutta et al., 2020) 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 12.8 and 54.9 lbs per dry ton, respectively. They are assumed to displace fossil-derived counterparts.

Figure 4 shows a simplified PFD of the ex situ CFP pathway. For details of the conversion process, see the full SOT report (Dutta et al., 2020). Despite a change in the feedstock option in the 2019 SOT, the feedstock specification assumption in the process model was unaltered from the design report (Dutta et al. 2015). Different biomass 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 2019 SOT case (Dutta et al., 2020).

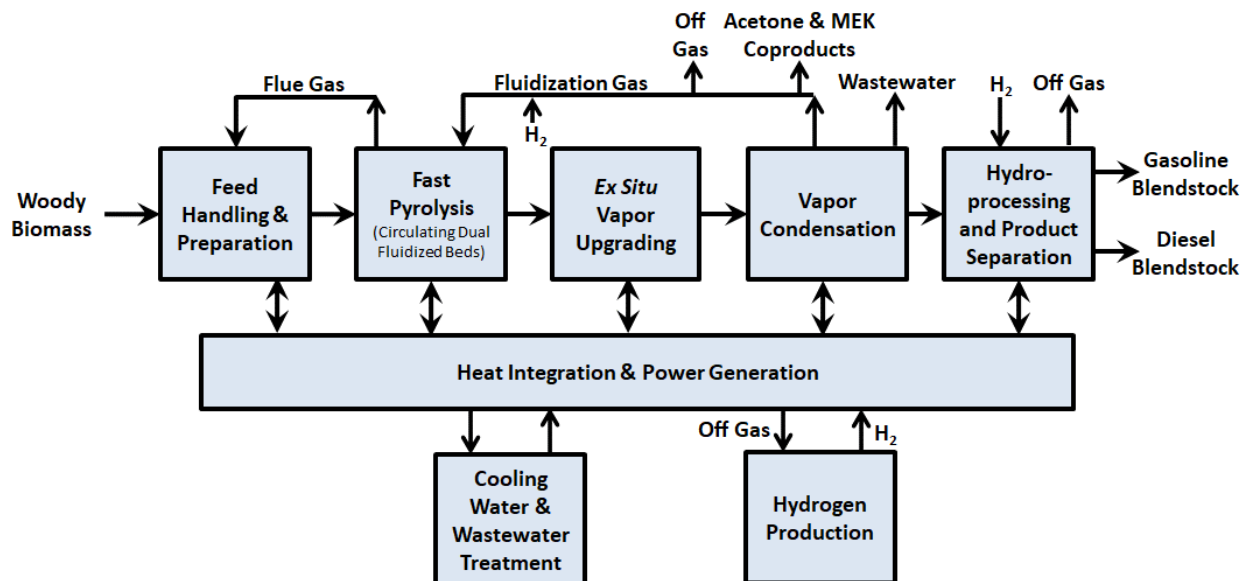


FIGURE 4 Simplified Process Flow Diagram for Fixed Bed Ex Situ Catalytic Fast Pyrolysis.

TABLE 8 Key Ex Situ Catalytic Fast Pyrolysis Process Parameters

	2019 SOT Value	Unit
RG yield	3.6	MMBtu/dry ton feedstock
RD yield	3.3	MMBtu/dry ton feedstock
Co-produced 2-butanone	0.8	Kg/MMBtu of RG and RD combined
Co-produced acetone	3.6	Kg/MMBtu of RG and RD combined
Surplus electricity	107,725	Btu/MMBtu of RG and RD combined
Diesel energy use	2,056	Btu/MMBtu of RG and RD combined
Natural gas use	11,414	Btu/MMBtu of RG and RD combined
Fixed-bed VPU catalyst (1% Pt/TiO ₂)	0.048	g/MMBtu of RG and RD combined
Sand	113	g/MMBtu of RG and RD combined
ZnO	0.065	g/MMBtu of RG and RD combined
Steam reforming catalyst	0.14	g/MMBtu of RG and RD combined
Shift catalyst	0.20	g/MMBtu of RG and RD combined
PSA adsorbent	4.9	g/MMBtu of RG and RD combined
Caustic	104.2	g/MMBtu of RG and RD combined
Water consumption	10.1	gal/MMBtu of RG and RD combined

2.2.3 Sludge Hydrothermal Liquefaction (HTL)

HTL is a process that 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., 2017). It is a technology that has a 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 that is co-located with a WWTP and a larger scale biocrude upgrading plant for production of hydrocarbon fuel blendstocks. Pacific Northwest National Laboratory (PNNL) conducted TEAs of sludge converted to RD and naphtha blendstocks via HTL in the 2019 SOT. 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 5.

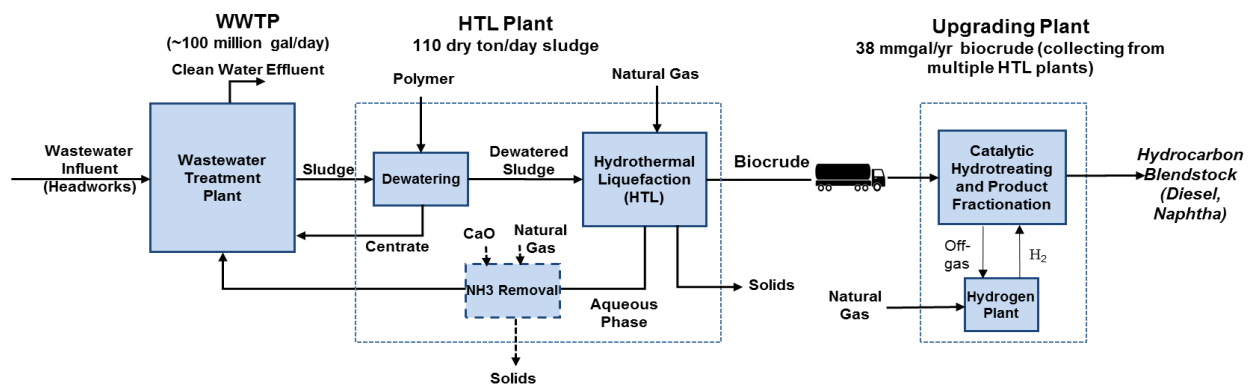


FIGURE 5 A Simplified Process Flow Diagram of the WWTP/HTL Plant and Centralized Biocrude Upgrading Plant Design

HTL Plant

The biocrude produced at the HTL plant contains a mixture of hydrocarbons with carbon numbers in the gasoline/jet/diesel range. However, because its oxygen and nitrogen content is higher than that of petroleum, it must be hydrotreated to make it fungible with petroleum fuels. Dewatering of sludge is necessary prior to HTL to minimize capital and operations cost. A dewatering polymer is used to enhance solid/liquid separation. After it is preheated and pressurized, the slurry enters the HTL reactor, where it undergoes depolymerization and its monomers are decomposed. The biocrude is then produced by recombining reactive fragments.

In addition to the biocrude production, which represents the oil phase in the HTL plant, there is also a solid phase with highly concentrated nutrients (e.g., phosphorus) and an aqueous phase. The residual solids consist of ash, char, moisture and low levels of organics, which are assumed to be transported and landfilled once removed. Because of its high ammonia content, the aqueous stream is treated with quicklime (CaO) to adjust the pH and then to air stripping to remove the ammonia before is sent to the WWTP. In addition to the ammonia removal scenario, we also include an alternative scenario in which the ammonia stripping process is not needed. The reason for this is that there is a high level of uncertainty around the need for removing ammonia from the HTL aqueous phase before recycling it back to the WWTP plant. Table 9 summarizes major inputs and outputs of the HTL process for all the cases investigated. The production pathways of the materials listed in Table 9 are available in GREET.

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 hydrocarbon fuel blendstock.

TABLE 9 Inputs and Outputs for HTL 2019 SOT Per MMBtu Biocrude Produced

		With Ammonia Removal	Without Ammonia Removal
<i>Inputs</i>			
Dewatered sludge	(dry kg)	77	77
Natural gas	(Btu)	233,779	168,321
Electricity	(Btu)	72,167	70,089
Dewatering polymer	(kg)	0.2	0.2
Quicklime (CaO)	(kg)	8.3	0
Cooling water makeup	(gal)	0.4	0.4
<i>Outputs</i>			
Biocrude	(MMBtu)	1	1
Solid	(wet kg)	48	48
Lime sludge	(wet kg)	18	0
Aqueous phase	(gal)	77	77

Upgrading Plant

Biocrude is converted into fuels such as gasoline, diesel, and jet range blendstocks at a centralized upgrading plant. Biocrude requires catalytic hydrotreating processing to remove oxygen, nitrogen, and sulfur to meet fuel specifications and become compatible with conventional petroleum fuels. As in petroleum refineries, a desalting process removes inorganic components from the biocrude to avoid deactivation of the hydrotreating catalyst. Hydrogen is an essential input for hydrotreating and hydrocracking, and it is assumed to be produced internally via steam reforming of the process off-gas and additional purchased natural gas. The hydrotreated effluent is cooled and fractionated into four boiling point cuts (C4, naphtha, diesel and heavy oil). A conventional hydrocracker is used to convert the heavy oil into additional naphtha and diesel-range products. The catalyst for the main dehydrotreating bed in the 2019 SOT case is switched from CoMo/Al₂O₃ in the 2018 SOT case to NiMo/Al₂O₃ in the 2019 SOT case. The hydrotreating guard bed continues to use CoMo/Al₂O₃ in the 2019 SOT case. Besides the change in the types of hydrotreating catalysts, there is a decrease in hydrotreating catalyst consumption in the 2019 SOT compared to the 2018 SOT case, owing to a demonstrated longer time on stream.

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. Table 10 presents the material and energy inputs and outputs of the upgrading plant. 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 Table 10 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.

TABLE 10 Material and Energy Inputs and Outputs of Upgrading Plant

	Unit	2019 SOT Case
<i>Inputs</i>		
Biocrude	mmBtu	1.42
Natural gas	Btu	104,872
Electricity	Btu	13,537
Cooling tower chemical	g	0.4
Boiler chemical	g	0.3
Hydrotreating catalyst CoMo/ γ -Al ₂ O ₃)	g	125
Hydrotreating catalyst NiMo/ γ -Al ₂ O ₃)	g	216
Hydrocracking catalyst	g	0.3
Hydrogen plant catalyst Ni)	g	0.4
Cooling water makeup	gal	7.1
Boiler feedwater makeup	gal	3.1
<i>Outputs</i>		
Diesel	mmBtu	1
Naphtha co-product)	mmBtu	0.3
Wastewater	gal	6.5

During RD production, naphtha is generated as a co-product, and again an energy allocation approach is used to allocate energy use and emissions to renewable diesel and naphtha.

2.2.4 Biochemical Conversion

Similar to the 2018 SOT case, 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 2019 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 6 shows 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 coproduct. 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 coproduct (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 coproduct recovery). Davis et al. (2020a) provides more details on the process design, performance targets, and TEA results.

Table 11 presents the energy and material inputs and outputs of the biochemical conversion pathways for both intermediate designs in the 2019 SOT.

The hydrocarbon fuel yield is significantly improved in the 2019 SOT cases compared to the 2018 SOT cases for both intermediate designs. 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. 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 11, reflects the net gas inputs after accounting for burner efficiency losses. Grid electricity import is required for both intermediate 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.

TABLE 11 Energy and Material Inputs and Outputs of the Biochemical Conversion Pathways for Both the Acids and BDO Intermediate Designs, in the 2019 SOT Case

	2019 SOT				Unit
	Acids Pathway		BDO Pathway		
	Burning lignin	Lignin upgrading to adipic acid	Burning lignin	Lignin upgrading to adipic acid	
Products					
Hydrocarbon fuel	4.1	4.1	4.4	4.5	mmBtu/dry ton
Co-products					
Adipic acid (polymer grade)	0	4.7	0	4.2	kg/mmBtu
Recovered sodium sulfate salt from wastewater treatment plant (WWTP)	24.5	45.3	23.3	39.2	kg/mmBtu
Resource Consumption					
Biomass feedstock	0.24	0.24	0.22	0.22	dry ton/mmBtu
Sulfuric acid	21.6	34.3	19.9	29.4	kg/mmBtu
Caustic	17.7	28.1	16.3	24.1	kg/mmBtu
Ammonia	3.5	6.3	3.2	5.5	kg/mmBtu
Glucose	4.2	4.2	3.9	3.9	kg/mmBtu
Corn steep liquor	3.1	3.1	2.3	2.3	kg/mmBtu
Corn oil	0.024	0.024	0.022	0.022	kg/mmBtu
Host nutrients	0.12	0.12	0.11	0.11	kg/mmBtu
Sulfur dioxide	0.029	0.029	0.027	0.027	kg/mmBtu
Diammonium phosphate	0.40	0.63	0.24	0.45	kg/mmBtu
Flocculant	0.99	0.99	0.96	0.95	kg/mmBtu
Toluene solvent makeup	0.24	0.24	0	0	kg/mmBtu
Hydrogen	0	0	1.9	2.3	kg/mmBtu
Ethanol	0	0.035	0	0.032	kg/mmBtu
Boiler chemicals	0	0	0	0.002	kg/mmBtu
FGD lime	0.30	0.55	0.27	0.47	kg/mmBtu
Wastewater plant polymer	0.15	0	0.13	0	kg/mmBtu
Cooling tower chemicals	0.008	0.005	0.005	0.005	kg/mmBtu
Makeup water	238.6	172.1	94.2	79.0	Gal/mmBtu
Natural gas for boiler	0	0	0	0.51	MMBtu/mmBtu
Natural gas for hot oil system	0.10	0.10	0	0	MMBtu/mmBtu
Grid electricity (net import)	21.6	147.9	47.4	104.8	kWh/mmBtu

2.2.5 Algae Hydrothermal Liquefaction (HTL)

In this SCSA, algae/woody biomass blend feedstock-based HTL was simulated and evaluated. An annual average blend of 59% saline algae and 41% logging residues by ash-free dry weight (AFDW) is formulated in the 2019 SOT case. Figure 7 shows the PFD for the algae/wood blend feedstock conversion via an HTL and upgrading system. Detailed process designs for co-feeding algae and woody biomass in an HTL and upgrading system to make renewable diesel and naphtha-range fuels are given in Zhu et al. (2020). Figure 7 shows a simplified conversion PFD of the HTL of co-fed algal and woody biomass for RD production.

