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ANL/ESD-15/24
Rev. 1

Supply Chain Sustainability Analysis of Indirect Liquefaction of Blended Biomass to Produce High Octane Gasoline

Energy Systems Division

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Supply Chain Sustainability Analysis of Indirect Liquefaction of Blended Biomass to Produce High Octane Gasoline

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March 2016

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ACKNOWLEDGEMENTS

This work was supported by the Office of Energy Efficiency and Renewable Energy of the United States Department of Energy, under contract DE-AC02-06CH11357. We acknowledge Kristen Johnson, Alicia Lindauer, and Zia Haq of the Bioenergy Technologies Office (BETO) for their support.

1 INTRODUCTION

The Department of Energy's (DOE) Bioenergy Technologies Office (BETO) aims at developing and deploying technologies to transform renewable biomass resources into commercially viable, high-performance biofuels, bioproducts and biopower through public and private partnerships (DOE, 2015). BETO and its national laboratory teams conduct in-depth techno-economic assessments (TEA) of biomass feedstock supply and logistics, conversion technologies to produce biofuels, and overall system sustainability. A design case is a TEA that outlines a target case for a particular biofuel pathway. It enables preliminary identification of data gaps and research and development needs, and provides goals and targets against which technology progress is assessed. On the other hand, a state of technology (SOT) analysis assesses progress within and across relevant technology areas based on actual experimental results 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 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, or 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 report describes the SCSA of the production of renewable high octane gasoline (HOG) via indirect liquefaction (IDL) of lignocellulosic biomass. This SCSA was developed for both the 2015 SOT (Hartley et al., 2015; ANL, 2016; DOE, 2016) and the 2017 design case for feedstock logistics (INL, 2014) and for both the 2015 SOT (Tan et al., 2015a) and the 2022 target case for HOG production via IDL (Tan et al., 2015b). The design includes advancements that are likely and targeted to be achieved by 2017 for the feedstock logistics and 2022 for the IDL conversion process. In the SCSA, the 2015 SOT case for the conversion process, as modeled in Tan et al. (2015b), uses the 2015 SOT feedstock blend of pulpwood, wood residue, and construction and demolition waste (C&D). Moreover, the 2022 design case for the conversion process, as described in Tan et al. (2015a), uses the 2017 design case blend of pulpwood, wood residue, switchgrass, and C&D. The performance characteristics of this blend are consistent with those of a single woody feedstock (e.g., pine or poplar). We also examined the influence of using a single feedstock type on SCSA results for the design case. These single feedstock scenarios could be viewed as bounding SCSA results given that the different components of the feedstock blend have varying energy and material demands for production and logistics.

Water resource consumption is intimately connected to sustainable energy production. The SCSA examines the water resource impacts of the HOG supply chain.

Figure 1 displays the stages in the supply chain that are considered in the SCSA. In this analysis, we consider the upstream impacts of producing each energy and chemical input to the supply chain.

