

**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 2018 State-of-Technology Cases and Design Cases**

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**Energy Systems Division**

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by

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# 1 INTRODUCTION

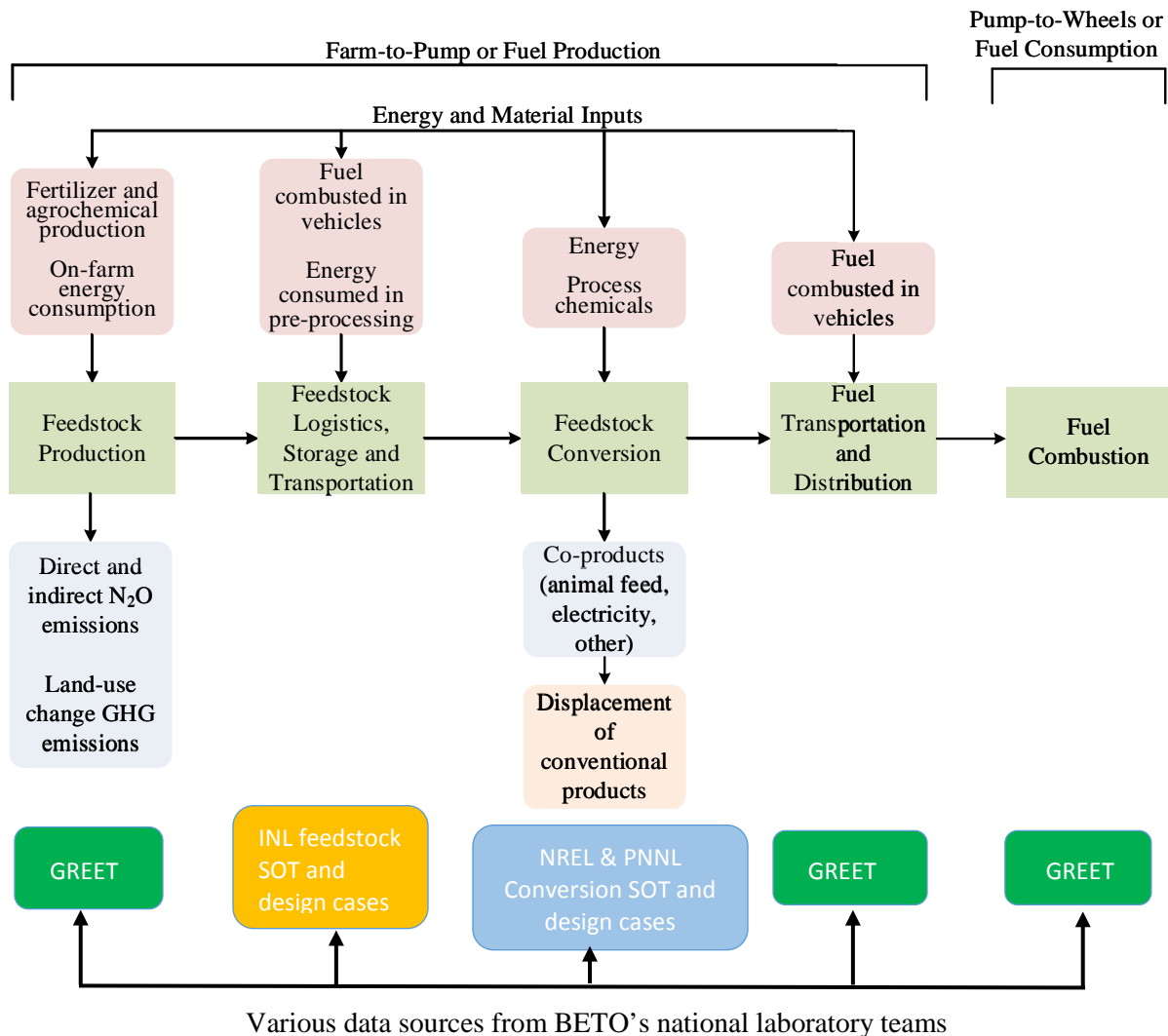
The Department of Energy's (DOE's) Bioenergy Technologies Office (BETO) aims to develop and deploy technologies to transform renewable biomass resources into commercially viable, high-performance biofuels, bioproducts and biopower through public and private partnerships (U.S. Department of Energy 2016). 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 more than 19 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 2018 SOT and 2022 design cases [Tan et al., 2018]); (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 2018 SOT cases, as well as in their design cases (future target projections). The results of these renewable hydrocarbon fuel pathways in these SCSA analyses update those for the respective 2015 and 2016 SOT cases (Edward Frank et al. 2016; Hao Cai et al. 2016, 2017; Cai et al. 2018) in the case of IDL, algae CAP, and biochemical conversion pathways. 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 2018 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<sup>®</sup>) model, which was released in October 2018 (Wang et al. 2018). These GREET updates include production of natural gas, electricity, and petroleum-based fuels that can influence biofuels' supply chain greenhouse gas (GHG) (CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O) emissions, water consumption and air pollutant emissions. GHG emissions, water consumption, and

nitrogen oxides (NO<sub>x</sub>) 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 produce the SCSA results for the 2016 SOT, 2017 SOT, 2018 SOT, and the design cases, wherever applicable, 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<sub>x</sub>, sulfur oxides (SO<sub>x</sub>), and particulate matter with an aerodynamic diameter below 10 micrometers (PM<sub>10</sub>) and below 2.5 micrometers (PM<sub>2.5</sub>), 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 2018 SOT case and 2022 design case, Idaho National Laboratory (INL) modeled herbaceous feedstock and woody feedstock used by the biochemical conversion, IDL, CFP, and algae-woody blend HTL pathways (Hartley et al. 2018; Roni et al. 2018). The National Renewable Energy Laboratory (NREL) modeled an algal feedstock (Davis et al., 2016; Davis et al., 2018a) 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 73% two-pass corn stover, 13% three-pass corn stover, 10% switchgrass, and 4% grass clippings in the 2018 SOT case, and it comprises 50% three-pass corn stover, 33% switchgrass, 12% two-pass corn stover, and 5% grass clippings in the 2022 design 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. These projected herbaceous feedstock blends are used by the biochemical conversion pathway in the 2030 design case.

The woody feedstock for the IDL pathway in both the 2018 SOT and 2022 design cases is logging residue. The woody feedstock for the CFP pathway is clean pine in the 2018 SOT case and a 75% logging residue and 25% clean pine blend in the 2022 design case. The logging residue in the blend has been sequentially air classified to remove soil ash and the light fractions are leached to remove alkali and alkaline earth metals.

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 (L. J. Snowden-Swan et al. 2017).

The total energy and material requirements of each supply chain operation for production of the herbaceous feedstock blend and the woody feedstock are summarized in Tables 1-4.

Six different logistics operations were used to harvest, collect and preprocess the various herbaceous biomass resources into the delivered herbaceous feedstock blend in the 2018 SOT and 2022 design cases. Not all operations were undertaken for every component of the feedstock blend. Two operations that are part of biomass cultivation operations — planting and fertilization — were considered for the production of switchgrass. The use of supplementary fertilizer to maintain the soil fertility, to compensate for the nutrients lost when corn stover is removed, is considered for corn stover. Diesel is consumed for planting, farming, harvesting, collection, and transportation of the biomass. Handling of biomass at the depot consumes primarily diesel and also electricity. Biomass storage, preprocessing, and blending operations consume only electricity. Preprocessing for biomass size reduction, separation, and pelleting is an energy-intensive step compared to other unit operations of biomass logistics. Compared to the 2018 SOT case, harvest and collection of corn stover become more energy efficient, although harvest and collection of switchgrass is projected to be energy-intensive in the 2022 design case because of anticipated additional harvesting activities in the integrated landscape design. Grass clippings require storage, preprocessing, handling, and blending to become part of the feedstock blend to deliver to the biorefinery. This feedstock component has no change in energy consumption from the 2018 SOT case to the 2022 design case.

There were five different logistics operations used to harvest, collect and preprocess the logging residue used by the HOG-via IDL pathway in the 2018 SOT and 2022 design cases. Both the unit operations and the associated energy consumption are the same in both cases.

The clean pine used by the CFP pathway in the 2018 SOT requires seven logistic operations: planting, fertilizing, harvesting, collecting, landing preprocess, depot receiving, handling, storing, and preprocessing the biomass into conversion-ready feedstock. Diesel is consumed for most of these operations, except for depot receiving and handling and depot preprocessing, which consume electricity. In the logging residue and pine blend used by the CPF pathway in the 2022 design case, the most significant difference is that the depot preprocessing is much more energy-intensive because the logging residue portion of the blend goes through additional energy-intensive air classification and leaching.

The material and energy requirements for algae cultivation and dewatering in the 2018 SOT and 2030 target cases (as well as an interim 2025 case) are presented in Table 4, based on inputs furnished by NREL (Davis et al., 2016; Davis et al., 2018a). All cases utilize the same basis-model framework for an open pond algae farm consisting of 5,000 acres of cultivation area (based on production ponds), followed by three-stage dewatering to concentrate the harvested biomass to 20 wt% ash-free dry weight (AFDW) solids, also including allowances for on-site inoculum production, CO<sub>2</sub> storage, and water circulation piping. The 2018 SOT was based on

cultivation data made available from the ATP3 and DISCOVR test-bed consortia (Knoshaug, et al., 2016), as well as the RACER project awarded under competitive DOE grant funding,<sup>1</sup> all attributed to cultivation experiments conducted at Arizona State University's AzCATI site.<sup>2</sup> The 2018 SOT data are based on seasonally rotated strains for cultivation of *Nannochloropsis oceanica*, *Scenedesmus acutus*, *Monoraphidium minutum*, and *Desmodesmus* sp., resulting in an annual average productivity of 11.7 g/m<sup>2</sup>/day AFDW. The final 2030 target case maintains a projected annual average productivity of 25 g/m<sup>2</sup>/day (Davis et al, 2018), with an interim 2025 case set at 20 g/m<sup>2</sup>/day.

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<sup>1</sup> <https://www.energy.gov/eere/bioenergy/articles/energy-department-announces-35-million-advancements-algal-biomass-yield>

<sup>2</sup> <http://www.azcati.com/>

**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 2018 SOT and the 2022 Design Cases for the Biochemical Conversion Pathway (Roni et al. 2018; Canter et al. 2016a; Canter et al. 2016b)**

	2018 SOT				2022 Design			
	3-Pass Corn Stover	2-Pass Corn Stover	Switchgrass	Grass Clippings	3-Pass Corn Stover	2-Pass Corn Stover	Switchgrass	Grass Clippings
Farming			67,477				67,477	
- Diesel			100%				100%	
Fertilizers and herbicides								
- Nitrogen	3,183 <sup>a</sup>	3,183 <sup>a</sup>	4,877 <sup>b</sup>		3,183 <sup>a</sup>	3,183 <sup>a</sup>	4,877 <sup>b</sup>	
- P <sub>2</sub> O <sub>5</sub>	2,273 <sup>a</sup>	2,273 <sup>a</sup>	2,308 <sup>b</sup>		2,273 <sup>a</sup>	2,273 <sup>a</sup>	2,308 <sup>b</sup>	
- K <sub>2</sub> O	13,641 <sup>a</sup>	13,641 <sup>a</sup>	3,200 <sup>b</sup>		13,641 <sup>a</sup>	13,641 <sup>a</sup>	3,200 <sup>b</sup>	
- CaCO <sub>3</sub>			5,847 <sup>b</sup>				5,847 <sup>b</sup>	
- Herbicides			53 <sup>b</sup>				53 <sup>b</sup>	
Harvest and collection	89,040	108,560	41,270		84,260	88,170	83,520	
- Diesel	100%	100%	100%		100%	100%	100%	
Storage	10,920	10,920	10,920	8,720	10,920	10,920	10,920	8,720
- Electricity	100%	100%	100%	100%	100%	100%	100%	100%
Preprocessing	236,870	236,870	318,000	317,190	246,570	246,570	318,000	317,190
- Electricity	100%	100%	100%	100%	100%	100%	100%	100%
Handling	7,720	7,720	7,750	10,360	7,710	7,710	7,330	10,360
- Diesel	89.5%	89.5%	89.4%	85.8%	89.5%	89.5%	89.4%	85.8%
- Electricity	10.5%	10.5%	10.6%	14.2%	10.5%	10.5%	10.6%	14.2%
Blending	440	440	610	9,140	430	430	420	9,140
- Electricity	100%	100%	100%	100%	100%	100%	100%	100%

<sup>a</sup> Canter et al. 2016b

<sup>b</sup> Farming energy consumption and the fertilizer use for production of switchgrass are based on the 2016 Billion Ton Study (Canter et al. 2016a)

**TABLE 2 Energy Consumption, in Btu/Bone Dry Ton, for Logging Residue Production and Logistics in the 2016 SOT, 2017 SOT, 2018 SOT and 2022 Design Cases for HOG via IDL (Hartley et al. 2018)**

Logging Residue	
Harvest and collection	132,180
- Diesel	100%
Landing preprocessing	185,360
- Diesel	100%
Receiving & handling	11,423
- Electricity	100%
Storage	8,720
- Diesel	100%
Preprocessing	160,960
- Electricity	100%

**TABLE 3 Energy Consumption, in Btu/Bone Dry Ton, Share of Fuel Type, and Fertilizer Application, in Grams/Bone Dry Ton, for Production and Logistics of Clean Pine in the 2018 SOT Case and 75% Logging Residue and 25% Clean Pine in the 2022 Design Case for RG via CFP (Hartley et al. 2018; Canter, Qin, et al. 2016)**

	2018 SOT	2022 Design
	100% Clean Pine	75% Logging Residue and 25% Clean Pine
Silviculture	144,177 <sup>a</sup>	36,044
- Diesel	100%	100%
Fertilizers		
- Nitrogen	2,839 <sup>a</sup>	710
- P <sub>2</sub> O <sub>5</sub>	1,523 <sup>a</sup>	381
- K <sub>2</sub> O	401 <sup>a</sup>	100
- CaCO <sub>3</sub>	16,619 <sup>a</sup>	4,155
Harvest and collection	139,910	134,113
- Diesel	100%	100%
Landing preprocessing	23,840	144,980
- Diesel	100%	100%
Receiving & handling	42	8,578
- Electricity	100%	100%
Storage	9,960	9,030
- Diesel	100%	100%
Preprocessing	568,010	2,186,945
- Electricity	100%	14.3%
- Natural gas		85.7%

<sup>a</sup> The silviculture energy consumption and the fertilizer use for production of pine are based on the 2016 Billion Ton Study (Canter, Qin, et al. 2016)



**TABLE 4 Cultivation Parameters for Algae Farm Model 2018 SOT, 2025 Projection, and 2030 Design Case Scenarios (All Based on Saline Cultivation)**

Resource Consumption	2018 SOT	2025 Design	2030 Design
Electricity demand, kWh/kg AFDW <sup>a</sup>	0.70	0.42	0.36
CO <sub>2</sub> , kg/kg AFDW	2.22	2.68	2.67
Ammonia, kg/kg AFDW	0.020	0.020	0.020
Diammonium phosphate, kg/kg AFDW	0.010	0.010	0.010
Process fresh water input <sup>b</sup>	0	0	0

<sup>a</sup> Ash free dry weight

<sup>b</sup> All based on saline algae cultivation (no fresh water used in algae farm model)

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 and design cases, are shown in Tables 5 and 6. 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 5 Herbaceous Biomass Transportation Parameters, 2018 SOT and 2022 Design Cases (Roni et al. 2018)**

			Truck Payload (Dry Tons)	Transportation Distance (Miles)	Transportation Moisture Content
2018 SOT	From fieldside to depot	3-Pass corn stover	17.7	15.2	25%
		2-Pass corn stover	17.7	26.2	25%
		Switchgrass	19.4	38.1	17.5%
		Grass clippings	21.2	220	10%
	From depot to biorefinery	3-Pass corn stover	20.9	64.6	11.5%
		2-Pass corn stover	20.9	75.7	11.5%
		Switchgrass	21.5	29.9	9%
		Grass clippings <sup>NN</sup>			
2022 design	From fieldside to depot	3-Pass corn stover	18.9	49.1	20%
		2-Pass corn stover	18.9	23.0	20%
		Switchgrass	19.5	36.8	17.3%
		Grass clippings	21.2	220	10%
	From depot to biorefinery	3-Pass corn stover	21.1	48.7	10.6%
		2-Pass corn stover	21.1	86.5	10.6%
		Switchgrass <sup>NN</sup>			
		Grass clippings <sup>NN</sup>			

<sup>NN</sup> Not needed

**TABLE 6 Woody Biomass Transportation Parameters for Transportation from the Landing to the Biorefinery, 2018 SOT and 2022 Design Cases (Hartley et al. 2018)**

	Truck Payload (Dry Tons)	Transportation Distance (Miles)	Transportation Moisture Content
Logging residue <sup>a</sup>	17.7	55.3	25%
Clean pine <sup>a</sup>	17.6	251.3	30%

<sup>a</sup> For both 2018 SOT and 2022 design cases

Dry matter losses of herbaceous and woody biomass during the storage and preprocessing steps, as shown in Table 7, 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 unit ton to the biorefinery for conversion.

**TABLE 7 Dry Matter Losses (in % by Mass) of Herbaceous and Woody Biomass, 2018 SOT and 2022 Design Cases (Hartley et al. 2018, 2018; Roni et al. 2018)**

		Depot Storage	Depot Preprocessing	Landing Preprocessing	Preprocessing
Herbaceous biomass	Corn stover	12% <sup>a</sup> , 7% <sup>b</sup>	2% <sup>c</sup>		
	Switchgrass	8% <sup>a</sup> , 7% <sup>b</sup>	2% <sup>c</sup>		
	Grass clippings		2.5% <sup>c</sup>		
Woody biomass	Logging residue			5% <sup>c</sup>	10% <sup>d</sup>
	Clean pine			5% <sup>c</sup>	13% <sup>c</sup>

<sup>a</sup> For 2018 SOT case

<sup>b</sup> For 2022 design case

<sup>c</sup> For both 2018 SOT and 2022 design cases

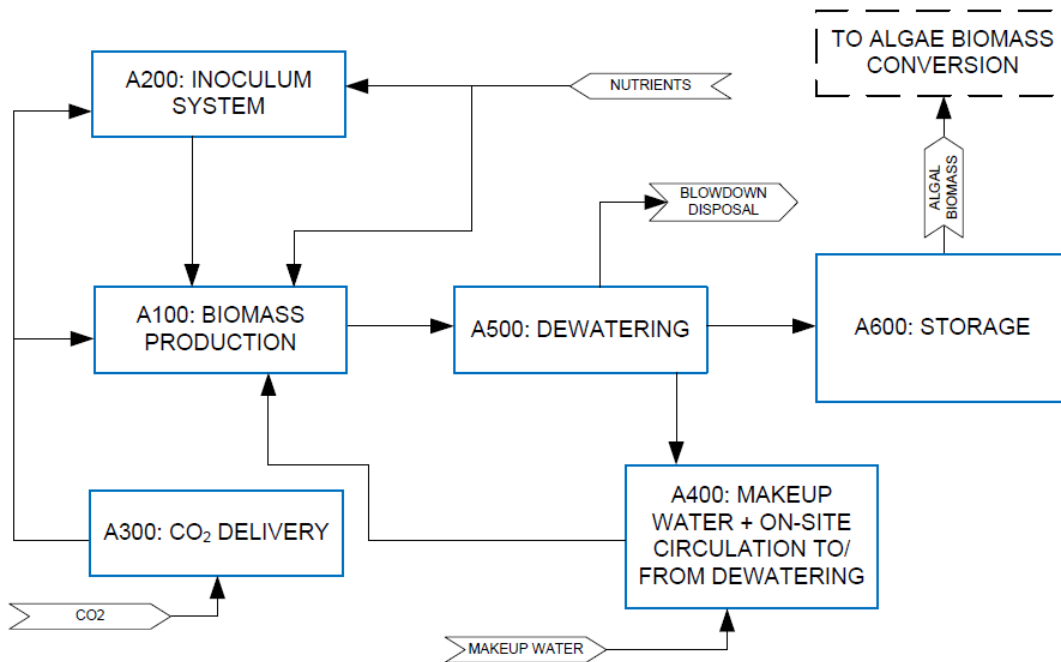
<sup>d</sup> For air classified and leached preprocessing only in the 2022 design case

### 2.1.2 Algae Biomass Cultivation

Algae cultivation for HTL and CAP conversion is modeled from the algae farm design report (Davis et al. 2016), which assumes sourcing of CO<sub>2</sub> 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 production of saline algae species in Florida (based on assumed 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, with annual biomass productivities of 10.3 g/m<sup>2</sup>/day in the 2017 SOT and 11.7 g/m<sup>2</sup>/day in the 2018 SOT, projected to increase to 20 g/m<sup>2</sup>/day by 2025 and ultimately 25 g/m<sup>2</sup>/day by the 2030 target case.