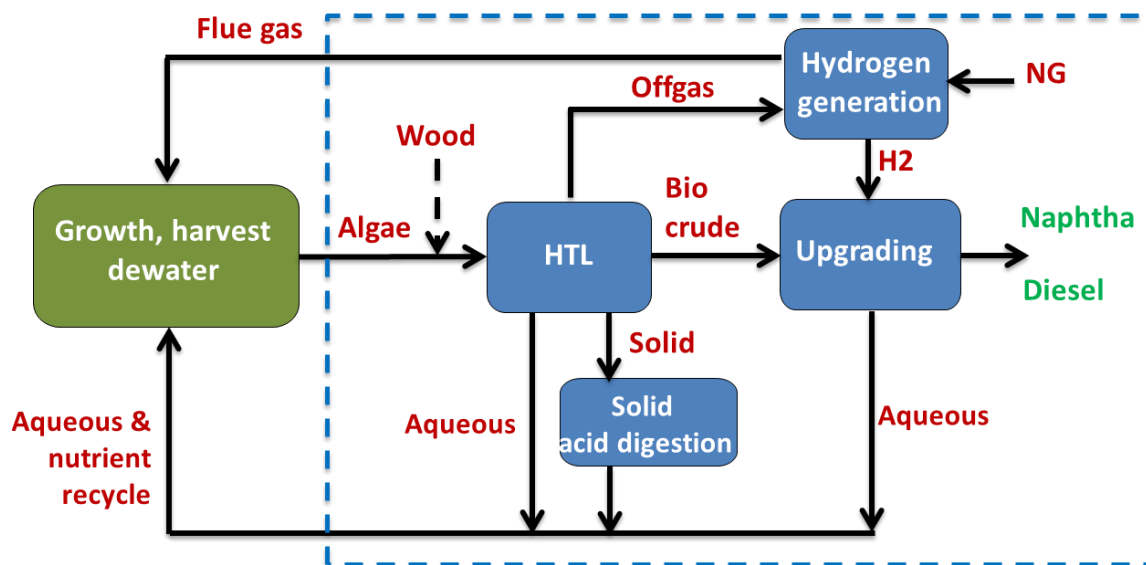


FIGURE 7 Process Flow Diagram for Hydrothermal Liquefaction of Co-Fed Algal and Woody Biomass for Renewable Diesel Production in the 2019 SOT.

Table 12 lists the direct material, energy, and water consumption for the modeled HTL conversion process at the plant in the 2019 SOT case.

TABLE 12 Material, Energy, and Water Consumption for the Modeled HTL Conversion and Upgrading Process in the 2019 SOT Case

	2019 SOT
Products	
Renewable diesel, GGE/hr	1,734
Naphtha, GGE/hr	827
Resource Consumption kg/hr	
Algae (AFDW basis), annual average	13,246
Wood (AFDW basis), annual average	9,374
Sum	22,620
HTL	
Sulfuric acid (96 wt% pure) makeup	968
Bio-crude upgrading	
HT main bed catalysts	1.53
HT guard bed catalyst	2.15
Natural gas for H ₂ generation	1,972
Process water makeup	13,389
Purchased electricity, kW	1,944
Output Streams, kg/hr	
Nutrient elements recycled to algae farm via aqueous recycle	
Carbon, C	5,871
Nitrogen, N	810
Phosphorus, P	39

2.2.6 Combined Algae Processing (CAP)

The CAP model is based on NREL’s previously 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 (Davis et al., 2020b). 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). For future scenarios moving to 2030, a portion of the lipids may be diverted away from fuels for production of polyurethane co-products, but this is not yet included in current SOT benchmarks. Figure 8 shows a block-flow diagram of the CAP conversion process. The 2019 SOT case reflects updated SOT algae farm model cultivation performance parameters, but the CAP conversion process model remains the same as that in the 2018 SOT case (Cai et al., 2018a).

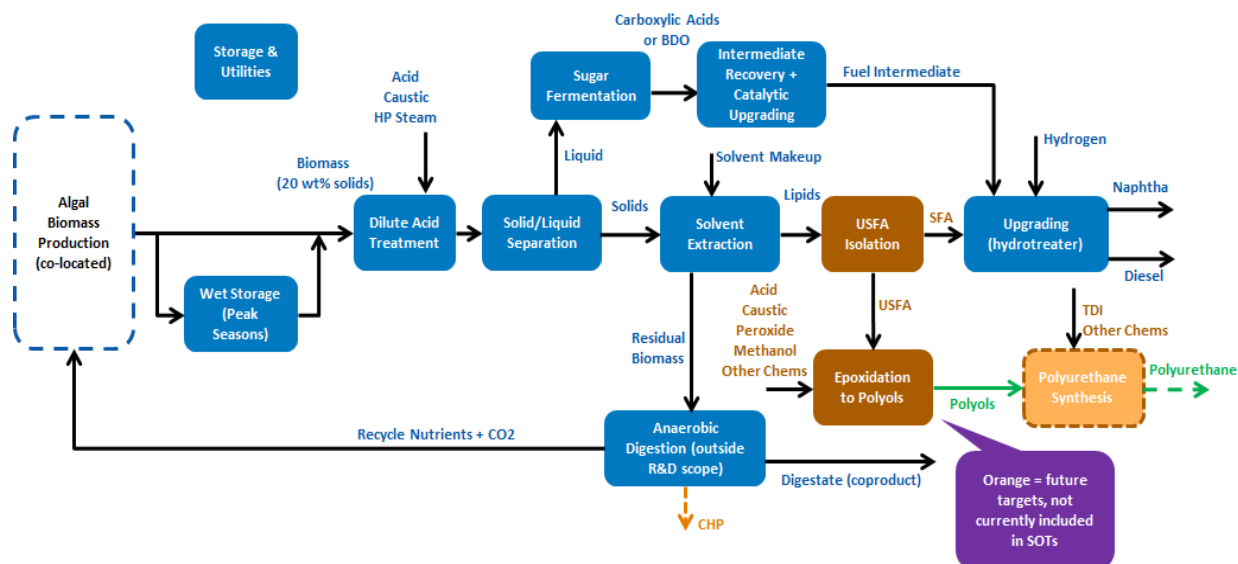


FIGURE 8 Block-Flow Diagram of the CAP Conversion Process

Table 13 lists the key process parameters and energy inputs for the modeled CAP conversion process in the 2019 SOT cases via either acids or BDO intermediate pathways for fuel production.

TABLE 13 Energy and Material Inputs and Outputs for the Modeled CAP Conversion Process in the 2019 SOT Cases via Acids and BDO as Intermediate Pathways for Fuel Production

	Via acids	Via BDO	
Products			
Diesel	91	109	mmBtu/hr
Naphtha	63	46	mmBtu/hr
Electricity Exported to Grid	0.02931	0.00422	kWh/MJ
Resource Consumption			
Algae (AFDW basis)	0.08148	0.08112	kg/MJ
Pretreatment Resource Consumption			
Sulfuric-Acid	0.00659	0.00656	kg/MJ
Ammonia	0.00229	0.00228	kg/MJ
Carboxylic Acid Conversion Resource Consumption			
Corn Steep Liquor	0.00430	0.00049	kg/MJ
DAP	0.00045	0.00006	kg/MJ
Membrane Flocculant	0.00045	0.00045	kg/MJ
Lipid extraction and Conversion to Fuels Resource Consumption			

	Via acids	Via BDO	
Hexane Requirement	0.00006	0.00043	kg/MJ
Ethanol Requirement	0.00018	0.00017	kg/MJ
Hydrogen	0.00082	0.00082	kg/MJ
Other Resource Consumption			
Supplemental Natural Gas	0.25183	0.11367	
Process Water	0.08362	0.11217	gal/MJ
Hydrotreating catalyst (5% Pd/C)	0.0000001		kg/MJ
Output Streams			
AD Digestate cake bioavailable N	0.00001	0.00001	kg/MJ
AD effluent NH ₃	0.00006	0.00005	kg/MJ
AD effluent DAP	0.00003	0.00002	kg/MJ

The fuel products from the CAP process consist of RD and naphtha in the 2019 SOT case.

Both the acids and BDO intermediate pathways co-produce electricity that is exported to the grid. As in the algae HTL case, there is a nutrient-rich effluent produced in the AD process that 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.

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% blending of clean pine and logging residue in the 2019 feedstock SOT.

3.1.1 Supply Chain Greenhouse Gas Emissions

For the HOG via IDL pathway, total GHG emission from the woody feedstock logistics in the SOT case was estimated at 113.4 kg CO₂e/dry ton, which is a sharp increase from the 69.5 kg CO₂e/dry ton in the 2022 design case (Cai et al., 2018a). The difference is mainly because that the feedstock used in the 2022 design case was logging residues to whose production no GHG emissions was allocated because it is a byproduct of wood production. The 2019 SOT case, on the other hand, used a 50%-50% mix of clean pine and logging residues as the feedstock. Production of clean pine would generate GHG emissions because it is the main product of harvesting.

The GHG emission intensity of HOG production in the biorefinery went down slightly from 2.6 g CO₂e/MJ in the 2019 SOT case, which was close to the 2.4 g CO₂e/MJ in the 2022 design case (Cai et al., 2018a). 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.

The 2019 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 9 shows the supply chain GHG emissions for 2019 SOT case.

The supply chain GHG emissions of HOG via IDL is 21 g CO₂e/MJ in the 2019 SOT case, which is an increase from the 16 g CO₂e/MJ in the 2018 SOT case (Cai et al., 2018a). This is attributable to higher emissions from feedstock production due to the use of clean pine.

Feedstock logistics are the dominant contributor to the supply chain GHG emissions. In particular, woody biomass preprocessing is the largest contributor to the supply chain GHG emissions (83%). Driving down the energy requirement for depot preprocessing by leveraging waste process heat from the conversion step is one effective measure that reduces the impact of depot preprocessing on supply chain GHG emissions, compared to previous logistics designs that

were evaluated (Cai et al., 2018a). The IDL conversion process contributes 12% (2.6 g CO₂e/MJ) of the supply chain GHG emissions for the 2019 SOT case. These do not change much compared to the 2018 SOT and 2022 design cases, given the same energy self-sufficient process design in these 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. Methane and N₂O emissions from the combustion of intermediate fuel gas and char are responsible for 26% of GHG emissions at the biorefinery in the 2019 SOT case,. Woody biomass harvest and collection contributed 32% of the supply chain GHG emissions in the 2019 SOT case, which is much higher than both the 2018 SOT (14%) and 2022 design (14%) cases due to use of clean pine.

Compared with petroleum-derived gasoline, HOG via IDL offers a significant supply chain GHG emission reductions of 78% in the 2019 SOT case.

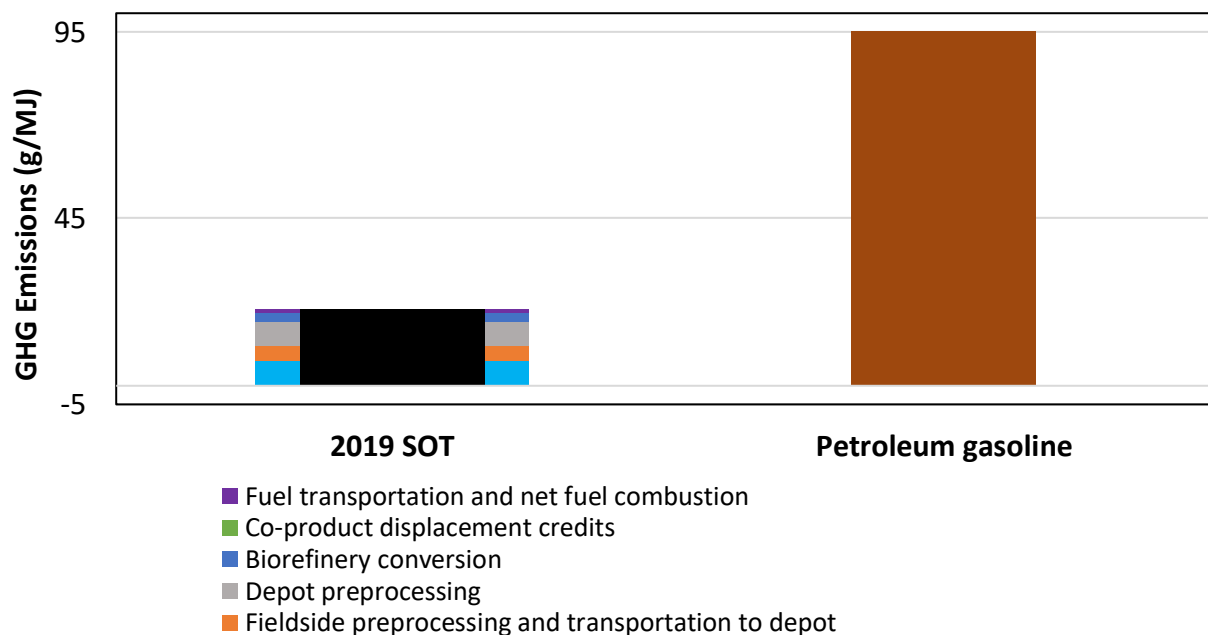


FIGURE 9 Supply Chain GHG Emissions (g CO₂e/MJ), High Octane Gasoline via IDL

3.1.2 Supply Chain Water Consumption

The supply chain water consumption of HOG produced via IDL is about 4.5 gal/gasoline gallon equivalent (GGE) in the 2019 SOT case, which is the same as in the 2018 SOT case (Cai et al., 2018a), compared to about 3.1 gal/GGE for petroleum gasoline blendstock (Wang et al., 2019).