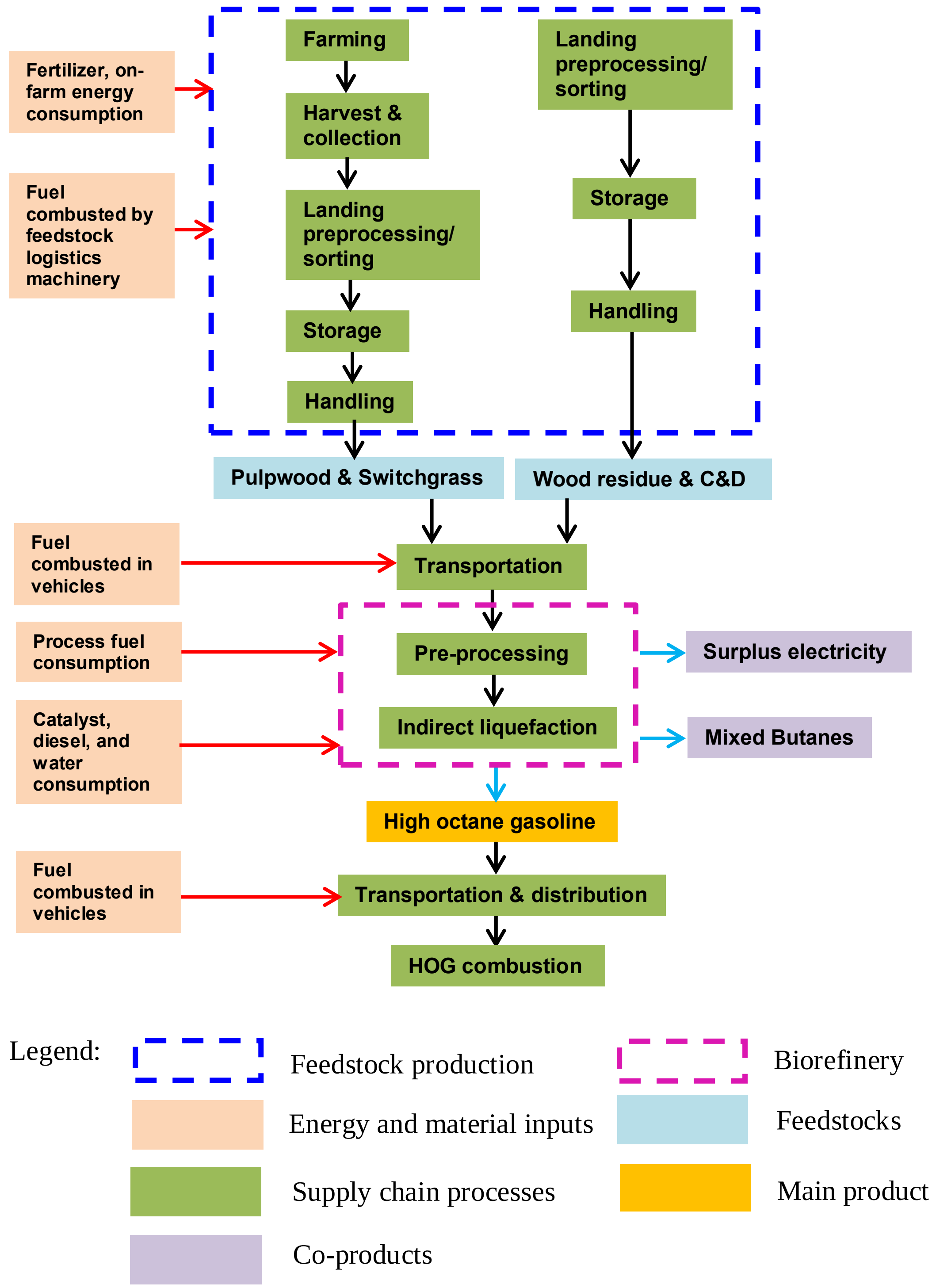

FIGURE 1 General Stages Considered in the Supply Chain Sustainability Analysis

2 METHOD AND DATA

Argonne National Laboratory's Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET^{TM})[1] model as released in October 2014 was used to produce the SCSA results. The GREET model, developed with the support of DOE, is a publicly available tool for the life-cycle analysis of transportation fuels that 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), emissions of greenhouse gases (GHG) (CO_2, CH_4, and N_2O), and 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 ($PM_{2.5}$). This version of GREET has been expanded to include water consumption factors for major fuel and chemical production pathways for estimation of life-cycle water consumption of various fuel production pathways (Lampert et al., 2014; Lampert et al., 2015; Lampert et al., 2016).

2.1 MATERIAL AND ENERGY REQUIREMENT OF FEEDSTOCK PRODUCTION AND LOGISTICS

INL modeled a blended feedstock for the 2015 SOT (Hartley et al., 2015; DOE, 2016) and the 2017 design cases (INL, 2014). The feedstock blend approach takes advantage of low cost resources (i.e., wood residues and C&D waste), while producing a feedstock with a low ash content. The blended feedstock comprises pulpwood (45 wt%), wood residues (35 wt%), and C&D waste (20 wt%) in the 2015 SOT, and pulpwood (45 wt%), wood residues (32 wt%), switchgrass (3 wt%), and C&D waste (20 wt%) in the 2017 design case.

The total energy requirements for feedstock production for each unit process is summarized in Table 1, with the shares of fuel type presented in Table 2. Note that we assumed that the farming of pulpwood feedstock requires equivalent amount of fertilizers as the farming of poplar does, as shown in Table 3, due to lack of the farming chemical inputs data for pulpwood.

There are seven possible feedstock logistics operations for all feedstocks. Farming, i.e., planting and fertilization, harvesting and collection are considered for the production of switchgrass and pulpwood. Diesel is consumed for these operations. Processing of all feedstocks, except switchgrass, includes a landing preprocessing/sorting operation, which consumes solely diesel in the 2015 SOT case and mostly diesel in the 2017 design case for steps including debarking, size reduction, sorting, and screening. Additional energy requirements are met by electricity in the design case. All feedstocks are subject to three additional stages. The transportation, storage stages consume diesel fuel whereas the handling stage consumes electricity in the 2015 SOT case. Regardless of feedstock, the main energy source for the preprocessing section in the 2015 SOTs is natural gas, with additional energy demand met by

[1] GREET model and documentation are available at http://greet.es.anl.gov

electricity (20%) and diesel (1%) in the 2015 SOT case. In the design case, the balance of energy demand is supplied solely by electricity (5%). Parameters used to determine energy consumed during feedstock transportation are shown in Table 4. Vehicle payloads were adopted from GREET (ANL, 2015), while other parameters, like transportation distance and moisture content, were provided by INL (INL, 2014; Hartley et al., 2015; ANL, 2016). These data were incorporated into the new HOG pathway 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 1 Energy Consumption, in Btu/dry ton, for Feedstock Production and Logistics in the 2015 SOT and the 2017 Design Cases

	2015 SOT				2017 Design Case				
	Pulpwood	Wood Residues	C&D Waste	Blended Feedstock	Pulpwood	Wood Residues	Switchgrass	C&D Waste	Blended Feedstock
Farming[a,b,c]	10,620			4,779	9,306		79,145		6,562
Harvesting and Collection[b,c]	208,580			93,861	182,780		122,850		85,937
Landing Preprocessing/Sorting[b]	609,010	639,890	22,110	502,438	231,520	110,250		22,110[2]	143,886
Storage[b,c]	9,360	9,360	9,360	9,360	8,460	8,460	21,830	8,460	8,861
Handling[b,c]	47,210	47,210	47,210	47,210	42,690	42,690	41,900	42,690	42,666
Transportation[a,b,c]	140,230	131,100	104,830	129,955	138,491	138,491	36,354	107,715	129,271
Preprocessing[b,c]	1,628,430	1,628,430	1,628,430	1,628,430	408,010	408,010	285,830	408,010	404,345

[a] ANL, 2015
[b] INL, 2014
[c] Hartley et al., 2015

[2] It is assumed that the energy consumption for separating and processing woody C&D waste to meet the feedstock quality requirement in the design case is the same as that in the 2015 SOT (Hartley et al., 2015). This revision from the data reported in the design case report (INL, 2014) reflects a methodological change in energy consumption accounting that previously burdened woody C&D waste with all the energy consumed in C&D waste separation to recover various materials, such as metals, rubber, and woody C&D waste. In the 2015 SOT case, woody C&D waste goes through two separation steps. The main purpose of the first step is to retrieve valuable materials from the waste. Subsequently, the raw woody C&D waste is treated as a burden-free by-product. This raw woody C&D waste goes through a second separation step and additional processing to meet the feedstock quality requirements, and the final woody C&D waste is burdened with the energy consumption in this process.

