

Supply Chain Sustainability Analysis of Fast Pyrolysis and Hydrotreating Bio-Oil to Produce Hydrocarbon Fuels

Energy Systems Division

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1 INTRODUCTION

The Department of Energy's (DOE) Bioenergy Technology 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 technologies to produce biofuels. These assessments evaluate feedstock production, logistics of transporting the feedstock, and conversion of the feedstock to biofuel. There are two general types of TEAs. A design case is a TEA that outlines a target case for a particular biofuel pathway. It enables 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 the TEA process, 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 renewable gasoline and diesel produced via fast pyrolysis of a blended woody feedstock. The metrics we consider in this analysis include supply chain greenhouse gas (GHG) emissions and water consumption. SCSAs for two types of feedstock blends supply system were developed for, the 2015 SOT (Hartley et al., 2015; Hartley, 2016; DOE, 2016) and the 2017 design case (INL, 2014). These feedstock cases were paired with the 2015 SOT (Jones et al., 2015) and the 2017 design cases for conversion (Jones et al., 2013), respectively. In general, the SOT feedstock and conversion cases reflect the current state of available technology, while the 2017 design cases include advancements that are likely and targeted to be achieved by 2017. The feedstock blend for the 2015 SOT case includes pulpwood, wood residues, and sorted construction and demolition (C&D) waste. In addition to the above components, the 2017 design case feedstock blend also includes switchgrass (Hartley et al., 2015).

