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Supply Chain Sustainability Analysis of Renewable Hydrocarbon Fuels via Indirect Liquefaction, Fast Pyrolysis, and Hydrothermal Liquefaction: Update of the 2016 State-of-Technology Cases and Design Cases

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Idaho National Laboratory

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1 INTRODUCTION

The Department of Energy's (DOE) Bioenergy Technologies Office (BETO) aims to develop and deploy technologies to transform renewable biomass resources into commercially viable, high-performance biofuels, bioproducts and biopower through public and private partnerships (DOE, 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, and life-cycle analysis of overall system sustainability.

In addition to developing a TEA for pathways 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 17 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 memorandum describes the SCSAs for the production of three renewable hydrocarbon transportation fuels: (1) renewable high octane gasoline (HOG) via indirect liquefaction (IDL) of woody lignocellulosic biomass; (2) renewable gasoline (RG) via fast pyrolysis of woody lignocellulosic biomass; and (3) renewable diesel via hydrothermal liquefaction of algae. This technical memorandum focuses on the 2016 State of Technology (SOT) technical, economic, and environmental performance of these three fuel production pathways, as well as the 2016 SOT woody feedstock blend production and the 2016 SOT for algae feedstock production. The results of these renewable hydrocarbon fuel pathways in these SCSA analyses update those for the respective 2015 SOT cases (Cai et al., 2016; Adom et al., 2016; Frank et al., 2016), and provide an opportunity to examine the impact of technology improvements of both biomass feedstock production and biofuel production that have been achieved since the 2015 SOTs on the sustainability performance of these renewable transportation fuels. Furthermore, they reflect updates to Argonne National Laboratory's Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET®) model, which was released in October 2016 (ANL, 2016). The 2015 SOT case was re-evaluated using this newly-released version, which includes updates to the production of natural gas, electricity, and liquid fuels that can influence biofuels' supply chain greenhouse gas (GHG) (CO_2, CH_4, and N_2O) emissions. These emissions and water consumption are the two sustainability metrics assessed in this analysis. The design cases (future target projections) for these three fuel production pathways were also re-evaluated using GREET 2016. In particular, the 2016 woody blend feedstock SOT was used in lieu of the previous design case woody blend feedstock, which utilized construction and demolition waste (INL, 2014). In the 2016 woody blend feedstock SOT, the construction and demolition waste was eliminated due to a lack of Renewable Identification Number (RINs) generation, and replaced with short rotation hybrid poplar in order to align with the woody feedstock blend that was chosen by the BETO Feedstock-Conversion Interface Consortium (FCIC) for the 2017 fast pyrolysis verification.

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 and RG from pyrolysis. National Renewable Energy Laboratory (NREL) conducted TEAs of algae feedstock production for the SOTs and target cases, which were coupled with the TEAs of algae hydrothermal liquefaction (HTL) conducted by Pacific Northwest National Laboratory (PNNL) for the SCSA of renewable diesel (RD) from algae HTL. In this analysis, we consider the upstream impacts of producing each energy and chemical input to the supply chain.

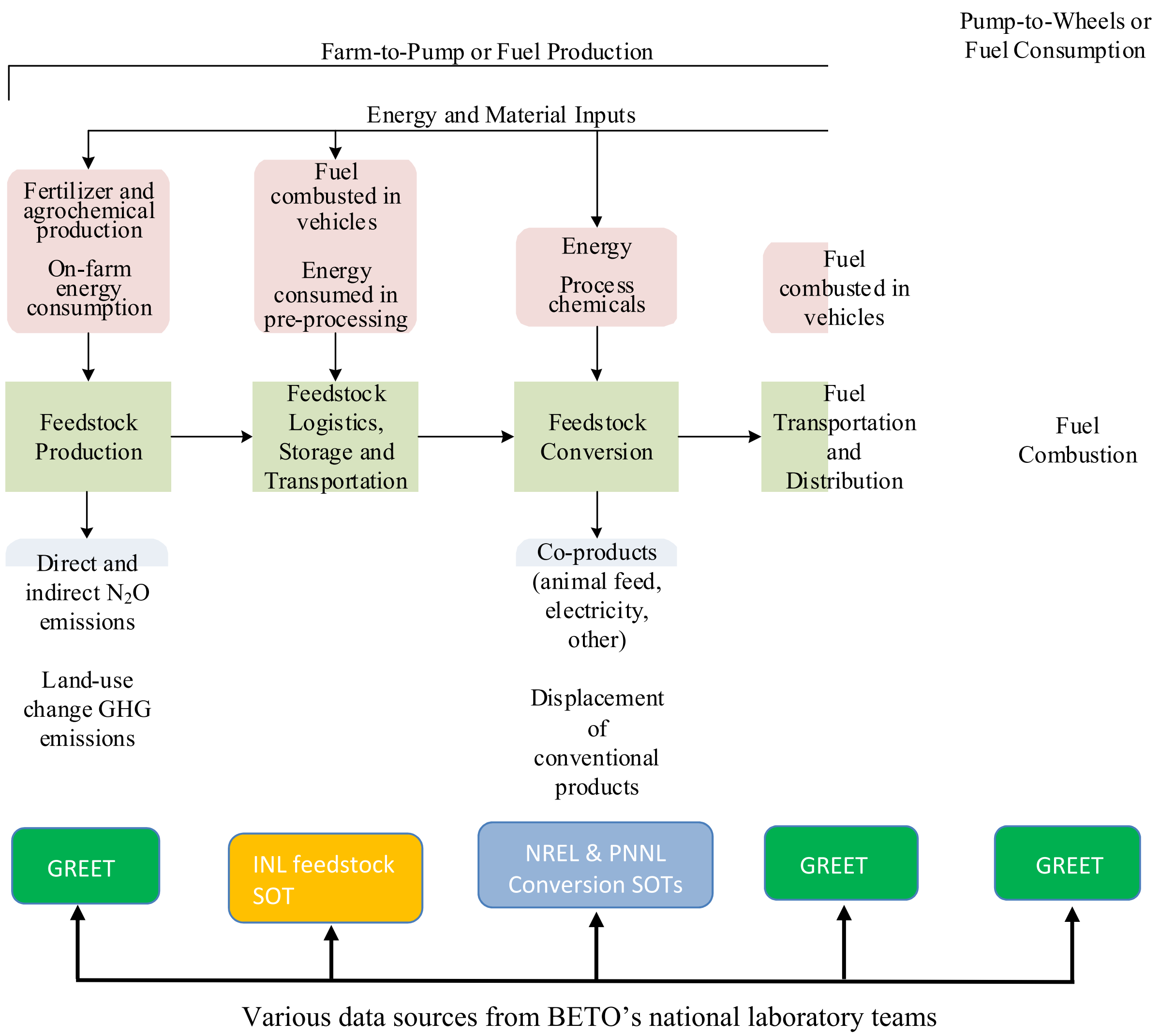

FIGURE 1 General Stages Considered and Data Sources Used in the Supply Chain Sustainability Analyses for HOG via IDL and RG from Pyrolysis.

2 METHODS AND DATA

Argonne National Laboratory's GREET model (ANL, 2016) was used to produce the SCSA results for the 2016 SOT cases and to update those for the 2015 SOT cases and the design cases. 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 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, emissions of six air pollutants: carbon monoxide (CO), volatile organic compounds (VOCs), nitrogen oxides (NO_x), sulfur oxides (SO_x), and particulate matter with an aerodynamic diameter below 10 micrometers (PM_{10}) and below 2.5 micrometers ($PM_{2.5}$), and water consumption in the various fuel production pathways.

2.1 MATERIAL AND ENERGY REQUIREMENT OF FEEDSTOCK PRODUCTION AND LOGISTICS

INL modeled a woody blended feedstock for the 2016 SOT that is used by the IDL and fast pyrolysis pathways (Hartley et al., 2016), while NREL modeled an algal feedstock that is used for the algae HTL pathway (Markham and Davis, 2017). The biomass blending approach to produce the woody blended feedstock takes advantage of low cost woody biomass resources (i.e., forest residues), while producing a feedstock with a low ash content. The blended feedstock comprises forest residues (60 wt%), clean pine (30 wt%), and hybrid poplar (10 wt%) in the 2016 SOT.

The total energy requirements for feedstock production for each supply chain operation are summarized in Table 1, with the shares of fuel type presented in Table 2. Note that the farming energy consumption and the fertilizer use for production of pine and poplar that we use in this analysis are based on the 2016 Billion Ton Study (ORNL, 2016), as shown in Table 3.