TABLE 1 Share (%) of Production and Logistics Stage Fuel Type for Each Feedstock (INL, 2014; Hartley et al., 2015; DOE, 2016)

	2015 SOT								
	Pulpwood			Wood Residue			C&D Waste		
	Diesel	*Natural Gas*	*Electricity*	*Diesel*	*Natural Gas*	*Electricity*	*Diesel*	*Natural Gas*	*Electricity*
Farming	100								
Harvest and Collection	100								
Landing Preprocessing/Sorting	100			100			99	0	1
Transportation	100			100			100		
Preprocessing	1	79	20	1	79	20	1	79	20
Storage	100			100			100		
Handling			100			100			100

	2017 Design Case											
	Pulpwood			Wood Residue			Switchgrass			C&D Waste		
	Diesel	*Natural Gas*	*Electricity*	*Diesel*	*Natural Gas*	*Electricity*	*Diesel*	*Natural Gas*	*Electricity*	*Diesel*	*Natural gas*	*Electricity*
Farming	100						100					
Harvest and Collection	100						100					
Landing Preprocessing/Sorting	87		13	87		13				87	13	
Transportation	100			100			100			100		
Preprocessing		95	5		95	5		95	5		95	5
Storage	100			100			100			100		
Handling	100			100			100			100		

TABLE 3 Fertilizer Usage, in Gram/Dry Ton, of Pulpwood and Switchgrass Farming (Wang et al., 2013)

	Nitrogen (N)	Phosphate (P_2O_5)	Potash (K_2O)
Pulpwood	2,743	914	1,828
Switchgrass	8,298	114	227

TABLE 4 Feedstock Transportation Parameters

	Transportation Mode[a]	Truck Payload (tons) [a]	Transportation Distance, 2015 SOT (miles) [b]	Transportation Distance, 2017 Design Case (miles)[c]	Transportation Moisture Content[c]	Moisture Content at Reactor Throat[c]
Pulpwood	Class 8b Heavy Duty Truck	25	68	50	30%	10%
Wood Residues	Class 8b Heavy Duty Truck	25	59	50	30%	10%
Switchgrass	Class 8b Heavy Duty Truck	25		15	20%	9%
C&D Waste	Class 8b Heavy Duty Truck	25	51	50	10%	10%

[a] ANL, 2015

[b] Hartley et al., 2015

[c] INL, 2014

2.2 MATERIAL, ENERGY, AND WATER REQUIREMENTS OF THE IDL PROCESSES

The 2015 SOT case and 2022 design cases for the IDL processes feature a processing capacity of 2,205 U.S. short tons of dry biomass per day. They have a HOG yield of 39.9 and 64.9 gallons per dry U.S. short ton of blend feedstock, respectively, at the biorefinery (Tan et al., 2015a; Tan et al., 2015b). In the 2015 SOT case, 17.7 gallons of mixed butanes per dry short ton of blend feedstock are a co-product (Tan et al., 2015a). At the biorefinery, diesel trucks carrying the biomass feedstock and a truck dumper that unloads the trucks into a hopper consume a small amount of diesel fuel. Char, fuel gas, an unreformed syngas slipstream, and a portion of unreacted syngas from the methanol synthesis reactor are combusted, producing sufficient energy for the process. No external energy is needed. In addition, a small amount of surplus electricity is produced at the biorefinery and is exported to the grid. A variety of catalysts, including a beta zeolite and a tar reformer catalyst are used for tar reforming, methanol synthesis, and the conversion of dimethyl ether (DME) to HOG. Consumptive water is required for cooling of the IDL system and for making up boiler feed water. Table 5 lists the direct material, energy, and water consumption for the modeled IDL conversion process at the plant in 2015 SOT and 2022 design cases (Tan et al., 2015a; Tan et al., 2015b).

We use the GREET catalyst module that we have recently developed (Wang et al., 2015) to estimate the emissions and water consumption associated with manufacturing and use of the catalysts required for the IDL process. For this SCSA, we developed new estimates of the energy consumed to produce zinc oxide (ZnO) and magnesium oxide (MgO) (Benavides et al., 2015; Wang et al., 2015). A number of compounds are consumed at low levels in the IDL process that are produced via complex, proprietary processes. These compounds include methyl diethanolamine, dimethyl sulfide, LO-CAT chemicals (chelated iron and caustics), boiler feed water chemicals (sodium sulfite, hydrazine, morpholine, etc.), and cooling tower chemicals (phosphates, azoles, copolymers, zinc). As no publicly-available material and energy flow data for the production of these compounds are available, these compounds have been excluded from the SCSA. We examine the influence of the exclusion of these compounds on supply chain GHG emissions in Section 3.2.

TABLE 5 Key Indirect Liquefaction Process Parameters

	2015 SOT Value	2022 Design Value	Unit
HOG yield	39.9	64.9	gal/dry ton feedstock
Surplus electricity	0.0132	0.013	kWh/gal of HOG
Mixed butanes	17.7	0	gal/dry ton feedstock
Diesel energy use	346	213	Btu/gal of HOG
Char produced and combusted	110,834	110,834	Btu/gal of HOG
Fuel gas produced and combusted	110,727	110,727	Btu/gal of HOG
Syngas produced and combusted	111,024	111,024	Btu/gal of HOG
Magnesium oxide consumption	0.86	0.5	g/gal of HOG
Fresh olivine consumption	67.2	41.3	g/gal of HOG
Tar reformer catalyst consumption	1.1	0.7	g/gal of HOG
Methanol synthesis catalyst consumption	0.73	0.4	g/gal of HOG
DME catalyst consumption	0.89	0.5	g/gal of HOG
Beta zeolite catalyst consumption	29.3	4.8	g/gal of HOG
Zinc oxide catalyst consumption	14.66	1.6	g/gal of HOG
Water consumption	9.7	1.8	gal/GGE[a] of HOG
HOG properties			
-Lower heating value	111,560	111,560	Btu/gallon
-Density	2,655	2,655	g/gallon
-Carbon content	83.37	83.37	%, by mass

