Life Cycle Assessment of Gasoline and Diesel Produced via Fast Pyrolysis and Hydroprocessing

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Executive Summary

Pyrolysis of biomass followed by hydroprocessing may provide infrastructure-compatible transportation fuels that present an advantage over bioethanol, which must be blended with gasoline for use in vehicles and does not address diesel demand. Recent studies analyzed the economics of pyrolysis-derived biofuels and suggested that these biofuels can be cost competitive with gasoline under "n^{th} plant" assumptions. With these advantages, pyrolysis has garnered greater research attention. Despite this, there have been few life cycle assessments (LCA) estimating greenhouse gas (GHG) emissions and net energy value (NEV) of a pyrolysis process.

In this work, an LCA of the production of gasoline and diesel from forest residues via fast pyrolysis and hydroprocessing, from production of the feedstock to end use of the fuel in a vehicle, is performed. The fast pyrolysis and subsequent hydrotreating and hydrocracking processes are based on a Pacific Northwest National Laboratory (PNNL) design report. Stages other than biofuels conversion, including forest residue production and harvesting, preprocessing, feedstock transportation, fuel distribution, and vehicle operation, are based on previous work. Probability distribution functions (PDFs) are assumed for key parameters involved in the pyrolysis process. These PDFs, along with PDFs previously used in other supply chain stages, are used as inputs for Monte Carlo uncertainty analysis.

This preliminary LCA for the production of gasoline and diesel via pyrolysis and upgrading assumes grid electricity is used and supplemental natural gas is supplied to the hydrogen plant. Monte Carlo uncertainty analysis shows a range of results, with all values besting conventional gasoline in 2005. Grid electricity accounts for 27% of the net GHG emissions in the base case. A sensitivity using biomass-derived electricity shows significant improvement in GHG emissions. Further research to achieve the target fuel yields is needed to reduce the uncertainty of the GHG and NEV results. In addition, other sensitivities, such as biomass-derived hydrogen and reduction in electricity demand through process optimization, should be explored in tandem with their associated technoeconomics.

Table ES-1. Summary of GHG and NEV Results for Reference and Sensitivity Cases

	Reference case: grid electricity, supplemental natural gas to H_2 plant	Sensitivity: biomass-derived electricity, supplemental natural gas to H_2 plant
GHG emissions, kg CO_2-equiv. per MJ		
Gasoline	0.049	0.035
Diesel	0.054	0.040
Net energy value, MJ per MJ of fuel		
Gasoline	0.38	0.56
Diesel	0.38	0.61
GHG reduction over gasoline in 2005	53%	65%

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Introduction

Because of recent national focus on increasing energy independence and curbing climate change, more attention and resources have been devoted to the research and production of cellulosic biofuels. The Energy Independence and Security Act (EISA) of 2007 mandated a Renewable Fuel Standard that set a production target of 36 billion gallons of biofuels by 2022 [1]. Of that total in 2022, 20 billion gallons are not restricted to a specific type of fuel such as ethanol or biodiesel.

Ethanol currently is produced commercially from starch sources such as corn grain and blended into gasoline. According to the Congressional Budget Office, 10.8 billion gallons of corn ethanol were produced in 2009 [2]. Ethanol production, from both corn and cellulosic sources, emits fewer greenhouse gases and has a higher net energy value than gasoline does [3-7]. However, ethanol suffers from several disadvantages. Ethanol can be blended at levels of up to 85% by volume with gasoline to form E85, but only specially purposed gas stations and flexible-fuel vehicles (FFV) can use this fuel. For older vehicles designed only for gasoline, the current maximum blend level of ethanol allowed by the Environmental Protection Agency (EPA) is 10% by volume. The Environmental Protection Agency (EPA) recently granted a waiver to approve raising the maximum blend level of ethanol to 15% by volume, but only for model year 2007 and newer light-duty vehicles designed for gasoline [8]. Auto and parts manufacturers resist increases in the ethanol blending percentage because of possible engine damage [9]. Ethanol also has a lower energy density than gasoline, which means that a vehicle travels fewer miles on a gallon of ethanol than on a gallon of gasoline. An infrastructure-compatible biofuel that substitutes for conventional gasoline or diesel would overcome these shortcomings.