There were seven different logistics operations utilized in the 2016 woody blend SOT to harvest, collect and preprocess the various woody biomass resources into the delivered woody feedstock blend. Not all operations were undertaken for every component of the feedstock blend. Two operations that are part of forestry operations, i.e., planting and fertilization, harvesting and collection, were considered for the production of pine and poplar. Diesel is consumed for these operations. Preprocessing of all biomass resources, except for poplar, included a landing preprocessing/sorting operation, which consumes solely diesel for steps including debarking, size reduction, sorting, and screening. All biomass sources were subject to four additional operations. The transportation operation consumes diesel fuel whereas the receiving, handling, and blending operations consume electricity. For forest residues and pine biomass, the preprocessing operations consume natural gas and electricity accounting for 81% and 19% of the process energy requirements, respectively. Note that preprocessing of forest residues involves air classification to remove contaminating soil ash, which is not required for preprocessing clean pine. This additional step in the preprocessing of forest residues consumes electricity, but is very small relative to the total electricity used for preprocessing the forest residues. As a result, the

TABLE 1 Energy Consumption, in Btu/Bone Dry Ton, for Feedstock Production and Logistics in the 2016 SOT Case for HOG via IDL and RG via Fast Pyrolysis (Hartley et al., 2016)

	Forest residue	Pine	Poplar
Silviculture		36,987	51,517
Harvest and collection	99,621	107,190	192,950
Landing preprocessing	185,360	310,960	
Receiving & handling	2,570	4,400	1,960
Preprocessing	1,596,650	1,601,770	1,852,470
Blending	3,070	3,390	3,390

TABLE 2 Share (%) of Production and Logistics Stage Fuel Type for Each Woody Biomass Resource (Hartley et al., 2016)

	Forest residue			Pine			Poplar		
	Diesel	Electricity	Natural gas	Diesel	Electricity	Natural gas	Diesel	Electricity	Natural gas
Silviculture				100%	0%	0%	100%	0%	0%
Harvest and collection	100%	0%	0%	100%	0%	0%	100%	0%	0%
Landing preprocessing	100%	0%	0%	100%	0%	0%			
Receiving & handling	0%	100%	0%	0%	100%	0%	0%	100%	0%
Preprocessing	0%	19%	81%	0%	19%	81%	0%	17%	83%
Blending	0%	100%	0%	0%	100%	0%	0%	100%	0%

TABLE 3 Fertilizer and Herbicide/Pesticide Usage, in Gram/Bone Dry Ton, of Pine and Poplar Silviculture (Canter et al., 2016; ORNL, 2016)

	Nitrogen (N)	Phosphate (P_2O_5)	Potash (K_2O)	Limestone ($CaCO_3$)	Herbicide	Insecticide
Pine	2,840	1,523	401	16,619	0	0
Poplar	1,970	591	522	23,237	62	12

clean pine and forest residues consume about the same amount of electricity. For poplar, natural gas and electricity accounted for 83% and 17% of the process energy requirements, respectively. Parameters used to determine energy consumed during feedstock transportation, which include transportation distance, truck payload, and feedstock moisture content, taken from the 2016 woody feedstock SOT, are shown in Table 4. These data were incorporated into the new HOG and RG 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 4 Woody Biomass Transportation Parameters for transportation from the landing to the biorefinery (forest residues and pine) or from the harvest site to the biorefinery (poplar), 2016 woody feedstock SOT (Hartley et al., 2016)

	Truck Payload (tons)	Transportation Distance (miles)	Transportation Moisture Content
Forest Residues	16.5	115.5	30%
Pine	17.7	71.3	30%
Poplar	11.8	115.5	50%

The 2016 SOT for the woody blended feedstock was used for both the HOG via IDL and the RG from fast pyrolysis pathways in both the 2016 SOTs and the design cases.

The material and energy requirements for algae cultivation and dewatering in the 2016 SOT case are presented in Table 5, based on inputs furnished by NREL (Markham and Davis, 2017). The 2016 SOT was based on cultivation data made available from the ATP3 consortium (Knoshaug, et al., 2016), attributed to ATP3's Florida Algae site making use of a strain rotation

TABLE 5 Farm model parameters for the 2015 SOT, the 2016 SOT, and the revised 2022 target cases

Materials and Energy Inputs	2015 SOT[a]	2016 SOT[b]	Revised 2022 Target[a]
Algal biomass (g afdw[c])	1.0	1.0	1.0
CO_2 (g/g afdw)	2.29	2.29	2.22
Ammonia (g/g afdw)	2.35×10^{-2}	2.20×10^{-2}	1.94×10^{-2}
Diammonium phosphate (g/g afdw)	1.18×10^{-2}	1.10×10^{-2}	9.69×10^{-3}
Electricity demand (kWh/g afdw)	9.61×10^{-4}	9.15×10^{-4}	4.54×10^{-4}
Total process water consumption (g/g afdw)	94.4	88.5	51.9
Water in biomass (g/g afdw)	4.12	4.10	4.03
Water lost to blowdown (g/g afdw)	36.9	34.5	12.2
Water lost to evaporation (g/g afdw)	52.7	49.2	35.7

[a]: Frank et al., 2016; [b]: Markham and Davis, 2017; [c]: Ash free dry weight.

strategy for cultivation of *Nannochloropsis maritama* (winter and spring) and *Desmodesmus sp.* (summer and fall), resulting in an annual average productivity of 9.1 g/m^2/day AFDW (Markham and Davis, 2017).

2.2 MATERIAL, ENERGY, AND WATER REQUIREMENTS OF THE IDL, FAST PYROLYSIS, AND HTL PROCESSES

The 2016 SOT case for the IDL processes features a processing capacity of 2,205 U.S. short tons of dry feedstock per day. The HOG yield is 60.5 gallons per dry U.S. short ton of blended feedstock at the biorefinery, with a small amount of surplus electricity as a co-product, which is assumed to be exported to the grid (Tan et al., 2016). At the biorefinery, diesel trucks carrying the biomass chips and a truck dumper that unloads the trucks into hoppers consumes a small amount of diesel fuel. The individual biomass sources are preprocessed into pellets and stored in separate bins. When needed, the pellets are blended at the appropriate ratio to form the blended feedstock, and then crumbled and fed to the reactor throat. Energy use upstream of the reactor throat are accounted for in the 2016 woody feedstock blend SOT data above. Figure 2 shows the process flow diagram (PFD) of the IDL pathway in the 2016 SOT case. For full details regarding the conversion process, see the full SCSA (Cai et al., 2016).

The 2016 SOT of the fast pyrolysis conversion process comprises fast pyrolysis of biomass, hydrotreating, product separation, and hydrocracking of diesel to help increase the fuel yield (Jones et al., 2016). Figure 3 shows the PFD of the fast pyrolysis pathway in the 2016 SOT case. For full details regarding the conversion process, see the full SCSA (Adom et al., 2016).

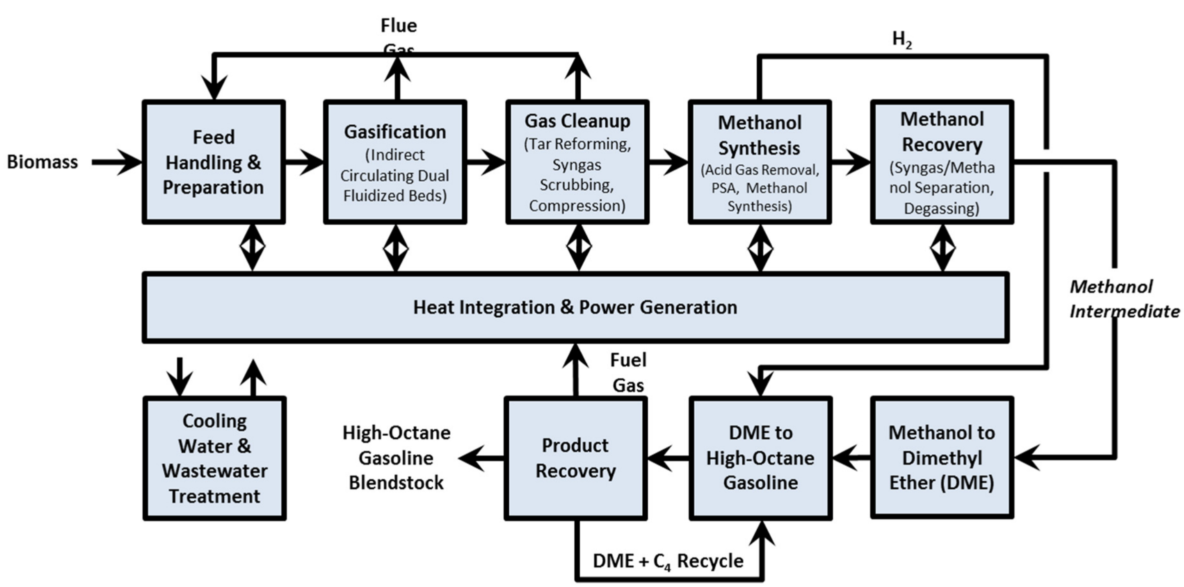

FIGURE 2 Process flow diagram for high octane gasoline via indirect liquefaction in the 2016 SOT (Tan, 2016)