Figure 10 shows the supply chain water consumption of HOG via IDL in gal/GGE. The largest contributor to the supply chain water consumption is the IDL process (i.e., biorefinery), accounting for about 65%, lower than the 2018 SOT (78%) and 2022 design (77%) cases (Cai et al., 2018a). The water is consumed for process cooling and boiler feed water makeup. Water consumption embedded in the production of upstream process energy (i.e., indirect water consumption) used at the biorefinery is a minor piece of the whole supply chain water consumption. Another step that consumes significant amounts of water in the IDL supply chain is the relatively energy-intensive depot preprocessing, accounting for about 22%, owing to water consumption associated with the production of process energy (electricity) which is used at this step. Fieldside preprocessing and biomass transportation to the depot, which consumes diesel, contributes to a relatively small portion of the supply chain water consumption in the 2019 SOT case.

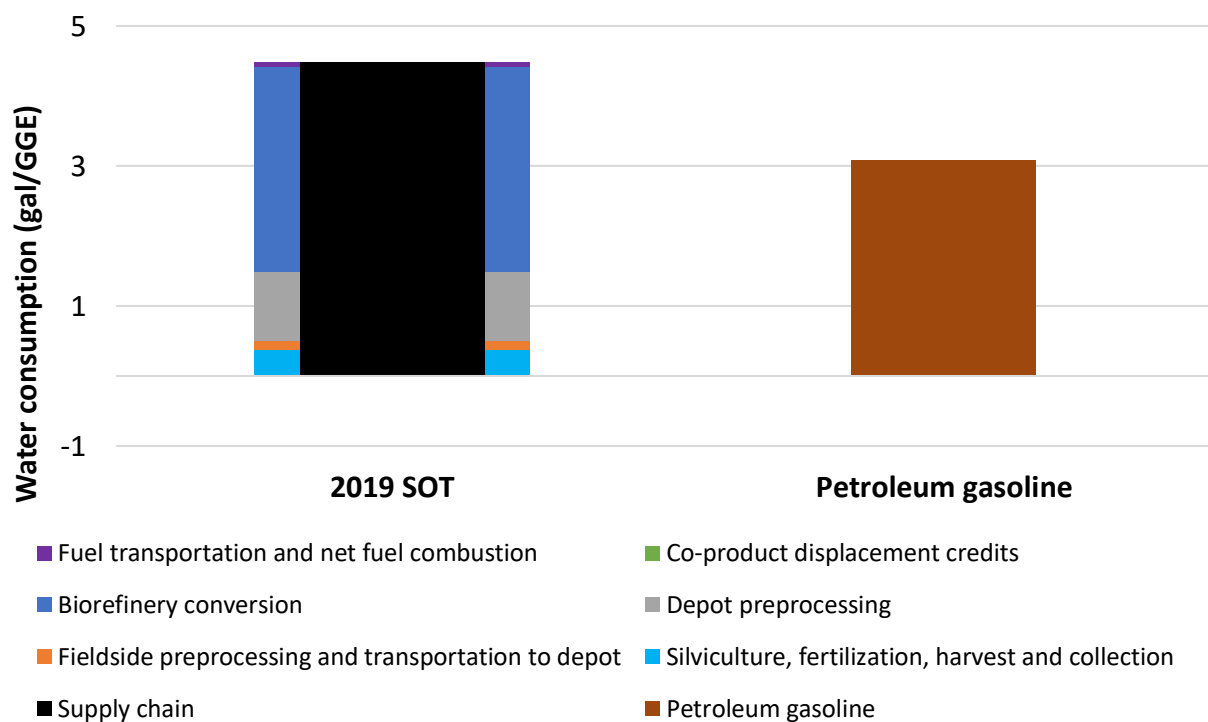


FIGURE 10 Supply Chain Water Consumption (gal/GGE), High Octane Gasoline via IDL, Compared with 3.1 gal/GGE for Petroleum Gasoline

The direct water consumption during the conversion process is reduced from 3.3 gal/GGE in the 2018 SOT case to 2.8 gal/GGE in the 2019 SOT case, which is a 16% reduction 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 0.18 g/MJ in the 2019 SOT case, compared to about 0.06 g/MJ for petroleum gasoline blendstock (Wang et al., 2019).

Figure 11 shows that NO_x emissions are mostly attributable to the IDL process and fieldside preprocessing and biomass transportation in the SOT and design cases. 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 to 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.

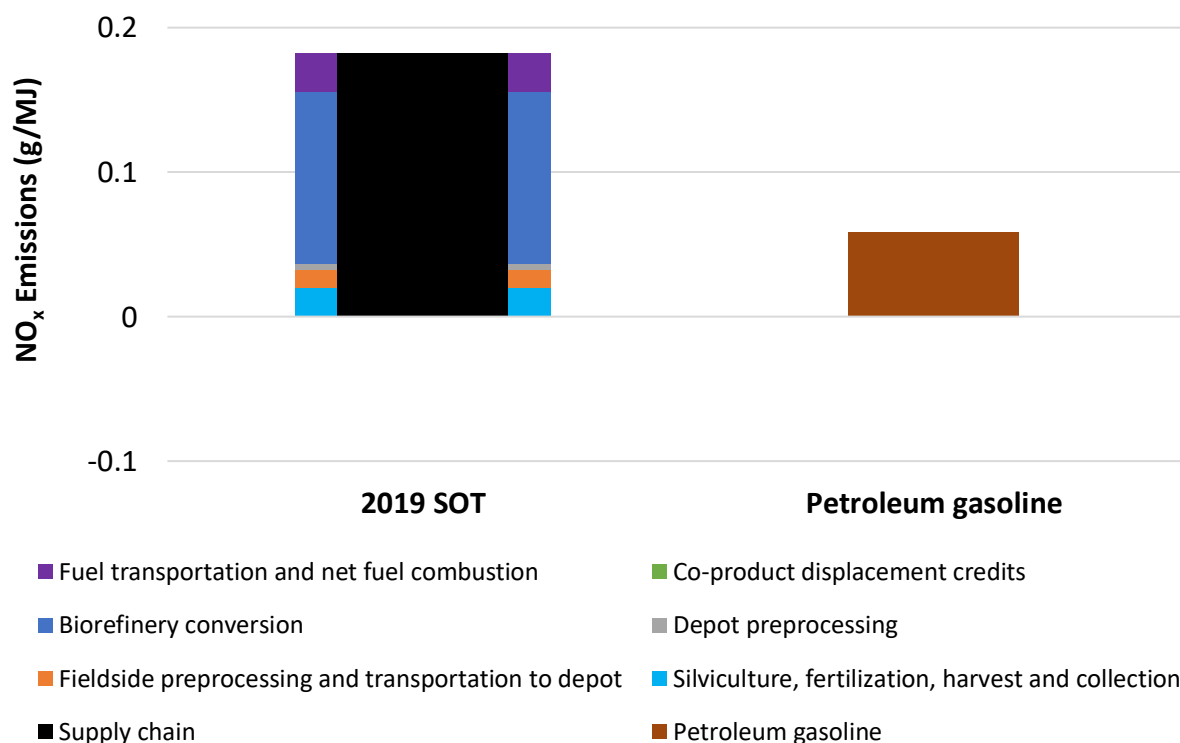


FIGURE 11 Supply Chain NO_x Emissions (g/MJ), High Octane Gasoline via IDL, Compared with 0.06 g/MJ for Petroleum Gasoline

3.1.4 Summary of Sustainability Metrics

Table 14 summarizes the supply chain sustainability metrics in different functional units that are evaluated for the 2019 SOT case of HOG via IDL.

TABLE 14 Supply Chain Sustainability Metrics for High Octane Gasoline via IDL

	2019 SOT	Petroleum Gasoline
Biofuel yield		
Million Btu/dry ton	6.3	
Fossil energy consumption		
MJ/MJ	0.20 (-84%)	1.25
Net energy balance		
MJ/MJ	0.80	
GHG emissions		
g CO ₂ e/MJ	21 (-78%)	95
g CO ₂ e/GGE	2,530	11,671
Water consumption		
gal/MJ	0.04	0.03
gal/ GGE	5	3
Total NO_x emissions		
g NO _x /MJ	0.18	0.06
g NO _x /GGE	22.3	7.1
Urban NO_x emissions		
g NO _x /MJ	0.021	0.024
g NO _x /GGE	2.5	2.9

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 16 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 84% in the 2019 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 0.80 MJ/MJ of HOG produced is

estimated for the 2019 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 14% reduction potential in urban NO_x emissions in the 2019 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 would likely 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 2019 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 2019 SOT case were estimated at 253.9 kg CO₂e/dry ton. An increase in GHG emission intensities from the 2018 SOT case (228.5 kg CO₂e/dry ton) to the 2019 SOT case reflects a change of the woody feedstock from 100% clean pine (Cai et al., 2018a) to 50% clean pine and 50% logging residues.

On the other hand, the GHG emission intensity of renewable fuel production in the CFP biorefinery is 1.0 g CO₂e/MJ which is slightly lower than the 2018 SOT case (1.1 g CO₂e/MJ), when the displacement credit of the coproducts (surplus electricity, acetone, and 2-butanone) is excluded. These conversion GHG emissions include direct emissions from combustion of intermediate process energy such as biochar, CO₂ emissions from on-site natural gas steam reforming for H₂ production, and upstream emissions associated with production of catalysts used in the conversion. The energy self-sufficient design of the CFP conversion processes contributes to the low emission intensity at the conversion. All SOT and design cases co-produce 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 12 shows the supply chain GHG emissions for RG and RD via CFP in the 2019 SOT case compared to petroleum gasoline. Compared to the 2018 SOT case (11.1 g CO₂e/MJ), use of the feedstock blend leads to increased GHG emissions from depot preprocessing (25.6 g CO₂e/MJ). Production of coproducts (especially acetone) generates a large amount of displacement credits for the 2019 SOT case (-20.7 g CO₂e/MJ) than the 2018 SOT case (-1.2 g CO₂e/MJ) where the only coproduct is a small amount of surplus electricity. The CFP conversion process contributes about 7% (1.0 g CO₂e/MJ) of the supply chain GHG emissions for the 2019 SOT case, given the energy self-sufficient process design in these cases. The process-derived

fuel gas (with almost negligible NG) combustion for the steam reforming and combustion of intermediate bio-char contribute to about 46% of the conversion emissions in the 2019 SOT case (all primarily from biogenic sources), while the remaining emissions are attributable to the production and use of catalysts.

The supply chain GHG emission intensities of RG and RD are estimated at 16.2 g CO₂e/MJ in the 2019 SOT case, relative to 26.4 g CO₂e/MJ in the 2018 SOT case. Compared with petroleum-derived gasoline, RG and RD via CFP offer a significant supply chain GHG emission reduction of 83% in the 2019 SOT case.

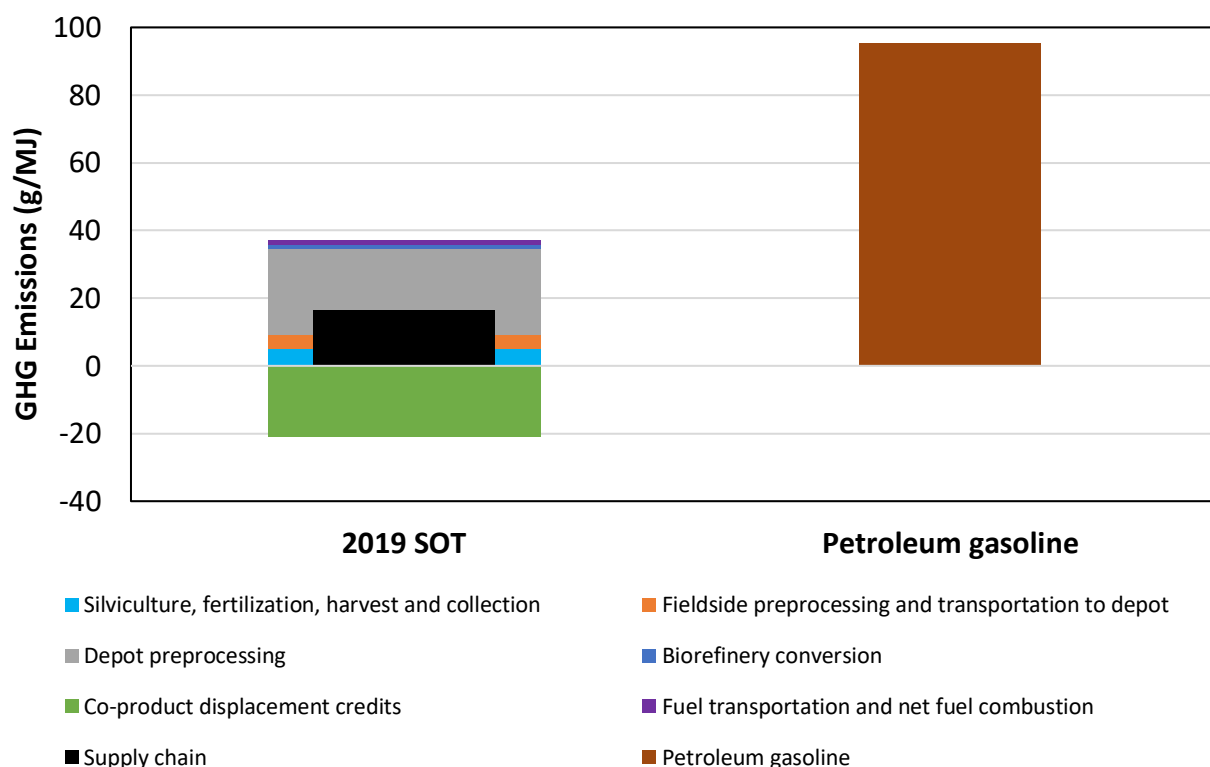


FIGURE 12 Supply Chain GHG Emissions (g CO₂e/MJ), Renewable Gasoline/Renewable Diesel via CFP

3.2.2 Supply Chain Water Consumption

The supply chain water consumption of RG and RD produced via CFP is about 3.6 gal/GGE in the 2019 SOT case, compared with about 3.1 gal/GGE for petroleum gasoline blendstock (Wang et al., 2019).

Figure 13 shows the supply chain water consumption of RG via CFP in gal/GGE. The largest contributor to the supply chain water consumption is depot preprocessing, which consumes a large amount of natural gas and electricity, accounting for about 46% of the supply chain water consumption. Process cooling and boiler feed water makeup in the CFP conversion processes, as well as water consumption embedded in the production of natural gas for steam

reforming and catalysts used at the conversion step account for about 40% of the supply chain total water consumption in the 2019 SOT case.