The NREL algae farm design report described in detail the notional algae cultivation system envisioned for future n<sup>th</sup>-plant design (Davis et al. 2016). Pure CO<sub>2</sub> 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 CO<sub>2</sub> is assumed for CO<sub>2</sub> capture and pipeline delivery (attributed to advanced second-generation carbon capture technologies). The process assumes a continuous mode of cultivation and harvesting to maximize 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 et al. 2016). Figure 2 shows a general block-flow diagram of the process (Davis et al. 2018). Further details of the process design are given in the report (Davis et al. 2016, 2018a). 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 Block-Flow Diagram of the Open Pond Algae Farm Model**

Table 8 summarizes material and energy inputs and outputs of the algae farm model SOT and future projection scenarios. 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 8 Algal Biomass Production and Resource Requirement**

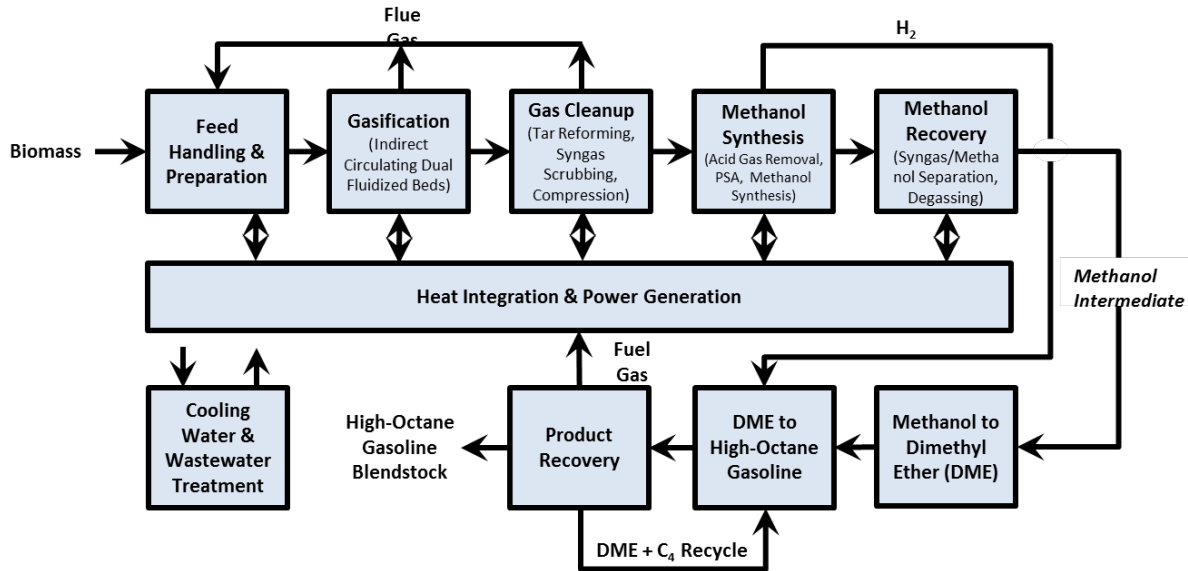
	2017 SOT	2018 SOT	2025 SOT	2030 SOT
<b>Products, kg/hr</b>				
Algal biomass (AFDW)	8,614	9,762	17,116	21,313
Algal biomass (total including ash)	8,828	10,004	17,541	21,842
<b>Resource Consumption, kg/hr</b>				
CO <sub>2</sub>	19,149	21,699	45,785	56,956
Ammonia	172	195	345	428
Diammonium phosphate	84	95	167	207
Total process water input (saline water)	480,461	484,631	3,447,791	1,748,168
Electricity demand, kW	6,667	6,820	7,245	7,767
Algae lost in blowdown	5	4	40	22

## 2.2 MATERIAL, ENERGY, AND WATER REQUIREMENTS OF CONVERSION PROCESSES

### 2.2.1 Indirect Liquefaction (IDL)

The 2018 SOT and 2022 design cases for the IDL pathway feature 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 51.4 and 56.0 gallons, or 5.8 and 6.3 MMBtu per dry U.S. short ton of logging residues, for the 2018 SOT and 2022 design cases, respectively, with a small amount of surplus electricity as a co-product, which is assumed to be exported to the grid (Tan et al. 2018). Figure 3 shows a simplified process flow diagram (PFD) of the IDL pathway. No change was made to the process design and configuration from the previous design report (Tan et al. 2015). 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 reports (Tan et al. 2015, 2018).

Table 9 lists the direct material, energy, and water consumption for the modeled IDL conversion process at the plant in the 2018 SOT and 2022 design cases (Tan et al. 2018). Boiler feed water chemicals and cooling tower chemicals are not considered in the analysis due to lack of information on their makeup. The impact of excluding such chemicals would likely be small, given their very low consumption levels (a combined 3.4 and 2.9 g/MMBTU of HOG in the 2018 SOT and 2022 design cases, respectively).



**FIGURE 3 Process Flow Diagram for High Octane Gasoline via Indirect Liquefaction in the 2018 SOT (Tan et al. 2018)**

**TABLE 9 Key Indirect Liquefaction Process Parameters**

	2018 SOT Value	2022 Design Value	Unit
HOG yield	51.4	56.0	Gal/dry ton feedstock
Surplus electricity	43	204	Btu/MMBtu of HOG
Diesel energy use	2,408	2,408	Btu/MMBtu of HOG
Char produced and combusted	998,430	905,775	Btu/MMBtu of HOG
Fuel gas produced and combusted	504,645	402,602	Btu/MMBtu of HOG
Magnesium oxide consumption	19.5	17.7	g/MMBtu of HOG
Fresh olivine consumption	452.3	410.3	g/MMBtu of HOG
Tar reformer catalyst consumption	8.2	7.4	g/MMBtu of HOG
Methanol synthesis catalyst consumption	4.5	4.1	g/MMBtu of HOG
DME catalyst consumption	5.7	4.9	g/MMBtu of HOG
Beta zeolite catalyst consumption	38.3	26.1	g/MMBtu of HOG
Zinc oxide catalyst consumption	2.1	1.9	g/MMBtu of HOG
LO-CAT chemicals	100.9	88.9	g/MMBtu of HOG
Dimethyl disulfide	1.8	1.6	g/MMBtu of HOG
Amine	3.2	2.9	g/MMBtu of HOG
Water consumption	28.7	24.3	gal/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 2018 SOT and 2022 design cases for the ex situ CFP processes use Pt/TiO<sub>2</sub> 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 48% RG and 52% RD by energy in both the 2018 SOT and 2022 design cases. The total RG and RD yields at the biorefinery are 70.2 and 75.1 gallons, or 8.3 and 8.9 MMBtu per dry U.S. short ton of biomass for the 2018 SOT (100% clean pine) and 2022 design (75% logging residue and 25% clean pine) cases, respectively. Surplus electricity is produced as a co-product and is assumed to be exported to the grid (Dutta et al. 2018).

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. 2018). Despite different feedstock options in the 2018 SOT and 2022 design cases, the feedstock specification assumption in the process model was unaltered from the 2015 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.

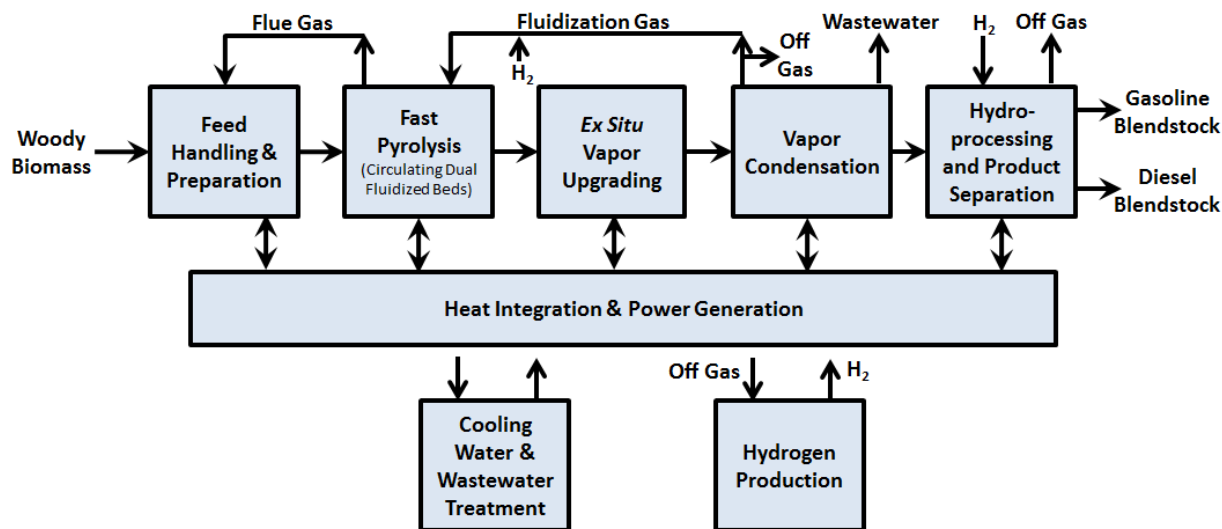


FIGURE 4 Simplified Process Flow Diagram for Fixed Bed Ex Situ Catalytic Fast Pyrolysis

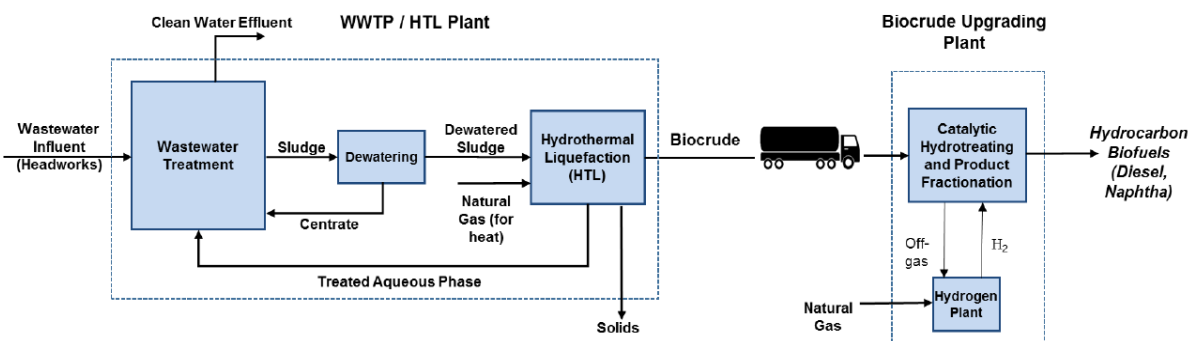
Table 10 lists the direct material, energy, and water consumption for the modeled ex situ conversion process at the plant in the 2018 SOT and 2022 design cases (Dutta et al. 2018).

**TABLE 10 Key Ex Situ Catalytic Fast Pyrolysis Process Parameters**

	2018 SOT Value	2022 Design Value	Unit
RG yield	4.0	4.3	MMBtu/dry ton feedstock
RD yield	4.3	4.7	MMBtu/dry ton feedstock
Surplus electricity	8,788	11,636	Btu/MMBtu of RG and RD combined
Diesel energy use	1,705	1,583	Btu/MMBtu of RG and RD combined
Natural gas use	3,902	2,713	Btu/MMBtu of RG and RD combined
Fixed-bed VPU catalyst (0.5% Pt/TiO <sub>2</sub> )	0.020	0.018	g/MMBtu of RG and RD combined
Hydrotreating catalyst	13.4	11.1	g/MMBtu of RG and RD combined
Hydrocracking catalyst	1.93	1.94	g/MMBtu of RG and RD combined
ZnO	0.022	0.015	g/MMBtu of RG and RD combined
Steam reforming catalyst	0.049	0.034	g/MMBtu of RG and RD combined
Shift catalyst	0.067	0.047	g/MMBtu of RG and RD combined
PSA adsorbent	1.68	1.17	g/MMBtu of RG and RD combined
Caustic	87.0	81.3	g/MMBtu of RG and RD combined
Water consumption	11.0	9.5	gal/MMBtu of RG and RD combined

### 2.2.3 Sludge Hydrothermal Liquefaction (HTL)

HTL is a process that uses hot, pressurized water (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). SCASAs of a sludge-to-fuel pathway via HTL and biocrude upgrading in the 2018 SOT case and a 2022 design case were conducted to evaluate its environmental and sustainability impacts in the current technology development and a future target scenario. 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 via HTL in the 2018 SOT and 2022 target cases. The SCASA 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 and an aqueous phase with highly concentrated nutrients. The residual solids consists 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 remove the ammonia before is sent to the WWTP. In addition to the ammonia removal scenario for both the 2018 SOT and 2022 design cases, 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 11 summarizes major inputs and outputs of the HTL process for all the cases investigated. The production pathways of the materials listed in Table 11 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 11 Inputs and Outputs of Two HTL Design Cases Per One MMBtu Biocrude Produced**

		With Ammonia Removal		Without Ammonia Removal	
		2018 SOT Case	2022 Target Case	2018 SOT Case	2022 Target Case
<b>Inputs</b>					
Dewatered sludge	(dry kg)	77	70	77	70
Natural gas	(Btu)	233,779	186,223	168,321	126,862
Electricity	(Btu)	72,167	46,714	70,089	44,829
Dewatering polymer	(kg)	0.2	0.2	0.2	0.2
Quicklime (CaO)	(kg)	8.3	7.5	0	0
Cooling water makeup	(gal)	0.4	0.4	0.4	0.4
<b>Outputs</b>					
Biocrude	(MMBtu)	1	1	1	1
Solid	(wet kg)	48	42	48	42
Lime sludge	(wet kg)	18	16	0	0
Aqueous phase	(gal)	77	52	77	52

## Upgrading Plant

An upgrading plants is where biocrude is converted into fuels such as gasoline, diesel, and jet fuels. 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.

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 content. Table 12 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 12 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 12 Material and Energy Inputs and Outputs of Upgrading Plant**

		2018 SOT Case	2022 Target Case
<b><i>Inputs</i></b>			
Biocrude	(mmBtu)	1.42	1.38
Natural gas	(Btu)	104,872	125,206
Electricity	(Btu)	13,537	12,885
Cooling tower chemical	(g)	0.4	0.4
Boiler chemical	(g)	0.3	0.3
Hydrotreating catalyst (CoMo/ $\gamma$ -Al <sub>2</sub> O <sub>3</sub> )	(g)	872	3.2
Hydrocracking catalyst (Pt/ Gamma Al <sub>2</sub> O <sub>3</sub> )	(g)	0.3	0.3
Hydrogen plant catalyst (Ni)	(g)	0.4	0.4
Cooling water makeup	(gal)	7.1	6.5
Boiler feedwater makeup	(gal)	3.1	2.9
<b><i>Outputs</i></b>			
Diesel	(mmBtu)	1	1
Naphtha (co-product)	(mmBtu)	0.3	0.3
Wastewater	(gal)	6.5	5.9

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.

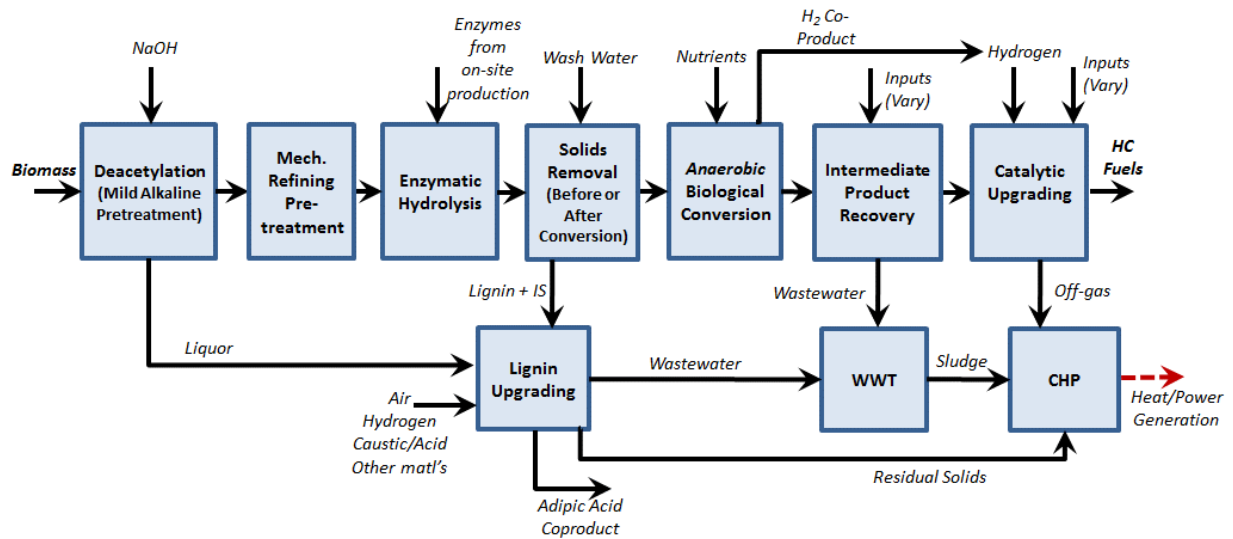
## 2.2.4 Biochemical Conversion

The biochemical conversion pathway to produce renewable hydrocarbon fuels (primarily in the diesel range) includes two designs that utilize acids and butanediol (BDO) as fermentation intermediates in the 2018 SOT and 2030 design cases. In the SCSAs, we focused on the conversion scenario of both design case pathways that co-produces 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 or involve different capital investment considerations are not included here, but may warrant assessment in future SCSAs to understand the sustainability implications of such alternative designs. The 2018 SOT and 2030 target cases for the biochemical conversion models reflect the feedstock quality and composition metrics associated with the 2018 SOT and 2022 INL design cases of herbaceous feedstock blends, respectively, as described in Section 2.1.1.

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 2,3-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. (2018b) provides more details on the process design, performance targets, and TEA results.

Table 13 presents the energy and material inputs and outputs of the biochemical conversion pathways for both intermediate designs in the 2018 SOT and the 2030 target cases.