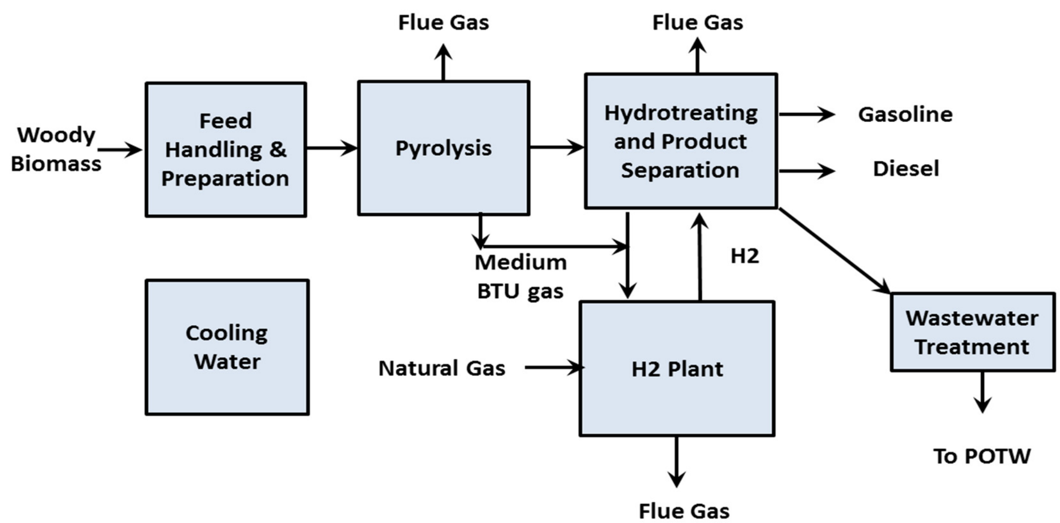

FIGURE 3 Process flow diagram for renewable gasoline from fast pyrolysis in the 2016 SOT (Jones and Zhu, 2016)

The 2016 SOT conversion of algal biomass to RD is achieved by HTL of whole algae followed by hydrotreating of HTL oil (Jones et al., 2014, Jones and Zhu, 2016), as shown in Figure 4.

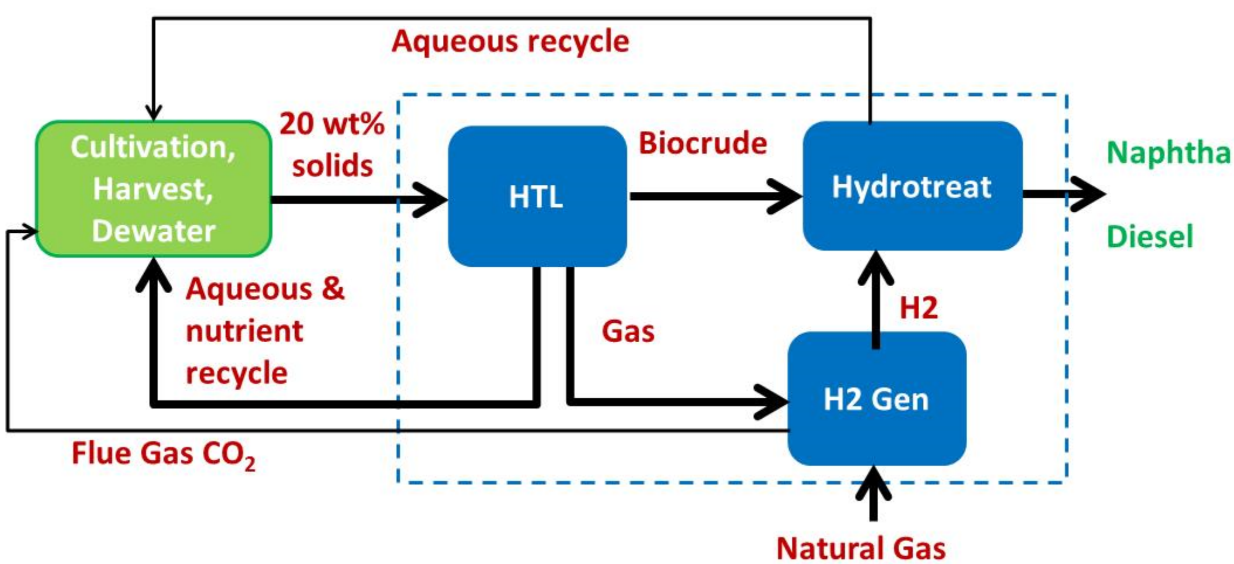

FIGURE 4 Process flow diagram for hydrothermal liquefaction of whole algal biomass for renewable diesel production in the 2016 SOT (Jones and Zhu, 2016)

Table 6 lists the direct material, energy, and water consumption for the modeled IDL conversion process at the plant in the 2016 SOT case (Tan et al., 2016). Table 7 summarizes the modeled pyrolysis conversion process parameters provided for the SOT case (Jones et al., 2016). Table 8 lists the direct material, energy, and water consumption for the modeled algae HTL process in the 2015 SOT, the 2016 SOT, and the 2022 revised target cases. For full details regarding the conversion process parameters in the design cases, see the full SCSAs (Cai et al., 2016; Adom et al., 2016; Frank et al., 2016).

TABLE 6 Key Indirect Liquefaction Process Parameters

	2015 SOT Value	2016 SOT Value	Unit
HOG yield	39.9	60.5	gal/dry ton feedstock
Mixed butane	17.7	0	gal/dry ton feedstock
Surplus electricity	0.12	0.02	kWh/MMBtu of HOG
Diesel energy use	3,101	2,034	Btu/MMBtu of HOG
Char produced and combusted	993,492	977,279	Btu/MMBtu of HOG
Fuel gas produced and combusted	992,535	448,005	Btu/MMBtu of HOG
Syngas produced and combusted	995,198	38,177	Btu/MMBtu of HOG
Magnesium oxide consumption	7.7	5.1	g/MMBtu of HOG
Fresh olivine consumption	602	394	g/MMBtu of HOG
Tar reformer catalyst consumption	9.9	6.4	g/MMBtu of HOG
Methanol synthesis catalyst consumption	6.5	4.1	g/MMBtu of HOG
DME catalyst consumption	8.0	5.0	g/MMBtu of HOG
Beta zeolite catalyst consumption	263	110	g/MMBtu of HOG
Zinc oxide catalyst consumption	131	55	g/MMBtu of HOG
LO-CAT chemicals	134	90.	g/MMBtu of HOG
Water consumption	84	47	gal/MMBtu of HOG

TABLE 7 Fast Pyrolysis Biorefinery Key Parameters (Jones et al., 2016)

Parameter	2015 SOT Case	2016 SOT Case	Units
Total yields of renewable gasoline and renewable diesel	10.0	10.1	MMBtu/dry ton
Share of renewable gasoline	45%	45%	%, by energy
Share of renewable diesel	55%	55%	%, by energy
Electricity consumed in pyrolysis process	693	883	Btu/lb main products
Natural gas consumed to produce hydrogen			
H_2 generation: conventional fixed bed	3,033	3,026	Btu/lb main products
Share of renewable gasoline produced by energy	45%	45%	
Water consumption	1.5	1.7	gal/GGE[a] of fuel output
Renewable gasoline			
Yield	39.9	40.2	gal/dry ton
LHV	18,800	18,810	Btu/lb
Density	6.07	6.06	lb/gal
Renewable diesel			
Yield	43.5	43.5	gal/dry ton
LHV	17,820	17,820	Btu/lb
Density	7.1	7.1	lb/gal

a: Gasoline gallon equivalent

TABLE 8 Materials and Energy Consumption for Algae HTL Process of the 2015 SOT, the 2016 SOT, and the Revised 2022 Target Cases

Parameter	2015 SOT[c]	2016 SOT[d]	Revised 2022 target[c]
Yield (g afdw[a]/g RDe[b])	2.96	2.96	2.06
(g RDe/g afdw)	0.33	0.33	0.49
Natural gas for H_2 production (kWh/g RDe)	9.93×10^{-4}	3.52×10^{-3}	8.34×10^{-4}
Natural gas for summer & spring drying (kWh/g RDe)	1.73×10^{-3}	1.91×10^{-3}	9.51×10^{-4}
Electricity consumed (kWh/g RDe)	3.65×10^{-4}	2.35×10^{-4}	2.31×10^{-4}
Process water demand (g/g RDe)	1.43	1.74	1.82
P recycle (g/g RDe)	0.0136	0.0123	0.0127
N recycle (g/g RDe)	0.17	0.15	0.102
CO_2 recycle in treated water (g/g RDe)	0.297	2.87	0.377

[a]: ash free dry weight; [b]: renewable design equivalent, defined in Frank et al. (2016); [c]: from Frank et al. (2016); and [d]: from Jones and Zhu (2016).