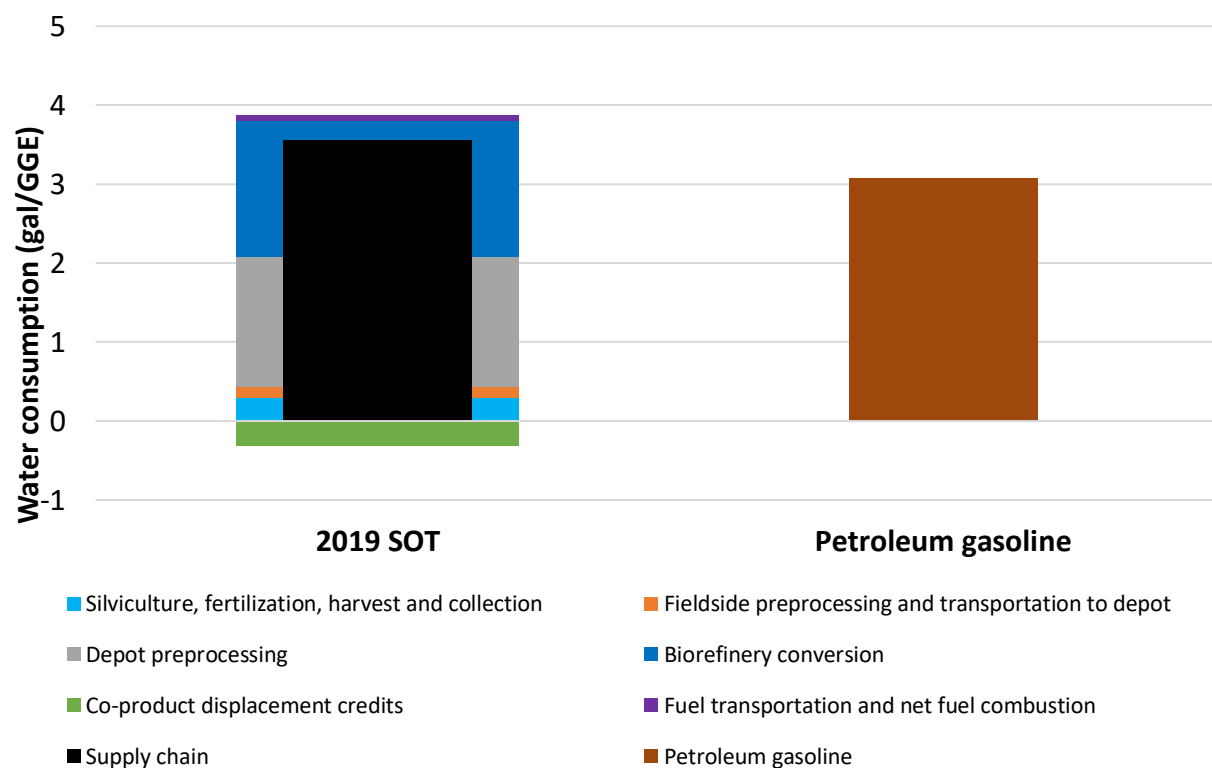


FIGURE 13 Supply Chain Water Consumption (gal/GGE), Renewable Gasoline/Renewable Diesel via CFP, Compared with 3.1 gal/GGE for Petroleum Gasoline

The direct water consumption during the conversion process is reduced from 1.3 gal/GGE in the 2018 SOT case to 1.2 gal/GGE in the 2019 SOT case, which is an 8% 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 0.3 g/MJ in the 2019 SOT case, compared with about 0.06 g/MJ for petroleum gasoline blendstock (Wang et al., 2019).

Figure 14 shows that NO_x emissions in the 2019 SOT case are mostly attributable to energy-intensive depot preprocessing, accounting for about 46% of the total emissions.

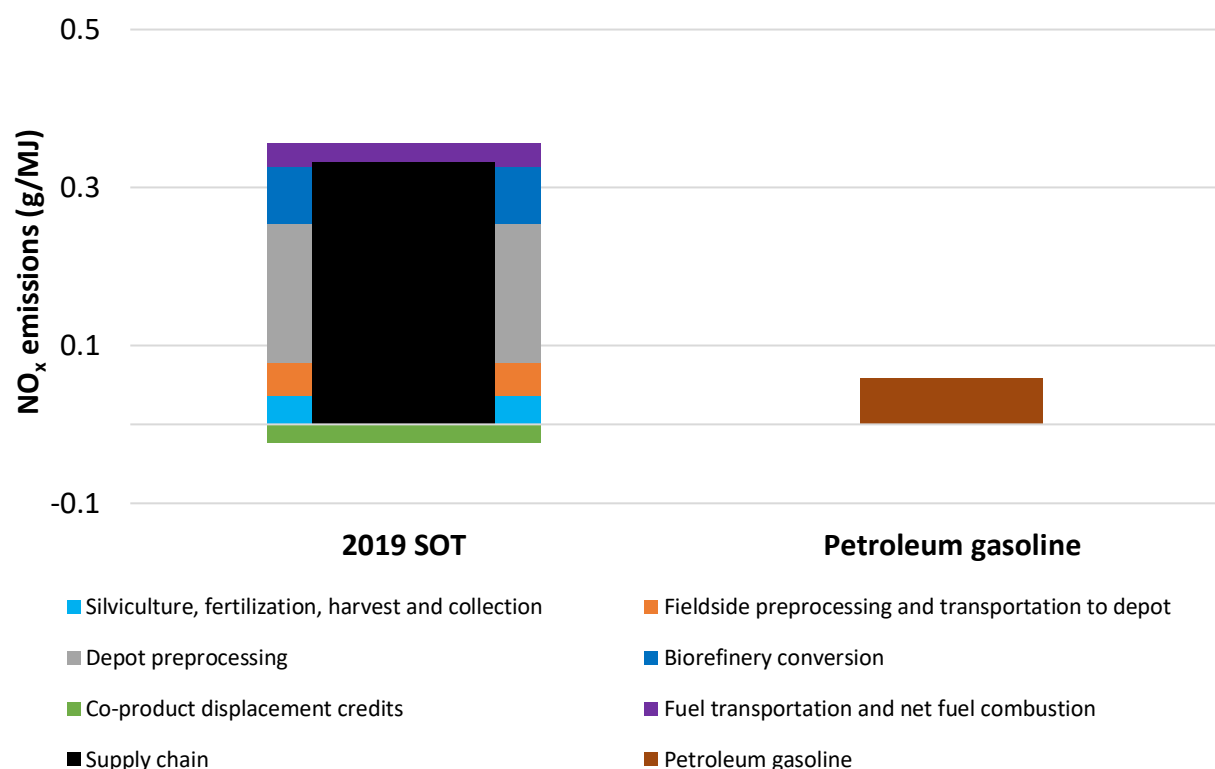


FIGURE 14 Supply Chain NO_x Emissions (g/MJ), Renewable Gasoline/Renewable Diesel via CFP, Compared with 0.06 g/MJ for Petroleum Gasoline

3.2.4 Summary of Sustainability Metrics

Table 15 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 2019 SOT case.

TABLE 15 Supply Chain Sustainability Metrics for Renewable Gasoline/Renewable Diesel via CFP

	2019 SOT	Petroleum Gasoline
Biofuel yield^a		
Million Btu/dry ton	6.9	
Fossil energy consumption		
MJ/MJ	0.19 (-81%)	1.25
Net energy balance		
MJ/MJ	0.81	

	2019 SOT	Petroleum Gasoline
GHG emissions		
g CO ₂ e/MJ	16 (-83%)	95
g CO ₂ e/GGE	1,985	11,671
Water consumption		
gal/MJ	0.03	0.03
gal/GGE	3.6	3.1
Total NO_x emissions		
g NO _x /MJ	0.33	0.06
g NO _x /GGE	40.6	7.1
Urban NO_x emissions		
g NO _x /MJ	0.020	0.024
g NO _x /GGE	2.4	2.9

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 0.81 MJ/MJ in the 2019 SOT case, indicating an 81% fossil energy saving potential for the RG and RD fuel produced, in the 2019 SOT case.

The CFP pathway in the 2019 SOT case shows about 17% reduction potential in urban NO_x emissions, compared with those of petroleum gasoline, since the biorefinery and depot preprocessing emissions that are the primary emission sources of RG are assumed to occur in rural, non-MSA areas where the biorefinery would likely be built.

3.3 Sludge Hydrothermal Liquefaction

The SCSA 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 15 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 2019 SOT case is compared with a life-cycle carbon intensity of 94 g CO₂e/MJ for petroleum diesel. The supply chain GHG emissions for the 2019 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 48% reduction compared with petroleum diesel. When NH₃ is not removed from the HTL aqueous, RD GHG emissions represent 66% reduction in the 2019 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.

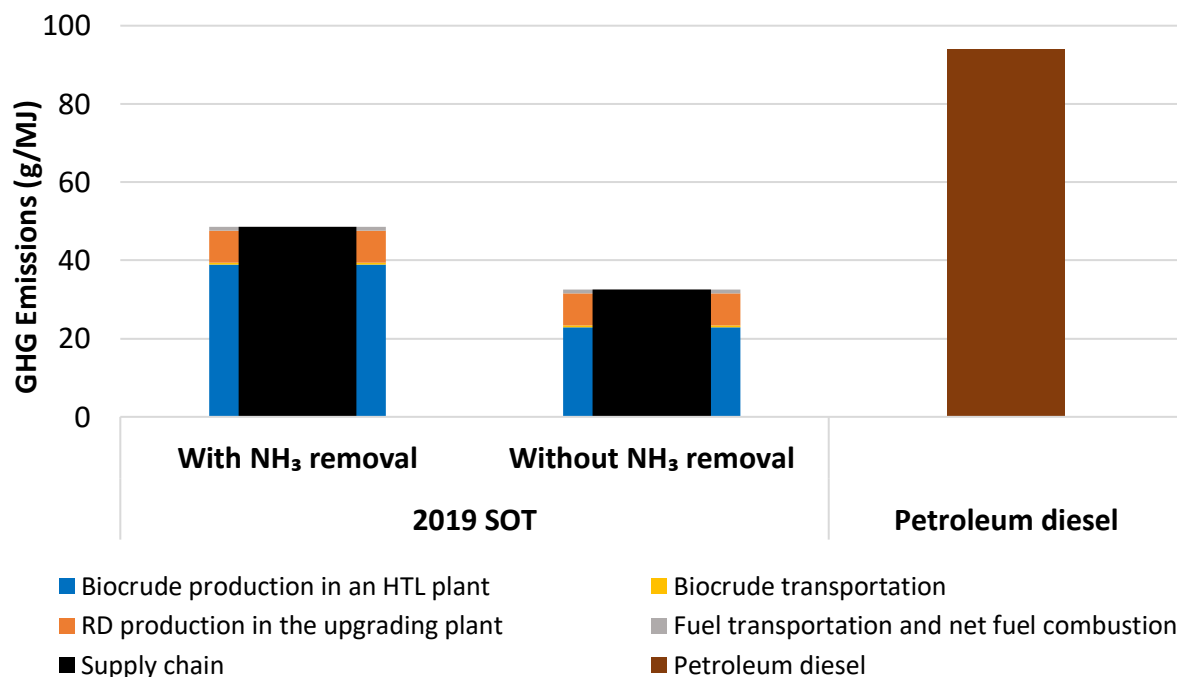


FIGURE 15 Supply Chain GHG Emissions (g CO₂e/MJ), Renewable Diesel via Sludge HTL gas and electricity otherwise required for the removal process

The major contributor to the supply chain GHG emissions are the emissions during the biocrude production in the HTL plant, accounting for about 80% of the total emissions with NH₃ removal, and for about 71% of the total emissions without NH₃ removal. When the HTL aqueous NH₃ is not removed, the supply chain GHG emission intensities are lowered by 16 g CO₂e/MJ in the 2019 SOT case.

3.3.2 Supply Chain Water Consumption

Figure 16 shows the supply chain water consumption for the production of one GGE of RD from sludge via the HTL and upgrading processes. The 2019 SOT “with NH₃ removal” scenario consumes 4.5 gal/GGE, compared to 2.7 gal/GGE for petroleum diesel. When ammonia stripping is no longer part of the process design, water use during the conversion of sludge to biocrude is reduced to 3.1 gal/GGE, as no CaO is needed.