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

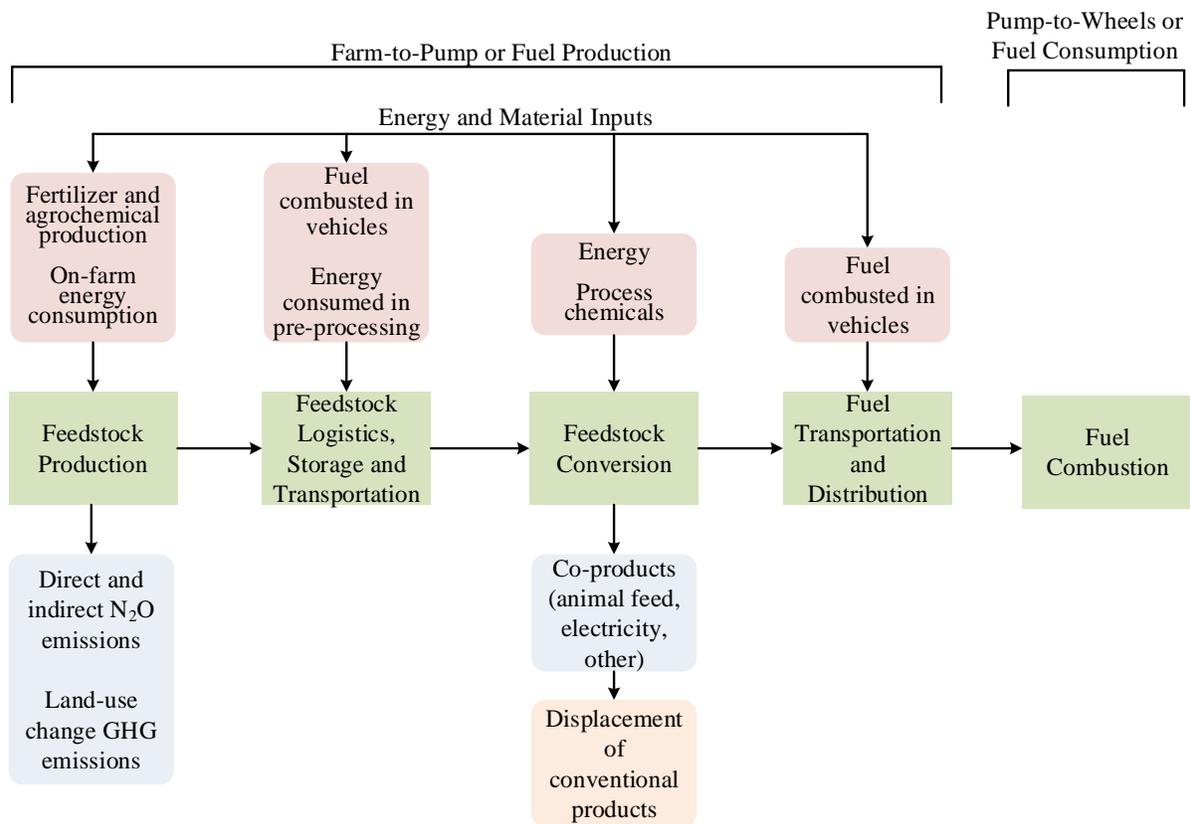


FIGURE 1 General Stages Considered in the Supply Chain Sustainability Analysis. Red boxes contain inputs to the supply chain. The energy and materials consumed to produce these inputs are rolled into the analysis. Blue boxes contain supply chain impacts and co-products.

2 METHOD AND DATA

Argonne National Laboratory's Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREETTM)¹ model as released in October 2015 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 and vehicle cycles. GREET computes fossil, petroleum, and total energy use (including renewable energy in biomass), emissions of GHGs (CO₂, CH₄, and N₂O), 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 a diameter below 10 micrometers (PM₁₀) and below 2.5 micrometers (PM_{2.5}). The 2015 version of GREET has the capability to estimate life-cycle water consumption of various fuel production pathways (Lampert et al., 2014; Lampert et al., 2015; Lampert et al., 2016). As a result, we incorporate supply chain water consumption for pyrolysis-derived fuels in this analysis.

Next, we summarize the material and energy consumption requirements for feedstock production and fast pyrolysis conversion process.

2.1 MATERIAL AND ENERGY REQUIREMENT OF FEEDSTOCK PRODUCTION AND LOGISTICS

The blended feedstock modeled by INL for both 2015 SOT and 2017 design cases was adopted for this study. In addition to producing a low ash content feedstock, the blended feedstock can be produced at a low cost through tapping wood residues and C&D waste. The 2015 SOT case blended feedstock consists of 45 wt% pulpwood, 35 wt% wood residues, and 20 wt% C&D waste. The 2017 design case blended feedstock consists of 45 wt% pulpwood, 32 wt% wood residues, 20 wt% C&D waste, and 3 wt% switchgrass. One reason for exclusion of switchgrass in the 2015 SOT blended feedstock is that large scale commercial harvest of dedicated energy crops like switchgrass is not anticipated until 2017.

In Table 1, we summarize the energy requirements for feedstock production for each processing step. Table 2 captures the shares of fuel type for each step reported in Table 1. Readers should note that we assumed that the farming of pulpwood feedstock requires the same amount of fertilizer as poplar farming does, as shown in Table 3, because we had insufficient information about pulpwood production.

In Table 1, we report seven different types of feedstock logistics operations for the production of blended feedstock. We include farming, harvesting and collection for pulpwood and switchgrass but not for wood residues and C&D waste. As reported in Table 2, diesel is the only fuel consumed in these three stages. Energy requirement for landing preprocessing/sorting is reported for all feedstocks but switchgrass. In the 2015 SOT case, the landing preprocessing/sorting step consumes largely diesel fuel. In the 2017 design case, however,

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

approximately 13% of this step's energy demand is met with electricity; consumption of diesel fuel meets the remainder (87%). Storage, handling, and transportation are three additional logistics operations reported in Table 1 for all feedstocks. The transportation and storage stages each consume solely diesel fuel in both the 2015 SOT and 2017 design cases. The feedstock handling stage differs in what type of energy it consumes between the 2015 SOT and 2017 design cases. In the former case, electricity is the primary type of energy consumed but in the latter, the main source of energy is diesel fuel. Overall, the preprocessing stage is dominated by natural gas consumption. The natural gas share for this stage is 95% in the 2017 design case. In the 2015 SOT case, this share is lower at 79%. In the design case, the balance of the energy demand is met with electricity. In the SOT case, aside from electricity (20%), diesel fuel constitutes 1% of the energy requirement for this stage.