There is a significant increase in the HOG yield from 2015 SOT to 2016 SOT, as shown in Table 6. Part of the reason is improved carbon conversion efficiency in the 2016 SOT case, which co-produces no more mixed butanes and leads to a significant decrease in intermediate carbon streams, particularly the syngas and fuel gas, which are combusted to provide process energy in both the 2015 SOT and 2016 SOT cases, as compared to those in the 2015 SOT case for the HOG via IDL pathway. Besides, the 2016 SOT case consumes lower amounts of process chemicals.

For the RG from fast pyrolysis pathway, a slightly higher RG yield is achieved in the 2016 SOT case, as shown in Table 7. However, the electricity consumption increases by about 27% from 2015 SOT to 2016 SOT for this pathway, whereas the natural gas consumption remains the same. The 2016 SOT includes catalyst regeneration and this accounts for the increased power demand. Besides, there is a small increase in the water consumption in the pyrolysis process from 2015 SOT to 2016 SOT.

In this study, conversion of algal biomass to RD is achieved by whole algae HTL (Jones et al., 2014). Wet algal biomass, as undisrupted cells, is converted into a liquid fuel with pressurized water in a condensed phase (Figure 4). The algal biomass cultivation and harvesting model used in this SCSA is the same one developed previously (Frank et al., 2016). After growth, algal biomass is dewatered in three stages up to a final solids content of 20% (on an ash free basis). The thickened solids then go to the algae HTL conversion process. Previous report (Frank et al., 2016) provides a detailed description of the dewatering processes, including parameters like efficiency and process energy. Algal biomass productivities are 8.5 g/m^2/day in the 2015 SOT, 9.1 g/m^2/day in the 2016 SOT, and 25 g/m^2/day in the revised 2022 target (Frank et al., 2016, Jones and Zhu, 2016, Markham and Davis, 2017). The 2015 and 2016 SOTs have the same elemental compositions, but the revised 2022 target case has higher carbon and less ash contents than the 2015 and 2016 SOT cases (see Table A1). The net nitrogen, phosphorus, and carbon demands were estimated from the mass balance based on the algal compositions and the recycled nitrogen and phosphorus as specified by the PNNL conversion model (Frank et al., 2016, Jones and Zhu, 2016). The same method was applied to the 2016 SOT case.

Table 8 lists the key process parameters and energy inputs for the modeled algae HTL conversion process in the 2015 SOT, the 2016 SOT, and the revised 2022 target cases. There is a significant increase in the RD yield from the 2015 and 2016 SOTs (0.33 g RDe/g afdw) to the revised 2022 target case (0.49 RDe/g afdw), which is due to high carbon content of the algae biomass (52%) in the revised 2022 target, combined with improved carbon conversion efficiency through HTL. The natural gas consumption increases by about 114% from the 2015 SOT case to the 2016 SOT case is mainly due to eliminated aqueous catalytic hydrothermal gasification (CHG) treatment (see Figure 4). Otherwise, CHG catalytically converts all organics in aqueous phase into CH_4 and CO_2, and the generated CH_4 is used for the hydrogen plant internally to generate hydrogen for the process of hydrotreating and fuel upgrading, which reduces natural gas use in the hydrogen plant (Jones et al., 2014). In the 2016 SOT case, all aqueous nutrients were directly recycled for algal cultivation. The demands for additional nutrients were calculated from algal biomass elemental compositions (see Table A1) and the recycled nutrients (see Table 8). Compared to the 2015 SOT case, the total recycled carbon as dissolved CO_2 and organic carbon, which is treated as an intermediate carbon stream, increases from 8% to 22%. The revised 2022 target has the least electricity and natural gas consumptions for hydrogen production and biomass drying in summer and spring.

3 RESULTS AND DISCUSSION

3.1 SUPPLY CHAIN GHG EMISSIONS

For both the HOG via IDL and RG from fast pyrolysis pathways, the same woody blended feedstock is used for the conversion processes. However, total GHG emissions[1] from feedstock logistics in the 2016 woody feedstock SOT were found to be 229 kg CO_2e/dry ton, which is a 19.7% reduction from the 285 kg CO_2e/dry ton reported in the 2015 woody feedstock SOT. On the other hand, the GHG emission intensity of HOG production in the biorefinery goes down from 6.9 g CO_2e/MJ in the 2015 SOT case to 3.9 g CO_2e/MJ in the 2016 SOT case for the HOG via IDL pathway, which is a 43% reduction in the conversion GHG emission intensity. For the RG via fast pyrolysis pathway, the GHG emission intensity of RG production in the biorefinery rises from 17.8 g CO_2e/MJ in the 2015 SOT case to 18.7 g CO_2e/MJ in the 2016 SOT case due to the higher process energy requirement with the addition of catalyst regeneration in the 2016 SOT case, while the RG yield remains relatively constant. Note that these conversion GHG emissions include both direct emissions from combustion or conversion of process energy during the conversion stage, as well as upstream emissions associated with production and transportation of the process energy and chemicals to the biorefinery.

3.1.1 HOG via IDL

In the 2016 SOT case, which represents an integration of the 2016 SOT case for woody feedstock production and logistics and the 2016 SOT case for the IDL processes, the IDL process produces HOG and co-produces a small amount of surplus electricity. We used the displacement co-product treatment method to account for the energy, emission, and water credits resulting from transmitting the surplus electricity to the grid and displacing the U.S. average electricity. Figure 5 shows the supply chain GHG emissions for HOG in the 2016 SOT, in comparison to the 2015 SOT and the 2022 design case.

The supply chain GHG emissions of HOG via IDL decreases from about 52.9 g CO_2e/MJ in the 2015 SOT case to about 34.9 g CO_2e/MJ in the 2016 SOT case, which represents a 34% reduction in the GHG emission intensity. This is mostly attributable to three factors: (1) woody biomass preprocessing to the feedstock blend, which is the largest contributor to the supply chain GHG emissions for both the 2015 SOT (50%) and 2016 SOT cases (49%), has significantly reduced the amount of energy it consumes for size reduction, drying, and densification of the feedstock compared to the 2015 feedstock SOT case. Two technological improvements are responsible for bringing about this change: replacement of a portion of the field-side preprocessing of forest residues with air classification during in-plant preprocessing, which removes soil ash from the feedstock with reduced dry matter loss and overall energy consumption; and replacement of the hammer mill for size reduction with rotary shear, which

[1] GHG emissions are reported as grams carbon dioxide equivalents per mega joule of fuel. Carbon dioxide equivalent emissions include CO_2 emissions and CH_4 and N_2O emissions multiplied by their 100-year global warming potentials according to the Fifth Assessment Report of the United Nations Intergovernmental Panel on Climate Change (IPCC)

reduces energy consumption and dry matter loss (Hartley et al., 2016); (2) a 59% reduction in energy consumption associated with feedstock landing preprocessing and sorting is achieved in the 2016 feedstock SOT. The use of air-classification during in-plant preprocessing eliminated the use of a chain flail on the landing to clean the residues, which caused a loss of 40% of the material. The avoidance of the chain flail and savings in lost material are the primary causes of the energy consumption change (Hartley et al., 2016); and (3) the elimination of construction and demolition waste (transported at 10% moisture) due to lack of RINs and their replacement with short rotation hybrid poplar (transported at 50% moisture) in the 2016 woody feedstock SOT causes more energy intensive transportation of the feedstock to the biorefinery on a dry ton basis as compared to the 2015 woody feedstock SOT (Hartley et al., 2016).

Figure 5 shows the contributions of various supply chain processes to the total GHG emissions of the HOG via IDL pathway. Woody biomass preprocessing is the largest contributor to the supply chain GHG emissions for both the 2015 SOT (50%) and 2016 SOT cases (49%). In the 2016 SOT case, natural gas and electricity consumption contribute 67% and 33% of GHG emissions from feedstock preprocessing, respectively, which is very similar to the breakdown of these emissions in the 2015 SOT case. Therefore, driving down energy consumption will be key to reducing the contribution of feedstock preprocessing to supply chain GHG emissions. Feedstock handling and logistics (woody biomass landing preprocessing and sorting, storage, and handling) contributes 8.2% of the supply chain GHG emissions in the 2016 SOT case, which represents a 71% GHG emission reduction in these supply chain operations as compared to the 2015 SOT case for the reasons describedabove. Landing preprocessing and sorting consumes diesel for woody biomass debarking, size reduction, sorting, and screening. This step contributes 17% and 7% of the supply chain GHG emissions for the 2015 SOT and 2016 SOT cases, respectively. The IDL conversion process contributes 13% (6.9 g CO_2e/MJ) and 10% (4.2 g CO_2e/MJ) of the supply chain GHG emissions for the 2015 SOT and 2016 SOT cases, respectively. The IDL process is almost 100% energy self-sufficient as previously described. With little contribution from energy consumption to GHG emissions from the IDL process, the production and use of catalysts become a significant contributor (82% for the 2015 SOT case and 83% for the 2016 SOT case) to the minimal GHG emissions from this supply chain step. Combustion of the syngas, fuel gas and char would produce CH_4 and N_2O 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_2O emissions from combustion of intermediate syngas, fuel gas, and char are responsible for about 18% and 17% of IDL GHG emissions for the 2015 SOT and 2016 SOT cases, respectively. Woody biomass transportation contributed 9% and 18% of the supply chain GHG emissions in the 2015 SOT and 2016 SOT cases, respectively, followed by woody biomass harvest and collection (3% for the 2015 SOT and 3% for the 2016 SOT cases), production and use of fertilizers (2% for the 2015 SOT and 3% for the 2016 SOT cases), and N_2O emissions from nitrogen fertilizers (2% for the 2015 SOT and 3% for the 2016 SOT cases). Compared to the 2016 SOT, the 2022 design case has lower GHG emissions from the woody biomass supply chain, owing to increased HOG yield. The IDL conversion process also reduced the GHG emissions in the 2022 design case, owing to reduced catalyst consumption.