**FIGURE 6 Process Flow Diagram of the Biochemical Conversion Design Case with Lignin-Derived Adipic Acid Production**

**TABLE 13 Energy and Material Inputs and Outputs of the Biochemical Conversion Pathways for Both the Acids and BDO Intermediate Designs, in the 2018 SOT and the 2030 Target Cases**

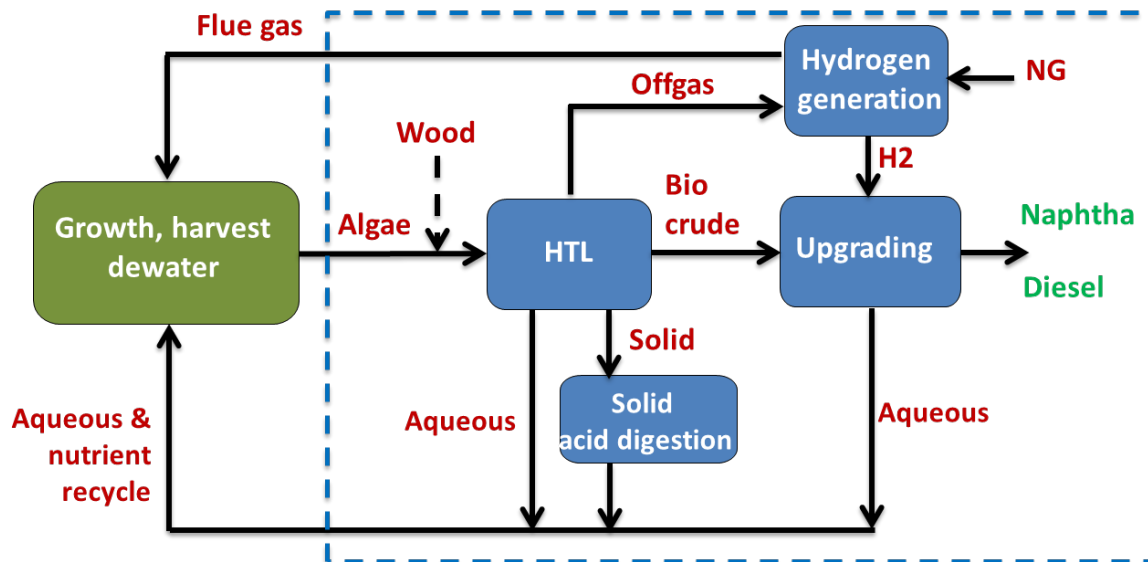
	Acids Pathway		BDO Pathway		Unit
	2018 SOT	2030 Target	2018 SOT	2030 Target	
<b>Products</b>					
Hydrocarbon fuel	75	121	87	116	MM kcal/hr (LHV)
<b>Co-products</b>					
Adipic acid (polymer grade)	1,716	10,770	1,686	11,092	kg/hr
Recovered sodium sulfate salt from wastewater treatment plant (WWTP)	15,164	13,871	14,311	14,163	kg/hr
<b>Resource Consumption</b>					
Biomass feedstock (20% moisture)	104,167	104,167	104,167	104,167	kg/hr
Sulfuric acid, 93%	12,421	10,531	11,622	10,835	kg/hr
Caustic (as pure)	9,523	8,235	8,908	8,494	kg/hr
Ammonia	2,653	1,359	2,404	1,238	kg/hr
Glucose	1,595	1,324	1,595	1,324	kg/hr
Corn steep liquor	1,132	1,478	849	800	kg/hr
Corn oil	9	7	9	7.3	kg/hr
Host nutrients	44	37	44	37	kg/hr
Sulfur dioxide	11	9	11	9	kg/hr
Diammonium phosphate	249	714	191	627	kg/hr
Flocculant	386	-	444	-	kg/hr
Toluene solvent makeup	90	90	-	-	kg/hr
Hydrogen	-	-	800	816	kg/hr
Ethanol	13	37	13	37	kg/hr
Boiler chemicals	0.3	0.2	0.6	0.2	kg/hr
FGD lime	212	97	207	103	kg/hr
WWTP polymer	-	-	2	-	kg/hr
Cooling tower chemicals	2	3	2	2	kg/hr
Makeup water	252,764	209,901	127,128	133,396	kg/hr
Natural gas for boiler	-	-	5,000	1,300	kg/hr
Natural gas for hot oil system	41	37	-	-	MMBtu/hr
Grid electricity (net import)	55,150	44,011	41,417	41,546	kW

The hydrocarbon fuel yield is significantly boosted in the 2030 target cases compared to the 2018 SOT cases for both intermediate designs, driven by reduced carbohydrate losses across deacetylation/alkaline pretreatment as well as improved hydrolysis sugar yields and fermentation intermediate yields. The better yields in the target cases are achieved with lower consumption of most process chemicals, e.g., sulfuric acid, caustic, ammonia, etc. Toluene solvent is used to assist in catalytic upgrading (condensation) in the acid pathway, but is not needed in the BDO pathway. About 87 kg/hr of the 90 kg/hr toluene solvent makeup ends up in the boiler and is combusted. The CO<sub>2</sub> emissions of toluene combustion are fully accounted for, and the emissions are considered fossil CO<sub>2</sub> emissions because toluene is made from fossil feedstock.

Supplemental hydrogen from external natural gas steam reforming is used for upgrading the intermediate BDO stream to hydrocarbon fuel in the BDO pathway, but is not required in the acids pathway beyond hydrogen internally co-produced from fermentation. 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 13, reflects the net gas inputs after accounting for burner efficiency losses. Grid electricity import is required for both intermediate designs in both the 2018 SOT and 2030 target cases, driven in part by high power/heat demands for the process and in part by diverting a portion of the residual solids (lignin) away from the boiler for adipic acid co-production.

### **2.2.5 Algae Hydrothermal Liquefaction (HTL)**

In this SCSA, algae/woody biomass blend feedstock-based HTL was simulated and evaluated. An annual average blend of 73% saline algae and 27% clean pine by ash-free dry weight (AFDW) is formulated in the 2017 SOT case, and an annual average blend of 76% saline algae and 24% logging residues by AFDW is formulated in the 2018 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 Jones and Anderson (2018) and Zhu et al. (2018). Blended feedstocks address seasonal variability in algal biomass productivity, show a synergistic effect on HTL bio-crude yields, and demonstrate cost advantages over algae only given lower feedstock costs for woody biomass than algae (Zhu et al. 2018). The design features recycling of nutrient elements (nitrogen [N], phosphorous [P], and carbon [C]) in raw HTL aqueous and upgrading effluents to the algae pond, which reduces external nutrient demand and cost for algal cultivation, and improves internal nutrient use efficiency. 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 2017 and 2018 SOTs**

Table 14 lists the direct material, energy, and water consumption for the modeled HTL conversion process at the plant in the 2017 SOT and 2018 SOT cases.

**TABLE 14 Material, Energy, and Water Consumption for the Modeled HTL Conversion and Upgrading Process in the 2017 SOT and 2018 SOT Cases**

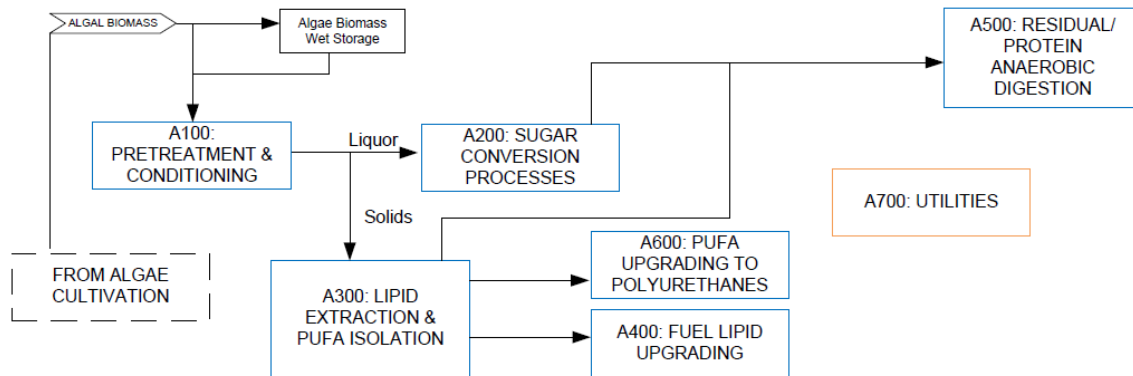
	2017 SOT	2018 SOT
<b>Products</b>		
Renewable diesel, GGE/hr	894	1,118
Naphtha, GGE/hr	457	505
<b>Resource Consumption kg/hr</b>		
Algae (AFDW basis), annual average	8,614	9,762
Wood (AFDW basis), annual average	3,156	3,093
Sum	11,770	12,855
<b>HTL</b>		
Sulfuric acid (96 wt% pure) makeup	631	725
<b>Bio-crude upgrading</b>		
HT main bed catalysts	1.54	0.95
HT guard bed catalyst	4.92	5.21
Natural gas for H2 generation	1,024	1,160
Process water makeup	6,970	7,635
Purchased electricity, kW	1,021	1,131

**TABLE 14 (Cont.)**

	2017 SOT	2018 SOT
<b>Output Streams, kg/hr</b>		
Nutrient elements recycled to algae farm via aqueous recycle		
Carbon, C	3,056	3,129
Nitrogen, N	528	606
Phosphorus, P	25	29

**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. 2018, 2014). 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 2,3-BDO fermentation intermediates in the SOT and target cases (similar to the sugar fermentation concepts discussed previously for biochemical conversion). In the 2025 and 2030 target cases, unsaturated fatty acids isolated from the extracted lipid fraction are upgraded to value-added polyurethane (PU) co-product to improve the biorefinery economic viability. Figure 8 shows a block-flow diagram of the CAP conversion process with PU co-production. In this case, pure algal biomass is evaluated without a second terrestrial biomass co-feed, utilizing a wet storage process as warranted to mitigate seasonal fluctuations. From there, the algal biomass is routed to the CAP conversion operations, including dilute acid pretreatment, fermentation, lipid extraction, and sugar fermentation to carboxylic acid intermediates or 2,3-BDO. This is followed by subsequent catalytic upgrading for fuels, isolation and upgrading of poly-unsaturated fatty acids (PUFAs) to PU (future target cases), and anaerobic digestion (AD) of the remaining protein-rich stillage. Details on the process design, performance targets, and TEA results are given in Davis et al. (2018, 2014).



**FIGURE 8 Block-Flow Diagram of the CAP Conversion Process with Polyurethane Co-Production**

Table 15 lists the key process parameters and energy inputs for the modeled CAP conversion process in the 2018 SOT and the future 2025 and 2030 target cases via either acids or 2,3-BDO intermediate pathways for fuel production.

**TABLE 15 Energy and Material Inputs and Outputs for the Modeled CAP Conversion Process in the 2018 SOT and the 2025 and 2030 Target Cases via Acids and 2,3-BDO as Intermediate Pathways for Fuel Production**

	Acids			2,3-BDO		
	2018 SOT	2025 Target	2030 Target	2018 SOT	2025 Target	2030 Target
<b>Products (kg/hr)</b>						
Diesel	1635	1659	2068	1956	2752	3430
Naphtha	1179	2742	3405	816	1752	2192
Polyurethane	0	3684	4592	0	3684	4592
Power exported to grid, kW	3262	1795	0	0	4560	4427
<b>Resource Consumption (kg/hr)</b>						
Feedstock (AFDW basis)	9762	17119	21365	9762	17119	21365
Power from grid, kW	0	0	707	45	0	0
<b>Pretreatment</b>						
<b>Resource Consumption (kg/hr)</b>						
Sulfuric acid (93% pure)	848	752	937	848	752	937
Ammonia	274	243	303	274	243	303
<b>Carboxylic Acid Conversion</b>						
<b>Resource Consumption (kg/hr)</b>						
Corn steep liquor	515	191	236	60	129	162
Diammonium phosphate	54	28	35	7	16	20
Toluene	0	10	13	0	0	0
Hydrogen	0	0	0	7	21	26
Natural gas (for hot oil system)	0	258	281	0	0	0
Membrane flocculant	56	86	108	55	86	108
<b>Polyurethane</b>						
<b>Resource Consumption (kg/hr)</b>						
Urea	0	43	53	0	43	53
Ethanol	0	424	529	0	424	529
Sulfuric acid (93% pure)	0	20	24	0	20	24
Acetic acid	0	185	235	0	185	235
H <sub>2</sub> O <sub>2</sub>	0	434	541	0	434	541
Sodium hydroxide	0	123	156	0	123	156
Fluoroboric acid	0	2	3	0	2	3
Methanol	0	145	181	0	294	367
Inert gas N <sub>2</sub>	0	408	508	0	408	508
Glycerol	0	641	799	0	641	799
Catalyst, T-amine	0	4	5	0	4	5
N-ethyl morpholine	0	7	9	0	7	9
Silicone surfactant	0	20	24	0	20	24
Stannous octoate	0	6	7	0	6	7



**TABLE 15 (Cont.)**

	Acids			2,3-BDO		
	2018 SOT	2025 Target	2030 Target	2018 SOT	2025 Target	2030 Target
Toluene diisocyanate	0	1429	1782	0	14299	1782
Methanol	0	149	186	0	0	0
<b><i>Lipid Extraction and Conversion to Fuels</i></b>						
<b><i>Resource Consumption (kg/hr)</i></b>						
Hexane requirement	8	100	124	52	100	125
Ethanol requirement	22	41	51	21	41	51
Hydrogen	102	6	7	94	132	163
<b><i>Other Resource Consumption (kg/hr)</i></b>						
Supplemental natural gas	655	1030	1262	285	2096	2804
Process water	39068	151037	246368	51441	100048	125089
Hydrotreating catalyst (5% Pd/C)	0	0.023	0.029	0	0.04	0.04
Catalyst ketonization (ZrO <sub>2</sub> )	0	0.017	0.022	0	0	0
Condensation catalyst (niobic acid)	0	0.127	0.127	0	0	0
Dehydration catalyst, copper based (Cu/SiO <sub>2</sub> -ZrO <sub>2</sub> or Cu/zeolite)			0	0	0.096	0.12
Oligomerization catalyst (Amberlyst-36 resin)	0	0	0	0	0.29024	0.34
<b><i>Output Streams (kg/hr)</i></b>						
AD digestate cake bioavailable N	14	23	30	13	23	29
AD effluent NH <sub>3</sub>	181	474	602	375	465	590
AD effluent diammonium phosphate	70	90	113	45	86	107
<b><i>Biomass Loss from Storage (kg/hr)</i></b>						
Alga biomass loss from wet storage	397	498	646	397	498	646

The fuel products from the CAP process consist of RD and naphtha. The fuel products shift from primarily RD (57% by energy) in the 2018 SOT case to primarily naphtha in the 2025 and 2030 target cases (63% by energy) when they are produced via acids. When the fuels are produced via 2,3-BDO, RD is the primary fuel product in the SOT (69% by energy) and target cases (60% by energy). When the fuel products are normalized by their energy contents to a RD equivalent (RDe) basis, the fuel yield decreases from the SOT case without PU co-product to the target cases with the co-product included in both the acids (by about 10%) and 2,3-BDO (by about 7%) cases, given that fuel yields from lipids are sacrificed by diverting a fraction of unsaturated fatty acids to the PU train.

The acids pathway also co-produces electricity that is exported to the grid in the 2018 SOT (0.027 kWh/MJ of RDe) and 2025 target cases (0.009 kWh/MJ of RDe), while the 2030 target case requires additional grid electricity (0.0029 kWh/MJ of RDe). For the BDO pathway, electricity is co-produced only in the 2025 (0.023 kWh/MJ of RDe) and 2030 (0.018 kWh/MJ of

RDe) target cases, while the 2018 SOT case requires a small amount of grid electricity (0.00037 kWh/MJ of RDe) to satisfy the process power demand. The sulfuric acid and ammonia use for pretreatment is significantly reduced in the target cases relative to the SOT case for both the acids and 2,3-BDO intermediate scenarios, due to a targeted reduction in pretreatment acid loading. For the acids pathway, natural gas is required for a hot oil system to satisfy heat demands in the target cases (as in the biochemical case discussed previously), while the corn steep liquor and diammonium phosphate use at this step are significantly reduced compared with that in the SOT case. For the BDO pathway, supplemental hydrogen that is assumed to be produced from natural gas steam reforming is required for both the SOT and target cases. Hexane, ethanol, and hydrogen are required for lipid extraction and conversion to fuels in both intermediate pathway designs.

Several chemicals, as shown in Table 15, are consumed to produce the PU co-product through a five-step conversion process (Davis et al., 2018). One of the chemicals, toluene diisocyanate (TDI), is consumed at a high quantity and may cause potentially high energy and environmental impacts. Given the lack of life-cycle inventory (LCI) of a conventional TDI production pathway, the fossil-based production pathway of benzene available in GREET is used as a surrogate for TDI, as benzene is a possible precursor of the TDI production process. About the same amount of PU is co-produced in both fuel pathway designs under their target cases (about 0.019 kg/MJ of RDe). Supplementary natural gas is consumed to meet the process heat demands. We use ZSM-5, an energy-intensive catalyst with an LCI available in GREET, as a surrogate for catalysts used for ketonization, condensation, dehydration, and oligomerization, as shown in Table 15, since LCIs for these catalysts are not available in GREET.

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  $\text{NH}_3$  and diammonium phosphate from the AD effluent reduce the nitrogen 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 incorporated logging residues evaluated in the 2018 feedstock SOT (Hartley et al. 2018) for the 2016 SOT case, 2017 SOT case, 2018 SOT case, and the 2022 design case. The logging residues do not require air classification or leaching preprocessing. The IDL feedstock options in the 2016 SOT and 2017 SOT cases represent an update to those analyzed in Cai et al. (2017).

#### 3.1.1 Supply Chain Greenhouse Gas Emissions

For the HOG via IDL pathway, total GHG emissions from the woody feedstock logistics in the SOT cases and the 2022 design case were estimated at 69.5 kg CO<sub>2e</sub>/dry ton.

The GHG emission intensity of HOG production in the biorefinery went down slightly from 3.6 g CO<sub>2e</sub>/MJ in the 2016 SOT case to 2.4 g CO<sub>2e</sub>/MJ in the 2022 design case. Note that these conversion GHG emissions include both direct emissions from 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.

All SOT and design cases co-produce a small amount of surplus electricity except for the 2016 SOT case, which requires a small amount of grid electricity. In the cases with 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 HOG in the 2016, 2017, and 2018 SOT cases, in comparison to the 2022 design case.

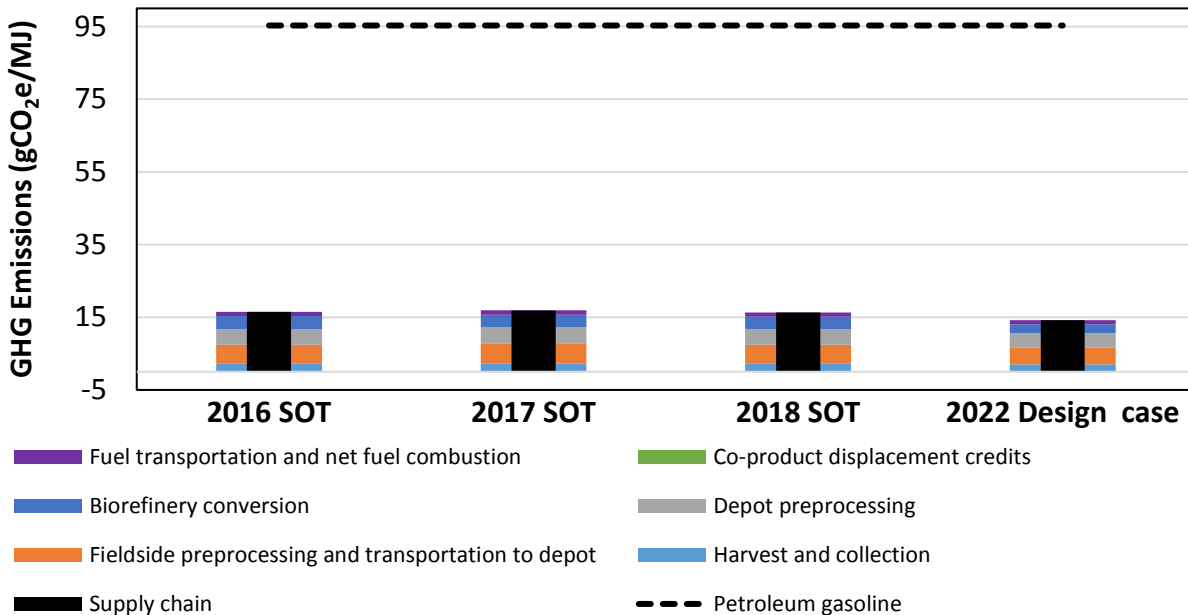
The supply chain GHG emissions of HOG via IDL decrease from about 16 g CO<sub>2e</sub>/MJ in the 2016 SOT case to about 14 g CO<sub>2e</sub>/MJ in the 2022 design case. This is attributable to better HOG yield in the design case.