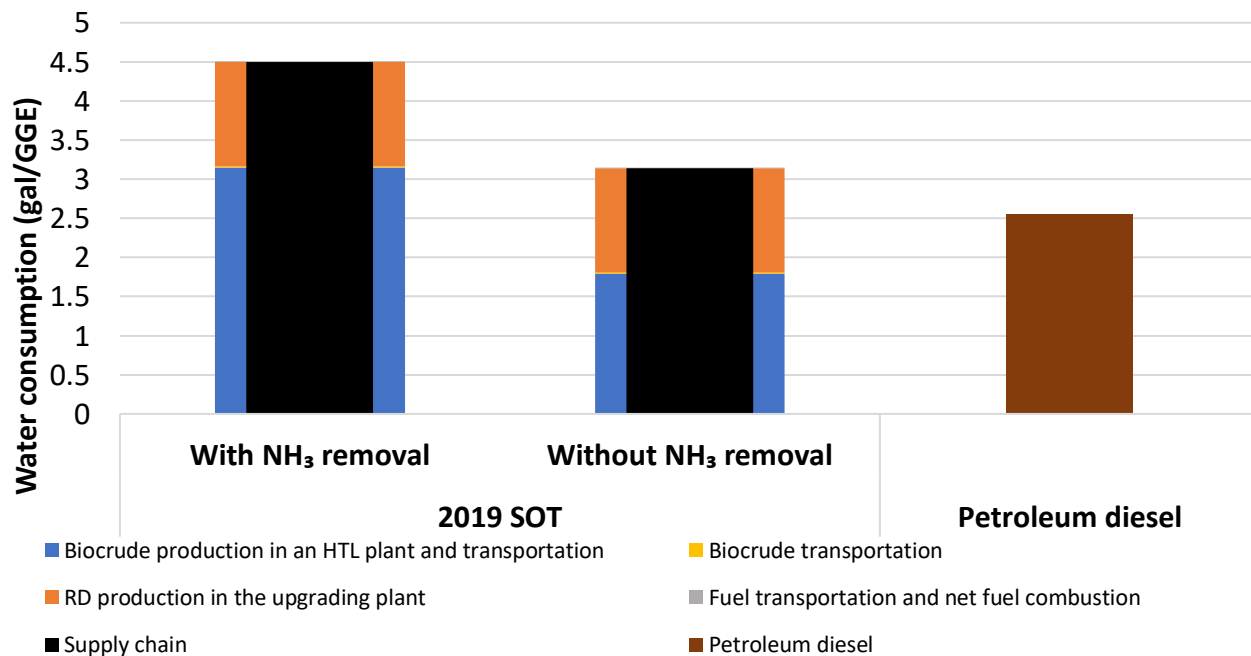


FIGURE 16 Supply Chain Water Consumption (gal/GGE) for Renewable Diesel via Sludge HTL, Compared to 2.7 gal/GGE for Petroleum Diesel

3.3.3 Supply Chain NO_x Emissions

Figure 17 shows that total supply chain NO_x emissions are about 0.07 and 0.06 g/MJ with and without NH₃ removal, respectively, in the 2019 SOT case. The main contributor of NO_x emissions is fuel combustion, which is assumed to be equivalent to that of petroleum diesel

combustion as modeled in GREET, and the second largest contributor is NO_x emissions associated with energy consumption during biocrude production.

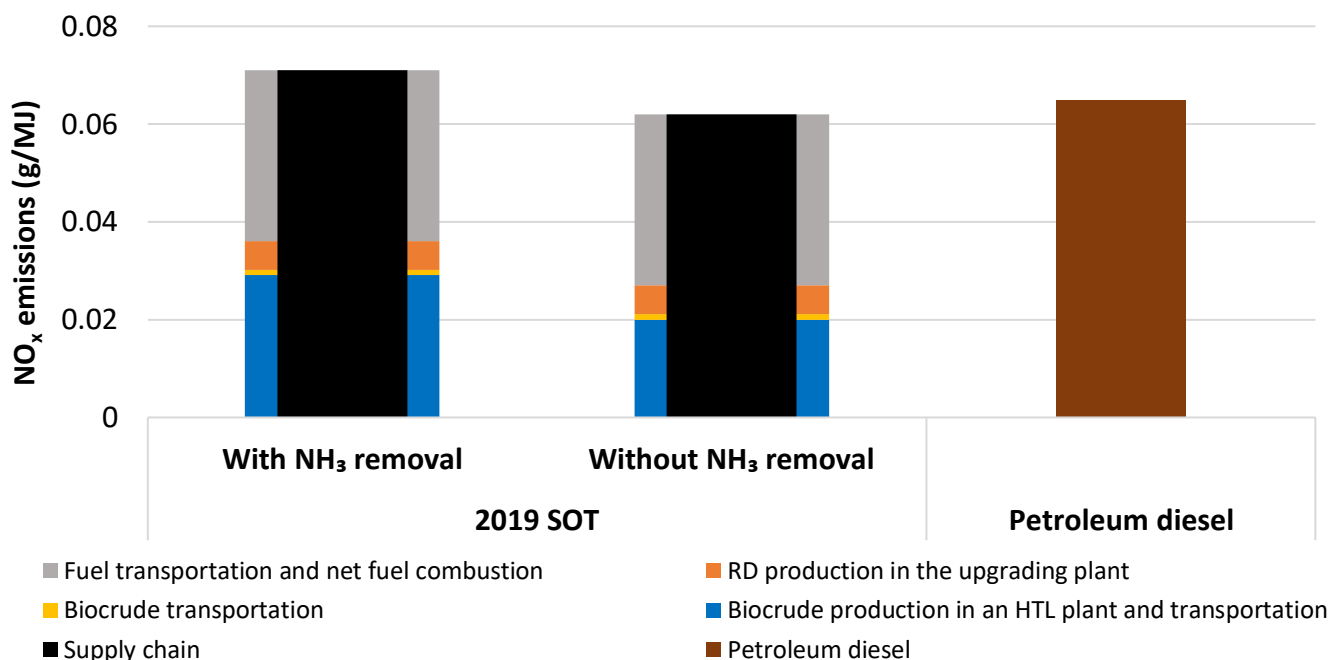


FIGURE 17 Supply Chain NO_x Emissions (g/MJ), Renewable Diesel via HTL, Compared to 0.07 g/MJ for Petroleum Diesel

3.3.4 Summary of Sustainability Metrics

Table 16 summarizes the SCSA sustainability metrics evaluated for the 2019 SOT case of RD production from wet sludge via the HTL and upgrading processes. The 2019 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. As presented in Table 16, the supply chain fossil energy consumption of the 2019 SOT cases is 0.58 and 0.46 MJ per MJ of RD, in the “with NH₃ removal” scenario and “without NH₃ removal” scenario, respectively. The NEB of RD is 0.42 MJ/MJ (with NH₃ removal) and 0.54 MJ/MJ (without NH₃ removal) for the 2019 SOT case of the sludge HTL pathway.

The sludge HTL pathway shows a minimal urban NO_x emission reduction potential in the 2019 SOT case, compared with those of petroleum diesel.

TABLE 16 Supply Chain Sustainability Metrics for Renewable Diesel via Sludge HTL

	2019 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	0.58 (-52%)	0.46 (-62%)	1.2
		Net energy balance	
MJ/MJ	0.42	0.54	
		GHG emissions	
g CO ₂ e/MJ	49 (-48%)	32 (-66%)	94
g CO ₂ e/ GGE	5,946	3,977	11,528
		Water consumption	
gal /MJ	0.037	0.026	0.02
gal/ GGE	4.5	3.1	2.7
		Total NO_x emissions	
g NO _x /MJ	0.07	0.06	0.07
g NO _x /GGE	8.7	7.6	7.9
		Urban NO_x emissions	
g NO _x /MJ	0.03	0.03	0.03
g NO _x /GGE	3.4	3.3	3.5

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 2019 SOT case of herbaceous feedstock blends with the 2019 SOT case of the biochemical conversion pathways via acids and BDO intermediates. The displacement method is applied to address the AA coproduct (Cai et al., 2018b).

3.4.1 Supply Chain Greenhouse Gas Emissions

Figure 18 shows the supply chain GHG emissions and their key contributing supply chain processes, in g CO₂e/MJ of RD, in the 2019 SOT case, compared with a life-cycle carbon intensity of 94 g CO₂e/MJ for petroleum diesel. The displacement method is applied to address the co-product effects. The results for two conversion process designs that either burn the lignin to generate heat and power for use by the conversion process or convert and upgrade the lignin to AA are presented. In both process designs, the conversion step is the major GHG emission source of the entire supply chain. In the lignin upgrading to AA case, large quantities of process

chemicals are consumed at

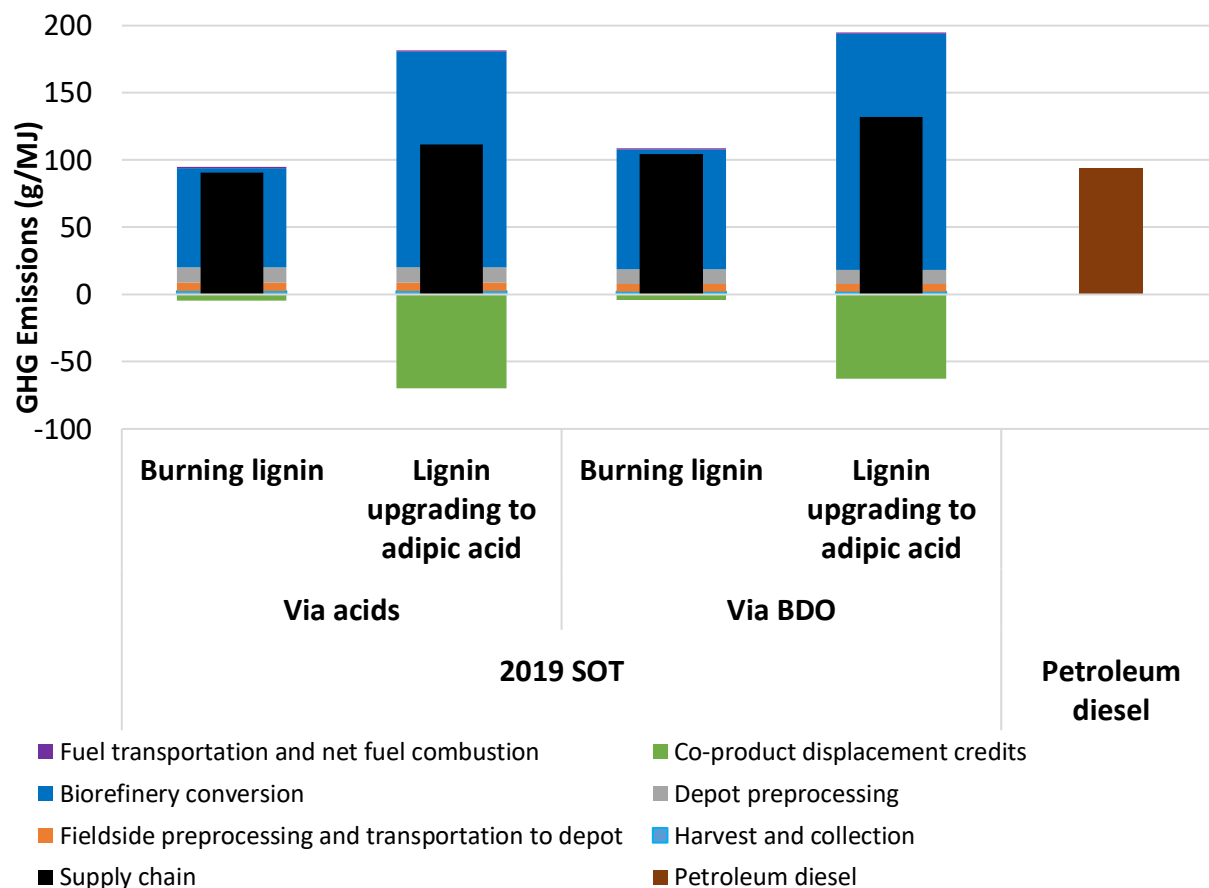


FIGURE 18 Supply Chain GHG Emissions (g CO₂e/MJ), Renewable Diesel via Biochemical Conversion

the DMR pretreatment step and later at the lignin upgrading step to produce AA coproduct. These chemicals are responsible for a significant amount of GHG emissions. With the displacement method, the lignin-derived AA, together with the recovered sodium sulfate salt from WWTP translates to a displacement emission credit of about 70 and 63 g CO₂e/MJ in the via acids and via BDO routes, respectively. 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 the via acids and via BDO cases because the emissions associated with the additional chemical and energy requirement to complete the conversion process with co-production of AA outweigh those displacement emission credits. The overall net GHG emission intensities of the fuel in these designs may offer little or no benefit for emission reductions in the 2019 SOT case (at the current SOT performance levels for converting lignin to AA), relative to burning lignin. However, the GHG emission intensities are projected to substantially improve in the 2030 target cases to surpass the 60% GHG reduction metric when applying the same displacement method to address the co-product effects (Cai et al., 2018a). Note that ANL is reevaluating how to assign

the GHG emission impacts of co-products between the fuel product and non-fuel co-products. These changes will be reflected in the upcoming 2020 SOT publications and future target cases, and in future updates to this document.

3.4.2 Supply Chain Water Consumption

Figure 19 shows that both 2019 SOT cases have higher water consumption than that of petroleum diesel, regardless of the intermediate pathway and coproduct handling method, owing to significant embedded water consumption associated with the process chemical use, as well as to makeup water requirements during the biochemical conversion process (driven by cooling demands in the process and utilities operations, as well as process water requirements and losses attributed to biochemical processing at 20-30 wt% solids with high water flows throughout). Direct water consumption for the conversion process within the biorefinery is 9 gal/GGE and 20 gal/GGE for the BDO and acids pathways respectively, excluding embedded water for process chemical use.

