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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, 2013). 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 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 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 or environmental 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 fast pyrolysis of two woody feedstocks, pine and forest residue, to renewable gasoline and diesel. For pine, SCSAs for two cases were developed, the 2014 state of technology (2014 SOT) and the 2017 design case (2017 design). The 2014 SOT reflects the current state of available technology (for both feedstock production [Cafferty and Hartely, 2015] and conversion), while the 2017 design includes advancements that are likely and targeted to be achieved by 2017 for the conversion process. The 2017 design case conversion process, as modeled in Jones et al. (2013) uses a low-ash feedstock with properties consistent with both a sole woody feedstock type (e.g., pine or forest residue) and with the feedstock blend that constitutes the 2017 feedstock design case, which includes pine, pine residues, sorted construction and demolition (C&D) waste, and switchgrass (Idaho National Laboratory [INL], 2014). The SCSA for the 2017 design case considers pine and forest residue feedstock cases separately rather than the 2017 feedstock design case (the blend) because life cycle inventory data are not available for C&D waste. These two cases could be viewed as bounding SCSA results because of the feedstocks in the 2017 feedstock design case, pine is the most energy- and GHG-intensive feedstock, whereas forest residue is a relatively low-impact feedstock. The 2014 SOT feedstock case includes only pine (Cafferty and Hartely, 2015) and an SCSA was developed solely for this feedstock in this scenario. A previously released SCSA (Dunn et al. 2013a) included an analysis of the pyrolysis pathway using hybrid poplar as a feedstock and the original conversion plant design case (Jones et al 2009) that has since been updated and is the basis of this analysis (Jones et al 2013).

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 input to the supply chain.

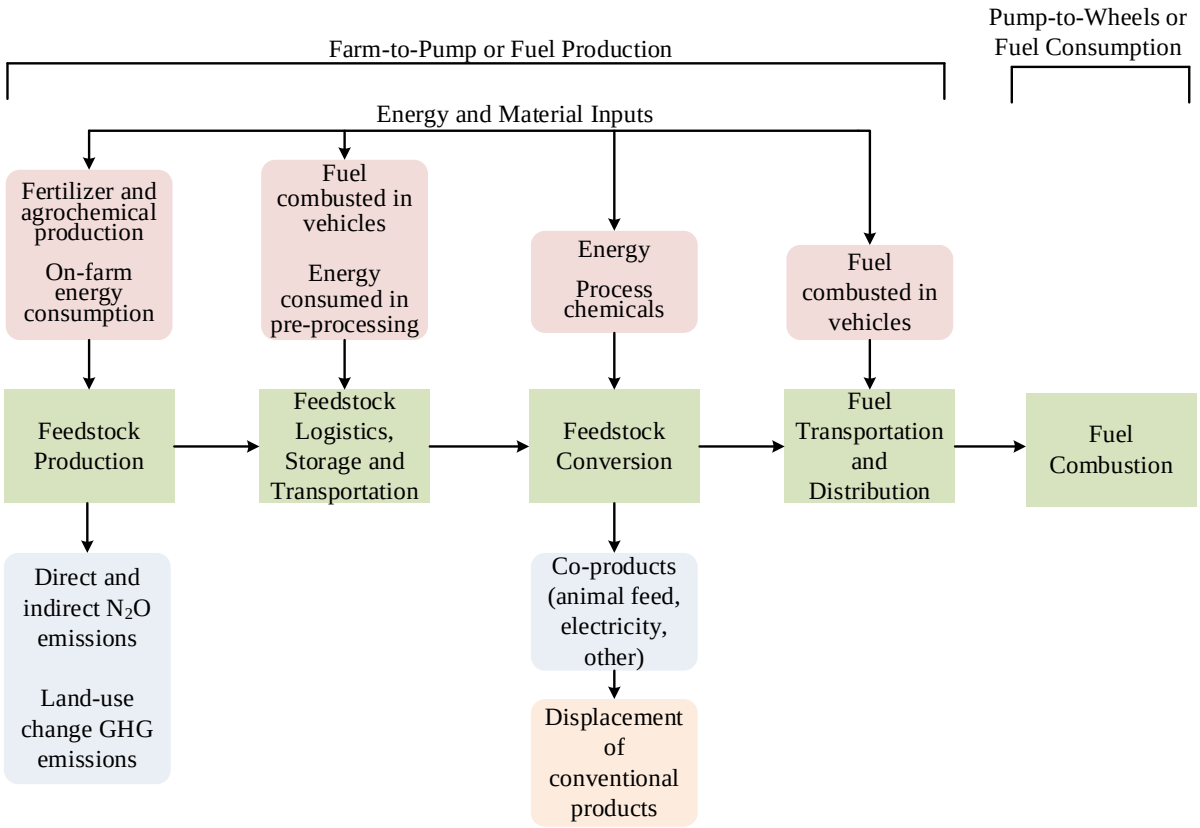

FIGURE 1 General Stages Considered in the Supply Chain Sustainability Analysis. Red boxes contain inputs to the supply chain. The energy and materials consumed to produce these inputs are rolled into the analysis. Blue boxes contain supply chain impacts and co-products.