One way to produce infrastructure-compatible biofuels is through fast pyrolysis followed by hydrotreating and hydrocracking. In fast pyrolysis, biomass is rapidly heated to temperatures around 400°C to 500°C in the absence of oxygen, causing thermal decomposition of the biomass and ultimately resulting in a bio-oil. This bio-oil resembles crude oil in appearance but has higher oxygen content and is more acidic. To convert bio-oil to usable transportation fuels, the bio-oil is upgraded through hydrotreating and hydrocracking. In hydrotreating, hydrogen is reacted with the bio-oil in order to remove sulfur and oxygen. In hydrocracking, the hydrotreated bio-oil is reacted again with hydrogen in order to create smaller chains of hydrocarbons to meet the specifications of gasoline and diesel fuels.

Economic analysis of a pyrolysis process design by Pacific Northwest National Laboratory has shown that for an "n[th] plant," the minimum fuel selling price is $2.04/gal of fuel (2007 dollar basis) [10]. A similar study by ConocoPhillips, Iowa State University, and NREL showed that an "n[th] plant" could result in a fuel product value (defined as the value that yields a net present value of zero with an internal rate of return of 10%) of just over $2 per gallon of gasoline equivalent (2007 dollar basis) [11, 12], which is lower than fuel product values from comparable studies on ethanol via a biochemical pathway [13] and gasoline/diesel via gasification followed by Fischer-Tropsch catalysis [14]. In addition to the competitive fuel prices, pyrolysis may have additional cost savings by potentially using existing petroleum refinery infrastructure for hydrotreating and hydrocracking [15].

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Although several techno-economic analyses have been applied to the production of biofuels via pyrolysis and subsequent hydroprocessing [10, 11, 16], few life cycle assessments (LCAs) on pyrolysis have been reported in the peer-reviewed literature. Other biofuel pathways—including ethanol from corn, ethanol from cellulosic biomass, and biodiesel from algae—have been the subject of more LCAs.[1] In order to improve energy independence and reduce climate change, biofuels will have to reduce greenhouse gas (GHG) emissions compared to gasoline and generate a positive net energy value (NEV). EISA legislation set biofuel GHG emissions requirements in comparison to conventional fuel emissions in 2005 [1]. Thus, the results of an LCA on biofuels from pyrolysis are of interest not only to research laboratories and academic institutions but also to the policy and investment communities.

This study aims to quantify the GHG emissions and NEV of infrastructure-compatible biofuels from pyrolysis and subsequent hydroprocessing of forest residues and to compare those results to the GHG emissions and NEV from gasoline and from ethanol produced via gasification. In addition, uncertainty results from a Monte Carlo analysis will be presented.

Methods

The life cycle assessment modeling approach follows the methodology described in Hsu et al. [3]. This study is based in the year 2022, when pyrolysis conversion technology is assumed to be commercial and advanced system designs are available for all stages of the fuel cycle. The modeling boundary for this study is from field to wheels. The scope of this work is attributional, where no indirect effects (such as indirect land use change) are considered. In addition, no soil carbon change is assumed as a result of production and harvesting of forest residues. The functional unit is 1 km traveled by a light-duty passenger vehicle operated on fuels generated via pyrolysis. Data are also reported for 1 MJ of fuel produced to facilitate comparisons with other LCAs. The data are based on extrapolation of national average data and anticipated learning and improvement. While this means the results are not indicative of any region of the country, uncertainty analysis can be used to explore regional variability.