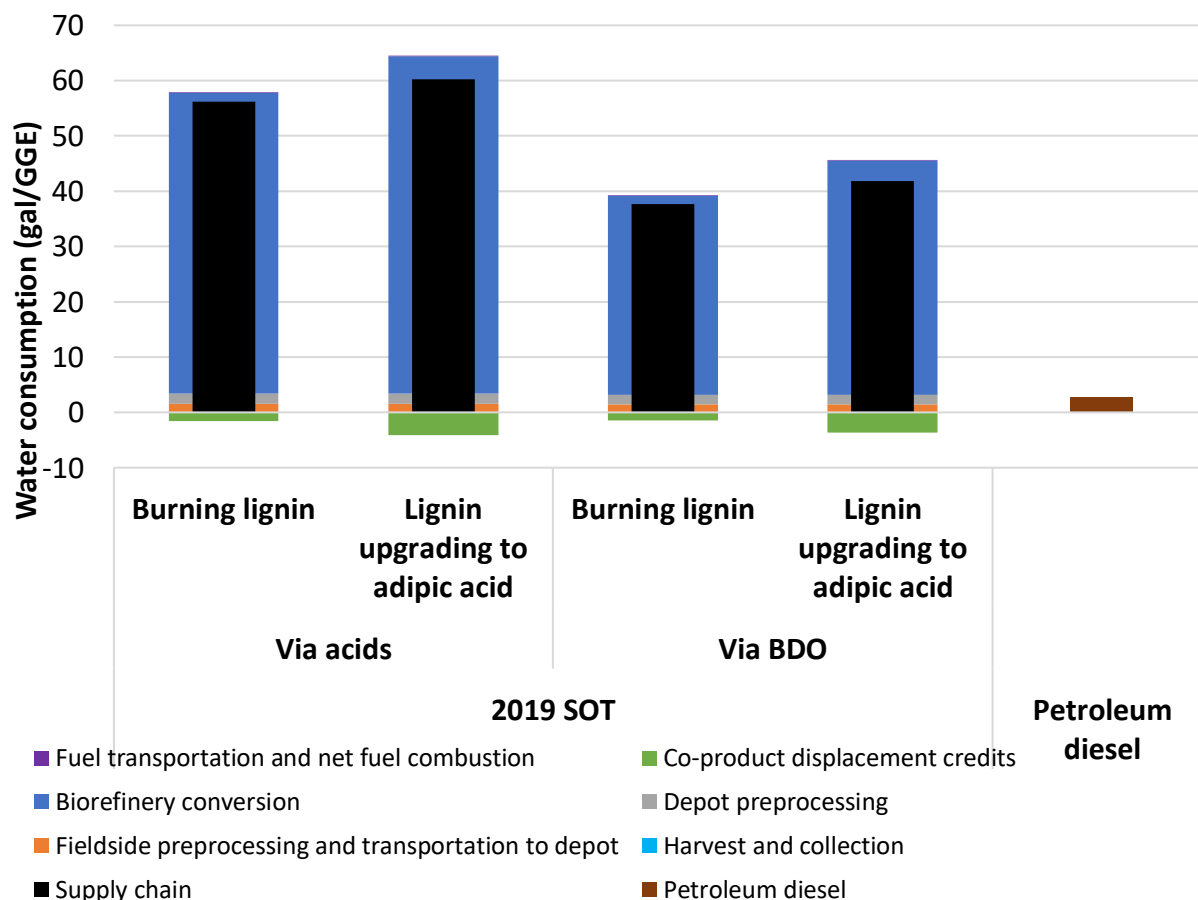


FIGURE 19 Supply Chain Water Consumption (gal/GGE), Renewable Diesel via Biochemical Conversion, Compared to 2.7 gal/GGE for Petroleum Diesel

3.4.3 Supply Chain NO_x Emissions

Figure 20 shows that total NO_x emissions are higher than those of petroleum diesel in the 2019 SOT case, regardless of the intermediate pathway and coproduct handling method used, with biorefinery conversion being the largest contributor to the NO_x emissions.

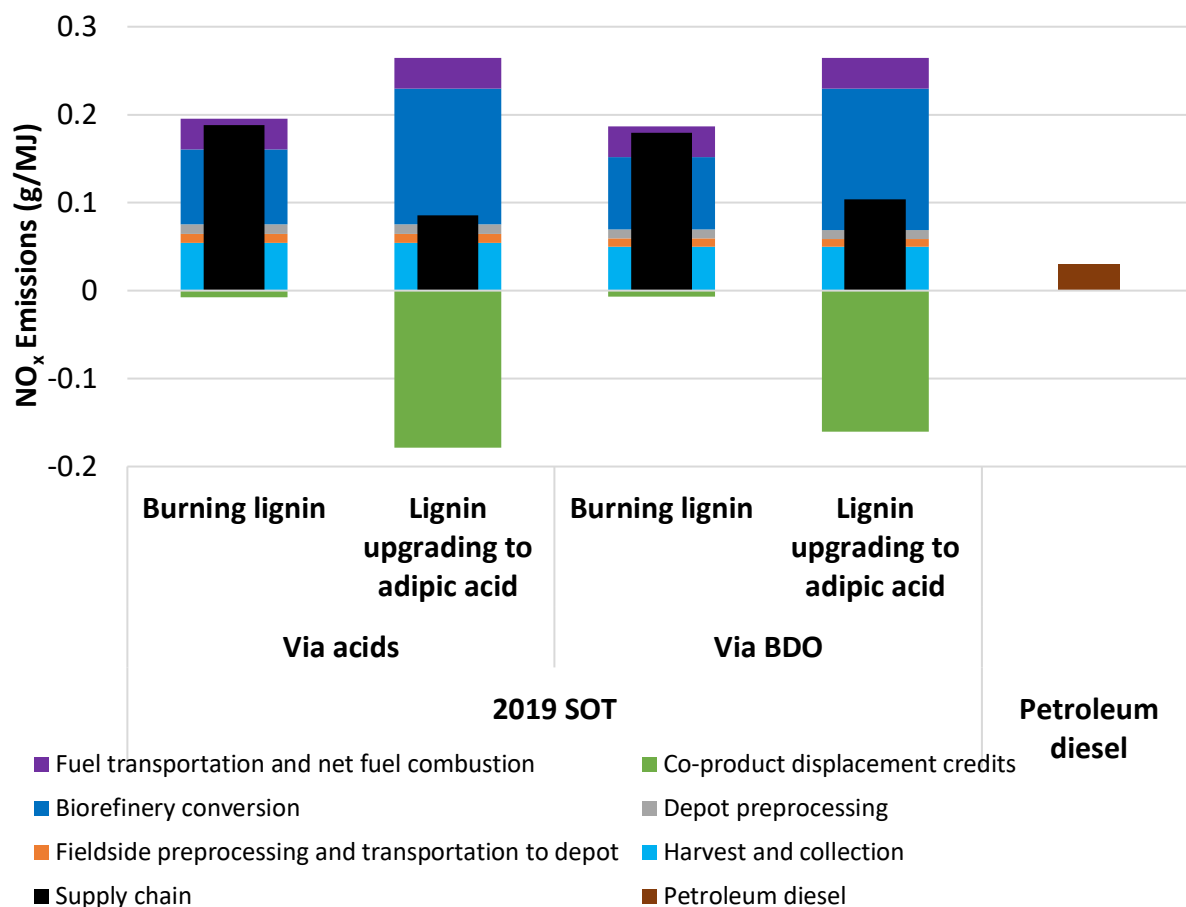


FIGURE 20 Supply Chain NO_x Emissions (g/MJ), Renewable Diesel via Biochemical Conversion, Relative to 0.07 g/MJ for Petroleum Diesel

3.4.4 Summary of Sustainability Metrics

Table 17 summarizes the supply chain sustainability metrics, including fossil energy consumption, NEB, GHG emissions, water consumption, and NO_x emissions of the renewable hydrocarbon fuels from these biochemical conversion designs. Again, these sustainability metrics are projected to substantially improve in the 2030 target cases with the displacement method to address the co-product effects, relative to those reflected here for the 2019 SOT cases (Cai et al., 2018a). Going forward, ANL is reevaluating how to address the GHG emission

impacts of co-products. These changes will be reflected in the upcoming 2020 SOT publications, and in future updates to this document.

TABLE 17 Supply Chain Sustainability Metrics for Renewable Diesel via Biochemical Pathway

	2019 SOT				
	Scenario 1: Via Acids		Scenario 2: Via BDO		Petroleum Diesel
	Burning lignin	Lignin upgrading to adipic acid	Burning lignin	Lignin upgrading to adipic acid	
Biofuel yield					
Million Btu/dry ton	4.1	4.1	4.4	4.5	
Co-product yield					
Adipic acid, Kg/mmBtu of biofuel	Not applicable	5	Not applicable	4	
Sodium sulfate, Kg/mmBtu of biofuel	Not applicable	45	Not applicable	39	
Fossil energy consumption					
MJ/MJ	1.3	1.7	1.5	2.14	1.2
Net energy balance					
MJ/MJ	-0.3	-0.7	-0.5	-1.14	
GHG emissions					
g CO ₂ e/MJ	91	112	104	132	94
g CO ₂ e/GGE	11,088	13,663	12,777	16,151	11,528
Water consumption					
gal /MJ	0.5	0.5	0.3	0.3	0.02
gal/GGE	56	60	38	42	2.7
Total NO _x emissions					
g NO _x /MJ	0.2	0.1	0.2	0.1	0.07
g NO _x /GGE	23.0	10.5	22.0	12.7	7.9
Urban NO _x emissions					
g NO _x /MJ	0.03	0.04	0.04	0.04	0.03
g NO _x /GGE	4.2	5.4	4.3	5.1	3.5

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

3.5 Algae Hydrothermal Liquefaction

The SCSA of the algae/woody blend HTL pathway incorporated the saline algae biomass cultivation data from the test-beds in the 2019 SOT case, the woody feedstock inputs from the 2019 logging residue SOT, and 2019 algae HTL SOT cases.

3.5.1 Supply Chain Greenhouse Gas Emissions

Figure 21 shows the supply chain GHG emissions and their key contributing supply chain processes, in g CO₂e/MJ, of RD in the 2019 SOT case, compared to a life-cycle carbon intensity of 94 g CO₂e/MJ for petroleum diesel. Figure 21 shows that RD reduces GHG emissions by 52% in the 2019 SOT case. The HTL conversion processes, due to their need for grid electricity, natural gas for hydrogen production, and chemicals and catalysts for biocrude production and upgrading, contribute to about 23.5 g CO₂e/MJ. The hydrogen production via steam methane reforming of natural gas is responsible for about 16.7 g CO₂e/MJ, which is the major source of GHG emissions. Electricity is consumed for algae cultivation and dewatering, and a parasitic electricity demand of 0.63 MJ/kg of CO₂ captured and transported to the algae farm is assumed (Davis et al., 2018), presenting another source of GHG emissions.

In the 2019 SOT case, co-feeding woody feedstock with algae has a small emission impact, accounting for about 4.3 g CO₂e/MJ.

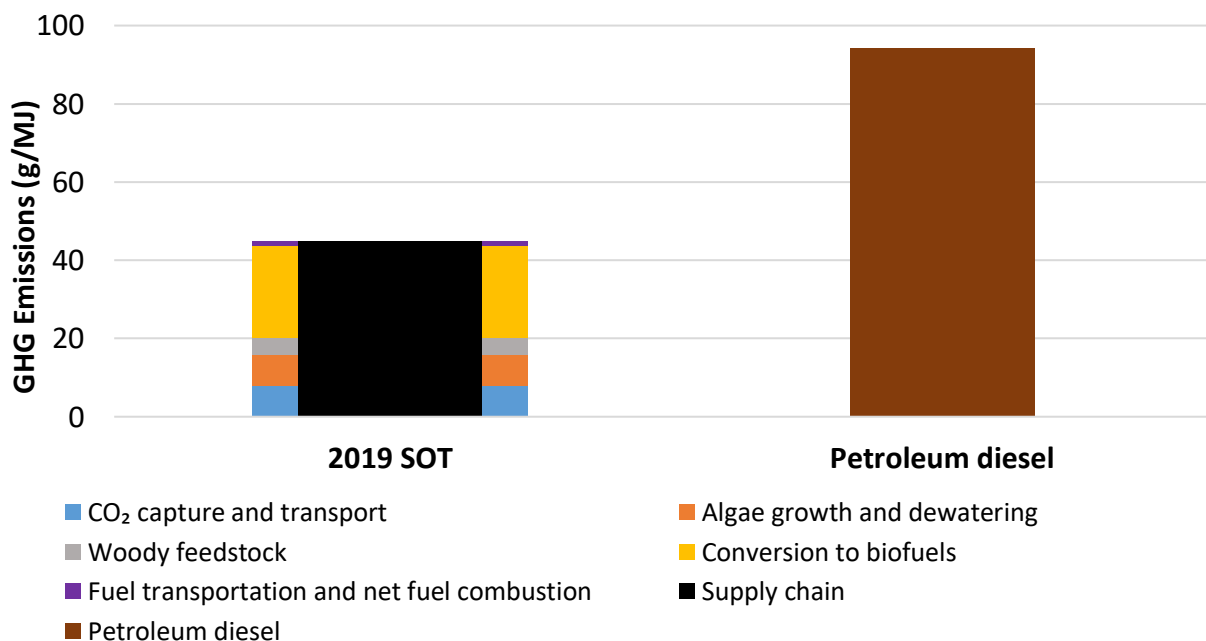


FIGURE 21 Supply Chain GHG Emissions (g CO₂e/MJ), Renewable Diesel via Algae HTL

3.5.2 Supply Chain Water Consumption

Figure 22 shows that in the 2019 SOT case, embedded water consumption associated with energy consumption for algae dewatering and for CO₂ capture and transportation to the algae farm is the major contributor to supply chain water consumption. Embedded water consumption associated with natural gas consumption for hydrogen production and with chemical and catalyst use during the HTL processes 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 fresh water consumption.