In Table 4, we summarize feedstock transportation parameters used to determine energy consumption. GREET data (GREET, 2015) were adopted for parameters such as payloads while other data such as transportation distances and moisture contents were provided by INL (INL, 2014; Hartley et al., 2015). Parameters for the last two stages of the supply chain, fuel transportation and distribution and fuel combustion, are from GREET.

2.2 MATERIAL, ENERGY, AND WATER REQUIREMENT OF FAST PYROLYSIS CONVERSION PROCESSES

The biorefinery conversion process comprises fast pyrolysis of biomass, hydrotreating, product separation, and hydrocracking of diesel to help increase the fuel yield (Jones et al. 2015). Table 5 summarizes the conversion process parameters provided for both the SOT and design cases (Jones et al., 2009; Jones et al., 2013; Jones et al. 2015). There are some differences in energy consumption for the 2015 SOT case compared to the 2017 design case. For example, the latter consumes 5% less electricity and hydrogen than the former. This is likely due to improvements in process performance (e.g., improved catalyst performance and reactor design). Also, the 2015 SOT case consumes process chemicals but the 2017 design case does not. Proxy compounds were used in the 2015 SOT case that may change.

In the next section, we present SCSA results for fast pyrolysis-derived fuels.

TABLE 1 Energy Consumption for All Unit Processes for Each Feedstock and the Feedstock Blend in the 2015 SOT Case and the 2017 Design Case

Feedstock Logistics Operation	2015 SOT Case				2017 Design Case				
	Pulpwood (Btu/dry ton)	Wood Residues (Btu/dry ton)	C&D Waste (Btu/dry ton)	Blended Feedstock (Btu/dry ton)	Pulpwood (Btu/dry ton)	Wood Residues (Btu/dry ton)	Switchgrass (Btu/dry ton)	C&D Waste (Btu/dry ton)	Blended Feedstock (Btu/dry ton)
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	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 GREET, 2015

^b INL, 2014

^c Hartley et al., 2015

TABLE 2 Share of Production and Logistics Stage Fuel Type for Each Feedstock (INL, 2014; Hartley et al., 2015)

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

Feedstock logistics operation	2017 Design Case											
	Pulpwood			Wood Residue			Switchgrass			C&D Waste		
	<i>Natural</i>			<i>Natural</i>			<i>Natural</i>			<i>Natural</i>		
	<i>Diesel</i>	<i>Gas</i>	<i>Electricity</i>	<i>Diesel</i>	<i>Gas</i>	<i>Electricity</i>	<i>Diesel</i>	<i>Gas</i>	<i>Electricity</i>	<i>Diesel</i>	<i>Gas</i>	<i>Electricity</i>
Farming	100								100			
Harvest and Collection	100								100			
Landing	87		13	87		13				87	13	
Preprocessing/Sorting												
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 ₂ O ₅)	Potash (K ₂ O)
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) ^c	Transportation Distance, 2017 Design Case (miles) ^b	Transportation Moisture Content ^b	Moisture Content at Reactor Throat ^b
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 GREET, 2015

^b INL, 2014

^b Hartley et al., 2015

TABLE 5 Biorefinery Key Parameters (Jones et al., 2013, Jones et al. 2015)

Parameter	2015 SOT Case	2017 Design Case	Units
Mass dry feedstock/mass main products	3.62	3.63	lb biomass / lb main products
Electricity consumed in pyrolysis process <i>H₂ generation</i>	693	660	Btu/lb main products
Natural gas consumed to produce hydrogen <i>H₂ generation: conventional fixed bed</i>	3,033	2,885	Btu/lb main products
Volumetric share of gasoline produced	48%	48%	
Volumetric share of diesel produced	52%	52%	
Consumption of process chemicals	890	-	g/dry ton
Water consumption	1.5	1.4	gal/GGE ^a of fuel output

TABLE 6 (Cont.)