Figure 9 shows the contributions of various supply chain processes to the total GHG emissions of the HOG via IDL pathway in the 2016, 2017, 2018 SOT cases and the 2022 design case. 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 for the 2016 (71%), 2017 (73%), and 2018 (72%) SOT cases and the 2022 (75%) design case. 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. 2017). The IDL conversion process contributes 21% (2.9 g CO<sub>2</sub>e/MJ) and 17% (2.4 g CO<sub>2</sub>e/MJ) of the supply chain GHG emissions for the 2018 SOT and 2022 design cases, respectively. These do not change much compared to the 2016 and 2017 SOT 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 CH<sub>4</sub> and N<sub>2</sub>O, 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 N<sub>2</sub>O emissions from combustion of intermediate fuel gas and char are responsible for about 20%-33% of GHG emissions at the biorefinery in the 2016, 2017, and 2018 SOT cases, and for about 20% in the 2022 design case. Woody biomass harvest and collection contributed 14% of the supply chain GHG emissions in both the 2018 SOT and 2022 design cases, followed by woody biomass transportation (13%) for both the 2018 SOT and 2022 design cases. The IDL conversion process also reduced the GHG emissions in the 2022 design case from the 2018 SOT case, owing to improved carbon efficiency and fuel yield (Tan et al. 2018).

Compared with petroleum-derived gasoline, HOG via IDL offers a significant supply chain GHG emission reductions of 83%, 82%, 83% and 85%, respectively, in the 2016 SOT, 2017 SOT, 2018 SOT, and 2022 design cases.

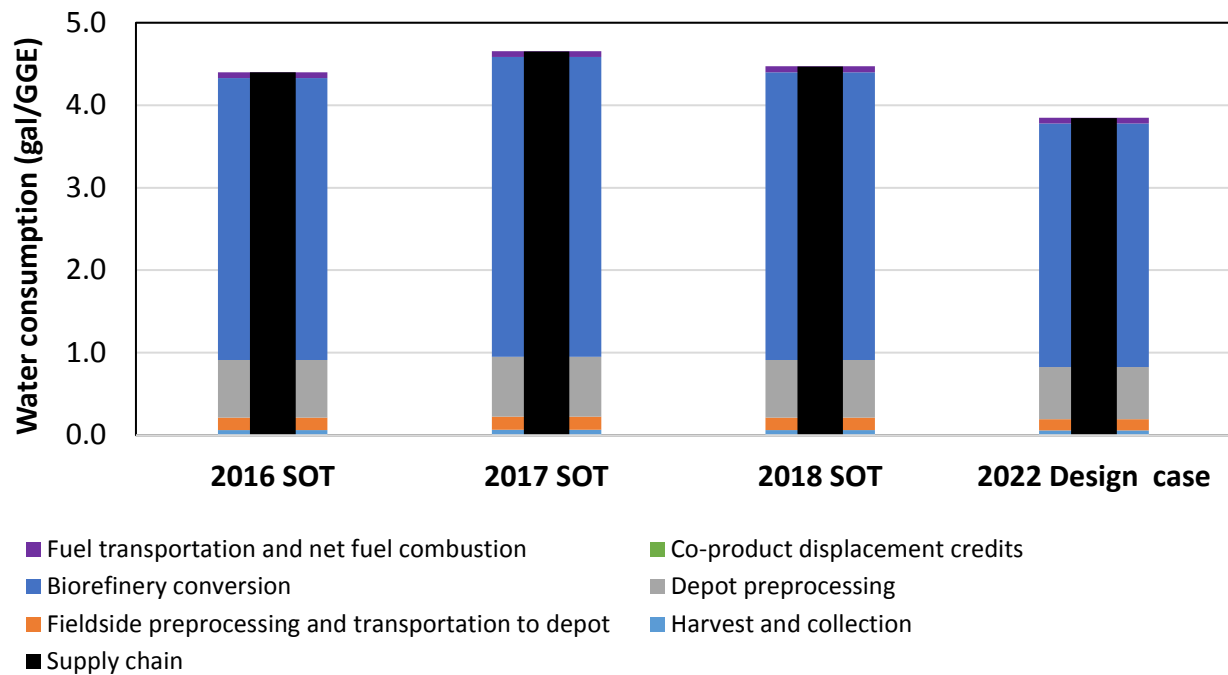


**FIGURE 9 Supply Chain GHG Emissions (g CO<sub>2</sub>e/MJ), High Octane Gasoline via IDL**

### 3.1.2 Supply Chain Water Consumption

The supply chain water consumption of HOG produced via IDL is about 4.4 gal/gasoline gallon equivalent (GGE) in the 2016 SOT case, about 4.7 gal/GGE in the 2017 SOT case, about 4.5 gal/GGE in the 2018 SOT case, and 3.8 gal/GGE in the 2022 design case, compared to about 3.1 gal/GGE for petroleum gasoline blendstock (Wang et al. 2018).

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 78%, 78%, 78%, and 77% in the 2016 SOT, 2017 SOT, 2018 SOT, and 2022 design cases, respectively, all of which use logging residues as the feedstock. 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 16% in all the cases, 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 2016 SOT, 2017 SOT, 2018 SOT, and 2022 design cases. Therefore, direct water consumption at the IDL process itself offers the biggest reduction potential for the supply chain water consumption of HOG in the SOT and the 2022 design cases.

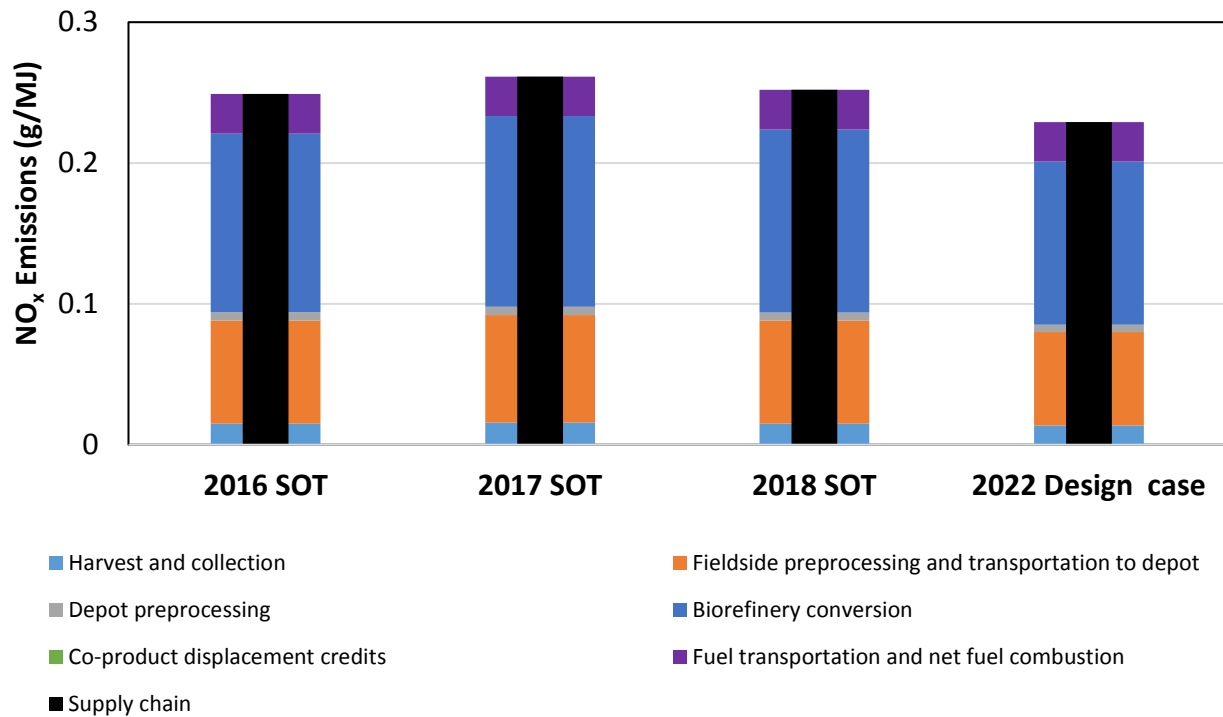


**FIGURE 10 Supply Chain Water Consumption (gal/GGE), High Octane Gasoline via IDL, Compared with 3.1 gal/GGE for Petroleum Gasoline**

### 3.1.3 Supply Chain NO<sub>x</sub> Emissions

The supply chain NO<sub>x</sub> emissions of HOG produced via IDL is about 0.25 g/MJ in the 2016 SOT case, about 0.26 g/MJ in the 2017 SOT case, about 0.25 g/MJ in the 2018 SOT case, and about 0.23 g/MJ in the 2022 design case, compared to about 0.06 g/MJ for petroleum gasoline blendstock (Wang et al. 2018).

Figure 11 shows that NO<sub>x</sub> emissions are mostly attributable to the IDL process and fieldside preprocessing and biomass transportation in the SOT and design cases. Combusting intermediate bio-char and fuel gas in boilers inside biorefinery for process heat purposes is the dominant cause for the conversion NO<sub>x</sub> 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 in all the SOT and design cases. Given the energy self-sufficient design of the IDL process, which heavily relies on combustion of intermediate bio-char and fuel gas to meet process heat demand, NO<sub>x</sub> emission control of this combustion source presents the greatest opportunity to mitigate the supply chain NO<sub>x</sub> emissions of the HOG via IDL pathway.



**FIGURE 11 Supply Chain NO<sub>x</sub> 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 16 summarizes the supply chain sustainability metrics in different functional units that are evaluated for the 2016 SOT case, 2017 SOT case, 2018 SOT case, and 2022 target case of HOG via IDL.

**TABLE 16 Supply Chain Sustainability Metrics for High Octane Gasoline via IDL**

	2016 SOT	2017 SOT	2018 SOT	2022 Design Case	Petroleum Gasoline
<b>Biofuel yield</b>					
Million Btu/dry ton	5.8	5.5	5.8	6.3	
<b>Fossil energy consumption</b>					
MJ/MJ	0.20 (-80%)	0.20 (-80%)	0.19 (-85%)	0.17 (-86%)	1.25
<b>Net energy balance</b>					
MJ/MJ	0.80	0.80	0.81	0.83	
<b>GHG emissions</b>					
g CO <sub>2</sub> e/MJ	16 (-83%)	17 (-82%)	16 (-83%)	14 (-85%)	95
g CO <sub>2</sub> e/GGE	2,020	2,065	1,993	1,735	11,671
<b>Water consumption</b>					
gal/MJ	0.04	0.04	0.04	0.03	0.03
gal/ GGE	4	5	4	4	3
<b>Total NO<sub>x</sub> emissions</b>					
g NO <sub>x</sub> /MJ	0.25	0.26	0.25	0.23	0.06
g NO <sub>x</sub> /GGE	30.5	32.0	31.0	28.2	7.1
<b>Urban NO<sub>x</sub> emissions</b>					
g NO <sub>x</sub> /MJ	0.020	0.020	0.020	0.020	0.024
g NO <sub>x</sub> /GGE	2.4	2.4	2.4	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 total GHG reduction of 85% compared to petroleum gasoline can be achieved by 2022 by reducing energy consumption in feedstock logistics, especially at the fieldside preprocessing and depot preprocessing steps, and improving HOG yield. The 2016 SOT and 2017 SOT cases show the tradeoff between higher biofuel yield with clean pine in the 2016 SOT case, which has higher GHG emissions associated with pine production requiring fertilizer application, and the lower biofuel yield in the 2017 SOT case with logging residue, which has lower GHG emission intensities than clean pine.

In addition to GHG emissions, water consumption, and total NO<sub>x</sub> 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 significant reductions, ranging from 70% in the 2017 SOT case to 86% in the design 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 0.81 and 0.83 MJ/MJ of HOG produced is estimated for the 2018 SOT and 2022 design cases, respectively, showing significant fossil energy saving benefits for HOG via IDL.

As air pollutant emissions, including NO<sub>x</sub> 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<sub>x</sub> emissions regardless of where they occur. HOG via IDL shows about 19% reduction potential in urban NO<sub>x</sub> emissions, 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 SCSA of the CFP pathway incorporated the 2017 SOT feedstock (clean pine), the 2018 SOT (clean pine), and the 2022 design, which consists of 75% air classified and leached logging residues and 25% clean pine, for the 2015-2017 SOT cases, the 2018 SOT case, and the 2022 design case, respectively.

#### **3.2.1 Supply Chain Greenhouse Gas Emissions**

For the CFP pathway, total GHG emissions from the woody feedstock production and logistics in the 2017 SOT, 2018 SOT and 2022 design cases were estimated at 191.5, 228.5 and 276.3 kg CO<sub>2e</sub>/dry ton, respectively. The change in emission intensities of feedstock logistics from the 2017 SOT to the 2018 SOT case reflects a change in the dry matter loss during depot preprocessing assumption, updates from GREET 2017 that were used for the SCSAs of the 2017 SOT case, and updates from GREET 2018 that were used for the 2018 SOT and 2022 design cases. A noticeable increase in GHG emission intensities from the 2018 SOT case to the 2022 design case reflects a change of the woody feedstock from 100% clean pine to 25% clean pine and 75% logging residues, which is subject to energy-intensive air classification and leaching at the preprocessing step to remove soil ash and alkali and alkaline earth metals (Hartley et al. 2018).

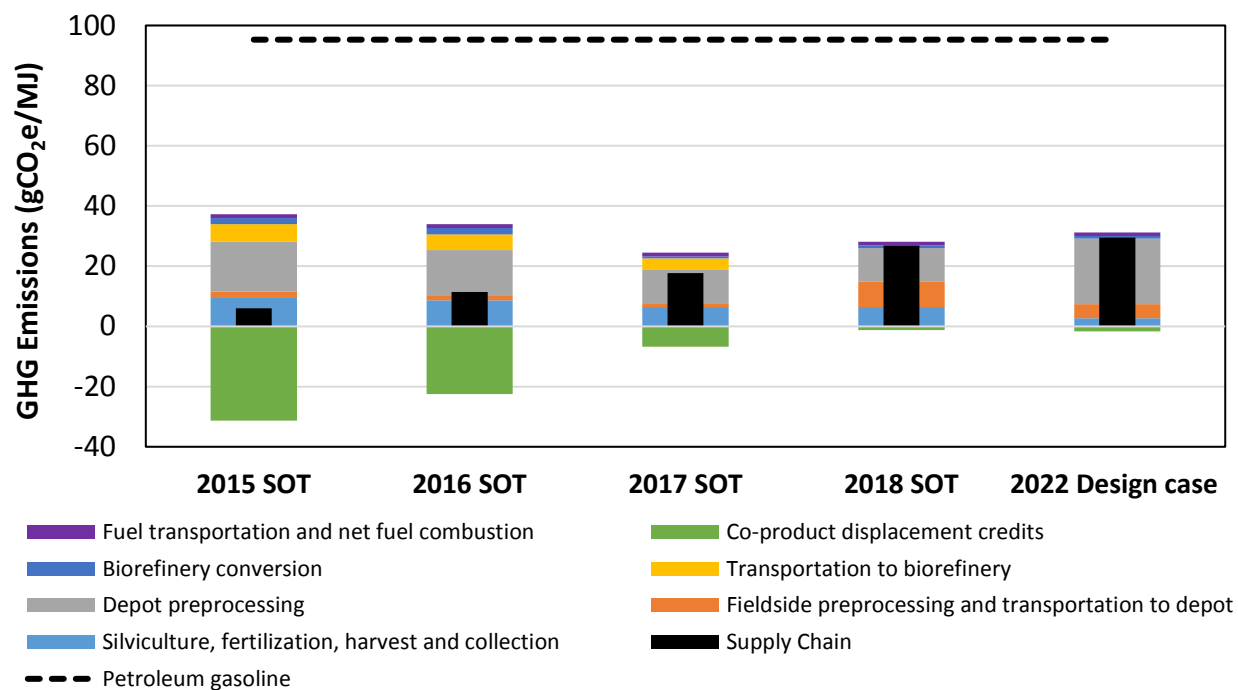
On the other hand, the GHG emission intensity of renewable fuel production in the CFP biorefinery goes down slightly, from 2.0 g CO<sub>2e</sub>/MJ in the 2015 SOT case to 0.8 g CO<sub>2e</sub>/MJ in



the 2022 design case, when the displacement credit of a small amount of surplus electricity (about 1% by energy of the total energy output) is excluded. These conversion GHG emissions include direct emissions from combustion of intermediate process energy such as biochar, CO<sub>2</sub> emissions from on-site natural gas steam reforming for H<sub>2</sub> production, and upstream emissions associated with production of catalysts used in the conversion. The energy self-sufficient design of the CFP conversion processes has contributed to the low emission intensity at the conversion step since the 2015 SOT case. 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. The amount of surplus electricity is significantly reduced from the 2015 SOT case to the 2022 design case because of the conversion efficiency improvements and because there is less surplus heat available for electricity production.

Figure 12 shows the supply chain GHG emissions for RG and RD via CFP in the 2015, 2016, 2017, and 2018 SOT cases, and the 2022 design case compared to petroleum gasoline. The significant surplus electricity displacement credit in the 2015 and 2016 SOT cases distorts the emission contribution of supply chain operations. Compared to the 2015 SOT, utilizing the logging residues that do not require emission-intensive fertilizer application in the 2022 design case lowers GHG emissions from the biomass production phase. Clean pine production and logistics are the dominant contributors to the supply chain GHG emissions in the 2018 SOT and 2022 design cases, accounting for 97% and 99% of the total emissions, respectively. In particular, driving down the energy requirement for depot preprocessing, especially in the 2022 design case, would be key to reducing the total supply chain emissions. The CFP conversion process contributes about 3% (0.6-0.9 g CO<sub>2</sub>e/MJ) of the supply chain GHG emissions for the 2017 and 2018 SOT cases and the 2022 design 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 64% of the conversion emissions in the 2018 SOT and 2022 design cases (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 increase from 6.0 g CO<sub>2</sub>e/MJ in the 2015 SOT case to about 29.6 g CO<sub>2</sub>e/MJ in the 2022 design case. Compared with petroleum-derived gasoline, RG and RD via CFP offer a significant supply chain GHG emission reduction that ranges from 94% in the 2015 SOT case to about 69% in the 2022 design case. The significantly reduced amount of surplus electricity production, which translates to a much lower emission displacement credit, is the major reason for this trend. This shows the emission intensity impact of the trade-off between increasing renewable fuel yield from 5.3 mmBtu per dry ton to 9.0 mmBtu per dry ton and decreasing surplus electricity production from 0.21 mmBtu of electricity per mmBtu of renewable fuel to 0.012 mmBtu of electricity per mmBtu of renewable fuel from the 2015 SOT case to the 2022 design case. Instead of focusing the emission impacts on the basis of the per-MJ results, biorefinery-level life-cycle GHG emission reduction benefits increase from the 2015 SOT case to the 2022 design case when the emission reduction benefits from the total production of biofuels and co-produced electricity in the biorefinery are combined, as a result of continuous improvement in biofuel yields that boosts the total biofuel production from processing the same amount of biomass feedstock.