2 METHOD AND DATA

Argonne National Laboratory's Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET™)[1] model as released in October 2013 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 (CO_2, CH_4, and N_2O), and emissions of six air pollutants: carbon monoxide (CO), volatile organic compounds (VOCs), nitrogen oxides (NOx), sulfur oxides (SOx), and particulate matter with a diameter below 10 micrometers (PM_{10}) and below 2.5 micrometers ($PM_{2.5}$).

Tables 1 to 3 document the material and energy intensity data for the feedstock production, transportation, and conversion steps of the supply chain. These data were incorporated into the GREET model. Data for the last two stages of the supply chain, fuel transportation and distribution and fuel combustion are from the GREET model.

One key difference in the SCSAs of the 2017 design case and the 2014 SOT case for pine is the underlying feedstock production data. The 2014 SOT case uses newly-developed data from INL. The 2017 design case pine production data is from Jones et al. (2013), which is based on earlier analysis at INL. For this reason, the burdens of pine production are not equivalent between the 2017 design case and the 2014 SOT case. Moreover, Jones et al. (2013) considered a case with forest residue as the feedstock. We include an SCSA of that scenario only for the 2017 design case. It is expected that the feedstock for pyrolysis will shift to a blend of pine, woody residue, the sorted fraction of C&D waste, and switchgrass (INL 2014). Future pyrolysis SCSAs will reflect this shift, as well as changes in feedstock logistics and the conversion process design.

To explore the effect of two key variables in the supply chain, a sensitivity analysis was conducted. First, as shown in Table 2, the energy consumed in de-ashing the feedstock could range from 80,000 Btu/dry ton to 830,000 Btu/dry ton (Jones et al. 2013). Results were generated at high, median, and low values of this range. Second, H_2 in the conversion process can be generated either in a conventional fixed bed or catalytic fluidized bed. The sensitivity analysis explored the latter scenario.

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

TABLE 1 Key parameters for pine and forest residue production (Jones et al., 2013, Wang et al., 2013)

	Value		
	Pine		Forest Residue
Parameter	2017 design	2014 SOT	2017 design
Production cycle (yr)	8	8	
Yield at end of cycle (dry tons/acre)	42	42	9
N fertilizer application rate (g/dry ton)	2,918	2,918	0
P fertilizer application rate (g/dry ton)	433	433	0
K fertilizer application rate (g/dry ton)	865	865	0
Lime application rate (g/dry ton)	21,592	21,592	0
Herbicide application rate (g/dry ton)	32	32	0
N_2O conversion rate of N fertilizer	1.525%[a]	1.525%[a]	--
Total harvest energy consumption (Btu/dry ton)	399,119	104,610	132,180
Harvesting (diesel)	86,420	51,430	--
Collection (diesel)	71,621	53,180	--
Fieldside delimbing (diesel)	126,279	--	--
Chipping (diesel)	114,799	--	--
Dry matter loss during storage	5%	5%	5%

[a] Wang et al. (2012)

TABLE 2 Feedstock transportation and preprocessing key parameters

	Value		
	Pine		
Parameter	2017 design	2014 SOT	Forest residue
Transportation			
Distance (miles)	50[a]	93[b]	90[c]
Heavy-duty truck fuel economy (miles/diesel gallon)	6[d]		6[d]
Payload (dry tons)	15[e]		15[e]
Preprocessing			
De-ashing energy consumption[f]			
Low (Btu/dry ton)	80,000		80,000
Median (Btu/dry ton)	460,000		460,000
High (Btu/dry ton)	830,000		830,000
Electricity consumed in feedstock Preprocessing (kWh/dry ton)[f]	37[g]	135[h]	37[g]
Natural gas consumed in feedstock drying (mmBtu/dry ton)	[i]	1.5[d]	[i]
Energy consumption during feedstock loading and unloading at storage facility (gal diesel/dry ton)	0.14 gal diesel/ dry ton	0.08 gal diesel/dry ton	0.14 gal diesel/ dry ton