The stages that occur before the conversion of biomass to biofuels are based entirely on previous work [3, 17], and no new LCA modeling of those stages is done for this study. Forest residues are the nonmerchantable portions of the harvested tree that are brought to the landing, typically discarded, and sometimes burned. Forest residue harvesting is modeled based on U.S. whole-tree logging operations [18]. The forest residues are chipped at the landing using standard industrial chipping equipment and then transported to the biorefinery.

SimaPro v.7.2 life cycle assessment modeling software [19] is used to develop and link primary unit processes. Ecoinvent v.2.1 [20] provides life cycle inventories for secondary materials and energy required in those primary unit processes.

Pyrolysis and Hydroprocessing
The pyrolysis of biomass to bio-oil and the subsequent hydroprocessing of bio-oil to transportation fuel are based on the Pacific Northwest National Laboratory design report by

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[1] From a July 2010 search of "pyrolysis life cycle" on Google Scholar, no peer-reviewed journal articles were found on the first five search pages for life cycle assessments on fuels generated from pyrolysis.

Jones et al. [10] and the associated CHEMCAD models and Microsoft Excel spreadsheets. The design report describes an "n^{th} plant" with the capacity to process 2,000 tonnes per day of bone dry hybrid poplar, and the report targets a case possible in 2015 to 2017. The design case uses electricity from the grid. This design case is assumed to be the average plant commercially available in 2022. A scenario based on biomass-derived electricity is not run explicitly in CHEMCAD, so the grid-electricity case serves as the reference case in our uncertainty analysis. The analysis approach in the pyrolysis design report mirrors the approach taken with the cellulosic ethanol design reports [21, 22] used in the Hsu et al. LCA study on ethanol [3], and as a result, comparisons can be made readily with the cellulosic ethanol LCA results.

The required material inputs and energy requirements for the process are from three CHEMCAD models. One CHEMCAD model describes the production of bio-oil from fast pyrolysis, and this is considered a separate process in SimaPro. Bio-oil could be an intermediate product for electricity rather than for fuels, but such use is not in the scope of this study. The other two CHEMCAD models describe the hydroprocessing of bio-oil and the steam reforming of natural gas to produce hydrogen needed for treating the bio-oil. These two models are considered one process in SimaPro.

In order to allow for uncertainty analysis, the CHEMCAD models are exercised for different bio-oil, water, char and ash, and gas yields resulting from fast pyrolysis and for different oil and gas amounts resulting from hydroprocessing. Varying these parameters allows for a range of results for overall fuel yield. Linear regression equations are developed for all of the inputs and outputs with the bio-oil yield and overall fuel yield as the independent variables. The carbon dioxide released in hydroprocessing is calculated by difference rather than by regression in order to ensure that carbon balances. The life cycle impacts of the hydroprocessing and upstream processes are allocated between gasoline and diesel on an energy-content basis (for the reference case, 43% is allocated to gasoline and 57% is allocated to diesel).

As with conceptual process models, the CHEMCAD models carry several assumptions, described in the Jones et al. report [10]. Of particular importance to this LCA are the assumptions around the production of fuel. The hydroprocessing model has a distillation process, which separates hydrocarbons into two streams. These two streams are in the gasoline and diesel distillation range and are assumed to be suitable for blending into finished fuel. The fuel properties of these hydrocarbon streams have not been experimentally tested. This LCA assumes that the gasoline and diesel streams could be used without blending as finished products in gasoline and diesel vehicles. Electricity use has been calculated in the Jones et al. report, but the calculation for the feed preparation and the hydrogen plant occurs outside the CHEMCAD model. For this study, electricity use is assumed not to change as fuel yield changes. However, natural gas usage will change with fuel yield. Lower liquid yields result in higher gas yields and subsequently lower natural gas usage in the hydrogen plant.