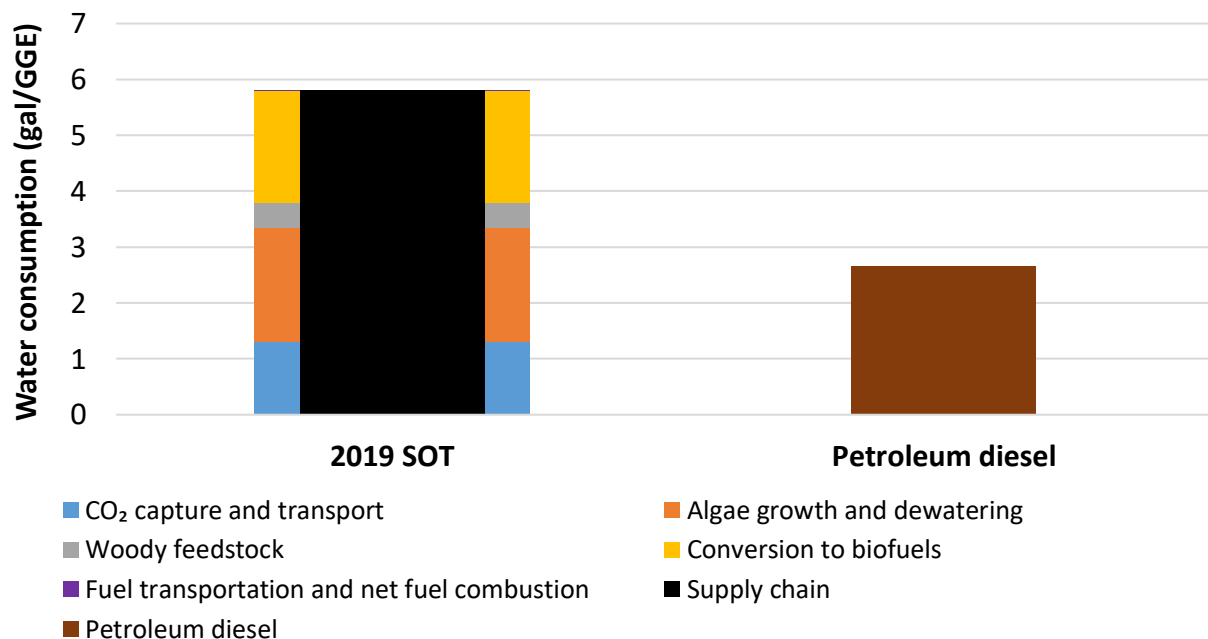


FIGURE 22 Supply Chain Water Consumption (gal/GGE), Renewable Diesel via Algae HTL, Compared with 2.7 gal/GGE for Petroleum Diesel

3.5.3 Supply Chain NO_x Emissions

Total NO_x emissions are about 33% higher in the 2019 SOT case than those of petroleum diesel. Figure 23 shows that combustion of the RD fuel is the largest emission source, given the assumption that the fuel has the same NO_x emission factor as petroleum diesel. The HTL conversion processes account for about 23% of the total emissions in both SOT cases, due to their energy and catalyst consumption. The emissions associated with the net nutrient consumption after recycled nutrients from HTL effluent reduce the virgin nutrient demand, and

the emissions associated with the electricity demand for CO₂

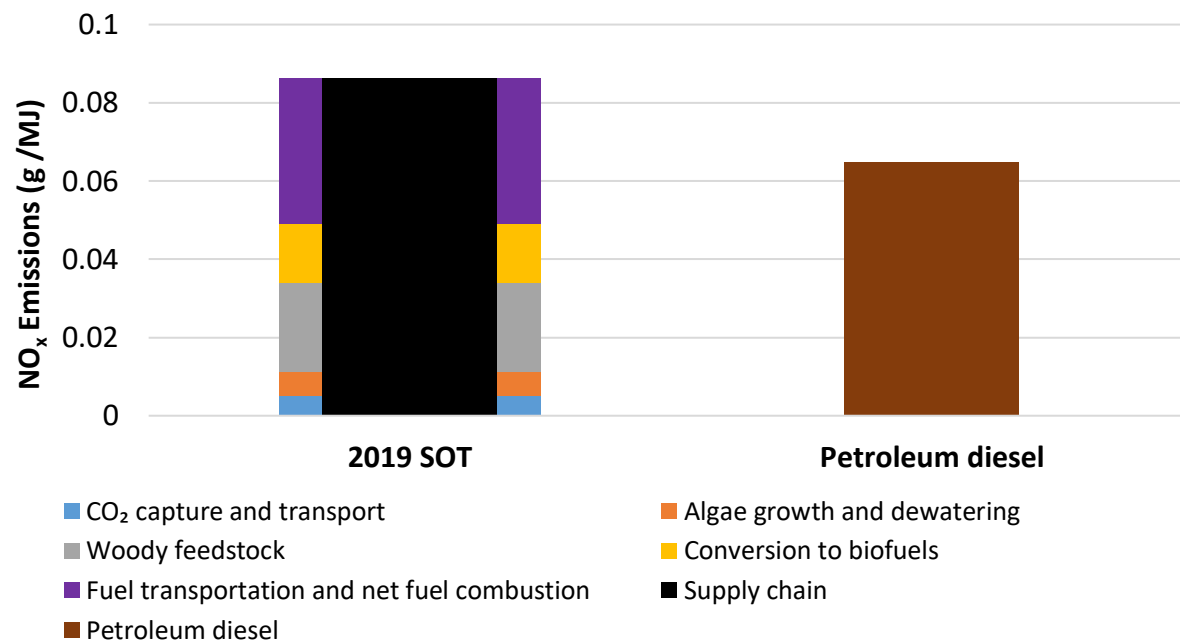


FIGURE 23 Supply Chain NO_x Emissions (g/MJ), Renewable Diesel via Algae HTL, Relative to 0.07 g/MJ for Petroleum Diesel

capture and transportation to the algae farm collectively contribute 8% of the total NO_x emissions in the 2019 SOT case. Again, co-feeding woody biomass with algae has a small NO_x emission impact.

3.5.4 Summary of Sustainability Metrics

Table 18 summarizes the supply chain sustainability metrics, including fossil energy consumption, NEB, GHG emissions, water consumption, and NO_x emissions, of RD from co-feeding algae with woody biomass via HTL in the 2019 SOT case. Fossil energy consumption is 49% lower compared with that of petroleum diesel, resulting in an NEB of about 0.39 MJ/MJ in the 2019 SOT case.

Despite somewhat higher total supply chain NO_x emissions than those of petroleum diesel, the algae HTL pathway sees benefits in urban NO_x emission reductions in the 2019 SOT case, since the algae farm, the woody feedstock logistics, and the HTL and upgrading plant that are important emission sources of RD are assumed to occur in rural, non-MSA areas.

TABLE 18 Supply Chain Sustainability Metrics for Renewable Diesel via Algae HTL

	2019 SOT	Petroleum Diesel
Biofuel yield		
Million Btu/dry ton	11.9	
Fossil energy consumption		
MJ/MJ	0.61 (-49%)	1.2
Net energy balance		
MJ/MJ	0.39	
GHG emissions		
g CO ₂ e/MJ	45 (-52%)	94
g CO ₂ e/GGE	5,500	11,528
Water consumption		
gal/MJ	0.05	0.02
gal/ GGE	6	2.7
Total NO_x emissions		
g NO _x /MJ	0.09	0.07
g NO _x /GGE	10.6	7.9
Urban NO_x emissions		
g NO _x /MJ	0.025	0.03
g NO _x /GGE	3.0	3.5

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

3.6 Combined Algae Processing

The SCSA of the CAP pathway incorporated the 2019 SOT case for algae biomass cultivation with unlined ponds using saline algae strains, as well as the 2019 SOT case for CAP conversion for both the acids and BDO pathway designs. A displacement method is applied to account for the displacement credits of surplus electricity exported to the grid.

3.6.1 Supply Chain Greenhouse Gas Emissions

Figure 24 shows the supply chain GHG emissions and their key contributing supply chain processes, in g CO₂e/MJ, of RD in the 2019 SOT case, compared with a life-cycle carbon intensity of 94 g CO₂e/MJ for petroleum diesel. GHG emissions of RD in the 2019 SOT cases are about 20% and 25% lower than those of petroleum diesel based on the acids and BDO pathways, respectively.

Manufacturing of chemicals and catalyst for use in the CAP conversion processes is the primary emission source in the 2019 SOT case. Beyond this, energy consumption for CO₂ capture and transportation to the algae farm and for algae growth and dewatering 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 shown below for the algae production phase. Similar to the Biochemical Conversion pathway discussed above, the GHG emissions profiles for the algae CAP pathway are expected to improve substantially moving forward to future 2030 projection cases, driven primarily by the future addition of a high-value co-product (polyurethane), relative to the 2019 SOT cases shown here.

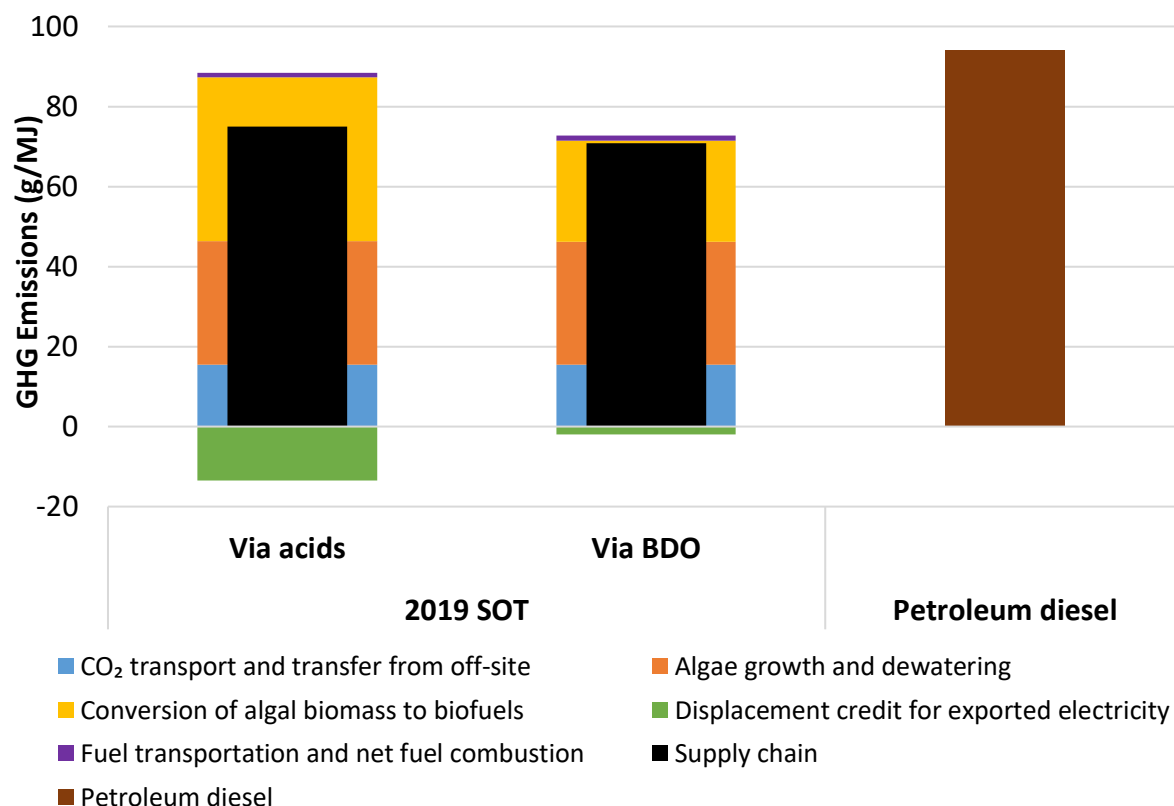


FIGURE 24 Supply Chain GHG Emissions (g CO₂e/MJ), Renewable Diesel via CAP

3.6.2 Supply Chain Water Consumption

Figure 25 shows that the 2019 SOT case has higher water consumption than that of petroleum diesel, owing to significant embedded water consumption associated with the process chemical and catalyst use, as well as to makeup water requirements for the CAP conversion process. Direct water consumption within the biorefinery process itself is 10 and 14 gal/GGE for the acids and BDO pathways, respectively (excluding water consumption embedded in chemical usage). Water consumption associated with electricity demands for algae cultivation and dewatering is another major driver. For the same reasons described in the biochemical conversion pathway, the co-product displacement credit has a much smaller impact on supply chain water consumption than on the GHG emissions. With the algae cultivation models all based on saline algae production (no freshwater inputs are required for the algae production models), the saline makeup water inputs for algae cultivation do not contribute to fresh water consumption for either the CAP or HTL pathways.

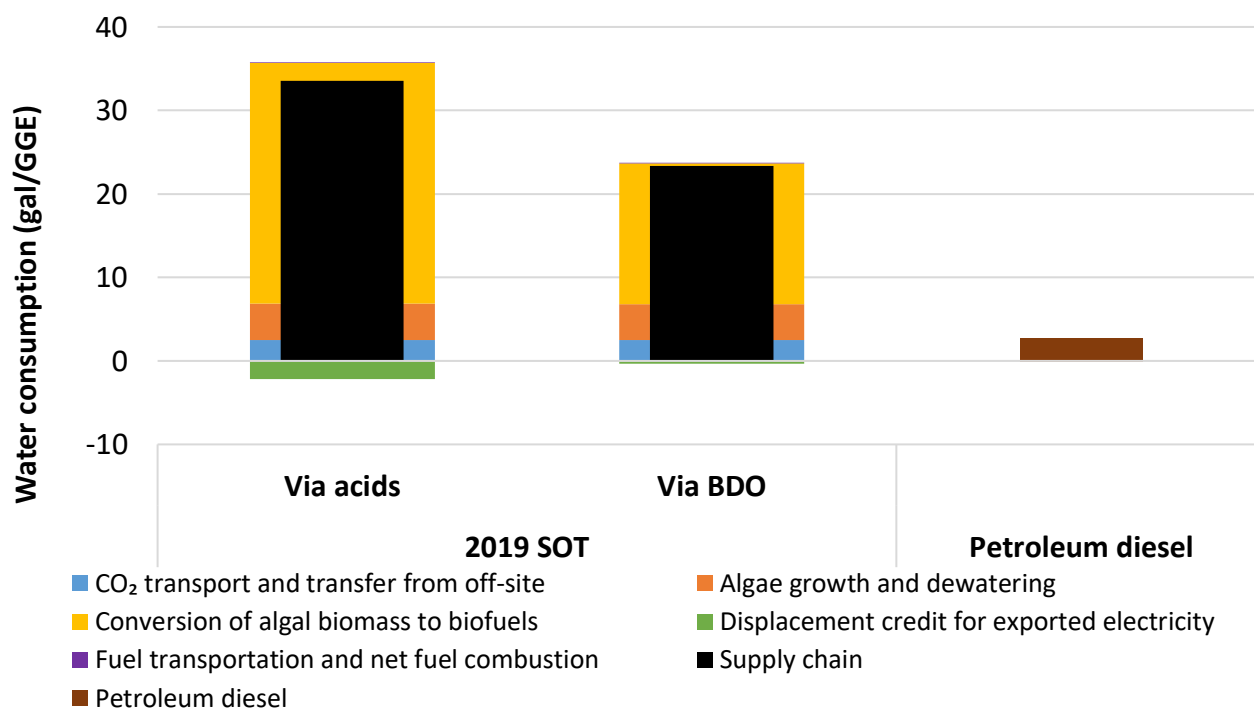


FIGURE 25 Supply Chain Water Consumption (gal/GGE), Renewable Diesel via CAP, Compared with 2.7 gal/GGE for Petroleum Diesel

3.6.3 Supply Chain NO_x Emissions

Figure 26 shows that total NO_x emissions from the 2019 SOT cases are 78% and 47% higher than petroleum diesel for the acids and BDO pathway designs, respectively. Embedded emissions from manufacturing the process chemicals and catalysts required for the CAP conversion is the major emission source.