[a] Searcy and Hess (2010)
[b] Cafferty and Hartley (2014)
[c] Wang et al. (2013)
[d] Cafferty and Hartley (2015)
[e] 30% moisture content at biorefinery gate
[f] The 2014 SOT case consumes electricity for de-ashing; the 2017 design case consumes diesel.
[g] Preprocessing steps include pumping de-ashing water, grinding, and dust collection
[h] Preprocessing steps include delimbing, grinding, densification (Cafferty and Hartley 2015)
[i] Will be incorporated in future SCSA along with additional updates to feedstock logistics

TABLE 3 Biorefinery key parameters (Jones et al., 2013, Jones et al. 2015)

Parameter	2014 SOT Case	2017 Design Case
Mass dry feedstock/mass main product	3.62	3.63
Electricity consumed in pyrolysis process		
H_2 generation: conventional fixed bed	621 Btu/lb main product	658 Btu/lb main product
H_2 generation: catalytic fluidized bed[a]	N/A	782 Btu/lb main product
Natural gas consumed to produce hydrogen		
H_2 generation: conventional fixed bed	2,894 Btu/lb main product	2,804 Btu/lb main product
H_2 generation: catalytic fluidized bed	N/A	2,383 Btu/lb main product
Volumetric share of gasoline produced	48%	48%
Volumetric share of diesel produced	52%	52%
Renewable gasoline		
Yield	39.9 gal/dry ton	39.9 gal/ dry ton
LHV	18,800 Btu/lb	18,900 Btu/lb
Density	6.07 lb/gal	6.06 lb/gal
Renewable diesel		
Yield	43.5 gal/dry ton	43.7 gal/dry ton
LHV	17,820 Btu/lb	17,930 Btu/lb
Density	7.13 lb/gal	7.08 lb/gal

[a] Not considered for the 2014 SOT case

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 first three steps in the supply chain of pyrolysis-derived gasoline to farm-to-pump GHG emissions.[3] For the 2017 design case with pine, the largest contributor (49%) to these emissions is CO_2 emissions from the biorefinery. 51% of biorefinery CO_2 emissions are from the steam methane reforming process, which produces H_2 from methane and steam and emits CO_2. 38% of the biorefinery CO_2 emissions are from electricity consumption at the biorefinery. The balance of CO_2 emissions are from natural gas recovery and processing upstream of the biorefinery. Feedstock preprocessing also is a significant contributor (20%) to farm-to-pump GHG emissions, followed by fertilizer production and use (12%) and farming activity (12%). Results are nearly identical for pyrolysis-derived diesel.

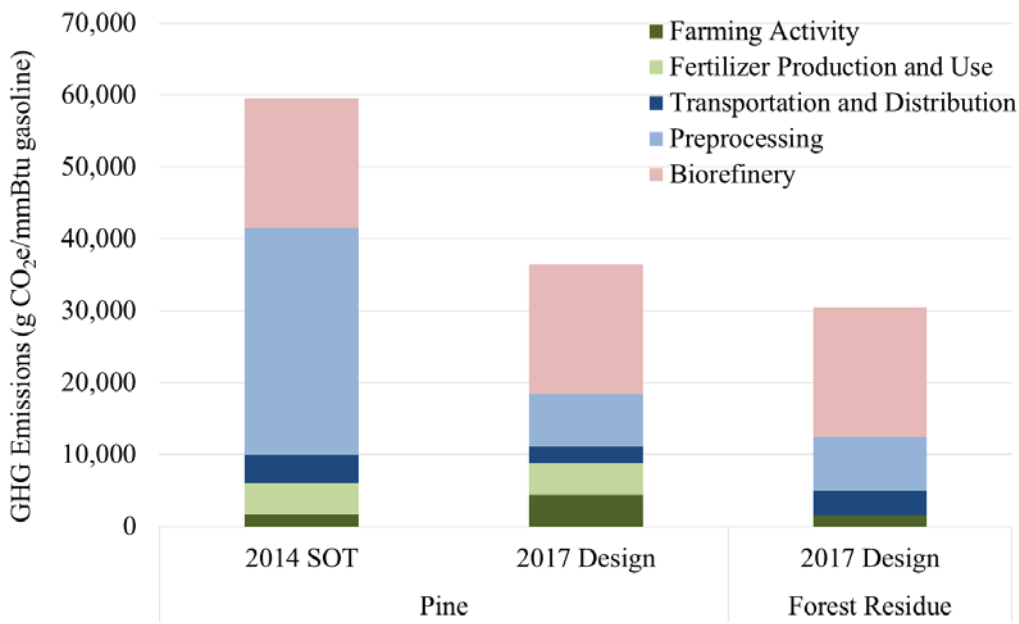

FIGURE 2 Breakdown of farm-to-pump GHG emissions in the pyrolysis-derived gasoline pathway of pine and forest residue

[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. Carbon dioxide equivalent emissions include CO_2 emissions and CH_4 and N_2O emissions multiplied by their 100-year global warming potentials.