[a] Gasoline gallon equivalent

3 RESULTS AND DISCUSSION

3.1 SUPPLY CHAIN GHG EMISSIONS

In both the 2022 design case, which represents an integration of the 2017 design case for feedstock production and logistics and the 2022 design case for the IDL processes, and the 2015 SOT case, which represents an integration of the 2015 SOT for feedstock production and logistics and the 2015 SOT for the IDL processes, the IDL process produces HOG and co-produces a small amount of surplus electricity. In the SOT case, the process also produces a significant amount of mixed butanes. We used the energy-based co-product allocation method to allocate the energy, emission, and water burdens between the products, which are all energy products. Figure 2 shows the supply chain GHG emissions[3] of the HOG fuel in the 2015 SOT and 2022 design cases.

Feedstock preprocessing is the largest contributor to the supply chain GHG emissions for both the 2015 SOT (57%) and 2022 design cases (31%). In the 2015 SOT case, natural gas and electricity consumption contribute 66% and 34% of GHG emissions from feedstock preprocessing, respectively. In the design case, 90% of the GHG emissions from this step are from natural gas consumption, with the balance of the emissions coming from electricity consumption. Therefore, driving down the energy that comminution, drying, and densification of the feedstock consumes will be key to reducing the contribution of feedstock preprocessing to supply chain GHG emissions, particularly in the 2015 SOT case. Feedstock handling and logistics (feedstock landing preprocessing and sorting, storage, handling, and transportation) contributes 25% and 27% of the supply chain GHG emissions for the 2015 SOT and 2022 design cases, respectively. Feedstock landing preprocessing and sorting, which consumes mostly diesel for feedstock debarking, size reduction, sorting, and screening, contributes 17% and 13% of the supply chain GHG emissions for the 2015 SOT and 2022 design cases, respectively. The IDL conversion process contributes 8% (3.5 g CO_2e/MJ) and 11% (1.7 g CO_2e/MJ) of the supply chain GHG emissions for the 2015 SOT and 2022 design 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 (76% for the 2015 SOT case and 61% for the 2022 design 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 29% of IDL GHG emissions for the 2015 SOT and 2022 design cases, respectively. Biomass feedstock transportation contributed 5% and 10% of the supply chain GHG emissions in the 2015 SOT and 2022 design case, respectively, followed by

[3] 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)

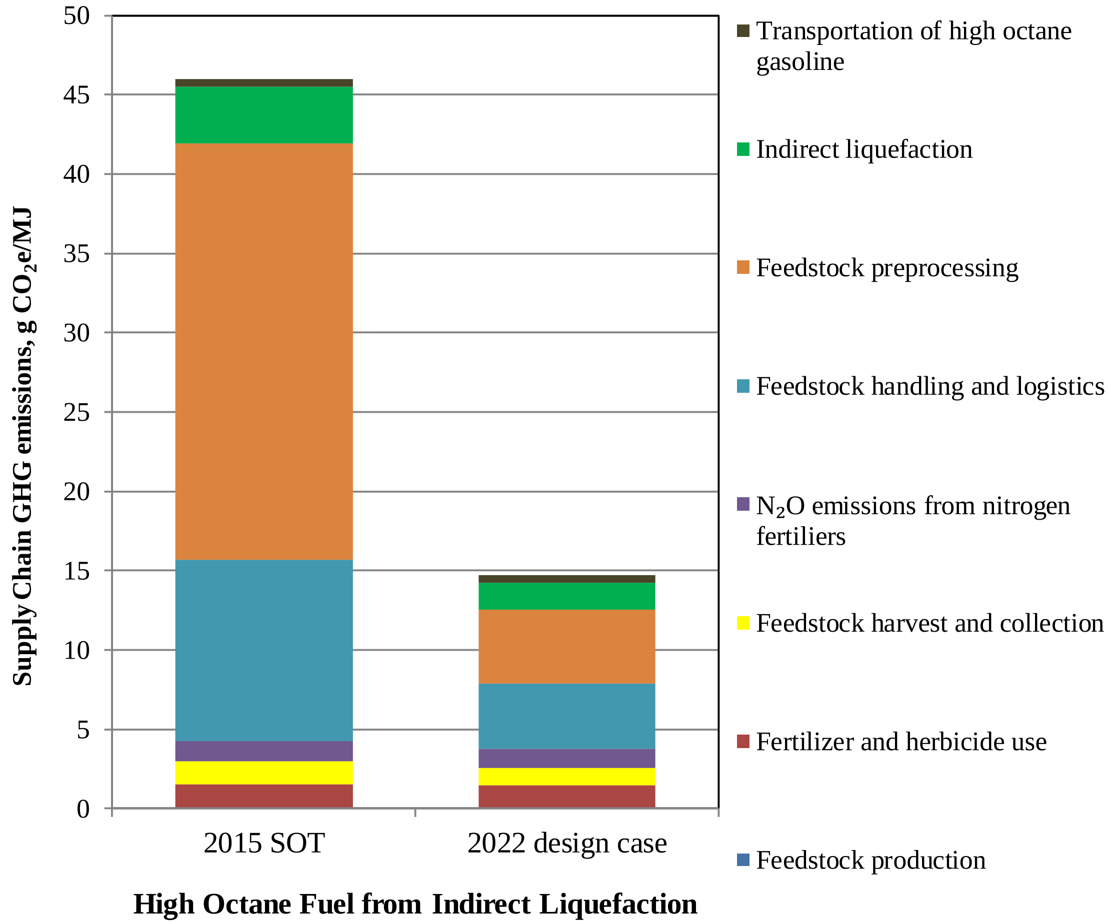

FIGURE 2 Supply Chain GHG Emissions of HOG Produced Via the IDL Process in the 2015 SOT and 2022 Design Cases

production and use of fertilizers (3% for the 2015 SOT and 9% for the 2022 design case), N_2O emissions from nitrogen fertilizers (3% for the 2015 SOT and 8% for the 2022 design case), and feedstock harvest and collection (3% for the 2015 SOT and 7% for the 2022 design case).