Fuel Distribution and Vehicle Operation
The fuels are transported to regional storage based on Ecoinvent processes [20]. The fuels are then used in vehicle operation. Diesel emissions are based on GREET 1.8c values for a CIDI (compression ignition direct injection) vehicle using conventional and low-sulfur diesel [23]. Gasoline emissions are based on GREET 1.8c values for a gasoline vehicle using conventional and reformulated gasoline [23]. Vehicle fuel economies are taken from the 2020 values in

GREET 1.8c [23]. Gasoline vehicles have an on-road fuel economy of 10.8 km per liter of gasoline (25.4 miles per gallon), and diesel vehicles have an on-road fuel economy of 13.0 km per liter of gasoline equivalent (30.5 miles per gallon of gasoline equivalent).

The fuel properties for renewable and conventional diesel vary in GREET 1.8c [23], and the properties for the diesel hydrocarbon stream from hydroprocessing are unknown. The mass density and the lower heating value of diesel fuel affect the LCA results through the fuel economy of the vehicle. Thus, these properties are set as parameters that can be varied in the uncertainty analysis.

Uncertainty Analysis

This study analyzes a projected system in 2022. This reference case reflects only one possible state of technology in 2022. Monte Carlo uncertainty analysis is used to investigate alternative scenarios. Probability distribution functions (PDFs) are assigned to input parameters. The reference case consists of each input parameter at its most frequent value. Parameters and input distributions varied for stages upstream of conversion are the same as what has been detailed in Hsu et al. [3] and the accompanying supporting information [17].

Ideally, for parameters specific to this study, distributional data would be based on empirical data from pyrolysis and upgrading facilities. But because sufficient data are lacking to define any other distribution, triangular distributions are selected. For the biofuel conversion stage, the fuel yield target is 417 L per dry tonne of wood [10], and the lower bound is set at 310 L per dry tonne of wood [24]. Diesel mass density and lower heating value are varied based on ranges for Renewable Diesel I (super cetane) and low sulfur diesel in GREET 1.8c, with the reference case based on conventional diesel [23]. Although regression equations are also generated for bio-oil yield, this is not exercised in the Monte Carlo analysis because bio-oil yield cannot vary independently of the fuel yield. The Monte Carlo uncertainty analysis consists of 1,000 trials. Standard descriptive statistics are used to evaluate the results.

Table 1. Triangular Distribution Information for Input Parameters Varied for Uncertainty Analysis

Parameter	Units	Reference case	Minimum	Maximum
Total fuel yield after hydroprocessing	L/dry tonne wood (gal/dry short ton)	417 (100) [10]	310 (75) [24]	417 (100) [10]
Diesel density	kg/L	0.8366 [23]	0.7489 [23]	0.8469 [23]
Diesel lower heating value	MJ/L	35.8 [23]	32.6 [23]	36.1 [23]

Analytical Methods

The impact of GHG emissions is calculated using the 100-year global warming potentials for all gases [25], but the main GHGs in this work are carbon dioxide, methane, and nitrous oxide. NEV is calculated as output energy minus input energy. In this study, no coproducts are produced and the only output energy is that from the transportation fuels produced by pyrolysis.

Results and Discussion

Figure 1 shows GHG emissions for the reference case. The pyrolysis fuel results are reported for a vehicle operating on each type of fuel. Diesel has lower GHG emissions on a per kilometer basis than gasoline does because diesel engines are more efficient than gasoline engines, even after accounting for the energy content differences. GHG emissions for the pyrolysis fuels reference case are 53% lower than conventional gasoline GHG emissions in 2005 (0.30 kg CO_2-equiv. per kilometer) based on U.S. LCI and GREET data [23, 26]. The NEV is 1.12 MJ per km for gasoline and 0.93 MJ per km for diesel, both higher than the NEV for gasoline of -1.2 MJ per km in 2005.