Similarly, for the 2017 design case with forest residue as a feedstock, the largest contributor to farm-to-pump emissions (59%) is biorefinery CO_2 emissions. Again, feedstock preprocessing is a significant contributor (24%) to farm-to-pump GHG emissions, followed by transportation of feedstock and fuel (11%) and farming activity (5%). While GHG emissions from the preprocessing and conversion steps are identical for the two pyrolysis feedstocks, the differences in impacts at the feedstock production stage are notable in Figure 2. Forest residue is treated as a waste product of commercial logging activity. Energy, however, is consumed to collect and preprocess it (Wang et al. 2013). Compared to the energy consumed in pine harvesting, however, the energy associated with producing forest residue as a biofuel feedstock is minimal. Additionally, no fertilizer consumption is assigned to the production of forest residue in this analysis. GHG emissions for feedstock transportation are higher for forest residue scenarios because the transportation distance exceeds that of pine by 40 miles (Table 2).

The GHG emissions attributed to the biorefinery in the 2017 design and 2014 SOT cases with pine as a feedstock are very similar because conversion process energy and material flows are very similar for the two cases (Table 3). This analysis does not account for the longer catalyst lifetime in the design case as compared to the SOT case. It does not include the impact of catalyst production and consumption because material and energy intensity data for the production and use of hydrotreating catalysts are still under development. Jones et al. (2013), however, expect catalysts to contribute less than 1% to GHG emissions from the biorefinery. Additionally, the 2017 design case uses waste heat to dry the feedstock, whereas feedstock drying is handled before the biorefinery gate in the 2014 SOT case. This shift in the location of feedstock drying does not cause a significant difference between biorefinery results for the two cases because based on a preliminary sensitivity analysis of the 2017 design case, the increased availability of low-quality heat at the conversion facility for other uses when drying is shifted to preprocessing does not significantly drive down GHG emissions from the biorefinery.

Although conversion step GHG emissions are similar between the 2017 design and 2014 SOT cases for conversion of pine to renewable gasoline, the contribution from feedstock preprocessing is significantly larger (53% compared to 20%). In the 2014 SOT case, pine is harvested and stored as logs rather than chips to reduce dry matter loss and degradation. Subsequently, the logs are transported to a processing location where they undergo grinding, drying, and densification and emerge as process feed-ready. In this overall preprocessing sequence, natural gas consumed for drying represents 76% of the energy consumed. Driving down this energy consumption associated with drying will be key to reducing the contribution of feedstock preprocessing to supply-chain GHG emissions. In the 2017 conversion design case (Jones et al. 2013), the feedstock is dried with low quality waste heat from the conversion facility. INL (2014) has developed a feedstock design case for 2017 in which the feedstock is dried through a process called high-moisture densification, which processes the feedstock while wet and then dries it in a less intense, cross-flow drier. When this feedstock design case is integrated with the conversion design case in future SCSAs, results may change.

Changes in assumptions about the equipment used in harvesting and collection cause the GHG contribution from farming activity in the 2014 SOT case for pine to be about one-third lower than in the design case. The 2014 SOT case uses a harvester that incorporates delimbing to replace the feller-buncher, and a forwarder to replace a grapple-skidder. Overall, these changes

improve the energy efficiency of harvesting and collection as compared to earlier analyses of these processes (Cafferty and Hartley 2015).

Figure 3 displays the supply chain GHG emissions for pyrolysis-derived gasoline from pine and forest residue in the 2017 design and 2014 SOT 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 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 3 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.