The supply chain GHG emissions of HOG produced via IDL are about 46 and 15 g CO_2e/MJ, respectively, for the 2015 SOT and 2022 design cases, in comparison to about 93 g CO_2e/MJ for gasoline blendstock produced from petroleum crudes. HOG produced via IDL with this feedstock blend therefore offers about a 50% and 84% GHG reduction for the 2015 SOT and 2022 design cases, respectively, as compared to conventional gasoline (Figure 3). The biogenic CO_2 credit from carbon uptake during the growth of biomass feedstocks is the major driver of the GHG emission reduction for HOG, and, in the 2022 design case, the feedstock and fuel production phase is also more favorable for HOG than petroleum gasoline blendstock, which has significant GHG emission burdens from crude refining and crude recovery.

We considered how results would vary if we used the displacement, or system expansion, co-product handling technique rather than the energy allocation technique. We assumed co-produced electricity would displace electricity generated with the United States average grid mix (Table 6). In the SOT case, we assumed the butanes displaced have about 1/3 of the carbon intensity of petroleum gasoline. With the displacement technique, the supply-chain GHG emissions for the 2015 SOT case increase to 60 g CO_2e/MJ (a 36% reduction). Design case supply chain GHG emissions exhibit a negligible change to 15.1 g CO_2e/MJ (an 84% reduction) for the 2022 design case.

TABLE 6 United States Average Grid Mix (ANL 2015)

	Share of National Grid
Residual Oil	0.45%
Natural Gas	26%
Coal	41%
Nuclear Power	19%
Biomass	0.32%
Hydroelectric	7.0%
Geothermal	0.42%
Wind	5.0%
Solar PV	0.40%
Others	0.41%

Figure 3 contains error bars that show the 10^{th} and 90^{th} percentile values of the net supply chain GHG emissions as determined through stochastic modeling with GREET. We used GREET's stochastic modeling feature to conduct simulations with probability distribution functions for key parameters. It is important to note that point values, rather than probability distribution functions, were used for the parameters in Tables 1 to 4 because there were insufficient data to generate distribution functions. Rather, the GREET stochastic simulations use the probability distribution functions in the model for many other parameters, such as energy consumed during fertilizer production and N_2O emission factors for nitrogen fertilizers.

Table 7 shows the median GHG emissions reductions of HOG from the blended feedstock compared to its counterpart derived from petroleum. Whereas the 2022 design case is estimated to achieve a greater than 60% reduction, GHG emissions reductions for the SOT case are significantly lower. Reducing the energy intensity of feedstock supply and logistics between 2015 and the 2017 feedstock design case will lower the supply-chain GHG emissions for this pathway.

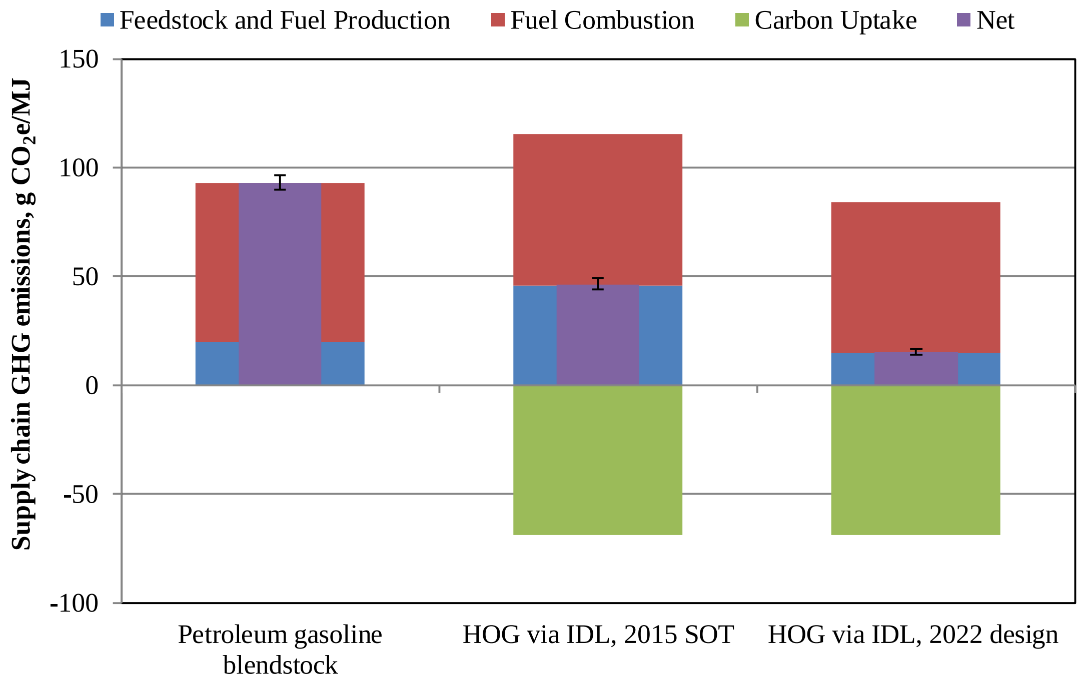

FIGURE 3 Supply Chain GHG Emissions of HOG Produced Via IDL, in Comparison to Petroleum Gasoline Blendstock

TABLE 7 Median GHG Emissions of HOG Via IDL and its GHG Emission Reduction Compared to that of Petroleum Gasoline

	HOG, 2015 SOT	HOG, 2022 Design	Petroleum gasoline
Median GHG emissions, g CO_2e/MJ	46.4	15.2	93.3
Median GHG emissions reductions, relative to petroleum gasoline	50%	84%	

3.2 SUPPLY CHAIN WATER CONSUMPTION

Figure 4 shows the supply chain water consumption of 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 largest contributor (67% for the 2015 SOT and 64% for the 2022 design 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 feedstock preprocessing (21% for the 2015 SOT and 5% for the 2022 design case), production and use of fertilizers (6% for the 2015 SOT and 20% for the 2022 design case), and feedstock handling and logistics (6% for the 2015 SOT and 8% for the 2022 design case). Water consumption embedded in the production of upstream process energy and chemicals (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.