Parameter	2015 SOT Case	2017 Design Case	Units
Renewable gasoline			
<i>Yield</i>	39.9	39.9	gal/ dry ton
<i>LHV</i>	18,800	18,900	Btu/lb
<i>Density</i>	6.07	6.06	lb/gal
Renewable diesel			
<i>Yield</i>	43.5	43.7	gal/dry ton
<i>LHV</i>	17,820	17,930	Btu/lb
<i>Density</i>	7.1	7.08	lb/gal

^a Gasoline gallon equivalent

3 RESULTS AND DISCUSSION

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.² Figure 2 shows the contribution of the different stages in the supply chain of pyrolysis-derived gasoline for farm-to-pump GHG emissions.³

For the 2015 SOT case, the largest contributor (47%) to the farm-to-pump GHG emissions is CO₂ from the biorefinery. 57% of biorefinery CO₂ emissions are from natural gas consumption for the steam methane reforming process, which produces H₂ from methane and steam and emits CO₂. 37% of the biorefinery CO₂ emissions are from electricity consumption at the biorefinery. The balance of CO₂ emissions are from natural gas recovery and processing upstream of the biorefinery. Preprocessing of blended feedstock is a significant contributor (46%) to farm-to-pump GHG emissions. Fertilizer production and use, farming activity and transportation each contributes approximately 2% towards the farm-to-pump GHG emissions. Results are nearly identical for pyrolysis-derived diesel.

For the 2017 design case, the largest contributor (64%) to supply chain GHG emissions is the biorefinery. Feedstock preprocessing also is a significant contributor (23%) to farm-to-pump GHG emissions, followed by fertilizer production and use and farming activity which contributes approximately 4% each. Results are nearly identical for pyrolysis-derived diesel.

A comparison between the 2015 SOT case and the 2017 design case indicates that the latter is 42% less GHG intensive than the former. The difference is attributable to the high preprocessing stage energy requirement in the 2015 SOT case. Approximately four times more energy is consumed to preprocess blended feedstocks in the 2015 SOT case than in the 2017 design case (see Table 1). Additionally, most of the energy demand (95%) for the preprocessing step for 2017 design case is met with natural gas with the remainder (5%) supplied by electricity. Electricity share (20%) is higher in the case of 2015 SOT making it more GHG intensive.

Readers should note that this analysis 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.

² See Wang et al. (2011) for a discussion of co-product handling methodology considerations for biofuel life cycle analyses.

³ GHG emissions are reported as grams carbon dioxide equivalents per million Btu of fuel (MMBtu). Carbon dioxide equivalent emissions include CO₂ emissions and CH₄ and N₂O emissions multiplied by their 100-year global warming potentials.