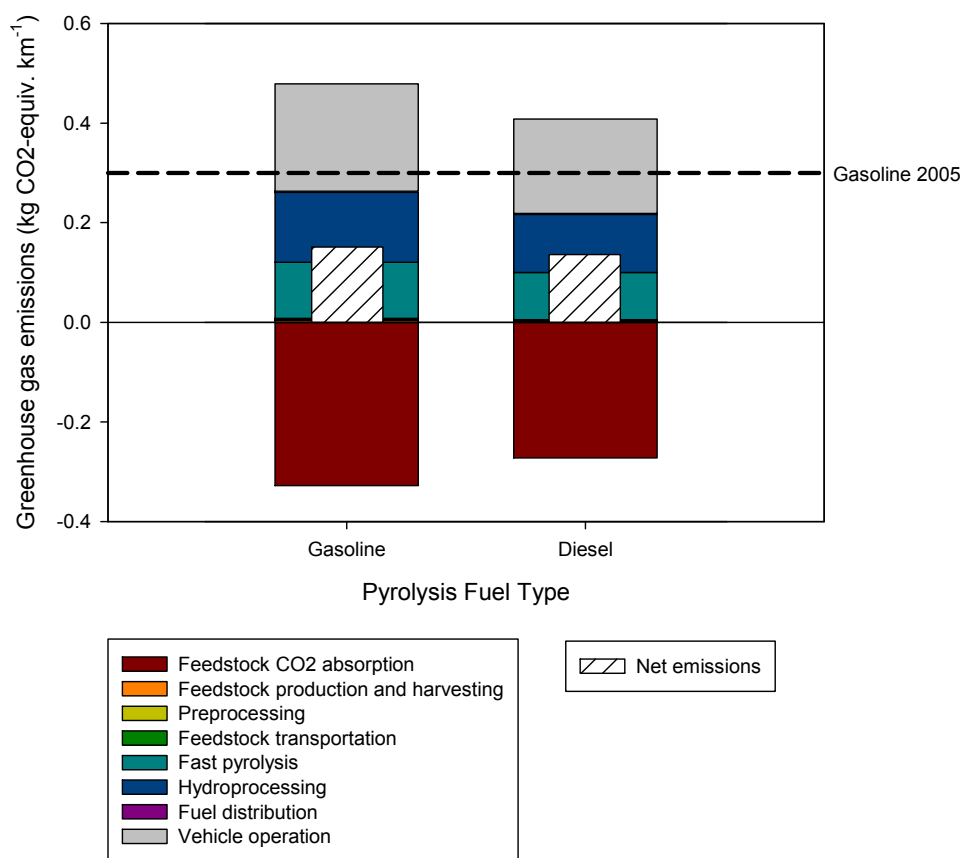**Figure 1. GHG emissions for a U.S. passenger car propelled 1 km using pyrolysis fuel. The stacked bar depicts the contribution from each life cycle stage. The bar inset in the stacked bar represents net life cycle GHG emissions (the result after summing the absorption of CO_2 with the process stages). The dashed line represents 1 km traveled by a U.S. passenger car using conventional gasoline in 2005.**

In a previous study [3], the forest residue feedstock was converted through gasification to ethanol and mixed alcohols based on the Phillips et al. design report [22]. The GHG emissions total based on 1 km traveled on E85 from that process is 0.13 kg CO_2-equivalent per km and the NEV is 1.58 MJ per km.[2] However, these LCA results also include the GHG emissions and NEV related to the gasoline portion of E85. When converted to a 1 MJ of ethanol basis, the GHG emissions results are 0.030 kg CO_2-equivalent per MJ of fuel and the NEV results are 0.88 MJ per MJ of fuel. These values can be directly compared to the pyrolysis results (Table 2).