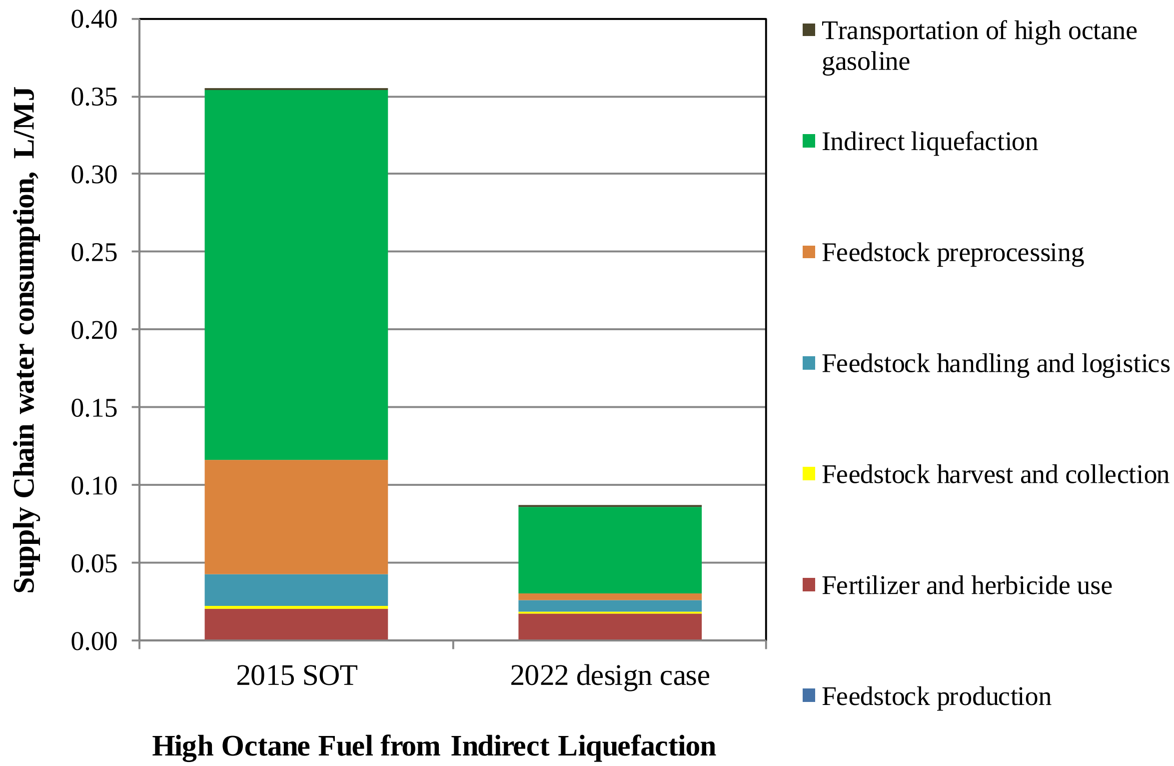

FIGURE 4 Supply Chain Water Consumption of HOG Produced Via IDL

Figure 5 shows that the supply chain water consumption of HOG produced via IDL is about 0.36 L/MJ, or 11.5 gal/GGE of HOG for the 2015 SOT, and 0.09 L/MJ, or 2.8 gal/GGE of HOG for the 2022 design case, in comparison to about 0.14 L/MJ, or 4.2 gal/GGE for petroleum gasoline blendstock. This difference represents approximately 38% less water consumption in the supply chain of HOG for the 2022 design case than in conventional gasoline’s supply chain. The main reason for this benefit is that production of the biomass feedstock for the HOG via IDL pathway for the 2022 design case is less water-intensive than crude oil recovery.