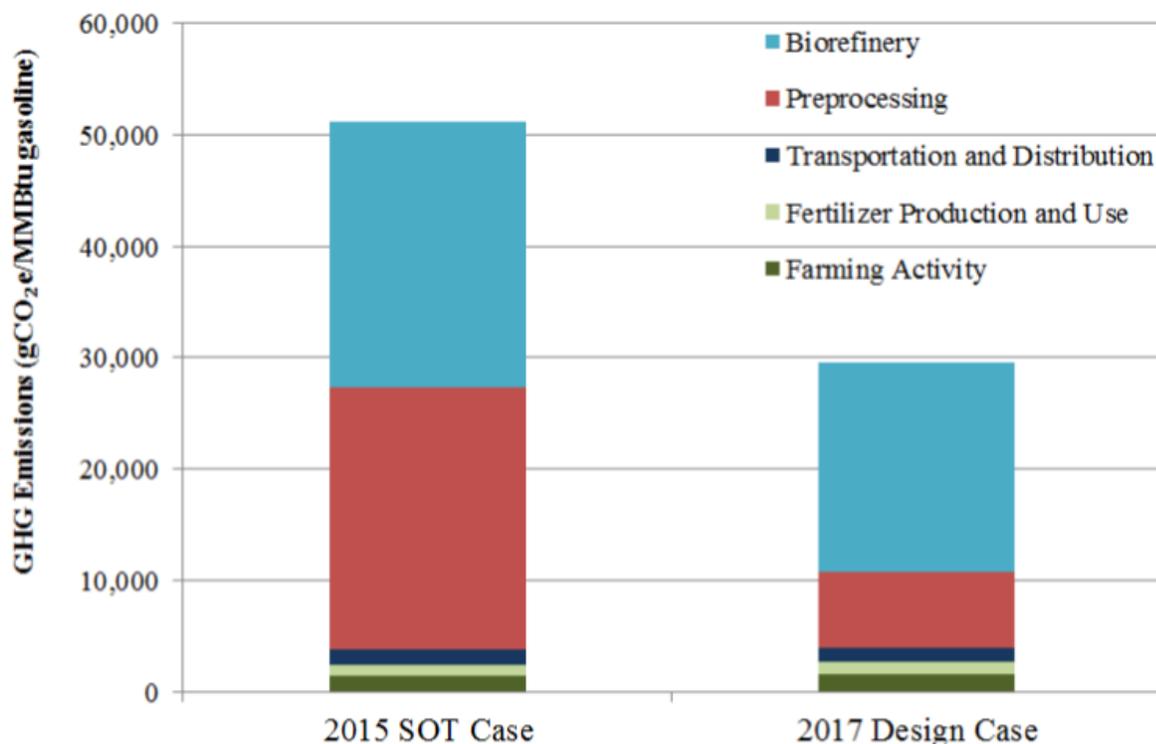


FIGURE 2 Breakdown of Farm-to-Pump GHG Emissions in the Pyrolysis-Derived Gasoline Pathway of Blended Feedstock

Figure 3 displays the supply-chain GHG emissions for pyrolysis-derived gasoline from blended feedstock for the 2015 SOT and 2017 design cases, along with supply chain GHG emissions for conventional gasoline. The GREET model includes a stochastic modeling tool to address the uncertainties of key parameters and their effects on energy consumption and GHG and air pollutant emission results. We used this tool to conduct stochastic 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. The error bars in Figure 3 show the P10 and P90 values of the net GHG emissions, where P10 and P90 represent the 10th and 90th percentiles, respectively, of the results.

Table 6 shows the median GHG emissions reductions of pyrolysis-derived fuels from blended feedstock compared to their counterparts derived from petroleum. Whereas design cases resulted in greater than 60% reduction, GHG emissions reductions for the SOT case are significantly smaller. Reducing the energy intensity of feedstock supply and logistics between the 2015 and the 2017 feedstock design cases will lower the supply-chain GHG emissions for this pathway.