Table 2. GHG and NEV Results for Pyrolysis and Gasification Biofuels
Reported per 1 MJ of fuel produced; diesel's lower heating value is not adjusted for greater engine efficiency

	GHG (kg CO_2-equiv. per MJ fuel)	NEV (MJ per MJ fuel)
Pyrolysis gasoline	0.049	0.38
Pyrolysis diesel	0.054	0.38
Pyrolysis gasoline with biomass-derived electricity (estimated)	0.035	0.56
Pyrolysis diesel with biomass-derived electricity (estimated)	0.040	0.61
Ethanol via gasification	0.030	0.88

Table 2 shows that pyrolysis gasoline has slightly fewer GHG emissions than pyrolysis diesel on a per MJ fuel basis. However, because a diesel engine is more efficient, fewer megajoules of diesel than of gasoline are needed for one kilometer of travel. The results using biomass-derived electricity are estimated.

Electricity use accounts for 27% of the net GHG emissions, and fossil-based hydrogen accounts for 6% of the GHG emissions. Both electricity and hydrogen could be produced from the biomass and/or bio-oil, but this would come at a loss to the fuel yield. Based on Wright et al. [11], supplying hydrogen internally would result in a 40% drop in fuel yield (electricity was still imported from the grid in the hydrogen purchase scenario). The electricity demand (24,600 kWh per hour) can be satisfied by a biomass boiler. Assuming an efficiency of 20% on an HHV basis (in the middle of the range given by Robinson et al. [27]) and an HHV of 8,405 Btu/lb (19.55 MJ/kg) [28] for hybrid poplar, the electricity demand can be satisfied by 1.1% of the incoming biomass. The decreased GHG emissions savings from the slightly lower fuel yield are more than offset by the GHG emissions savings from not using fossil-based electricity. For the calculations in this report, the results from a biomass-derived electricity scenario are calculated by assuming that the fuel yield is reduced by 1.1% and that there are no net emissions from electricity generation. The result is 0.104 kg CO_2-equiv. per kilometer traveled—roughly 65% better than gasoline emissions in 2005. While producing electricity from biomass may be technically

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[2] These values differ from what was reported in Hsu et al. [3]. In that paper, the carbon dioxide in the conversion process was calculated using the regression equations. In this analysis, the carbon dioxide is calculated by difference for a fair comparison to pyrolysis. In addition to this change, a few corrections were made to the ethanol LCA model.

feasible, the economics are not considered in this study. Reducing electricity usage through optimization of drying, grinding, and other process areas is also an area of research.