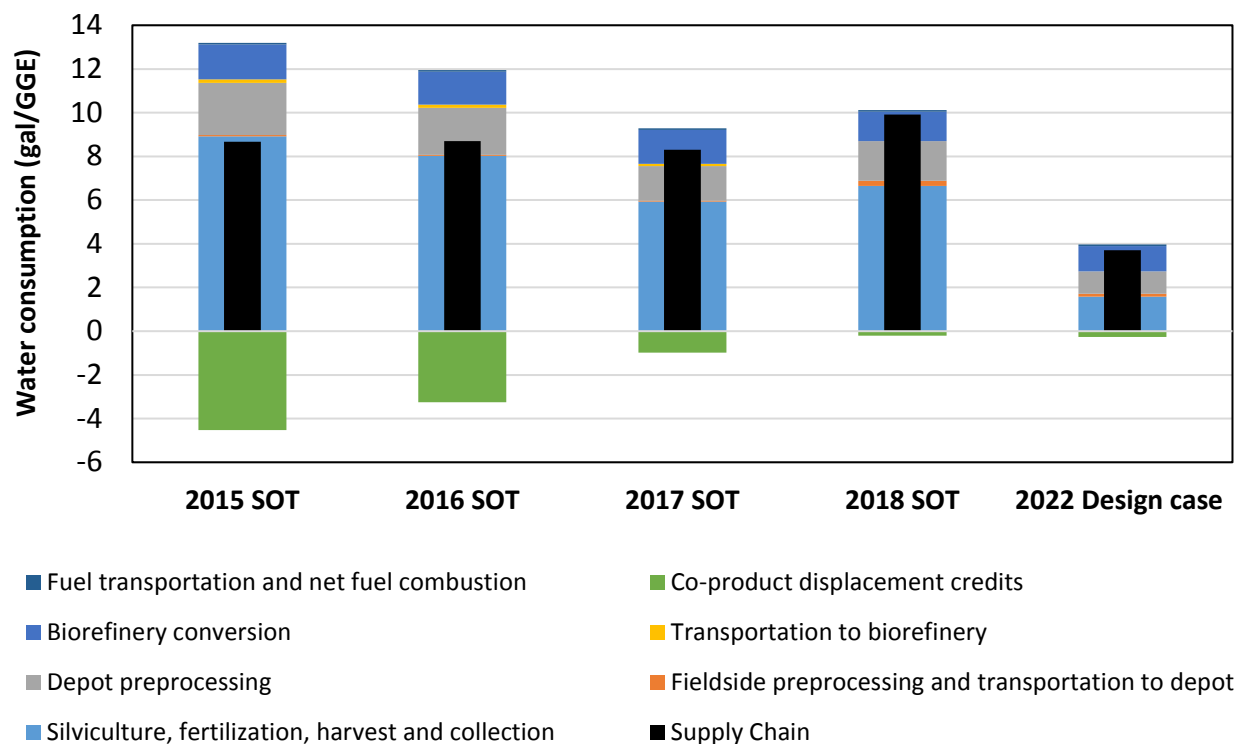


**FIGURE 12 Supply Chain GHG Emissions (g CO<sub>2</sub>e/MJ), Renewable Gasoline/Renewable Diesel via CFP**

### 3.2.2 Supply Chain Water Consumption

The supply chain water consumption of RG and RD produced via CFP is about 8.7 gal/GGE in the 2015 SOT case, about 8.7 gal/GGE in the 2016 SOT case, about 8.3 gal/GGE in the 2017 SOT case, about 9.9 gal/GGE in the 2018 SOT case, and about 3.7 gal/GGE in the 2022 design case, compared with about 3.1 gal/GGE for petroleum gasoline blendstock (Wang et al. 2018).

Figure 13 shows the supply chain water consumption of RG via CFP in gal/GGE. The largest contributor to the supply chain water consumption in all cases, except for the 2022 design case, is the farming of clean pine, which consumes a large amount of limestone for soil amendment (Canter, Qin, et al. 2016). Limestone production consumes a large quantity of water (Lampert, Cai, and Elgowainy 2016). A much lower supply chain water consumption in the 2022 design case results from both a substitution of logging residues that do not consume water-intensive limestone for 75% of the clean pine and a switch from using entirely electricity for preprocessing clean pine in the SOT cases to using primarily natural gas for preprocessing logging residues for air classification, leaching, and drying. Electricity generation is much more water intensive than natural gas production (Lampert, Cai, and Elgowainy 2016). Water consumption for 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, contribute to about 31% of the total supply chain water consumption in the 2022 design case.



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

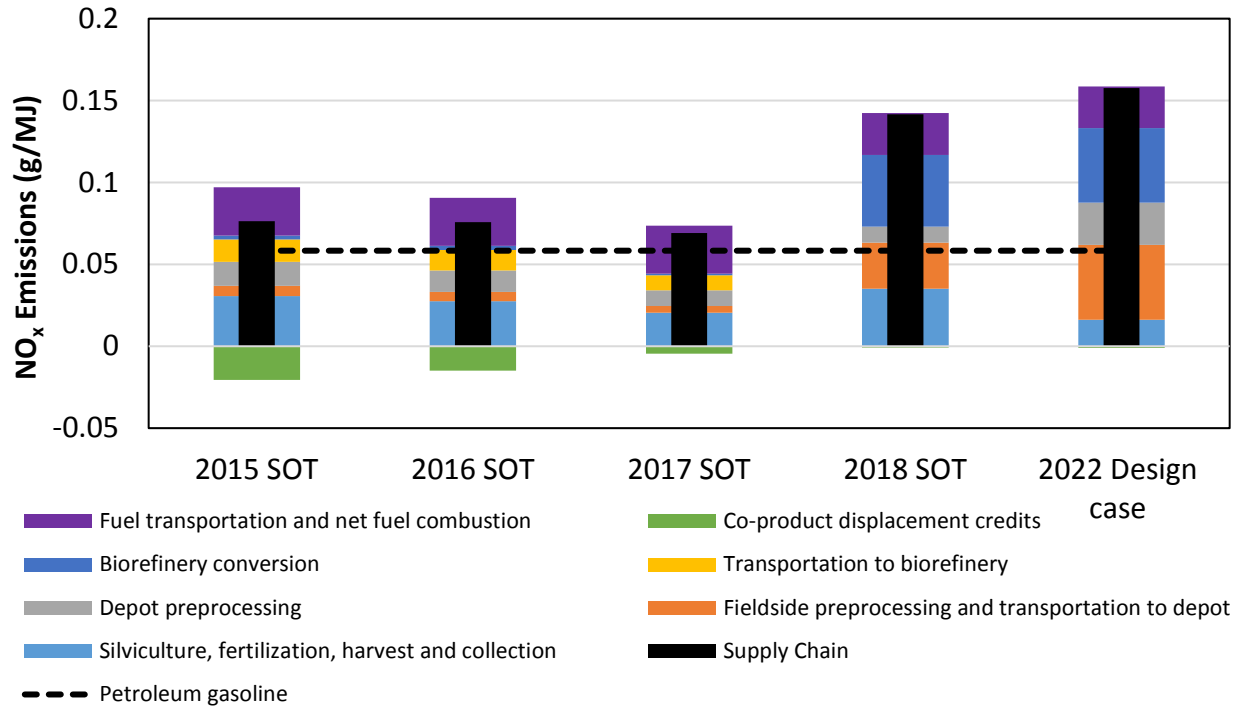
Since the 2015 SOT, slightly improved water efficiency at the conversion step has contributed to a continuous reduction in supply chain water consumption of the RG and RD via CFP pathway. The conversion water consumption in the 2022 design case, which is about 1.2 gal/GGE, however, is still about twice as high as that of petroleum gasoline refining (Lampert, Cai, and Elgowainy 2016). Therefore, driving down the conversion water consumption remains an opportunity for further mitigating the supply chain water consumption of the CFP pathway.

### 3.2.3 Supply Chain NO<sub>x</sub> Emissions

The supply chain NO<sub>x</sub> emissions of RG and RD via CFP are about 0.08 g/MJ in the 2015 SOT case, about 0.08 g/MJ in the 2016 SOT case, about 0.07 g/MJ in the 2017 SOT case, about 0.14 g/MJ in the 2018 SOT case, and about 0.16 g/MJ in the 2022 design case, compared with about 0.06 g/MJ for petroleum gasoline blendstock (Wang et al. 2018).

Figure 14 shows that NO<sub>x</sub> emissions in the 2015, 2016, and 2017 SOT cases are mostly attributable to transportation of RG and RD by diesel truck and combustion of RG and RD, operation of diesel-fueled machinery for biomass harvest and collection, fieldside preprocessing that involves a diesel-powered loader, and energy-intensive depot preprocessing. However, the CFP processes involved in the combustion of intermediate bio-char to meet process power and

heat demand are the primary single source for NO<sub>x</sub> emissions, accounting for about 30% of the total emissions.



**FIGURE 14 Supply Chain NO<sub>x</sub> Emissions (g/MJ), Renewable Gasoline/Renewable Diesel via CFP, Compared with 0.06 g/mJ for Petroleum Gasoline**

Given the energy self-sufficient design of the CFP processes, which heavily rely on the combustion of intermediate bio-char to meet process heat demand, controlling the NO<sub>x</sub> emissions of this combustion source presents an opportunity to mitigate the overall supply chain NO<sub>x</sub> emissions of the RG and RD via the CFP pathway. The energy-intensive preprocessing step that consumes a large amount of natural gas for air classifying and leaching the logging residues at the depot is another major NO<sub>x</sub> emission source in the 2022 design case.

### 3.2.4 Summary of Sustainability Metrics

Table 17 summarizes the supply chain sustainability metrics, including fossil energy consumption, net energy balance, greenhouse gas emissions, water consumption, and NO<sub>x</sub> emissions of RG and RD from CFP for the 2015 SOT case, 2016 SOT case, 2017 SOT case, 2018 SOT case, and 2022 target case. Table 17 shows that the CFP pathway consumes little fossil energy when the fossil energy displacement credit from the co-produced electricity is accounted for in the 2015 and 2016 SOT cases. More fossil energy is consumed in later cases, especially in the 2022 design case, because significantly more fossil energy, i.e., natural gas, is used for the air classification, leaching, and drying operations to preprocess logging residues. As

a result, the NEB of RG and RD from CFP ranges from about 0.6 MJ/MJ in the 2015 SOT to about 0.58 MJ/MJ, indicating a 58% fossil energy saving potential for the RG and RD fuel produced, in the 2022 design case. Despite the trade-off of continuous improvement of biofuel yields since the 2015 SOT case and the decreased NEB, the total fossil energy savings benefit from the total biofuel production from converting one ton of biomass feedstock in the 2022 design case is about the same as that in the 2015 SOT case.

**TABLE 17 Supply Chain Sustainability Metrics for Renewable Gasoline/Renewable Diesel via CFP**

	2015 SOT	2016 SOT	2017 SOT	2018 SOT	2022 Design Case	Petroleum Gasoline
<b>Biofuel yield<sup>a</sup></b>						
Million Btu/dry ton	5.3	5.9	8.0	8.3	9.0	
<b>Fossil energy consumption</b>						
MJ/MJ	0.4 (-97%)	0.11 (-91%)	0.19 (-85%)	0.33 (-74%)	0.42 (-66%)	1.25
<b>Net energy balance</b>						
MJ/MJ	0.6	0.89	0.81	0.67	0.58	
<b>GHG emissions</b>						
g CO <sub>2</sub> e/MJ	6.0 (-94%)	11.5 (-88%)	17.7 (-81%)	26.9 (-72%)	29.6 (-69%)	95
g CO <sub>2</sub> e/ GGE	738	1,402	2,171	3,292	3,619	11,671
<b>Water consumption</b>						
gal /MJ	0.071	0.071	0.068	0.081	0.030	0.03
gal/GGE	8.7	8.7	8.3	9.9	3.7	3.1
<b>Total NO<sub>x</sub> emissions</b>						
g NO <sub>x</sub> /MJ	0.08	0.08	0.07	0.14	0.16	0.06
g NO <sub>x</sub> /GGE	9.4	9.3	8.5	17.7	19.2	7.1
<b>Urban NO<sub>x</sub> emissions</b>						
g NO <sub>x</sub> /MJ	0.018	0.019	0.021	0.021	0.020	0.024
g NO <sub>x</sub> /GGE	2.3	2.4	2.5	2.5	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.

<sup>a</sup> Including both renewable gasoline and renewable diesel

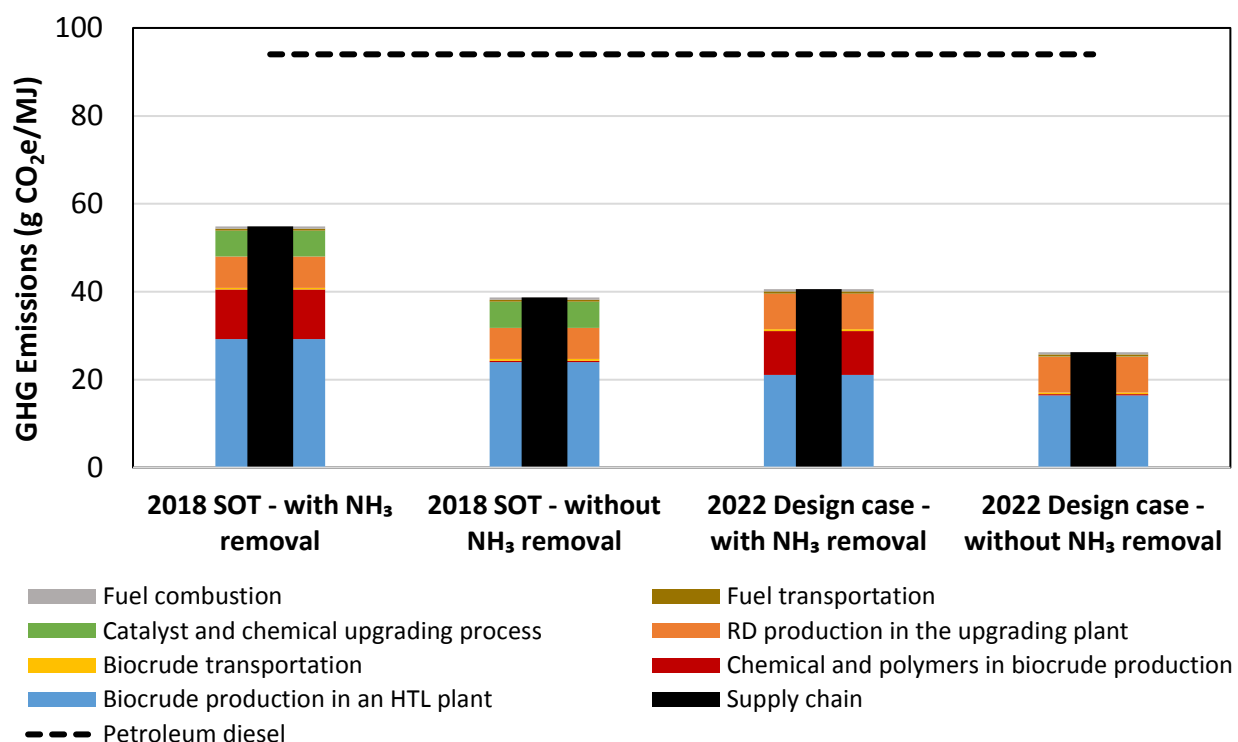
The CFP pathway in the 2022 design case shows about 15% reduction potential in urban NO<sub>x</sub> emissions, compared with those of petroleum gasoline, since the biorefinery and depot preprocessing emissions that are the primary emission sources of RG are assumed to occur in rural, non-MSA areas where 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 CO<sub>2</sub>e/MJ of RD produced from sludge via the HTL and upgrading processes. The GHG emissions reductions of the SOT and design cases are compared with a life-cycle carbon intensity of 94 g CO<sub>2</sub>e/MJ for petroleum diesel. The supply chain GHG emissions for both the 2018 SOT and 2022 design cases are lower than those for petroleum diesel, especially in the scenarios without NH<sub>3</sub> removal. In the scenario with NH<sub>3</sub> removal, RD GHG emissions represent 42% and 57% reductions in the 2018 SOT and 2022 design cases, respectively, compared with petroleum diesel. When NH<sub>3</sub> is not removed from the HTL aqueous, RD GHG emissions represent 59% and 73% reductions in the 2018 SOT and 2022 design cases, respectively, compared with petroleum diesel. Higher GHG emissions reductions when NH<sub>3</sub> is not removed are achieved by avoiding quicklime (CaO) use and reducing the use of the natural gas and electricity otherwise required for the removal process. In the 2022 design case, GHG emissions are reduced by another 14 and 12 g CO<sub>2</sub>e/MJ for scenarios with and without NH<sub>3</sub> removal, respectively, owing to improved conversion efficiency and reduced energy requirements at both the HTL plant that produces biocrude and later at the upgrading plant that produces the RD, with a significant reduction (99.6%) in the hydrotreating catalyst needed.

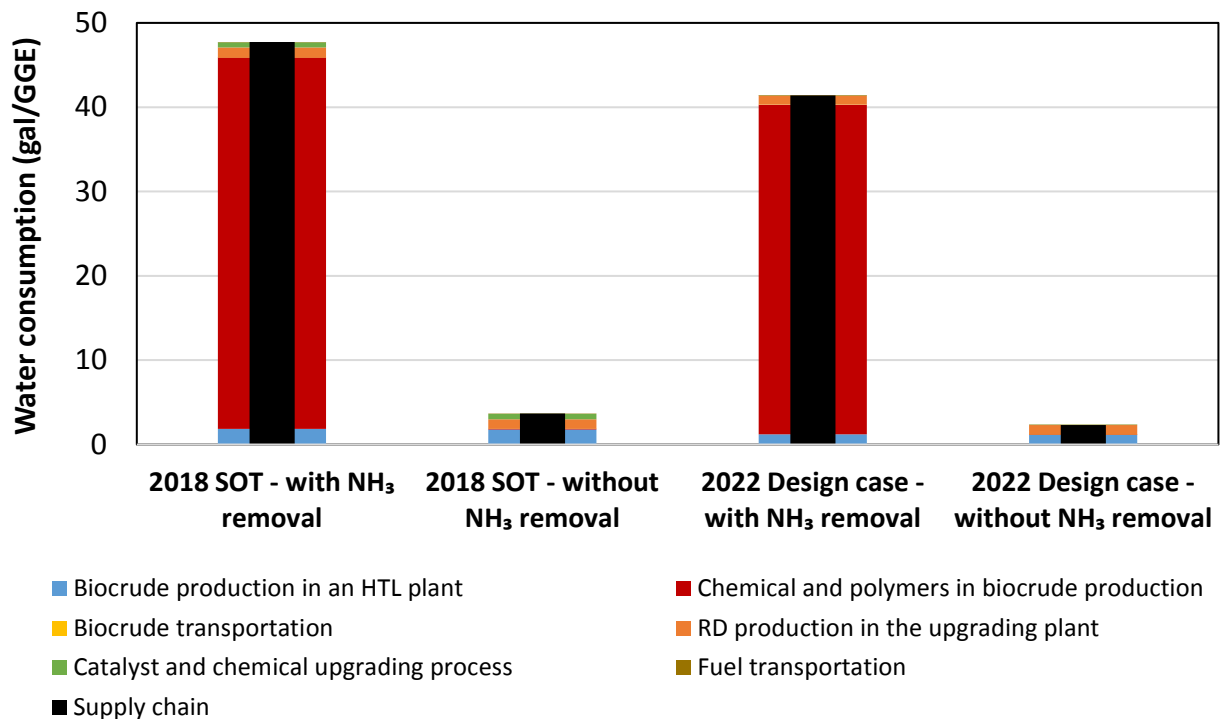


**FIGURE 15 Supply Chain GHG Emissions (g CO<sub>2</sub>e/MJ), Renewable Diesel via Sludge HTL**

In all scenarios, the major contributor to the supply chain GHG emissions are the emissions during the biocrude production in the HTL plant, accounting for about 54% of the total emissions in both the 2018 SOT and 2022 design cases with NH<sub>3</sub> removal, and for about 64% of the total emissions in both the 2018 SOT and 2022 design cases without NH<sub>3</sub> removal. Natural gas consumption for HTL heat and thermal oxidation unit to destroy NH<sub>3</sub> in the “with NH<sub>3</sub> removal” scenario, as well as electricity consumption for HTL and for biological processing of HTL aqueous chemical oxygen demand in WWTP treatment, account for 72% and 68% of the total HTL emissions in the “with NH<sub>3</sub> removal” scenario of the 2018 SOT and 2022 design cases, respectively, with the remaining emissions embedded in the production and use of quicklime. The biocrude production process in the 2022 design case improves the energy efficiency of converting sludge into biocrude significantly over the 2018 SOT case, reducing the natural gas and electricity consumption by 12% and 29%, respectively, in the “with NH<sub>3</sub> removal” scenario, and by 17% and 29%, respectively, in the “without NH<sub>3</sub> removal” scenario. When the HTL aqueous NH<sub>3</sub> is not removed, the supply chain GHG emission intensities are lowered by 11 and 10 g CO<sub>2</sub>e/MJ in the 2018 SOT and 2022 design cases, respectively. Significant redesign and improvement of catalysts and chemicals for the upgrading process in the 2022 design case contribute to reducing the embedded emissions by about 6 g CO<sub>2</sub>e/MJ. Collectively, the energy efficiency improvement at the HTL plant and the catalyst innovation contribute to a 39% reduction (with NH<sub>3</sub> removal) and a 46% reduction (without NH<sub>3</sub> removal) in GHG emissions in the 2022 design case compared with the 2018 SOT target 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 2018 SOT “with NH<sub>3</sub> removal” scenario consumes 48 gal/GGE, compared to 41 gal/GGE for the 2022 design case. For both the SOT and design cases, supply chain water consumption of RD is significantly higher than that of petroleum diesel. The major contributor is the water used in the production of chemicals such as CaO and the dewatering polymer used in the biocrude production. However, when ammonia stripping is no longer part of the process design, water use during the conversion of sludge to biocrude diminishes significantly: by 92% and 94% in the 2018 SOT and 2022 design cases, respectively, as no CaO is needed. Meanwhile, energy efficiency improvements and catalyst innovation as described above contribute to a reduction in water consumption from 4 gal/GGE in the 2018 SOT case to 2 gal/GGE in the design case, which is below that of petroleum diesel.