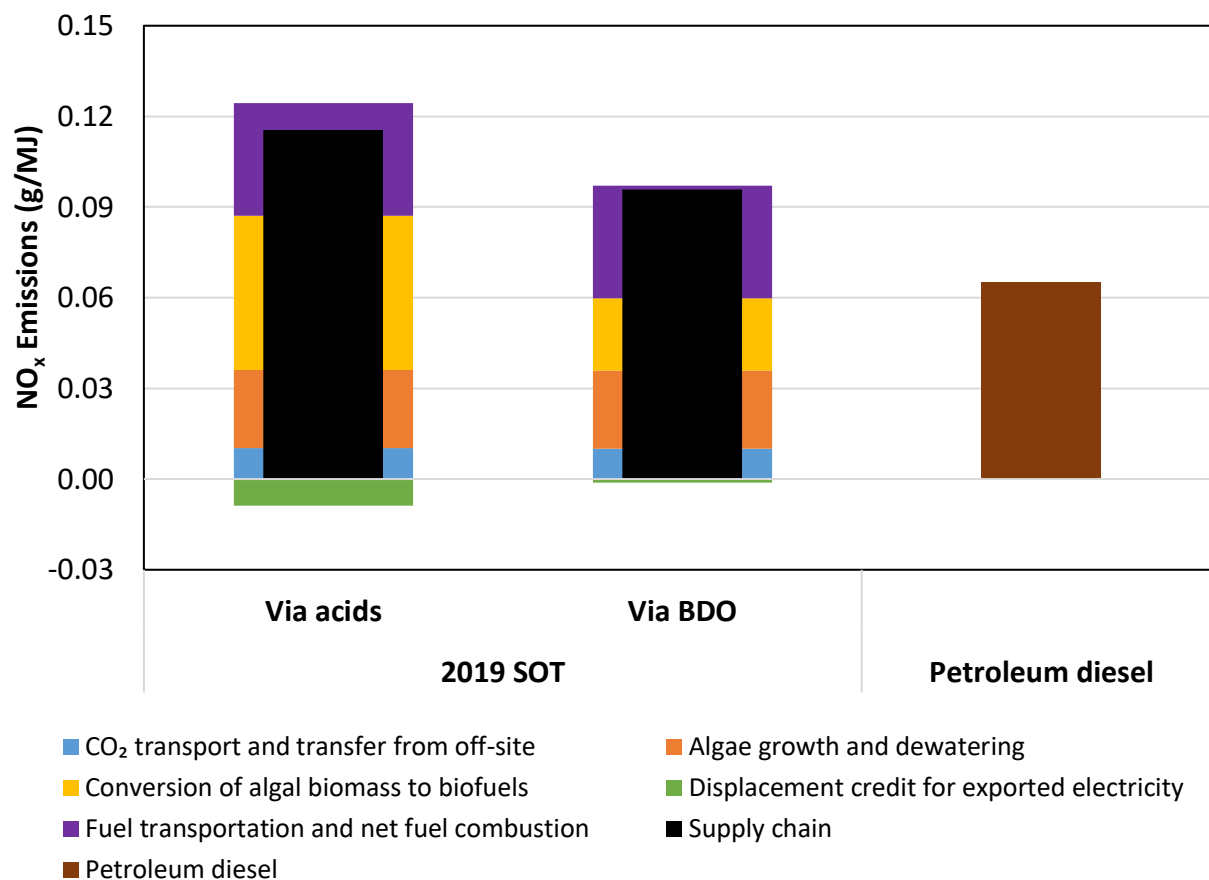


FIGURE 26 Supply Chain NO_x Emissions (g/MJ), Renewable Diesel via CAP, Compared with 0.07 g/MJ for Petroleum Diesel

3.6.4 Summary of Sustainability Metrics

Table 19 summarizes the supply chain sustainability metrics, including fossil energy consumption, NEB, GHG emissions, water consumption, and NO_x emissions of RD from these CAP conversion design 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 the fresh makeup requirements of such nutrients in the algae cultivation phase. Again, these sustainability metrics are projected to substantially improve in the future by 2030 with the addition of co-products, when reflected with the displacement method to address the co-product effects (Cai et al., 2018a). Again, ANL is reevaluating how to address the GHG emission impacts of co-products. These changes will be reflected in the upcoming 2020 SOT publications, in future updates to this document, and in those projection cases presented in the previous SCSA report (Cai et al., 2018a).

TABLE 19 Supply Chain Sustainability Metrics for Renewable Diesel via CAP

	2019 SOT		Petroleum Diesel
	Via acids	Via BDO	
Million Btu/dry ton	10.6	Biofuel Yield 10.6	
MJ/MJ	1.03 (-14%)	Fossil energy consumption 0.99 (-18%)	1.2
MJ/MJ	-0.03	Net energy balance 0.01	
g CO ₂ e/MJ	75 (-20%)	GHG emissions 71 (-25%)	94
g CO ₂ e/ GGE	9,185	8,664	11,528
gal /MJ	0.27	Water consumption 0.19	0.02
gal/ GGE	33.5	23.4	2.7
g NO _x /MJ	0.12	Total NO_x emissions 0.10	0.07
g NO _x /GGE	14.1	11.7	7.9
g NO _x /MJ	0.03	Urban NO_x emissions 0.03	0.03
g NO _x /GGE	3.8	4.0	3.5

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

4 CONCLUSIONS

Producing HOG via IDL from logging residues in the 2019 SOT case yields a fuel that is 78% 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 the 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 2019 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 an 83% reduction in GHG emissions for the 2019 SOT case. Among the different supply chain stages, biomass field and depot preprocessing were the largest contributors to the supply chain GHG emissions. Coproducts, especially acetone, generates significant GHG emission credits 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. Driving down conversion water consumption remains an opportunity for further mitigating the supply chain water consumption of the CFP pathway.

Controlling NO_x emissions from combusting intermediate bio-char to meet process heat demand presents an opportunity to mitigate the supply chain NO_x emissions. The energy-intensive preprocessing step is another major opportunity to mitigate NO_x emissions in the 2019 SOT case. The NEB of RG and RD from CFP is about 0.81 MJ/MJ in the 2019 SOT case.

Producing RD via sludge HTL in the 2019 SOT case offers 48% and 66% GHG emission reductions with and without NH_3 removal, respectively. Supply chain water consumption is 4.5 gal/GGE and 3.1 gal/GGE with and without NH_3 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 (Cai et al., 2018a). The sludge HTL pathway has a NEB of 0.42 MJ/MJ (with NH_3 removal) and 0.54 MJ/MJ (without NH_3 removal) in the 2019 SOT case.

For the biochemical conversion pathway producing AA as a co-product from lignin upgrading, the conversion step is the primary GHG emission source in the 2019 SOT case, owing to large quantities of process chemicals required for pretreatment operations and for upgrading the lignin stream to AA. In the burning lignin case, supply chain GHG emissions are 91 g CO₂e/MJ and 104 g CO₂e/MJ for the SOT acids and BDO intermediate pathways, respectively. In the lignin upgrading to AA case, supply chain GHG emissions are 112 g CO₂e/MJ and 132 g CO₂e/MJ for the SOT acids and BDO intermediate pathways, respectively, when the coproduct AA is handled with the displacement method. Significant embedded water consumption associated with the process chemical use, as well as makeup water requirements during the biochemical conversion process, lead to higher water consumption in the 2019 SOT case, compared with that of petroleum diesel.

RD biofuel produced from co-feeding algae and woody biomass to the HTL processes offers a 52% reduction in GHG emissions in the 2019 case compared with those of petroleum diesel. 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 the 2019 SOT case. Embedded water consumption associated with energy consumption for algae cultivation and dewatering and for CO₂ capture and transportation to the algae farm are the major contributors to supply chain water consumption in the 2019 SOT case. Increasing algal biomass productivity and reducing energy consumption for algal biomass cultivation and dewatering and HTL conversion would be key to mitigating water consumption as well as NO_x emissions.

In the 2019 SOT case, the algae CAP pathway has 20% and 25% lower GHG emission intensity via the acids and BDO intermediate pathways, respectively, 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 both 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.

Finally, it must be emphasized that the SCSA results presented here are reflective of current SOT performance benchmarks for all process pathways evaluated. They do not represent best-case results. Many pathways are projected to significantly improve moving forward to future design case targets by 2030 (Cai et al., 2018a), tied both to further research performance improvements as well as further introduction or optimization of coproducts, which can significantly change biorefinery SCSA results relative to those presented here for SOT baselines. In future design cases that include production of a significant amount of coproducts, ANL is reevaluating how to address the impacts of co-products on the sustainability performance of the fuel products in such cases. The changes will be reflected in the upcoming 2020 SOT publications, in future updates to this document, and in those future design cases presented in the previous SCSA report (Cai et al., 2018a)..

5 BIBLIOGRAPHY

ANL, NREL, PNNL. 2012. Renewable Diesel from Algal Lipids: An Integrated Baseline for Cost, Emissions, and Resource Potential from a Harmonized Model. ANL/ESD/12-4; NREL/TP-5100-55431; PNNL-21437. Argonne, IL: Argonne National Laboratory; Golden, CO: National Renewable Energy Laboratory; Richland, WA: Pacific Northwest National Laboratory. <https://www.nrel.gov/docs/fy12osti/55431.pdf>.

Cai, Hao, Thathiana Benavides, Uisung Lee, Michael Wang, Eric Tan, Ryan Davis, Abhijit Dutta, Mary Bidy, Jennifer Clippinger, Nicholas, Ling Tao, Damon Hartley, Mohammad Roni, David Thompson, Lesley Snowden-swan, Yunhua Zhu, Suanne Jones. 2018a. Supply chain sustainability analysis of renewable hydrocarbon fuels via indirect liquefaction, ex situ catalytic fast pyrolysis, hydrothermal liquefaction, and biochemical conversion: update of the 2018 state-of-technology cases and design cases. https://greet.es.anl.gov/publication-supply_renewable_hc

Cai, Hao, Jeongwoo Han, Michael Wang, Ryan Davis, Mary Bidy, and Eric Tan. 2018b. Life-Cycle Analysis of Integrated Biorefineries with Co-Production of Biofuels and Bio-Based Chemicals: Co-Product Handling Methods and Implications. *Biofuels, Bioproducts and Biorefining* 12 (5): 815–33. <https://doi.org/10.1002/bbb.1893>.

Canter, Christina E., Zhangcai Qin, Hao Cai, Jennifer Dunn, and Michael Wang. 2016. Update to Herbaceous and Short Rotation Woody Crops in GREET® Based on the 2016 Billion Ton Study. <https://greet.es.anl.gov/publication-bts-2016>.

Davis, Ryan, Andre Coleman, Mark Wigmosta, Jennifer Markham, Christopher Kinchin, Yunhua Zhu, Suzanne Jones, et al. 2018. “2017 Algae Harmonization Study: Evaluating the Potential for Future Algal Biofuel Costs, Sustainability, and Resource Assessment from Harmonized Modeling.” NREL/TP-5100-70715.

Davis, Ryan and Lieve Laurens. 2020. Algal Biomass Productino via Open Pond Algae Farm Cultivation: 2019 State of Technology and Future Research. National Renewable Energy Laboratory, Technical Report, NREL/TP-5100-76569.

Davis, Ryan, Andrew Bartling, and Ling Tao. 2020a. Biochemical Conversion of Lignocellulosic Biomass to Hydrocarbon Fuels and Products: 2019 State of Technology and Future Research. National Renewable Energy Laboratory, Technical Report, NREL/TP-5100-76567.

Davis, Ryan and Matthew Wiatrowski. 2020b. Algal Biomass Conversion to Fuels via Combined Algae Processing (CAP): 2019 State of Technology and Future Research. National Renewable Energy Laboratory, Technical Report, NREL/TP-5100-76568.

Dutta, Abhijit, Kristiina Iisa, Michael Talmadge, Calvin Mukarakate, Michael Griffin, Eric Tan, Nolan Wilson, et al. 2020. Ex Situ Catalytic Fast Pyrolysis of Lignocellulosic Biomass to Hydrocarbon Fuels: 2019 State of Technology and Future Research. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5100-76269.

Hartley, Damon S, Thompson, David N, and Cai, Hao. 2020. "Woody Feedstocks 2019 State of Technology Report". United States. INL/EXT-20-57181-Rev000. doi:10.2172/1607741

Roni, Mohammad, Yingqian Lin, David Thompson, Damon Hartley, Mike Griffel, and Hao Cai. 2020. Herbaceous Feedstock 2019 State of Technology Report. INL/EXT-20-57182.

Snowden-Swan, Lesley, R. Hallen, Yunhua Zhu, T. Hart, M. Bearden, J. Liu, T. Seiple, et al. 2017. Conceptual Biorefinery Design and Research Targeted for 2022: Hydrothermal Liquefaction Processing of Wet Waste to Fuels, 89.

Tan, Eric C.D., Dan Ruddy, Connor Nash, Dan Dupuis, Kylee Harris, Abhijit Dutta, Damon Hartley, and Hao Cai. 2019. High-Octane Gasoline from Lignocellulosic Biomass via Syngas and Methanol/Dimethyl Ether Intermediates: 2019 State of Technology. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5100-76619.

U.S. Department of Energy. 2016. Multi-Year Program Plan. <http://energy.gov/eere/bioenergy/downloads/bioenergy-technologies-office-multi-year-program-plan-march-2016>.

Wang, Michael, Amgad Elgowainy, Uisung Lee, Thathiana Benavides, Andrew Burnham, Hao Cai, Qiang Dai, Troy Hawkins, et al. 2019. Argonne GREET Publication: Summary of Expansions and Updates in GREET® 2019. <https://greet.es.anl.gov/publication-greet-2019-summary>.

Zhu, Yunhua, Susanne Jones, Andrew Schmidt, Justin Billing, Michael Thorson, Daniel Santosa, and Richard Hallen, Daniel Anderson. 2020. Algae/Wood Blends Hydrothermal Liquefaction and Upgrading: 2019 State of Technology. PNNL-29861. Richland, WA: Pacific Northwest National Laboratory.



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