In Table 2, pyrolysis fuels show higher GHG emissions and lower NEV than cellulosic ethanol from the same feedstock does, despite the pyrolysis fuels generating 41% more kilometers traveled than the high-blend E85 with cellulosic ethanol from the same mass of forest residues does. The conversion stage is more energy- and GHG-intensive in pyrolysis than in gasification because fossil energy is used in the pyrolysis process (Figure 2) while the gasification process design requires no fossil energy inputs. In pyrolysis, electricity is imported from the grid and natural gas is used to produce hydrogen needed for hydroprocessing. While input fossil energy in the hydroprocessing step dwarfs that in the fast pyrolysis step (Figure 2), the GHG emissions differences are not as dramatic (Figure 1) because the production of hydrogen from natural gas is not as GHG emissions-intensive as the production of electricity is in the United States. The gap between NEV for pyrolysis fuels and ethanol via gasification is reduced by using biomass-derived electricity. The use of hydrogen produced from natural gas accounts for part of the remaining difference in NEV between the gasification and pyrolysis processes.
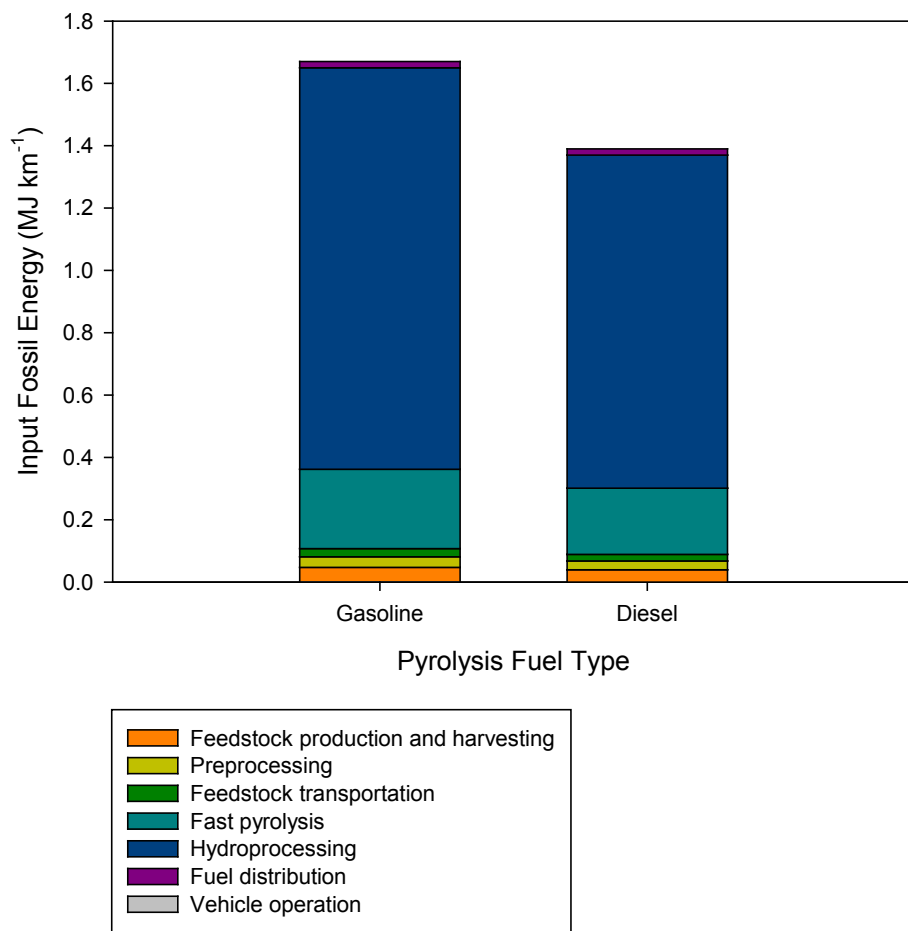
Figure 2. Input fossil energy projected for a U.S. passenger car propelled 1 km using pyrolysis fuel. The stacked bar depicts the contribution from each life cycle stage. Conventional gasoline in 2005 requires 4.5 MJ per kilometer traveled.

Uncertainty Analysis

As shown in Figure 3 and Figure 4, the reference case result is near the outside 25th percentile of the GHG emissions and NEV distributions. The results are sensitive to the PDFs assumed, and the pyrolysis-specific input parameters all have skewed triangular distributions. The offset of the reference case from the median of the Monte Carlo analysis is a result of the fuel yield PDF. If the fuel yield is set to the median value of the PDF (387 L/dry tonne) rather than the maximum/mode of the PDF (417 L/dry tonne [same as with the reference case]), then the GHG emissions and NEV equal that of the median distribution. The forest residue feedstock, in a previous work, showed minimal skewness related to feedstock production and preprocessing [3]. Pyrolysis of biomass for fuels has been less well studied than gasification, and the greater uncertainty range around fuel yield contributes to the more skewed uncertainty distribution.