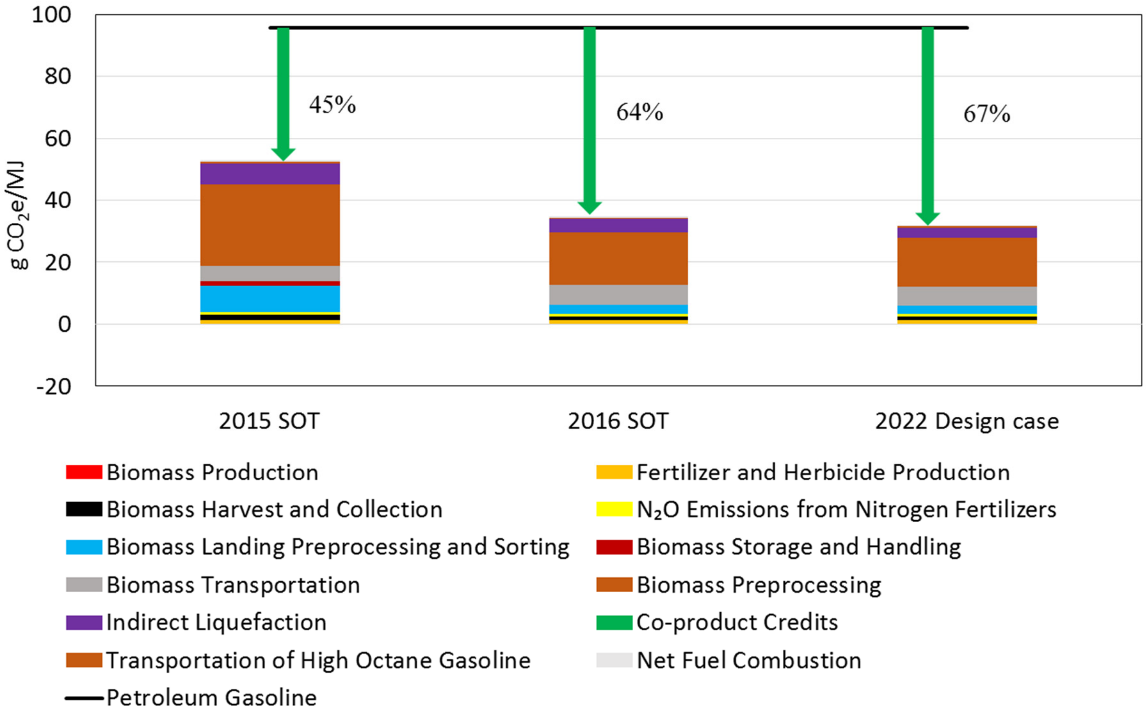

FIGURE 5 Supply Chain GHG Emissions of HOG Produced Via the IDL Process in the 2016 SOT Case, in Comparison to the 2015 SOT Case and the 2022 Design Case

With supply chain GHG emissions of 52.9, 34.9, and 32.0 g CO_2e/MJ, HOG produced via IDL for the 2015 SOT, 2016 SOT, and 2022 design cases offers about 45%, 64%, and 67% supply chain GHG emission reduction, respectively, in comparison to about 95.5 g CO_2e/MJ for gasoline blendstock produced from petroleum crudes. The biogenic CO_2 credit from carbon uptake during the growth of woody biomass is the major driver of the GHG emission reduction for HOG, and, in all cases, the fuel production phase is also more favorable for HOG than petroleum gasoline blendstock, which has significant GHG emission burdens from crude refining. Changing the co-product handling methods would have a negligible change to these results for the 2016 SOT case because of its very small amount of surplus electricity.

3.1.2 RG from fast pyrolysis

The pyrolysis process produces gasoline and diesel fuels. In this analysis, process energy and emissions burdens are assigned between these two co-products with energy allocation. The supply chain GHG emissions of RG via fast pyrolysis, as shown in Figure 6, decrease from about 46.7 g CO_2e/MJ in the 2015 SOT case to about 39.9 g CO_2e/MJ in the 2016 SOT case, which translates to a 51% and 58% reduction in the GHG emission intensity, respectively, relatively to that of petroleum gasoline. There is a reduction of about 2 g CO_2e/MJ for the 2015 SOT case in this analysis, using GREET 2016, as compared to what we did using GREET 2015 (Adom et al., 2016). The major drivers for the reduction in GHG emission intensity from the 2015 SOT case to the 2016 SOT case are the improvements made in woody biomass landing preprocessing and in-plant biomass preprocessing operations, as discussed earlier.

Figure 6 shows the contribution of the different stages in the supply chain of pyrolysis-derived gasoline for the total supply chain GHG emissions. For the 2016 SOT case, the largest contributor (47%) to the supply chain GHG emissions is GHG emissions from the biorefinery, of which 49% are from natural gas consumption for the steam methane reforming process, which produces H_2 from methane and steam and emits CO_2, 38% are from electricity consumption at the biorefinery, and the balance are from natural gas recovery and processing upstream of the biorefinery. Preprocessing of the woody biomass sources to the feedstock blend is a significant contributor (29%) to supply chain GHG emissions. woody biomass transportation and landing preprocessing account for 11% and 5% of the supply chain GHG emissions, respectively. Fertilizer production and use, woody biomass harvest and collection, and transportation of renewable gasoline each contribute approximately 2% towards the supply chain GHG emissions.

With supply chain GHG emissions of 46.7, 39.9, and 38.0 g CO_2e/MJ, RG produced from fast pyrolysis for the 2015 SOT, 2016 SOT, and 2017 target cases offers about 51%, 58%, and 60% supply chain GHG emission reduction, respectively, in comparison to about 95.5 g CO_2e/MJ for gasoline blendstock produced from petroleum crudes.

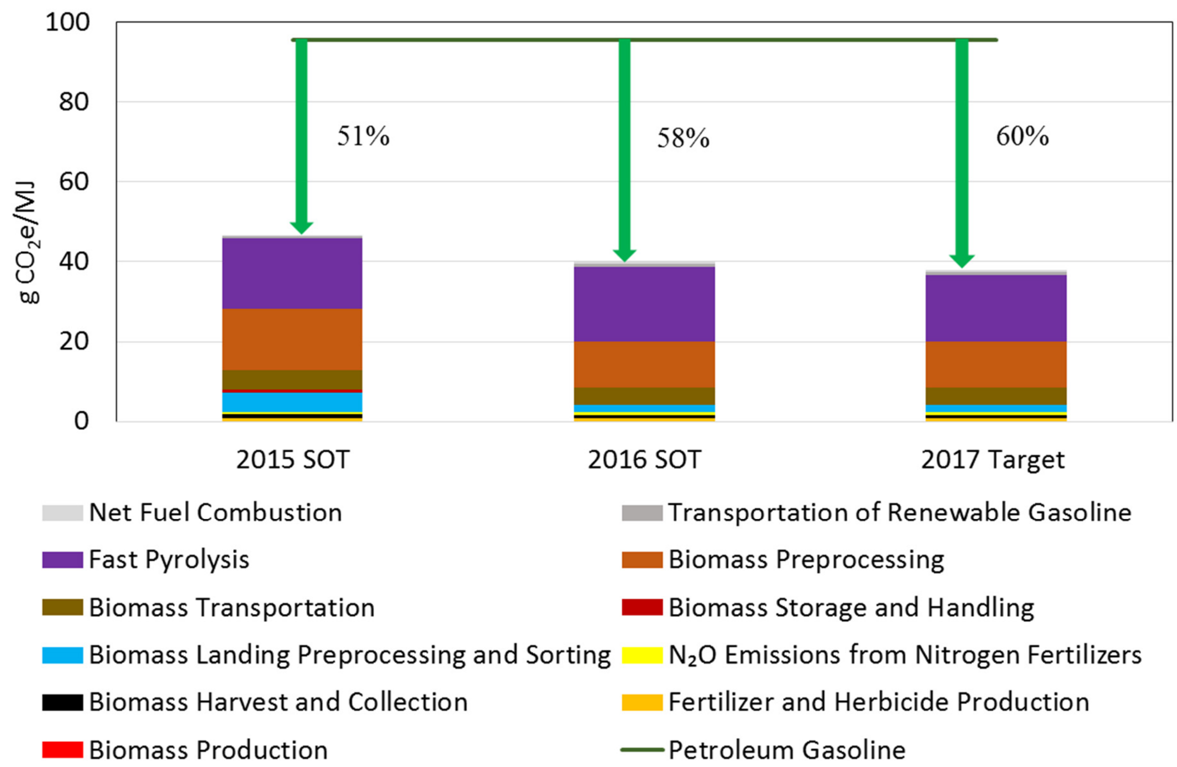

FIGURE 6 Supply Chain GHG Emissions of RG from the Fast Pyrolysis Process in the 2016 SOT Case, in Comparison to the 2015 SOT Case and the 2017 Target Case