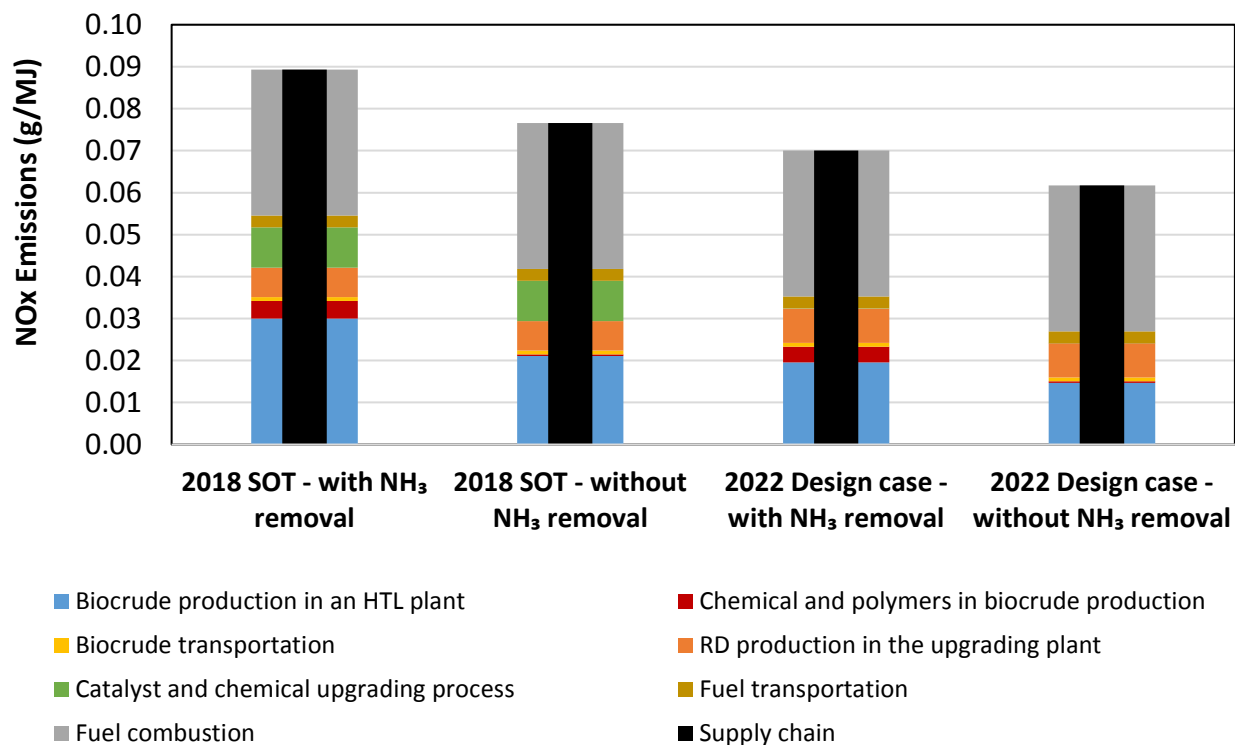
**FIGURE 16 Supply Chain Water Consumption (gal/GGE), Renewable Diesel via Sludge HTL, Renewable Gasoline/Renewable Diesel via CFP, Compared with 2.7 gal/GGE for Petroleum Diesel**

### 3.3.3 Supply Chain NO<sub>x</sub> Emissions

Figure 17 shows that total supply chain NO<sub>x</sub> emissions are about 0.09 and 0.08 g/MJ with and without NH<sub>3</sub> removal, respectively, in the 2018 SOT case, and NO<sub>x</sub> emissions are slightly reduced, to 0.07 and 0.06 g/MJ, in both scenarios in the 2022 design case, owing to fewer chemical and energy inputs during the conversion of sludge to biocrude. The main contributor of NO<sub>x</sub> emissions in both the SOT and design cases 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<sub>x</sub> emissions associated with energy consumption during biocrude production. With energy efficiency improvements in the design case, the NO<sub>x</sub> emission intensity in the “without NH<sub>3</sub> removal” scenario is slightly below that of petroleum diesel.



**FIGURE 17 Supply Chain NO<sub>x</sub> Emissions (g/MJ), Renewable Diesel via HTL, Compared to 0.07 g/MJ for Petroleum Diesel**

### 3.3.4 Summary of Sustainability Metrics

Table 18 summarizes the SCSA sustainability metrics evaluated for the 2018 SOT and 2022 target case of RD production from wet sludge via the HTL and upgrading processes. Both the 2018 SOT and 2022 design cases involve 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 18, the supply chain fossil energy consumption of the 2018 SOT cases is 0.7 and 0.5 MJ per MJ of RD, which is reduced to 0.5 and 0.4 MJ per MJ of RD in the 2022 target cases: a 27% reduction in the “with NH<sub>3</sub> removal” scenario and a 31% reduction in the “without NH<sub>3</sub> removal” scenario. The NEB of RD is 0.52 MJ/MJ (with NH<sub>3</sub> removal) and 0.63 MJ/MJ (without NH<sub>3</sub> removal) for the 2022 design case of the sludge HTL pathway, which shows a significant improvement of fossil energy savings benefit over that of the 2018 SOT case owing to improvements in the design case described above.

The sludge HTL pathway shows an urban NO<sub>x</sub> emission reduction potential of about 6-23% in the 2018 SOT case and a potential reduction of about 34-41% in the 2022 design case, compared with those of petroleum diesel, because biorefinery emissions that are an important emission source of RD are assumed to occur in rural, non-MSA areas where the biorefinery would likely be built.

**TABLE 18 Supply Chain Sustainability Metrics for Renewable Diesel via Sludge HTL**

	Scenario 1: With NH <sub>3</sub> Removal		Scenario 2: Without NH <sub>3</sub> Removal		Petroleum Diesel
	2018 SOT	2022 Design Case	2018 SOT	2022 Design Case	
	<b>Biofuel yield</b>				
Million Btu/dry ton	11.0	12.4	11.0	12.4	
	<b>Fossil energy consumption</b>				
MJ/MJ	0.66 (-45%)	0.48 (-60%)	0.54 (-56%)	0.37 (-69%)	1.2
	<b>Net energy balance</b>				
MJ/MJ	0.34	0.52	0.46	0.63	
	<b>GHG emissions</b>				
g CO <sub>2e</sub> /MJ	54 (-42%)	39 (-57%)	38 (-59%)	26 (-73%)	94
g CO <sub>2e</sub> / GGE	6,657	4,647	4,911	3,150	11,528
	<b>Water consumption</b>				
gal /MJ	0.39	0.36	0.03	0.02	0.02
gal/ GGE	48	41	4	2	3
	<b>Total NO<sub>x</sub> emissions</b>				
g NO <sub>x</sub> /MJ	0.09	0.07	0.08	0.06	0.07
g NO <sub>x</sub> /GGE	10.9	8.6	9.4	7.6	7.9
	<b>Urban NO<sub>x</sub> emissions</b>				
g NO <sub>x</sub> /MJ	0.03	0.02	0.02	0.02	0.03
g NO <sub>x</sub> /GGE	3.3	2.3	2.7	2.1	3.5

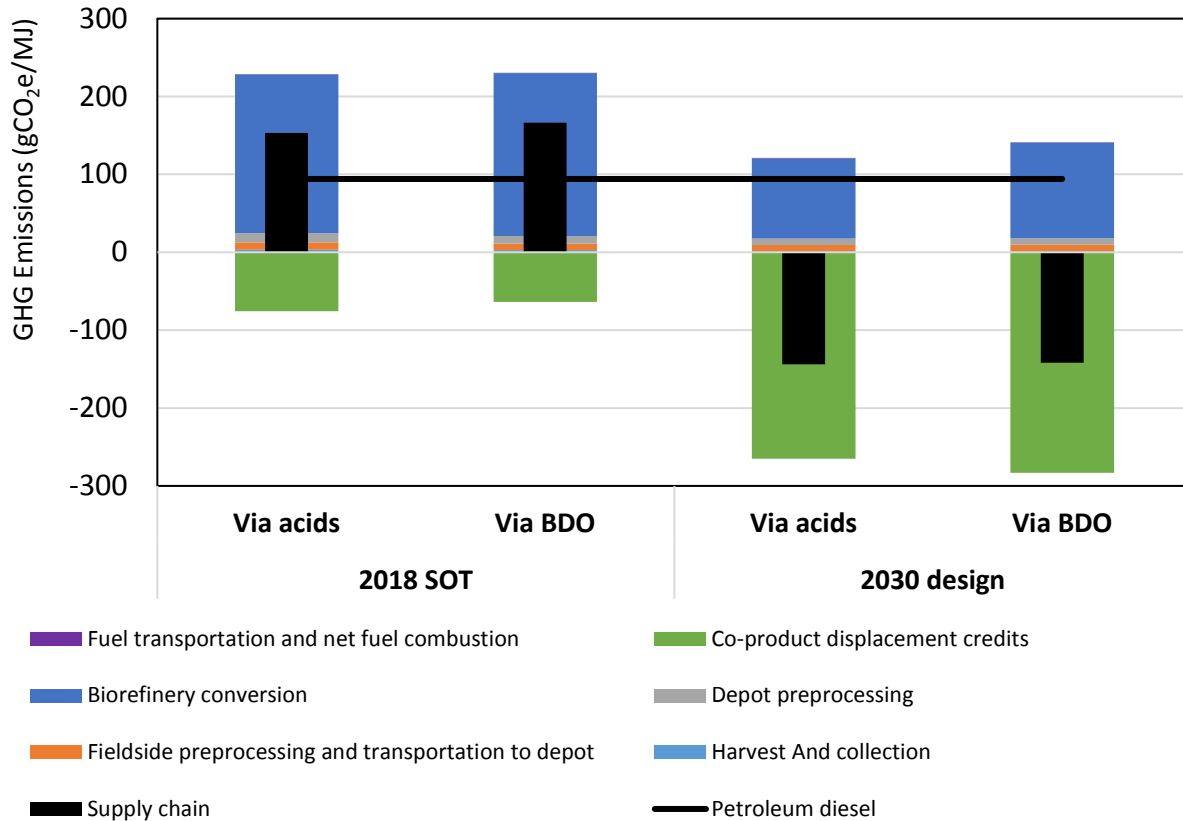
Note: The values in parentheses are the percentage of difference compared to the petroleum diesel pathway. Reduction is represented with negative values.

### 3.4 BIOCHEMICAL CONVERSION

The SCSA of the biochemical pathway incorporated the 2018 SOT and 2022 design cases of herbaceous feedstock blends with the 2018 SOT and 2030 design cases of the biochemical conversion pathways, respectively, via acids and BDO intermediates.

### 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 CO<sub>2</sub>e/MJ of RD, in the 2018 SOT and the 2030 design cases, compared with a life-cycle carbon intensity of 94 g CO<sub>2</sub>e/MJ for petroleum diesel. In both the 2018 SOT and the 2030 design cases, the conversion step is the major GHG emission source of the entire supply chain. Large quantities of process chemicals are consumed at the DMR pretreatment step and



**FIGURE 18 Supply Chain GHG Emissions (g CO<sub>2</sub>e/MJ), Renewable Diesel via Biochemical Conversion**

later at the lignin upgrading step to produce AA coproduct. These chemicals are responsible for a significant amount of GHG emissions, which translate to over 200 g CO<sub>2</sub>e/MJ in the 2018 SOT case and over 100 g CO<sub>2</sub>e/MJ in the 2030 design case (gross emissions prior to accounting for coproduct GHG credits), regardless of the intermediate pathway to produce the RD fuel (although it should be noted that a significant fraction of those GHG emissions attributed to the AA coproduct train are also included in these per-MJ fuel values). However, after including coproduct credits, overall net GHG emission intensities are considerably lower in all cases, and decrease substantially in the 2030 design case compared to those in the 2018 SOT case, for both the acids and BDO intermediate pathways. Considerable improvement in biofuel yields, significantly larger co-product yields, reduction in process energy consumption, and reduction in

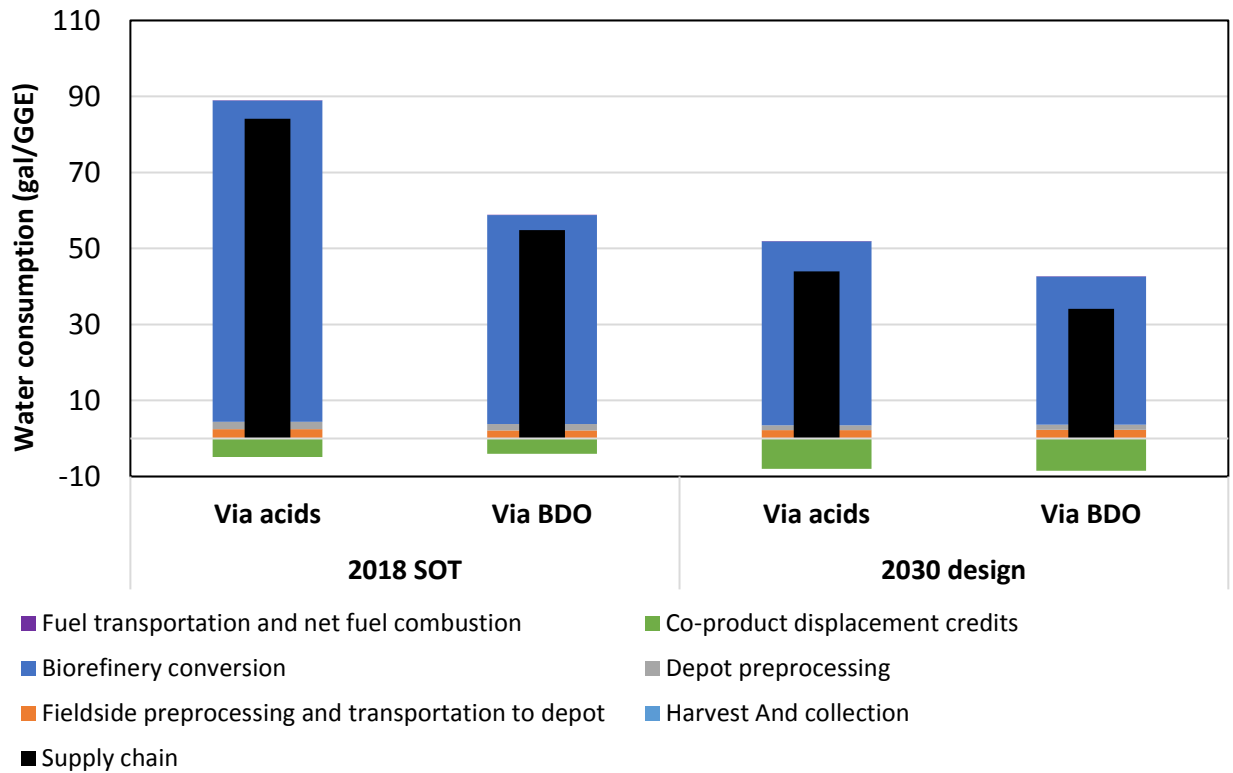
chemical consumption are the key drivers of a shift in the GHG emission intensities from 153-167 g CO<sub>2</sub>e/MJ in the 2018 SOT case to negative GHG emission intensities of -144 and -142 g CO<sub>2</sub>e/MJ in the 2030 design case, for the acids and BDO intermediate pathways, respectively.

In both the SOT and design cases, a displacement method is used to account for the emission credits resulting from displacing a fossil-derived AA product with the lignin-derived AA (this is also the case in the algae CAP pathway discussed below for co-production of polyurethane). A similar process design that co-produces a large amount of AA, and its emission implications when the displacement method is used rather than another LCA allocation method, is discussed in detail by Cai et al. (2018). Given the pros and cons of different co-product handling options, the displacement method is used here as the only traditional method that fully reflects the total emission reduction benefits of a biorefinery that produces both fuel and AA products (or other coproduct options) by normalizing significant co-product displacement credits to the biofuel product. In the case of AA, as well as numerous other bio-derived coproduct opportunities (particularly those containing oxygen), these co-product displacement credits tend to be large, reflecting the energy-intensive nature of traditional methods and process chemistries to produce such products from conventional fossil routes (from petroleum feedstocks that lack oxygen) compared with production from biomass (the molecular structures of which contain oxygen) (Schaidle et al. 2017)

This highlights an important benefit for biorefineries configured to produce bio-advantaged products from biomass, which allows for significantly less energy- and GHG-intensive routes for producing such products compared with traditional petrochemical routes. However, in light of current regulations, which are fuel-focused, the only means to fully account for this important benefit when co-producing both fuels and non-fuel bio-derived products is to credit the GHG benefits for the bio-product onto the fuel product using the displacement method, although this must be subject to reasonable co-product volume outputs relative to the overall market volume for that product (Cai et al. 2018). Given the potential for significant variations in LCA results, depending on the coproduct handling method selected, these GHG emission results need to be interpreted with caution (Cai et al. 2018).

### **3.4.2 Supply Chain Water Consumption**

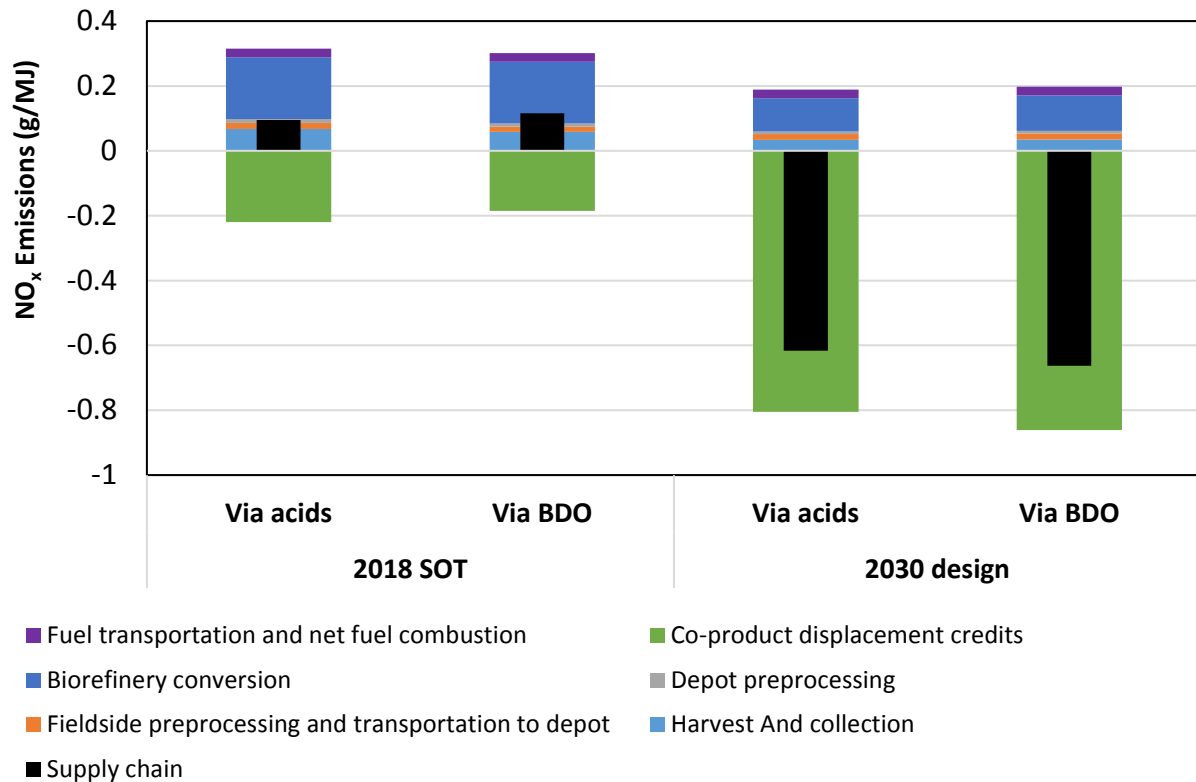
Figure 19 shows that both the 2018 SOT and the 2030 design cases have significantly higher water consumption than that of petroleum diesel, owing to significant embedded water consumption associated with the process chemical use, as well as to makeup water requirements during the biochemical conversion 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). The water displacement credit with the AA co-product offers a relatively small offset of the water impact compared to its impact on the GHG emissions, which incorporate the significant biogenic carbon credit of lignin-derived AA compared with its fossil-derived counterpart that is not applicable in its water consumption impact. However, with improved biofuel and co-product yields, and a reduction in process energy and chemical consumption, water consumption is noticeably reduced in the 2030 design case for both the acids and BDO intermediates scenarios.