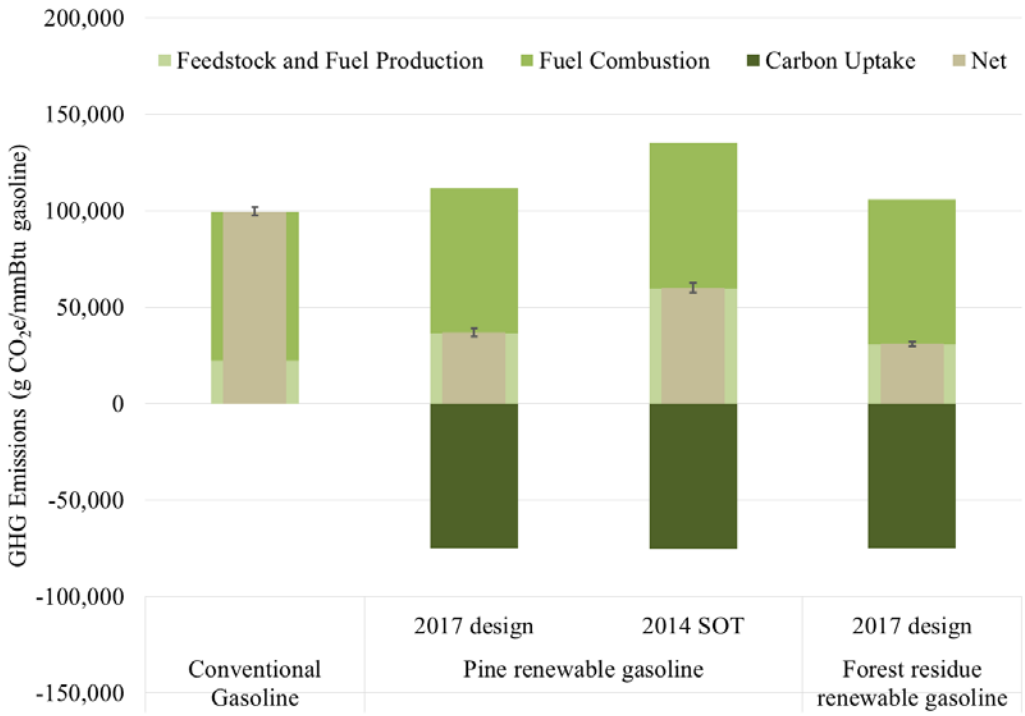

FIGURE 3 Supply chain GHG emissions for pyrolysis-derived and conventional gasoline

Table 4 shows the median GHG emissions reductions of pyrolysis-derived fuels from pine and forest residue compared to their counterparts derived from petroleum. Whereas both design cases are 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 2014 and the 2017 design case will lower the supply-chain GHG emissions for this pathway. This reduction in energy consumption will stem from moving towards a blended feedstock approach and through advanced logistics operations that increase energy efficiency.

TABLE 4 Median GHG emissions reductions of pyrolysis-derived gasoline and diesel compared to conventional gasoline and diesel

	Pine		Forest residue
	2017 design	2014 SOT	2017 design
Pyrolysis-derived gasoline	63%	40%	69%
Pyrolysis-derived diesel	64%	41%	70%

Table 5 shows the results of the sensitivity analysis. Variations in de-ashing energy consumption could increase or decrease GHG emissions by about 8,000 g CO_2e/mmBtu gasoline. Hydrogen generation in a catalytic fluidized bed, rather than a catalytic fixed bed, decreases GHG emissions by about 400 g CO_2e/mmBtu gasoline compared to the base case.

TABLE 5 Results of sensitivity analysis for 2017 design cases

Cases		Supply chain GHG emissions (g CO_2e/mmBtu gasoline)	
Steam methane reforming technology	De-ashing energy consumption	Pine	Forest residue
Conventional fixed bed	Median	37,000	31,000
	Low	33,000	27,000
	High	41,000	35,000
Catalytic fluidized bed	Median	37,000	30,000

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. 2013b), including soil organic carbon (SOC). Forest 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. Estimates of LUC impacts of pine production as a biofuel feedstock are sparse and SOC implications of pine production are not

clear. There is some indication, for example, that conversion of lands (specifically native forest or pastures) to pine plantations may decrease SOC by between 12-15% (Guo and Gifford 2002). Yet, the soil carbon impacts of pine plantations are strongly influenced by a number of variables including soil type, prior land use, and climate, making a prediction of pine production's impact on soil carbon quite difficult without further research.

4 CONCLUSIONS

SCSAs of the 2017 design case for pyrolysis of pine and forest residue to yield renewable gasoline and diesel revealed that these pathways offer GHG emissions reductions from a supply chain perspective when compared to their fossil fuel counterparts. GHG emissions reductions were lower for the 2014 SOT case with pine as a feedstock. In the design case SCSA, GHG emissions from the biorefinery were the largest contributors among the five steps considered for the farm-to-pump stage. Research and development efforts to further reduce life-cycle GHG emissions could focus on reduced consumption of process energy and other inputs. Given the key contribution of feedstock preprocessing in the SOT case, more efficient pine harvests, transportation and preprocessing technologies, and lower chemical and energy inputs for growing pine would also benefit GHG emissions reductions of the renewable gasoline and diesel produced. Future SCSAs of this pathway will consider advances in feedstock blends logistics as INL (2014) describes. Incorporation of these changes will affect SCSA results.

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