Readers should note that this analysis of the RG from the pyrolysis pathway excludes the impact of catalyst production and consumption in the pyrolysis pathway because material and energy intensity data for the production and use of hydrotreating catalysts are still under development. Snowden-Swan et al. (2016), however, have reported that catalyst could contribute 0.5% to 5% to conversion stage GHG emissions depending on catalyst lifetime and identity.

3.1.3 RD from algae HTL

The supply chain GHG emissions of algal RD via algae HTL increased from 81 g CO_2e/MJ in the 2015 SOT case to 84 g CO_2e/MJ in the 2016 SOT case, as shown in Figure 7. Compared to a life cycle carbon intensity of 94 g CO_2e/MJ for conventional low sulfur petroleum diesel, the 2015 SOT, the 2016 SOT, and the 2022 target cases reduce supply chain GHG emissions by 14%, 10%, and 52%, respectively. As shown in Figure 7, the 2016 SOT case has smaller GHG emission reduction than the 2015 SOT case mostly due to increased conversion natural gas consumption by about 250%, which more than offsets the GHG emission credit from recycled carbon. Compared to the 2015 SOT case, GHG emissions associated with CO_2 supply and recycle in the 2016 SOT decrease by 50%, due to the elimination of aqueous treatment by CHG. Compared to the 2015 SOT case, the 2016 SOT case has similar GHG emissions from algae cultivation and dewatering and biomass drying natural gas. The algae cultivation and dewatering are the largest contributors to the supply chain GHG emissions for both the 2015 SOT (44%) and the 2016 SOT (41%) cases. Natural gas consumption for HTL conversion and natural gas consumption for biomass dying contribute about 25% and 13%, respectively, to the supply chain GHG emissions for the 2016 SOT cases, while CO_2 supply and recycle and natural gas consumption for biomass dying contribute about 26% and 13%, respectively, to the supply chain GHG emissions for the 2015 SOT case.

A total GHG reduction of 52% compared to conventional low sulfur petroleum diesel can be achieved by 2022 through increasing algal productivity, decreasing natural gas demand, and increasing fuel yield relative to the 2016 SOT case. The revised 2022 target assumes that the algal productivity increases to 25 g/m^2/day, which is the largest contributor to the reduction in supply chain GHG emissions, compared to the 2016 SOT case (Frank et al., 2016). The energy use for culture circulation per unit of algal biomass in the revised 2022 target is lower than both the 2015 SOT and the 2016 SOT cases, owing to short residence times of algal biomass in the pond when its productivity is high. Overall, captured CO_2 supply (39%) and algae cultivation and dewatering (26%) are the two largest contributors to the supply chain GHG emissions in the revised 2022 target case. Note that the scenarios shown here were all based on captured CO_2 from power plant flue gas. The process of CO_2 capture reduces the electrical efficiency of the power plant. Thus, additional fuel must be consumed to maintain the base power plant output. The emissions associated with the addition fuel in the process of CO_2 capture were added to the LCA GHG emissions (Frank et al., 2016). An alternate CO_2 sourcing is the short-distance low-pressure pipeline delivery of flue gas, which will be revisited in the ongoing harmonization modeling efforts by ANL, NREL, PNNL, and ORNL.

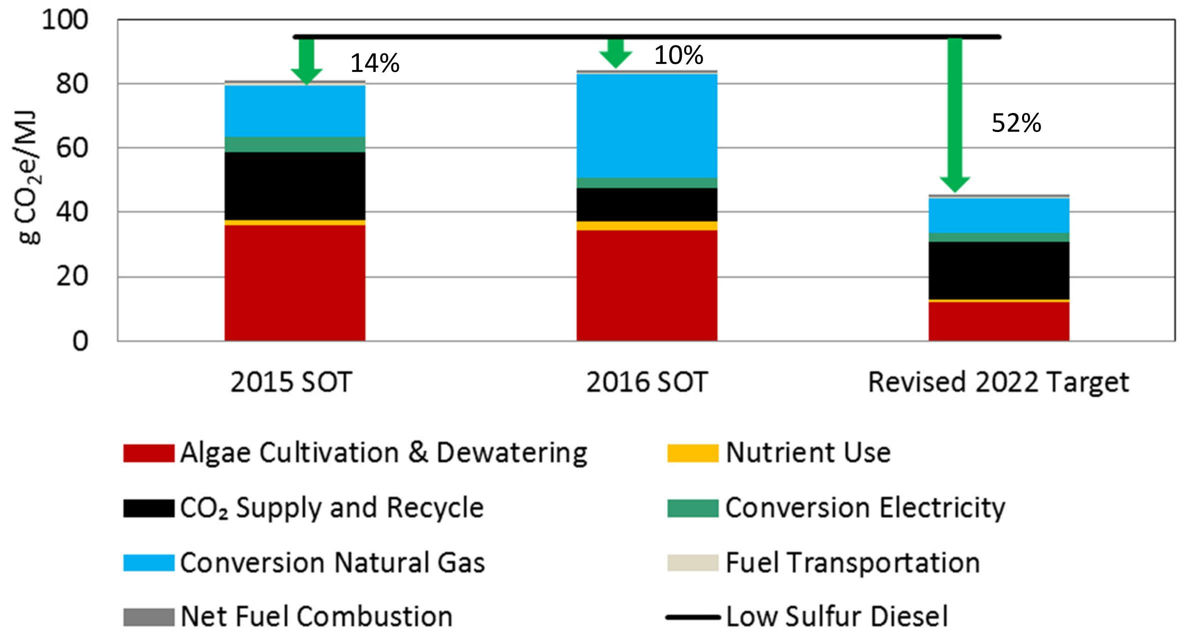

FIGURE 7 Supply chain GHG Emissions of Algal Renewable Diesel via Hydrothermal Liquefaction in the 2016 SOT Case, in Comparison with the 2015 SOT and 2022 Revised Target Case

3.2 SUPPLY CHAIN WATER CONSUMPTION

3.2.1 HOG via IDL

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. The supply chain water consumption of HOG produced via IDL is about 0.45 L/MJ, or 14.5 gal/GGE of HOG for the 2015 SOT case, 0.31 L/MJ, or 10.0 gal/GGE of HOG for the 2016 SOT case, and 0.18 L/MJ, or 5.9 gal/GGE of HOG for the 2022 design case, in comparison to about 0.10 L/MJ, or 3.1 gal/GGE, for petroleum gasoline blendstock (ANL, 2016).