**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<sub>x</sub> Emissions

Figure 20 shows that total NO<sub>x</sub> emissions could be lower than those of petroleum diesel in the 2030 design case when the significant co-product displacement credits are included. Significantly higher co-product yields contribute to substantial reductions in total NO<sub>x</sub> emissions in the 2030 design case for both the acids and BDO pathway scenarios, compared to the 2018 SOT case.



**FIGURE 20 Supply Chain NO<sub>x</sub> 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 19 summarizes the supply chain sustainability metrics, including fossil energy consumption, NEB, GHG emissions, water consumption, and NO<sub>x</sub> emissions of the renewable hydrocarbon fuels from these biochemical conversion designs. With the displacement method applied, the supply chain results of these metrics represent a biorefinery-level assessment that considers the impacts of all the finished products from biorefineries of such designs.

**TABLE 19 Supply Chain Sustainability Metrics for Renewable Diesel via Biochemical Pathway**

	Scenario 1: Via Acids	Scenario 2: Via BDO	Scenario 1: Via Acids	Scenario 2: Via BDO	Petroleum Diesel
	2018 SOT Case	2018 SOT Case	2030 design Case	2030 Design Case	
			<b>Biofuel yield</b>		
Million Btu/dry ton	3.2	3.8	5.2	5.0	
			<b>Co-product yield</b>		
Adipic acid, Kg/mmBtu of biofuel	6	5	23	24	
Sodium sulfate, Kg/mmBtu of biofuel	51	41	29	31	
			<b>Fossil energy consumption</b>		
MJ/MJ	2.2	2.5	-1.3	-1.2	1.2
			<b>Net energy balance</b>		
MJ/MJ	-1.2	-1.5	2.3	2.2	
			<b>GHG emissions</b>		
g CO <sub>2</sub> e/MJ	153	167	-144	-142	94
g CO <sub>2</sub> e/ GGE	18,759	20,396	-17,615	-17,366	11,528
			<b>Water consumption</b>		
gal /MJ	0.7	0.4	0.4	0.3	0.02
gal/ GGE	84	55	44	34	2.7
			<b>Total NO<sub>x</sub> emissions</b>		
g NO <sub>x</sub> /MJ	0.1	0.1	-0.6	-0.7	0.07
g NO <sub>x</sub> /GGE	11.7	14.2	-75.6	-81.2	7.9
			<b>Urban NO<sub>x</sub> emissions</b>		
g NO <sub>x</sub> /MJ	0.04	0.04	0.03	0.03	0.03
g NO <sub>x</sub> /GGE	5.3	4.8	3.1	3.2	3.5

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

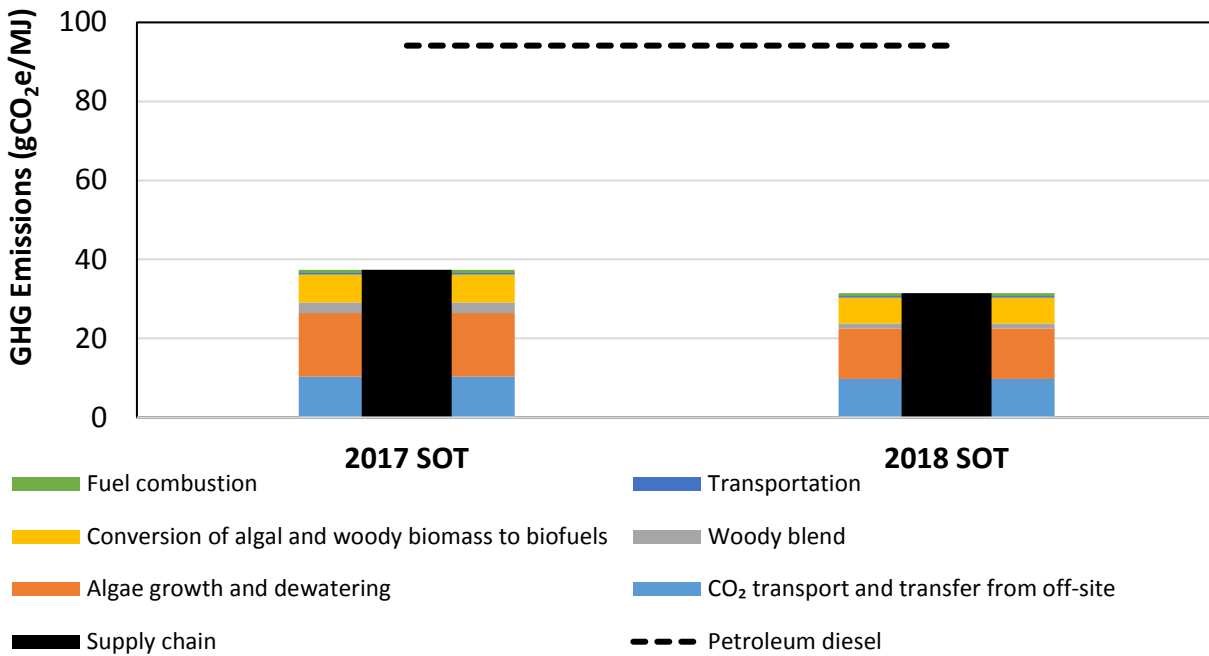
### 3.5 ALGAE HYDROTHERMAL LIQUEFACTION

The SCSA of the algae/woody blend HTL pathway incorporated the saline algae biomass cultivation data from the test-beds in both the 2017 and 2018 SOT cases, the woody feedstock inputs from the 2017 clean pine SOT and the 2018 logging residue SOT, and the 2017 and 2018 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 CO<sub>2</sub>e/MJ, of RD in the 2017 SOT and 2018 SOT cases, compared to a life-cycle carbon intensity of 94 g CO<sub>2</sub>e/MJ for petroleum diesel. Figure 21 shows that RD reduces GHG emissions by 60% and 67% in the 2017 SOT and 2018 SOT cases, respectively. In 2017 SOT and 2018 SOT cases, electricity is consumed for algae cultivation and dewatering, and a parasitic electricity demand of 0.63 MJ/kg of CO<sub>2</sub> captured and transported to the algae farm is assumed (Davis et al. 2018). As a result, electricity consumption for algae growth and dewatering and for CO<sub>2</sub> capture and transportation to the algae farm is the major source of GHG emissions. 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 7.1 and 6.6 g CO<sub>2</sub>e/MJ in the 2017 and 2018 SOT cases, respectively.

In both SOT cases, co-feeding woody feedstock with algae has a small emission impact, accounting for about 2.6 and 1.2 g CO<sub>2</sub>e/MJ in the 2017 SOT and 2018 SOT cases, respectively. Increased biofuel yield in the 2018 SOT case is a key driver of the increased GHG emission reductions over the 2017 SOT case.

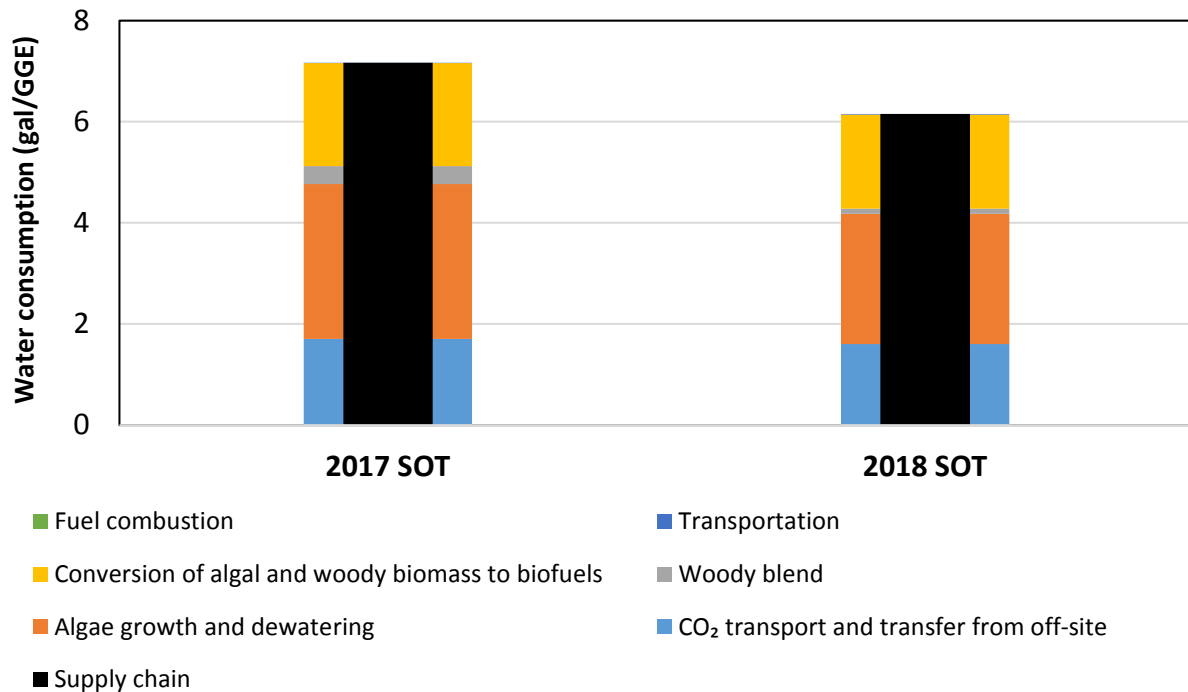


**FIGURE 21 Supply Chain GHG Emissions (g CO<sub>2</sub>e/MJ), Renewable Diesel via Algae HTL**



### 3.5.2 Supply Chain Water Consumption

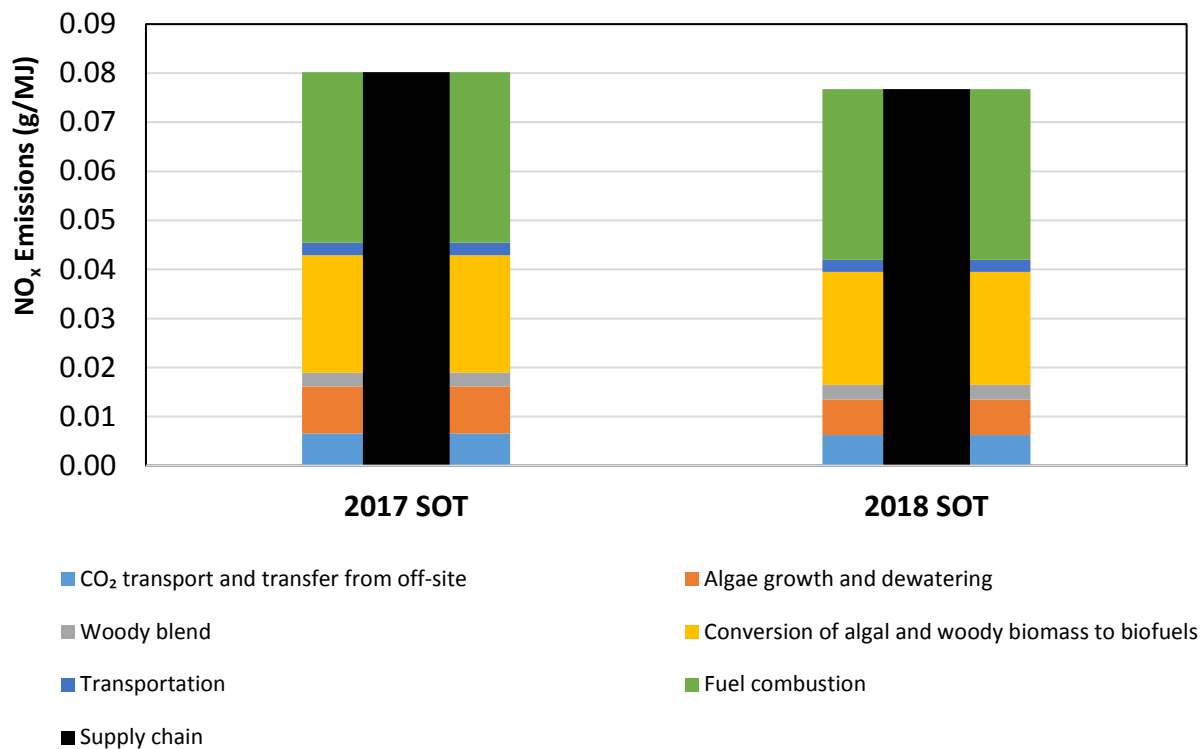
Figure 22 shows that in the 2017 SOT and 2018 SOT cases, embedded water consumption associated with energy consumption for algae dewatering and for CO<sub>2</sub> capture and transportation to the algae farm are the major contributors to supply chain water consumption. Embedded water consumption associated 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<sub>x</sub> Emissions

Total NO<sub>x</sub> emissions are about 23% and 18% higher in the 2017 SOT and 2018 SOT cases, respectively, 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<sub>x</sub> emission factor as petroleum diesel. The HTL conversion processes account for about 30% 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 CO<sub>2</sub>



**FIGURE 23 Supply Chain NO<sub>x</sub> 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 12% and 9% of the total NO<sub>x</sub> emissions in the 2017 SOT and 2018 SOT cases, respectively. Again, co-feeding woody biomass with algae has a small NO<sub>x</sub> emission impact in both SOT cases.

### 3.5.4 Summary of Sustainability Metrics

Table 20 summarizes the supply chain sustainability metrics, including fossil energy consumption, NEB, GHG emissions, water consumption, and NO<sub>x</sub> emissions, of RD from co-feeding algae with woody biomass via HTL in the 2017 and 2018 SOT cases. Fossil energy consumption is 42%-49% lower in the SOT cases, compared with that of petroleum diesel, resulting in an NEB of about 0.30 and 0.39 MJ/MJ in the 2017 SOT and 2018 SOT cases, respectively.

Despite somewhat higher total supply chain NO<sub>x</sub> emissions than those of petroleum diesel, these algae HTL pathways might see benefits in urban NO<sub>x</sub> emission reductions, 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 20 Supply Chain Sustainability Metrics for Renewable Diesel via Algae HTL**

	2017 SOT	2018 SOT	Petroleum Diesel
		<b>Biofuel yield</b>	
Million Btu/dry ton	12.1	13.3	
		<b>Fossil energy consumption</b>	
MJ/MJ	0.70 (-42%)	0.61 (-49%)	1.2
		<b>Net energy balance</b>	
MJ/MJ	0.30	0.39	
		<b>GHG emissions</b>	
g CO <sub>2</sub> e/MJ	37 (-60%)	31 (-67%)	94
g CO <sub>2</sub> e/ GGE	4,571	3,856	11,528
		<b>Water consumption</b>	
gal /MJ	0.06	0.05	0.02
gal/ GGE	7.2	6.2	2.7
		<b>Total NO<sub>x</sub> emissions</b>	
g NO <sub>x</sub> /MJ	0.08	0.08	0.07
g NO <sub>x</sub> /GGE	9.8	9.4	7.9
		<b>Urban NO<sub>x</sub> emissions</b>	
g NO <sub>x</sub> /MJ	0.025	0.025	0.03
g NO <sub>x</sub> /GGE	3.1	3.1	3.5

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

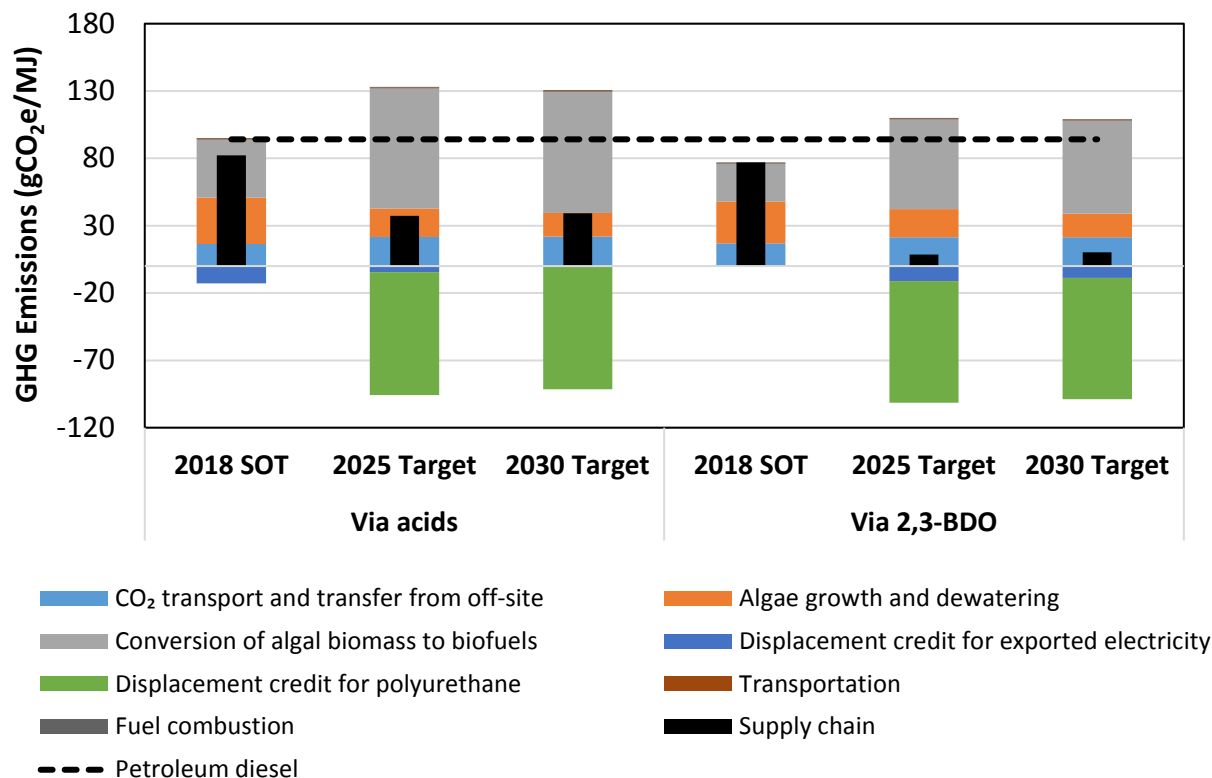
### 3.6 COMBINED ALGAE PROCESSING

The SCSA of the CAP pathway incorporated the 2018 SOT case and the projected 2025 and 2030 cases for algae biomass cultivation with unlined ponds using saline algae strains, as well as the 2018 SOT case and the projected 2025 and 2030 cases for CAP conversion for both the acids and 2,3-BDO pathway designs. The co-produced algae-derived PU (applicable for future projection cases) is treated with a displacement credit in the SCSA for replacement of petroleum-derived PU rigid foam. The results of the LCA on petroleum-derived PU production that was conducted by Davis (Davis et al. 2018) are adopted in this SCSA. The same displacement method is also 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 CO<sub>2</sub>e/MJ, of RD in the 2018 SOT, 2025 target, and 2030 target cases via acids or 2,3-BDO fuel pathways, compared with a life-cycle carbon intensity of 94 g CO<sub>2</sub>e/MJ for petroleum diesel. GHG emissions of RD in the 2018 SOT cases are about 13% and 18% lower than those of petroleum diesel based on the acids and BDO pathways, respectively. As an alternative case to evaporation rates based on Gulf Coast (Florida) conditions, if the 2018 SOT saline algae cultivation model was instead based on evaporation rates associated with the AzCATI location in Arizona (and resultant higher algae farm blowdown disposal rates), the supply chain GHG emissions in the 2018 SOT cases would be 90 and 85 g CO<sub>2</sub>e/MJ via the acids and BDO pathway cases, respectively, which are about 8 g CO<sub>2</sub>e/MJ higher than the Gulf Coast/Florida evaporation base case. The 2025 and 2030 target cases have much lower net GHG emissions than those of petroleum diesel for either the acids or BDO pathways when the significant emission displacement credit of co-produced PU is accounted for. The net GHG emission reductions are about 60% and 58% in the 2025 and 2030 target cases via the acids pathway and about 91% and 89% in the 2025 and 2030 target cases via the BDO pathway.