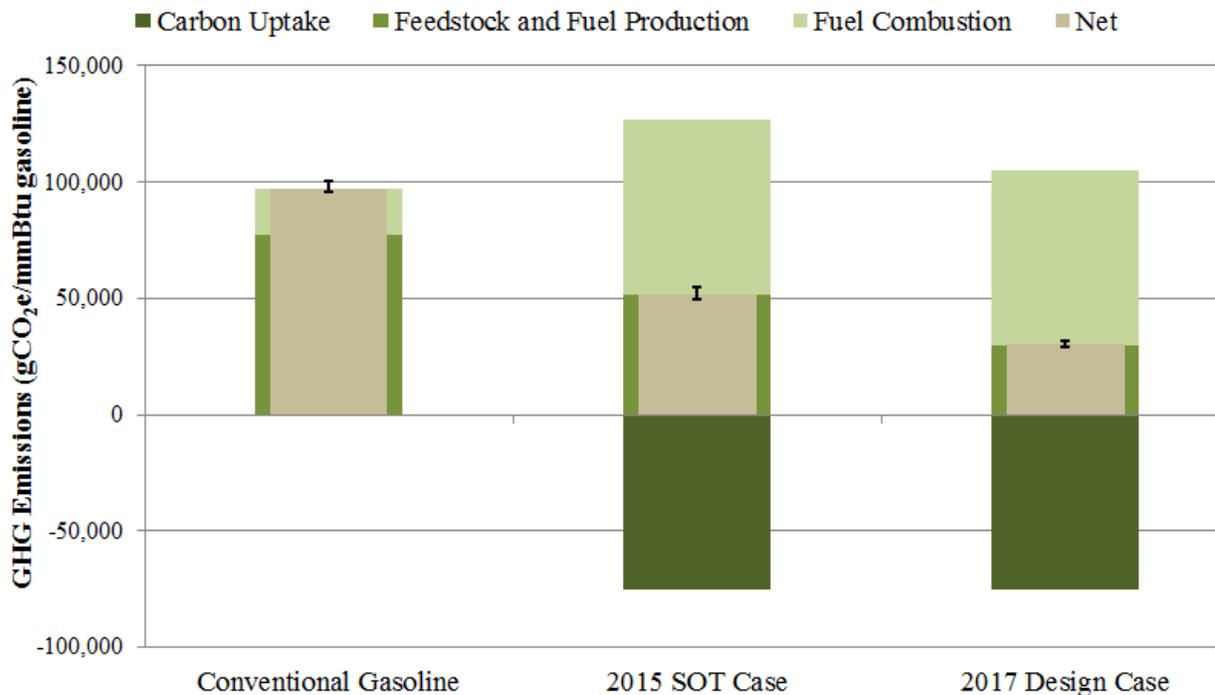


FIGURE 3 Supply Chain GHG Emissions for Pyrolysis-Derived Gasoline and Conventional Gasoline

Finally, for this analysis, we do not include land use change (LUC) GHG emissions associated with feedstock production. These emissions are a combination of estimates of land transitions to feedstock production estimated by economic models and the carbon stock of the converted lands (Dunn et al. 2013), including soil organic carbon (SOC). Woody residue is unlikely to have LUC associated with its collection and use as a biofuel feedstock (78 FR 43). At present, it is not expected that the removal of forest residue will significantly alter SOC (Wang et al. 2013), although this topic remains a point of research. C&D waste is also expected to have negligible LUC associated with it. LUC of woody feedstocks is a subject of active research while converting certain types of lands to switchgrass production (Qin et al. 2016) can incur soil carbon gains. We may incorporate these considerations quantitatively into future SCSAs.

TABLE 7 Median GHG Emissions Reductions of Pyrolysis-Derived Gasoline and Diesel Compared to Conventional Gasoline and Diesel

	Blended Feedstock	
	2017 Design	2015 SOT
Pyrolysis-derived gasoline	70%	47%
Pyrolysis-derived diesel	71%	48%

The supply chain water consumption analysis for the 2017 design and 2015 SOT cases in comparison with conventional gasoline is exhibited in Figure 4 on a gasoline gallons equivalent (GGE) basis. 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. Conventional gasoline consumes 3.7 gallons per GGE, SOT 2015 and design case 2017 consumes approximately 6.0 and 3.8 gallons per GGE respectively.

Water consumption for feedstock production, fertilizer and herbicide use, and harvest and collection feedstock stage between the 2015 SOT and 2017 design cases are comparable but the water consumption of these two cases differs significantly at the preprocessing stage in Figure 4. In the preprocessing stage, 2017 design case water consumption is seven times lower compared to the 2015 SOT case. There is no direct water consumption in the preprocessing stage, so this water consumption is entirely attributable to water consumed in the generation of energy used in preprocessing. Preprocessing consumes four times less energy in the 2017 design case than the 2015 SOT case. About 3.8 gallons per GGE (62%) of water consumption is attributable to the fuel production stage for the 2015 SOT case. Consumption of process chemicals in the conversion process contributes 14% of this value, consumption of natural gas and electricity contributes the remainder.