Figure 8 shows the supply chain water consumption of HOG via IDL on a gasoline gallon equivalent (GGE) basis. The largest contributor (57% for the 2016 SOT and 53% for the 2015 SOT case) to the supply chain water consumption is the IDL process (i.e., biorefinery), which consumes water for process cooling and boiler feed water makeup. Other steps that consume significant amounts of water in the IDL supply chain include production and use of fertilizers and herbicides/pesticides (29% for the 2016 SOT and 32% for the 2015 SOT case), woody biomass preprocessing (11% for the 2016 SOT and 9% for the 2015 SOT case), and biomass handling and logistics (3% for the 2016 SOT and 6% for the 2015 SOT case). Water consumption embedded in the production of upstream process energy and chemicals

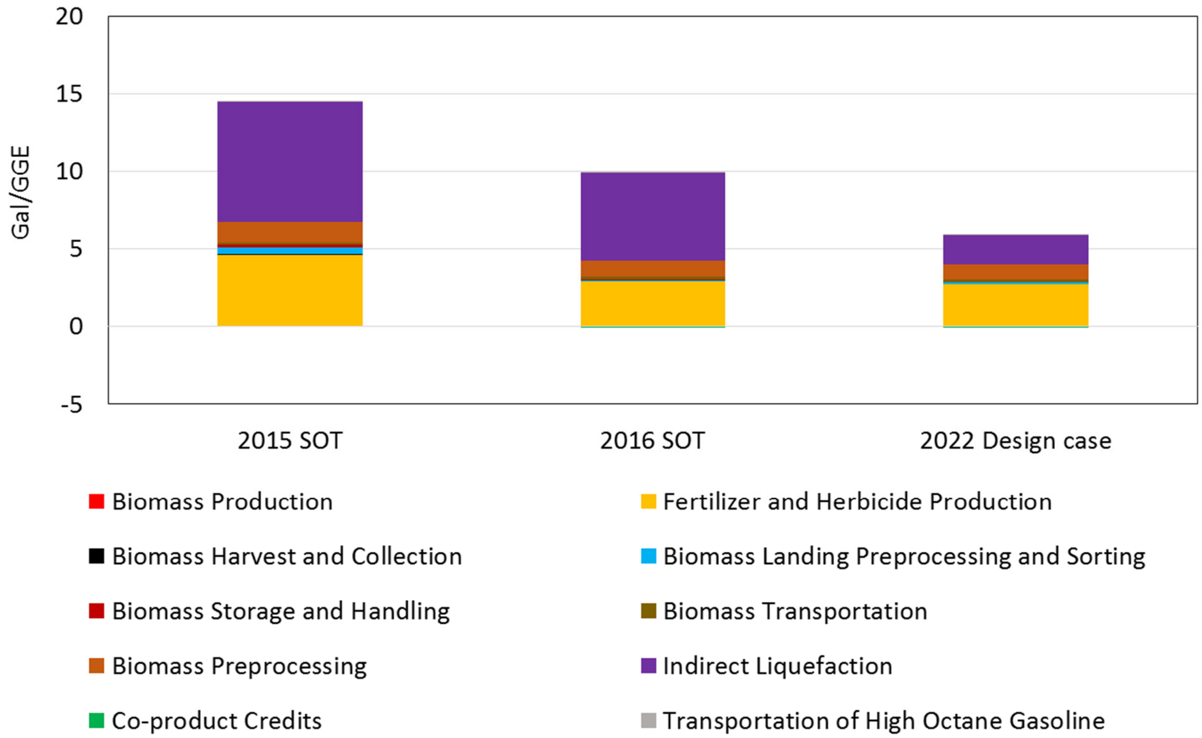

FIGURE 8 Supply Chain Water Consumption of HOG Via IDL in the 2016 SOT Case, in Comparison to the 2015 SOT Case and 2022 Design Case

(i.e., indirect water consumption) used at the biorefinery is a minor piece of the whole supply chain water consumption. Therefore, the direct water consumption at the IDL process presents the largest reduction potential for the supply chain water consumption of HOG.

3.2.2 RG from fast pyrolysis

The supply chain water consumption of RG produced from fast pyrolysis is about 0.20 L/MJ, or 6.5 gal/GGE of RG for the 2015 SOT case, 0.18 L/MJ, or 5.7 gal/GGE of RG for the 2016 SOT case, and 0.16 L/MJ, or 5.2 gal/GGE of RG for the 2017 target case, in comparison to about 0.10 L/MJ, or 3.1 gal/GGE for petroleum gasoline blendstock.

The supply chain water consumption analysis for the 2016 SOT case in comparison with the 2015 SOT case is shown in Figure 9 on a GGE basis. Water consumption for biomass production, harvest, and collection, and biomass preprocessing between the 2015 SOT and 2016 SOT cases are comparable, but the water consumption of these two cases differs at the fertilizer and herbicide production stage, which contributes about 42% and 34%, respectively, to water consumption. The fast pyrolysis stage contributes 38% and 48%, respectively, to the supply chain water consumption, as shown in Figure 9. About 2.8 gallons per GGE of water

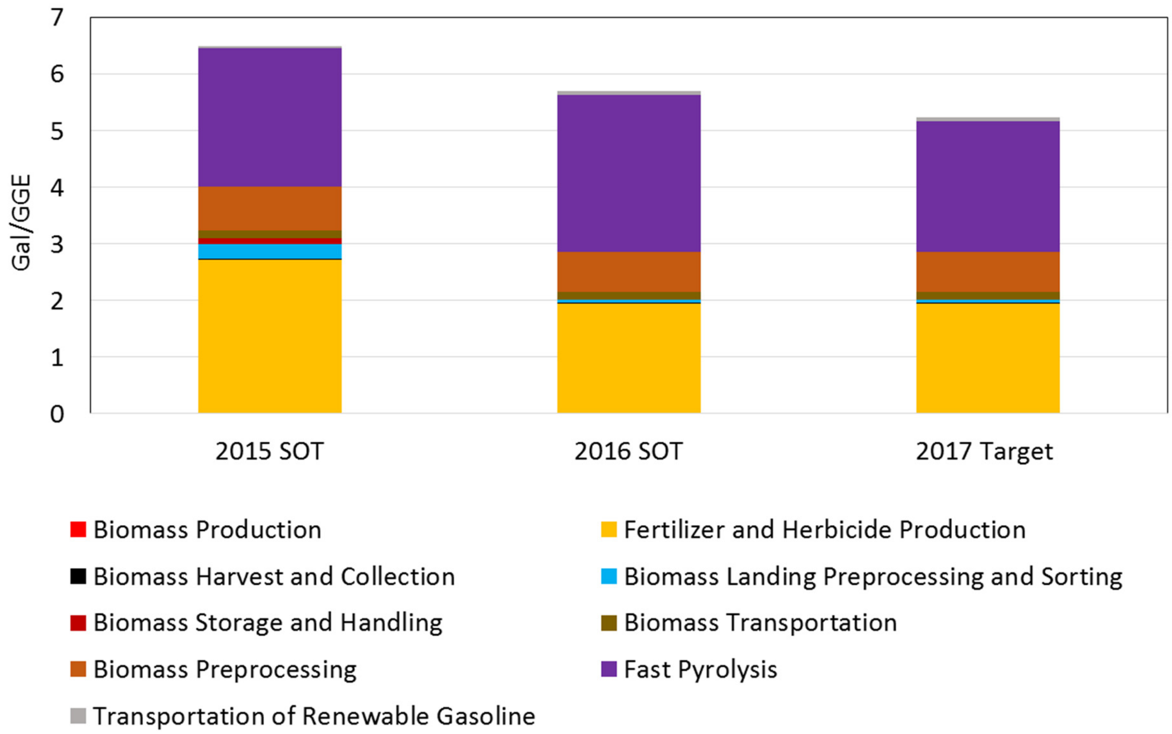

FIGURE 9 Supply Chain Water Consumption of RG from Fast Pyrolysis in the 2016 SOT Case, in Comparison to the 2015 SOT Case and 2017 Target Case

consumption are attributable to the fuel production stage for the 2016 SOT case, which is about 0.3 gallons per GGE higher than that in the 2015 SOT case. For the 2016 SOT case, consumption of process chemicals in the conversion process contributes 18% of this value, consumption of natural gas and electricity contributes the remainder. Further reduction in supply chain water consumption for the 2017 target case as compared to the 2016 SOT case is mostly attributed to reduction in water consumption in the fast pyrolysis stage.

3.2.3 RD from algae HTL

Figure 10 shows estimated supply chain water consumption for the 2015 SOT, 2016 SOT, and two alternate 2022 target cases. For the 2015 and 2016 SOT cases, saline water is utilized for all makeup water to the algae pond and attributed to the use of saline strains in NREL's 2015 and 2016 SOT models (ATP3 cultivation data were based on saline strains for both SOT cases), resulting in zero freshwater consumption during algae growth. Electricity consumption during the conversion stage is the dominant contributor to the total water consumption in both the 2015 and 2016 SOT cases, accounting for about 75% and 68%, respectively, of the supply chain water consumption. As shown in Figure 10, when fresh water is assumed for algae growth for the revised 2022 target case, cultivation makeup water to offset pond evaporation (52 Gal/GGE) and blowdown (18 Gal/GGE) is the key contributor to the total