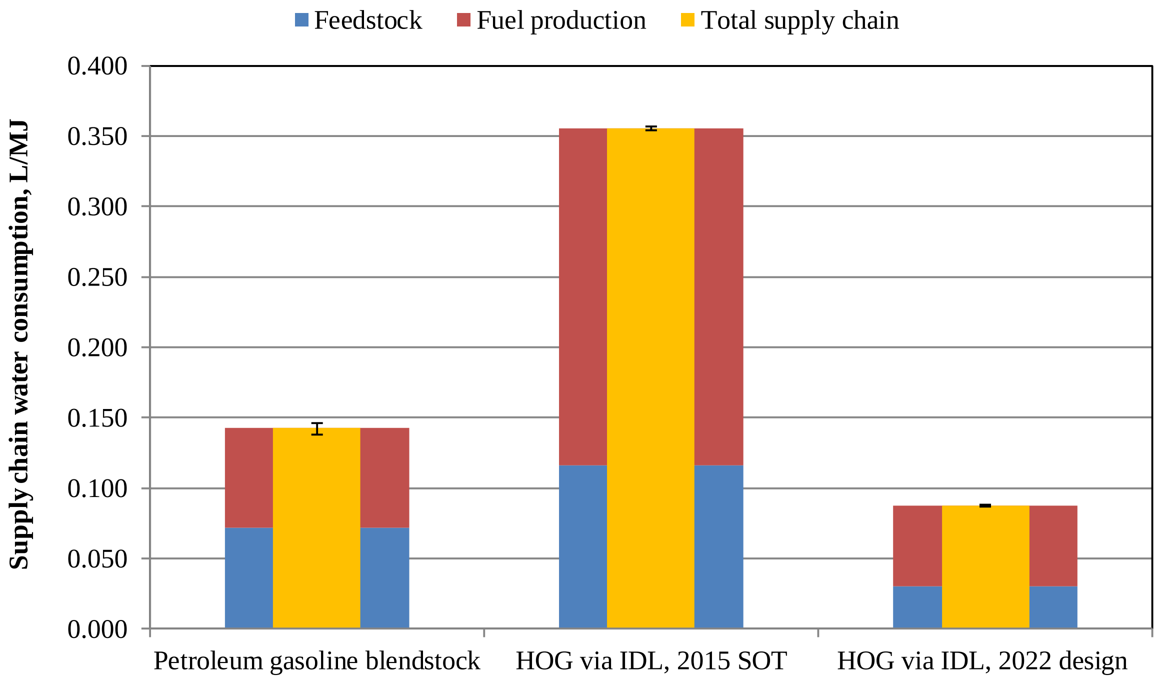

FIGURE 5 Supply Chain Water Consumption of HOG Produced Via IDL in Comparison to Water Consumption of Petroleum Gasoline Blendstock

3.2 SENSITIVITY ANALYSIS

In Section 2.2, we described how chemicals consumed at low levels that lack publicly available data regarding the material and energy intensity of their production were excluded from the analysis. For the 2022 design case, together, these inputs constitute 17% (10.1 g/gal) of the mass of process inputs. LO-CAT chemicals make up the largest portion (90%) of this mass. One way to test the sensitivity of results to exclusion of these compounds is to increase the flow of the most GHG-and energy-intensive process input by the total mass of the excluded compounds. We therefore increased the input mass of the beta zeolite catalyst, which has a GHG intensity of 7.2 kg CO_2e/kg, by 10.1 g/gal. As a result, supply chain GHG emissions of HOG increase by 4% to 16 g CO_2e/MJ, which is still an approximately 83% reduction in supply chain GHG emissions as compared to conventional gasoline. Because the bulk of these excluded process inputs are LO-CAT chemicals which contain a significant amount of chelated iron and caustics, it is likely that the GHG intensity of beta zeolite catalysts overestimates the GHG intensity of these compounds. For example, GHG emissions for a representative caustic, sodium hydroxide, are about one-third of those for the beta zeolite catalyst (ANL 2015). Overall, the exclusion of these chemicals is expected to have only a minor influence on the supply chain GHG emissions of the HOG product.

Taking the 2022 design case as an example, a sensitivity analysis was conducted to examine the effect of the biomass feedstock blend ratio on the supply chain GHG emissions and water consumption, with a focus on extreme scenarios where a single type of biomass feedstock is used for the HOG production via IDL.

Figure 6 (a) shows the effect of using a single feedstock for HOG production on the supply chain GHG emissions and water consumption of this fuel, compared to the design case, which uses a blended feedstock. We found that producing HOG purely from C&D waste would have lower GHG emissions and water consumption than when the blended feedstock is used, reducing GHG emissions and water consumption by about 38% and 26%, respectively. These reductions come about mostly because fertilizer is avoided and only a small amount of energy is required to separate and process this woody feedstock (Table 1). Producing HOG purely from wood residue would also provide significantly lower GHG emissions and water consumption than when the blended feedstock is used, reducing these metrics by about 28% and 23%, respectively, mostly because fertilizer and irrigation water consumption are reduced for feedstock production. On the other hand, if either switchgrass or pulpwood is used as the sole feedstock for HOG production, both GHG emissions and water consumption would increase to varying extents. For example, about 54% more GHG emissions and 2% more water consumption than those for the blended feedstock case are expected when switchgrass is the sole feedstock, compared to about 33% and 28% higher GHG emissions and water consumption when pulpwood is the sole feedstock. The much higher demand for nitrogen fertilizers for production of switchgrass than that for production of pulpwood (Table 3, Wang et al., 2013) is the main cause of the higher increase in GHG emissions for using exclusively switchgrass. It is important to note, however, that switchgrass fertilizer requirements are spatially dependent and subject to improvements in switchgrass agricultural practices, which are still emerging. HOG produced from 100% pulpwood has higher water consumption than that from 100% switchgrass mostly because this feedstock is expected to consume more potassium and phosphate fertilizers, the production of which are water-intensive (Lampert et al., 2014; Wang et al., 2013). Again, fertilizer requirements are spatially-dependent and will evolve as production of this feedstock matures. This sensitivity analysis reveals that C&D waste is, in the case of this analysis, the most desirable feedstock for both GHG emission reduction and water consumption reduction, as shown in Figure 6 (b). Considerations such as feedstock GHG- and water-intensity may be taken into account in addition to economic factors when selecting a feedstock blend. It should be pointed out that, for this sensitivity analysis, individual feedstock compositions are assumed to be identical for IDL and we assumed constant HOG yield regardless of feedstock. In reality, feedstock compositions and properties, for example, the energy content and ash content of each individual feedstock, are different, which could have significant impact on the product yield and in turn will affect the life-cycle GHG emissions and water consumption at the IDL phase.