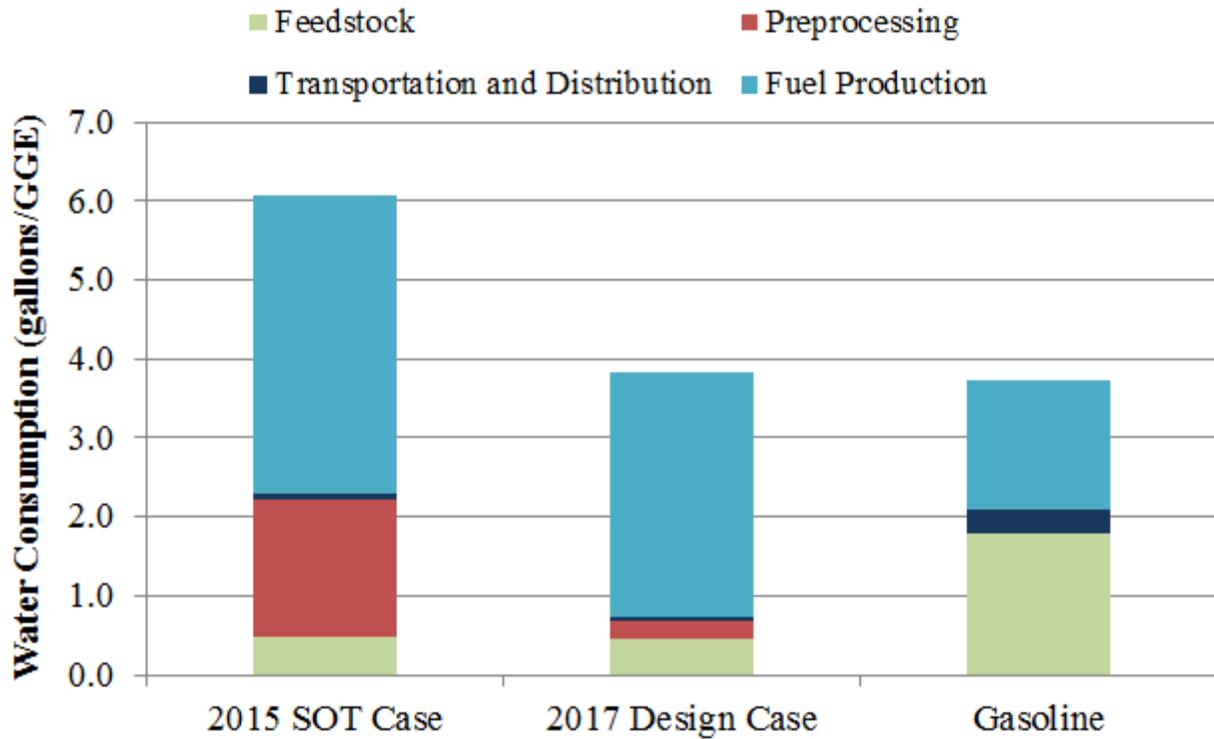


FIGURE 4 Supply Chain Water Consumption for Pyrolysis-Derived and Conventional Gasoline

4 CONCLUSIONS

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 47% reduction in GHG emissions for the 2015 SOT case; this reduction was higher (70%) for the 2017 design case. Among the different supply chain stages, the biorefinery was the largest contributor to the farm-to-pump GHG emissions, contributing 47% and 64% for 2015 SOT and 2017 design case respectively. To reduce the life-cycle GHG emissions of the pyrolysis pathway, research and development efforts could focus on reducing consumption of process energy and other inputs. Due to the significant contribution of blended feedstock preprocessing to supply chain GHG emissions, increasing the energy efficiency of blended feedstock 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.

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APPENDIX: SCSA RESULTS IN DIFFERENT UNITS

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

TABLE A.1 Pyrolysis SCSA Results in Different Units

	Unit	2015 SOT Case	2017 Design Case
		Value	Value
Greenhouse gas emissions	g CO ₂ e / MJ	49	28
	g CO ₂ e /mmBtu	51,739	30,086
	g CO ₂ e / GGE	6,006	3,493
Water consumption	Gal / mmBtu	52	33
	L / MJ	0.19	0.12
	Gal / GGE	6.0	3.8



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