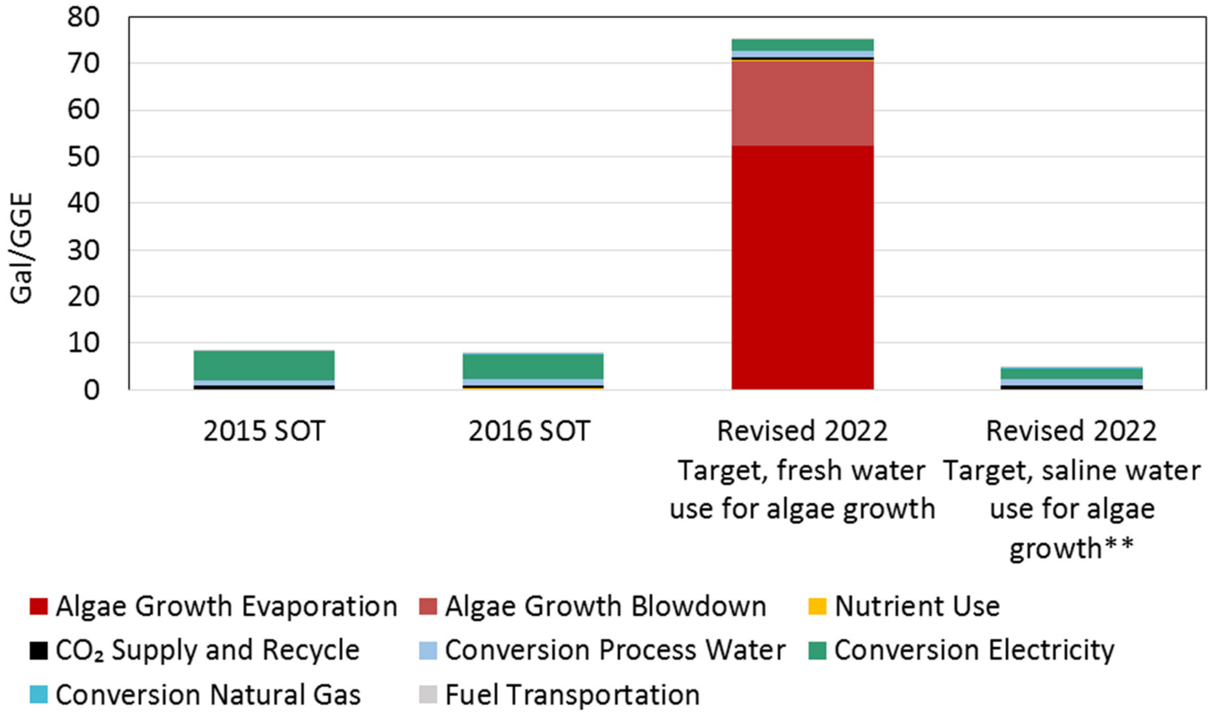

FIGURE 10 Supply Chain Water Consumption of RD from Algae HTL in the 2016 SOT Case, in Comparison to the 2015 SOT Case and 2022 Revised Target Case
**This case assumes that saline water is used for algae growth without impacting the algae yield and other process requirement.

water consumption in the supply chain, accounting for 94% of the total supply chain water consumption. Using a saline algal strain for the 2022 target case is currently under consideration, which would result in zero freshwater consumption for these water-intensive algae growth activities, as shown in Figure 10. In this case, the supply chain water consumption estimates assume comparable productivity and process assumptions to the revised 2022 target case consuming fresh water. This alternate 2022 case will be revisited as additional harmonization modeling efforts continue between ANL, NREL, PNNL, and ORNL for use of saline versus fresh water.

3.3 SUPPLY CHAIN GHG EMISSIONS AND WATER CONSUMPTION FOR DESIGN CASES

INL will modify the woody feedstock blend in the 2017 design case by taking out construction and demolition waste that was in the original 2017 design case (INL, 2014). Removal of the construction and demolition waste was necessitated by the lack of verifiable RINs for this biomass source. At this point, detailed information about the energy consumption associated with the woody biomass logistics in the 2017 SOT is not available. In this memorandum, we used the same 2016 woody feedstock SOT to couple with the design case

TEAs on conversion to analyze the supply chain GHG emissions and water consumption for design cases of the HOG via IDL and RG from fast pyrolysis pathways.

The supply chain GHG emissions and water consumption for design cases of the HOG via IDL, RG from fast pyrolysis, and RD from algae HTL pathways are provided in Table A2. Compared to petroleum gasoline, HOG (2022 Design case), RG (2017 Target case), and RD (2022 Target case) have a supply chain GHG emission reduction of 67%, 60%, and 52%, respectively. This reduction in GHG emissions by 60% compared to conventional gasoline for pyrolysis-derived RG reflects the shift to a state-of-technology blended feedstock that has higher moisture content at harvest than the design case blended feedstock used in the previous analysis. This result for the pyrolysis design case will be updated when a design case feedstock blend is finalized.

Note that the reductions of GHG emissions from the 2016 SOT cases to the design cases for the HOG via IDL and RG from fast pyrolysis pathways are driven solely by improvement of conversion technologies that exhibit higher fuel yields and lower process energy and material requirement. We will update these design case results when information on the revised woody blend feedstock design case is finalized.

4 CONCLUSIONS

Producing HOG via IDL from a blended biomass feedstock consisting of forest residues, pine, and poplar in the 2016 SOT case yields a fuel that is 64% less GHG-intensive throughout its supply chain than conventional gasoline. GHG emissions from the biomass preprocessing were the largest contributor 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, biomass landing preprocessing and sorting, and reduction of biomass moisture content before transportation. Although relatively water efficient, the IDL process is the most water-intensive step in the supply chain and represents the largest potential to further reduce water consumption for the pathway.

SCSAs for renewable gasoline production from a blended feedstock via fast pyrolysis indicate that these fuels offer GHG emissions reductions compared to conventional gasoline. We estimated a 51% reduction in GHG emissions for the 2015 SOT case; this reduction was higher (58%) for the 2016 SOT case. Among the different supply chain stages, the biorefinery was the largest contributor to the field-to-pump GHG emissions, contributing between 38% for the 2015 SOT and 44% for the 2016 SOT case. To reduce the supply chain GHG emissions of the pyrolysis pathway, research and development efforts could focus on reducing consumption of process energy and other inputs associated with the pyrolysis process. Due to the significant contribution of biomass preprocessing to supply chain GHG emissions, increasing the energy efficiency of biomass preprocessing technologies would notably decrease GHG emissions of pyrolysis-derived fuels. Future SCSAs of this pathway will consider the impact of catalyst production and consumption.

Algal biofuel produced via algae HTL in the 2016 SOT case has 10% fewer GHG emissions throughout its supply chain compared to conventional low sulfur petroleum diesel. The 2016 SOT case demands higher energy (primarily conversion natural gas) use than the 2015 SOT case, which leads to relative higher GHG emissions than those of the 2015 SOT case. Algal biomass cultivation and dewatering has the largest contribution to supply chain GHG emissions. Research and development efforts to further reduce supply chain GHG emissions should focus on increasing algal biomass productivity and reducing energy consumption for algal biomass drying and HTL conversion.

With further improvement on the conversion technologies in the design case, HOG via IDL, RG from fast pyrolysis, and RD from algae HTL reduce supply chain GHG emissions by 67%, 60%, and 52%, respectively, compared to petroleum gasoline or diesel.

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APPENDIX

Table A.1 presents the elemental composition of algal biomass for HTL processes. Table A.2 presents the IDL, fast pyrolysis, and HTL SCSA results for GHG emissions and water consumptions in different units.

TABLE A1 Elemental Composition of Algal Biomass for HTL Processes of the 2015 SOT, the 2016 SOT, and the Revised 2022 Target Cases (Jones and Zhu, 2016)

Ultimate Analysis, weight %	2015 SOT[a]	2016 SOT[a]	Revised 2022 Target[a]
C	38.6%	38.6%	52.0%
H	5.3%	5.3%	7.5%
O	27.5%	27.5%	22.0%
N	5.0%	5.0%	4.8%
S	1.6%	1.6%	0.6%
Ash	22.0%	22.0%	13.0%
P	0.4%	0.4%	0.6%
TOTAL[a]	**100.40%**	**100.40%**	**100.50%**

a: The total percentage is not exactly 100% due to rounding errors.

TABLE A.2 IDL, Fast Pyrolysis, and HTL SCSA Results in Different Units

Pathways	Metrics	Unit	2015 SOT Value	2016 SOT Value	Design case
HOG via IDL	Greenhouse gas emissions	g CO_2e/MJ	53	35	32
		g CO_2e/MMBtu	55,794	36,733	33,766
		g CO_2e/GGE	6,477	4,269	3,920
	Water consumption	gal/MMBtu	125.0	85.9	51.0
		L/MJ	0.45	0.31	0.18
		gal/GGE	14.5	10.0	5.9
RG from fast pyrolysis	Greenhouse gas emissions	g CO_2e/MJ	47	40	38
		g CO_2e/MMBtu	49,317	42,136	40,118
		g CO_2e/GGE	5,725	4,892	4,657
	Water consumption	gal/MMBtu	56	49	45
		L/MJ	0.20	0.18	0.16
		gal/GGE	6.5	5.7	5.2
RD from HTL	Greenhouse gas emissions	g CO_2e/MJ	81	84	46
		g CO_2e/MMBtu	85,265	88,929	48,213
		g CO_2e/GGE	9,898	10,324	5,597
	Water consumption	gal/MMBtu	72.5	67.8	648
		L/MJ	0.26	0.24	2.32
		gal/GGE	8.4	7.9	75.2

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