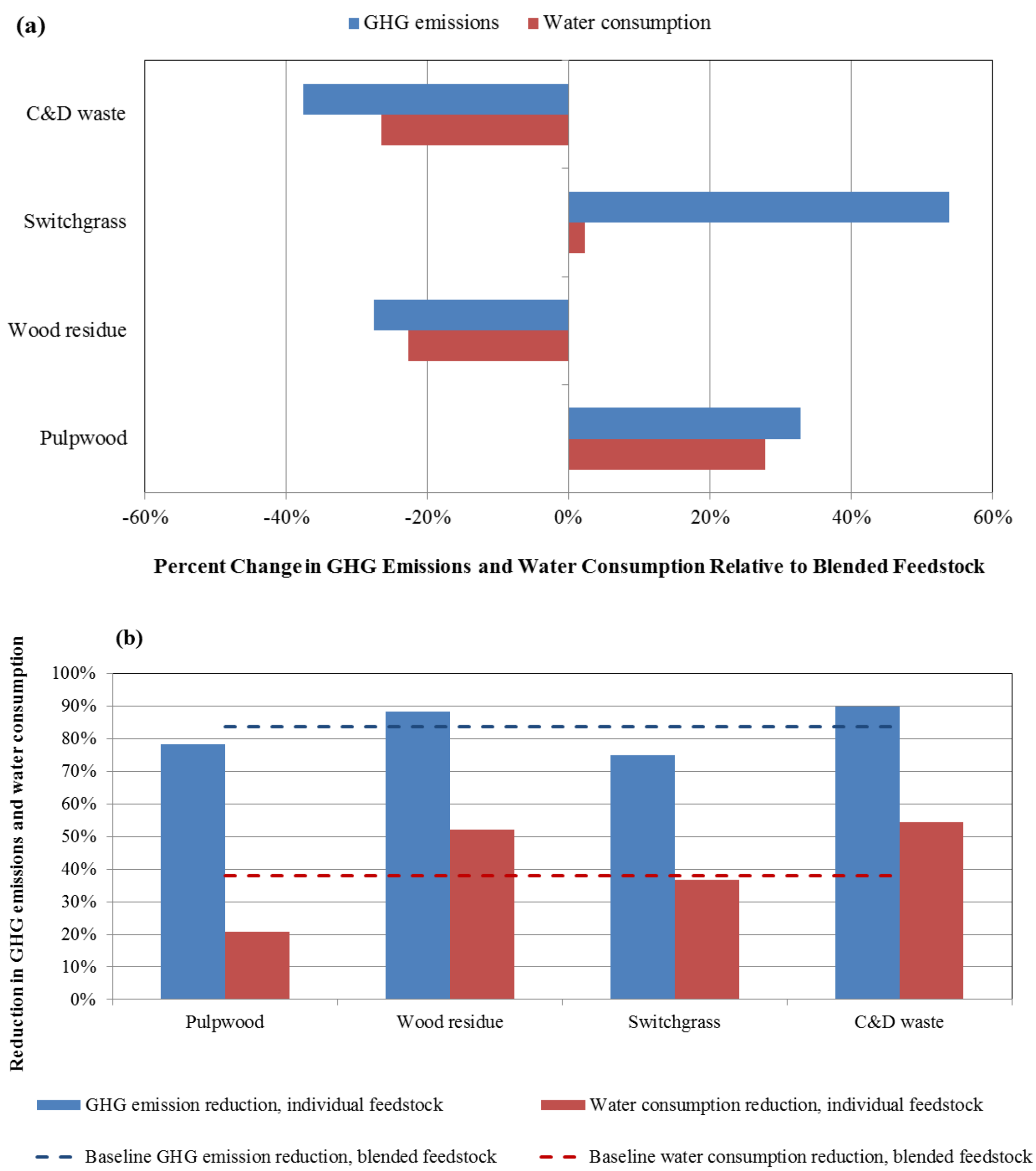

FIGURE 6 Sensitivity Analysis of Feedstock Choices, 2022 Design Case: (a) changes in supply chain GHG emissions and water consumption of HOG produced with individual feedstock, relative to blended feedstock (baseline values: 15.2 g CO_2e/MJ, 0.09 L/MJ) and (b) comparison of blended feedstock and feedstock-specific reductions in supply chain GHG emissions and water consumption of HOG, relative to petroleum gasoline blendstock (baseline values: 93.4 g CO_2e/MJ, 0.14 L/MJ)

Land use change GHG emissions are not included in this analysis. C&D waste and forest residue would likely have little or no LUC associated with them. Direct LUC to production of switchgrass could see soil organic carbon (SOC) increases, resulting in some carbon sequestration in soils (Qin et al., 2015). Conversion of lands to produce pulpwood could cause SOC increases, but the influence of LUC on soil carbon stocks is highly dependent on land-use history, local soil and climate conditions, and local feedstock yields.

4 CONCLUSIONS

Producing HOG via IDL from a biomass feedstock blend consisting of pulpwood, wood residue, switchgrass, and C&D waste yields a fuel that is 50% and 84% less GHG-intensive for the 2015 SOT and 2022 design cases, respectively, and 38% less water-intensive for the 2022 design case throughout its supply chain than conventional gasoline. GHG emissions from the feedstock preprocessing were the largest contributor to supply chain GHG emissions among the feedstock 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 feedstock preprocessing, feedstock landing preprocessing and sorting, minimization of feedstock losses, and boosting of the HOG fuel yield. 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. Sensitivity analysis shows that a change in the feedstock blend ratio can significantly change the GHG emissions and water consumption of the HOG via IDL pathway, increasing or decreasing its potential to reduce GHG emissions and water consumption, relative to its petroleum gasoline blendstock counterpart.

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APPENDIX: SCSA RESULTS IN DIFFERENT UNITS

Table A.1 presents the IDL SCSA results for GHG emissions and water consumptions in different units.

TABLE A.1 IDL SCSA Results in Different Units

	Unit	IDL, 2015 SOT Value	IDL, 2022 Design Value
Greenhouse gas emissions	g CO_2e/MJ	46	15
	g CO_2e/mmBtu	48,970	16,004
	g CO_2e/GGE	5,685	1,858
Water consumption	gal/mmBtu	99	24
	L/MJ	0.36	0.09
	gal/GGE	11.50	2.83

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