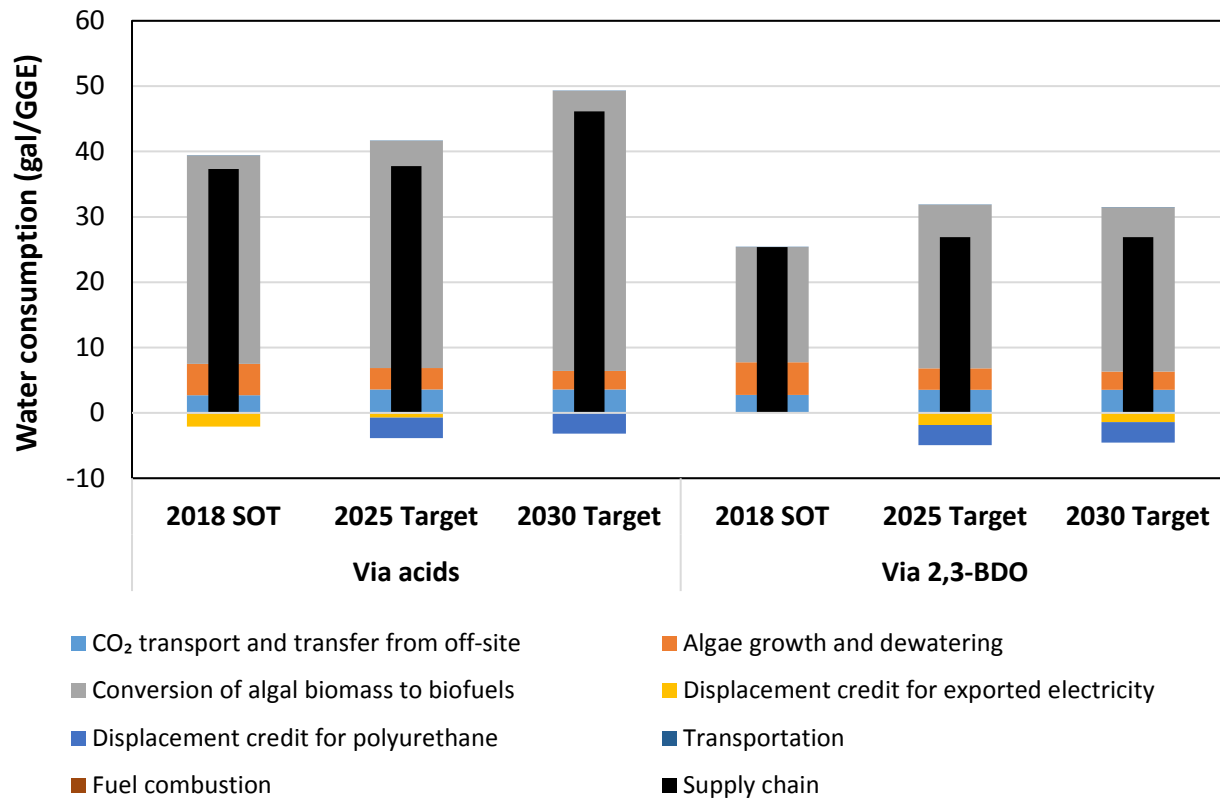
As in the discussion of the biochemical conversion case above, the emission reduction benefits attributed to the displacement method (Cai et al. 2018) reflect overall GHG benefits contributed by both the renewable fuel products and the bio-derived co-products in the context of an integrated biorefinery producing both outputs. Manufacturing of chemicals and catalyst for consumption during the CAP conversion processes, and particularly consumption of a large quantity of TDI in the PU production process, is the primary emission source in the 2018 SOT, 2025, and 2030 target cases. Beyond this, energy consumption for CO<sub>2</sub> 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.



**FIGURE 24 Supply Chain GHG Emissions (g CO<sub>2</sub>e/MJ), Renewable Diesel via CAP**

### 3.6.2 Supply Chain Water Consumption

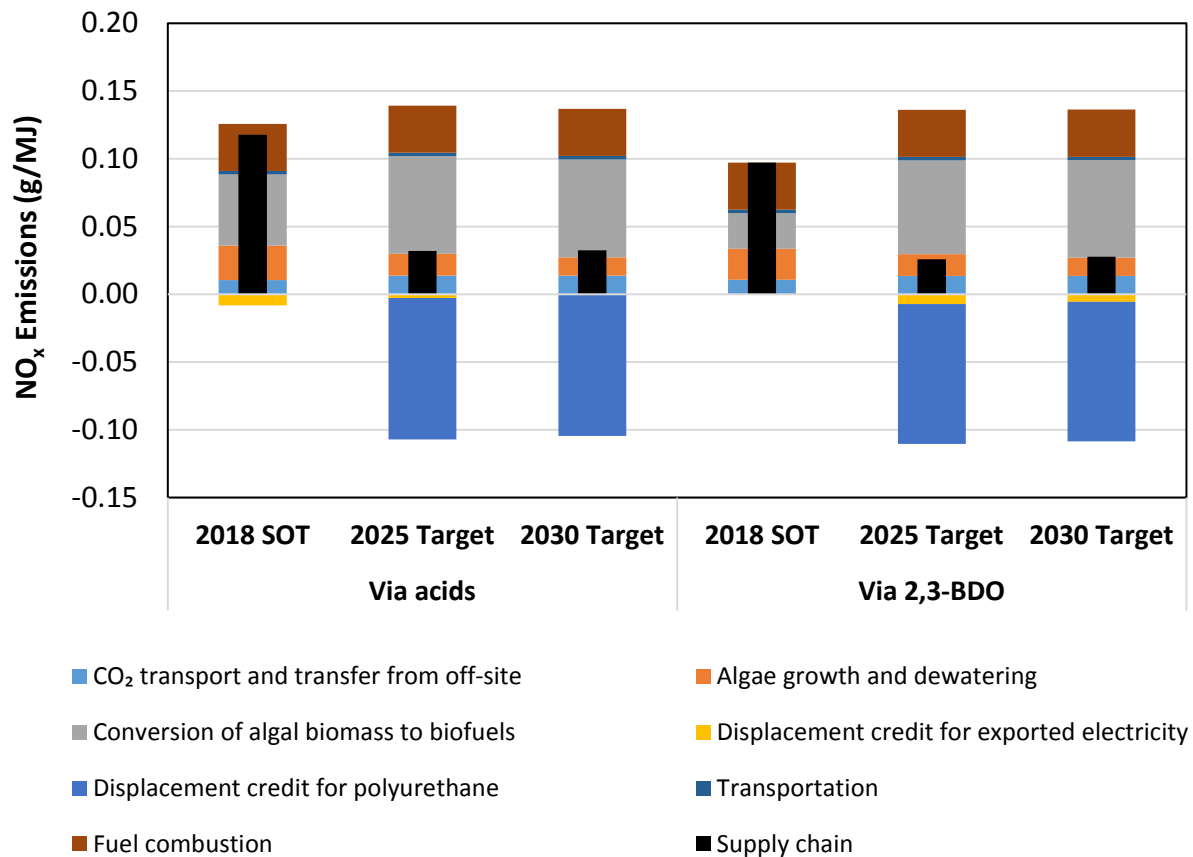
Figure 25 shows that the 2018 SOT and the 2025 and 2030 target cases have significantly higher water consumption than that of petroleum diesel, owing to significant embedded water consumption associated with the process chemical and catalyst use, as well as to makeup water requirements for the CAP conversion process. 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<sub>x</sub> Emissions

Figure 26 shows that total NO<sub>x</sub> emissions are reduced significantly from the 2018 SOT case to the 2025 and 2030 target cases for both the acids and BDO pathway designs. With the significant co-product displacement emission credit for PU, the 2025 and 2030 target cases could bring the NO<sub>x</sub> emissions below the level of petroleum diesel. Embedded emissions from manufacturing the process chemicals and catalysts required for the CAP conversion and PU co-production operations is the major emission source for the 2018 SOT and the 2025 and 2030 target cases.



**FIGURE 26 Supply Chain NO<sub>x</sub> Emissions (g/MJ), Renewable Diesel via CAP, Compared with 0.07 g/MJ for Petroleum Diesel**

### 3.6.4 Summary of Sustainability Metrics

Table 21 summarizes the supply chain sustainability metrics, including fossil energy consumption, NEB, GHG emissions, water consumption, and NO<sub>x</sub> emissions of RD from these CAP conversion design scenarios. Again, a key issue in dealing with co-products from these CAP conversion cases is how to capture their environmental impacts, especially under the current fuel-focused GHG regulations. For biorefineries co-producing significant quantities of bio-derived chemical co-products, only the displacement method can fully account for the GHG emissions reduction and other sustainability metrics benefits offered by PU compared to traditional (energy-intensive) PU production from petroleum feedstocks and to other allocation-based co-product methods (Cai et al. 2018). Therefore, the supply chain results of these metrics represent a biorefinery-level assessment that considers the impacts of all the finished products from biorefineries of such designs. 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.

**TABLE 21 Supply Chain Sustainability Metrics for Renewable Diesel via CAP**

	Scenario 1: Via Acids			Scenario 2: Via 2,3-BDO			Petroleum Diesel
	2018 SOT	2025 Design Case	2030 Design Case	2018 SOT	2025 Design Case	2030 Design Case	
	<b>Biofuel yield</b>						
Million Btu/dry ton	10.8	9.7	9.7	10.6	9.8	9.8	
	<b>Co-product yield</b>						
Polyurethane, kg/mmBtu of biofuel	0	20.0	20.1	0	19.8	19.8	
Electricity, kWh/mmBtu of biofuel	28.1	9.8	0	0	24.6	19.1	
	<b>Fossil energy consumption</b>						
MJ/MJ	1.1	0.69	0.71	1.03	0.11	0.14	1.20
	<b>Net energy balance</b>						
MJ/MJ	-0.1	0.31	0.29	-0.03	0.89	0.86	
	<b>GHG emissions</b>						
g CO <sub>2</sub> e/MJ	82 (-13%)	37 (-60%)	39 (-58%)	77 (-18%)	8 (-91%)	10 (-89%)	94
g CO <sub>2</sub> e/ GGE	10,078	4,569	4,792	9,426	1,036	1,244	11,528
	<b>Water consumption</b>						
gal /MJ	0.30	0.31	0.38	0.21	0.22	0.22	0.02
gal/ GGE	37.3	37.7	46.1	25.4	26.9	26.9	2.7
	<b>Total NO<sub>x</sub> emissions</b>						
g NO <sub>x</sub> /MJ	0.12	0.03	0.03	0.10	0.03	0.03	0.07
g NO <sub>x</sub> /GGE	14.4	3.9	4.0	11.9	3.2	3.4	7.9
	<b>Urban NO<sub>x</sub> emissions</b>						
g NO <sub>x</sub> /MJ	0.03	0.03	0.03	0.03	0.03	0.03	0.03
g NO <sub>x</sub> /GGE	4.0	3.8	3.9	4.2	3.8	3.8	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 2018 SOT and 2022 design cases yields a fuel that is 83% and 85% 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<sub>x</sub> emission source, and thus NO<sub>x</sub> emission control of this combustion source presents the greatest opportunity to mitigate the supply chain NO<sub>x</sub> emissions of the HOG via IDL pathway. HOG via IDL shows significant reduction potential in fossil energy consumption, owing mostly to energy self-sufficient IDL processes and the use of excess process heat from the IDL processes for feedstock depot preprocessing, reducing the need for external energy. As a result, HOG via IDL offers significant fossil energy-saving benefits, as indicated by its NEB values of 0.81 and 0.83 MJ/MJ in the 2018 SOT and 2022 design cases, respectively.

SCSAs for RG and RD production from a clean pine or a blend of clean pine and logging residues via ex situ catalytic fast pyrolysis indicate that these fuels offer GHG emission reductions compared to conventional gasoline. We estimated a 72% and 69% reduction in GHG emissions for the 2018 SOT and 2022 design cases, respectively. Among the different supply chain stages, biomass field and depot preprocessing were the largest contributors to the supply chain GHG emissions, contributing between 72% for the 2018 SOT and 90% for the 2022 design case. 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. Feedstock options and the resulting water consumption greatly impact the supply chain water consumption, and driving down conversion water consumption remains an opportunity for further mitigating the supply chain water consumption of the CFP pathway.

Controlling NO<sub>x</sub> emissions from combusting intermediate bio-char to meet process heat demand presents an opportunity to mitigate the supply chain NO<sub>x</sub> emissions. The energy-intensive preprocessing step, which consumes a large amount of natural gas for air classifying and leaching the logging residues at the depot, is another major opportunity to mitigate NO<sub>x</sub> emissions in the 2022 design case. The NEB of RG and RD from CFP ranges from about 1 MJ/MJ in the 2015 SOT, owing to a significant displacement credit of a large amount of surplus electricity, to about 0.58 MJ/MJ, indicating a 58% fossil energy saving potential for the fuels produced in the 2022 design case. Despite a shift from producing both biofuel and surplus electricity in the 2015 SOT case to primarily biofuel production in the 2022 design case, the total fossil energy savings benefit from the biofuel production in the 2022 design case is about the

same as that from both biofuel and electricity production in the 2015 SOT case on the basis of converting one ton of biomass feedstock.

Producing RD via sludge HTL in the 2018 SOT and 2022 design cases offers 59% and 73% GHG emission reductions, respectively. Collectively, energy efficiency improvement at the HTL plant and catalyst innovation contribute to a 39% reduction (with NH<sub>3</sub> removal) and a 46% reduction (without NH<sub>3</sub> removal) in GHG emissions in the 2022 design case compared to the 2018 SOT target case. Ammonia stripping using water-intensive CaO has a significant impact on supply chain water consumption. Without NH<sub>3</sub> removal, water use during conversion of sludge to biocrude diminishes significantly — by over 90% in the 2018 SOT and 2022 design cases. Together with improvements in energy efficiency and catalyst innovation, supply chain water consumption is reduced from 4 gal/GGE in the 2018 SOT case to 2 gal/GGE in the design case, which is below that of petroleum diesel. Fuel combustion and HTL for biocrude production are the primary contributors to NO<sub>x</sub> emissions. With improvement in HTL energy efficiency, the design case has a slightly lower NO<sub>x</sub> emission intensity than that of petroleum diesel.

The sludge HTL pathway has an NEB of 0.52 MJ/MJ (with NH<sub>3</sub> removal) and 0.63 MJ/MJ (without NH<sub>3</sub> removal) in the 2022 design case, as a result of a 27% reduction (with NH<sub>3</sub> removal) and 31% reduction (without NH<sub>3</sub> removal) in supply chain fossil energy consumption. For this pathway, wet sludge from the WWTP is treated as a burden-free waste stream, and its alternative fate if it were not taken as a feedstock for the HTL processes is not considered in this SCSA. This so-called counterfactual scenario of the sludge may lead to various possibilities for its end of life, and thus may have carbon implications for using sludge for the purpose of transportation fuel production if such a counterfactual scenario could be defined and evaluated with sufficient evidence and data. Another issue that may warrant further analysis is the end of life of CaCO<sub>3</sub> in the solid stream from the HTL aqueous treatment. Whether CaCO<sub>3</sub> is qualified as a soil amendment agent, and if so, how much of the carbon therein may be sequestered in the soil and how much may be released to the atmosphere as CO<sub>2</sub> emissions, may impact the carbon intensity of the sludge HTL-derived biofuel. Sufficient data are needed to address this issue adequately. Moreover, carbon in the HTL solids originates from the sludge. This carbon source may undergo potentially different transformations depending on whether it is subject to HTL processes or to a more regular treatment such as AD or landfill as part of the sludge. The difference in such alternative treatment purposes may lead to a distinctive end of life of the carbon therein, impacting the carbon intensity of the biofuel from utilizing the sludge carbon, which might warrant further analysis.

For the biochemical conversion pathway with a lignin-to-AA coproduct, the conversion step is the major GHG emission source in both the 2018 SOT and the 2030 design cases, owing to large quantities of process chemicals required for pretreatment operations and for upgrading the lignin stream to AA. Considerable improvement in biofuel yields, significantly larger coproduct yields, reduction in process energy consumption, and reduction in chemical consumption contribute to negative GHG emission intensities in the 2030 design case when a significant coproduct displacement credit is reflected onto the fuel product. Significant embedded water consumption associated with the process chemical use, as well as makeup water requirements during the biochemical conversion process, lead to significantly higher water consumption in both the 2018 SOT and the 2030 design cases, compared with that of petroleum diesel. Improved

biofuel and co-product yields and a reduction in process energy and chemical consumption are the keys to lowering water consumption considerably in the 2030 design case for both the acids and BDO pathway scenarios. A key issue in dealing with co-products from these biochemical conversion designs is how to capture their environmental impacts, especially under the current fuel-focused GHG regulations. For biorefineries co-producing significant quantities of bio-derived chemical co-products, only the displacement method can fully account for the GHG emission reduction benefits and other sustainability metrics considered here that are offered by non-fuel products (compared with other allocation-based co-product methods) (Cai et al., 2018).

RD biofuel produced from co-feeding algae and woody biomass to the HTL processes offers a 60% and 67% reduction in GHG emissions in the 2017 and 2018 SOT cases, respectively, compared with those of petroleum diesel. This shows a significant improvement compared to a 10% emission reduction potential in the 2016 SOT case (Cai et al., 2017). Increased biofuel yield in the 2018 SOT case is a key driver of its greater GHG emission reductions than the 2017 SOT case. Research and development efforts to further reduce supply chain GHG emissions could focus on increasing algal biomass productivity and reducing energy consumption for algal biomass cultivation and dewatering and HTL conversion, as these remain the primary emission sources in the 2018 SOT case. Embedded water consumption associated with energy consumption for algae cultivation and dewatering and for CO<sub>2</sub> capture and transportation to the algae farm are the major contributors to supply chain water consumption in the 2017 and 2018 SOT cases. 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<sub>x</sub> emissions.

In the 2018 SOT case, the algae CAP pathway has 13% and 18% lower GHG emission intensity via the acids and 2,3-BDO intermediate pathways, respectively, compared to petroleum diesel. When PU coproduction is implemented in the 2025 and 2030 target cases, significantly greater GHG emission reductions, roughly 60% and 58% in the 2025 and 2030 target cases via the acids pathway, and roughly 91% and 89% in the 2025 and 2030 target cases via the BDO pathway, can be achieved. As in the AA coproduct findings for the biochemical conversion case, such emission implications reflect accounting for the emission reduction benefits of both the fuel and non-fuel PU products when the displacement method is used to handle co-products. 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 the fuel and PU 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<sub>x</sub> emissions.

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