Figure 3. Boxplot of the Monte Carlo uncertainty results for field-to-wheels, projected greenhouse gas emissions for a U.S. passenger car in 2022 using fuels from pyrolysis. The reference case scenario (red line) is computed based on the mode of the distribution for each input parameter. The edges of the boxes represent the 25th and 75th percentiles of the distribution. The whiskers represent the 10th and 90th percentiles. The circles represent the 5th and 95th percentiles. The mean of the output distribution is represented by a blue dashed line and the median is represented by a solid line within the box.
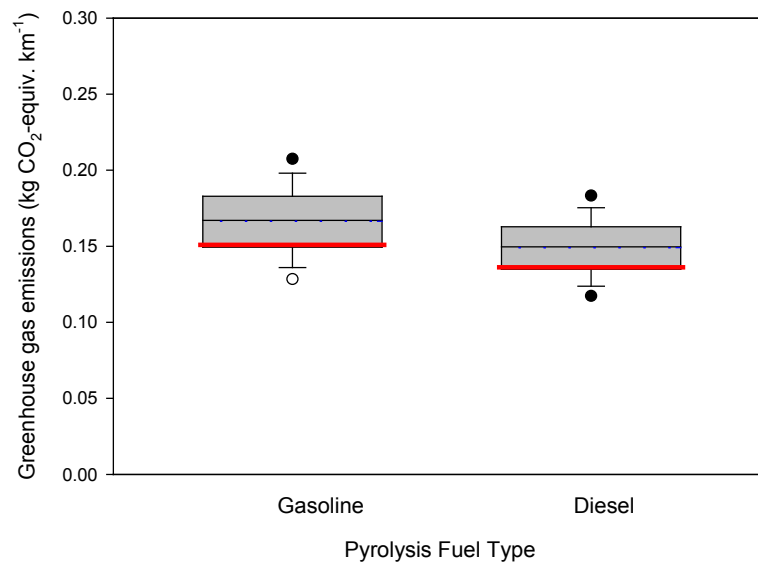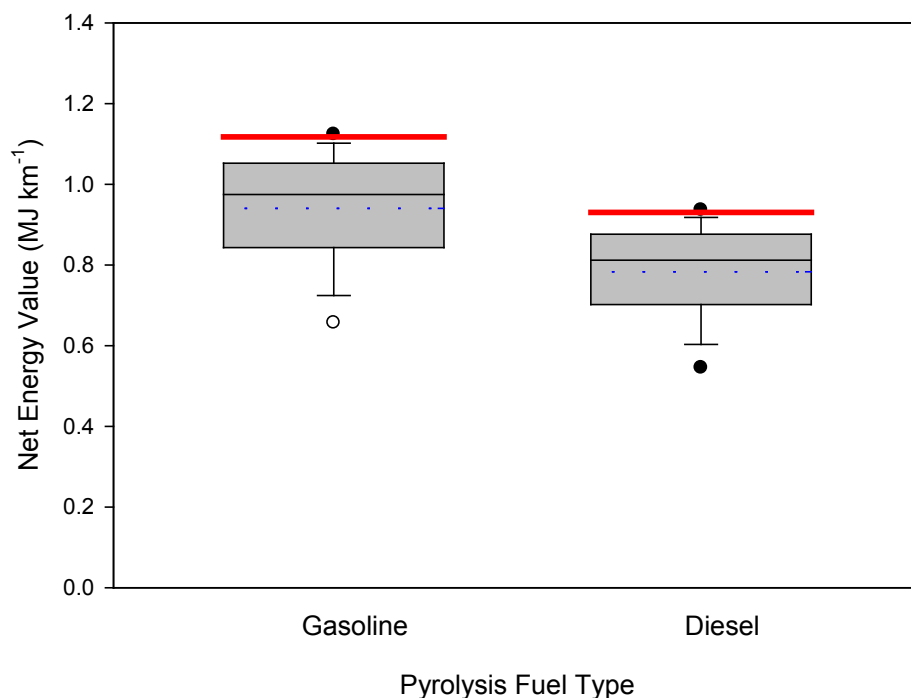
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Figure 4. Boxplot of the Monte Carlo uncertainty results for field-to-wheels, projected net energy value for a U.S. passenger car in 2022 using fuels from pyrolysis. The reference case scenario (red line) is computed based on the mode of the distribution for each input parameter. The edges of the boxes represent the 25th and 75th percentiles of the distribution. The whiskers represent the 10th and 90th percentiles. The circles represent the 5th and 95th percentiles. The mean of the output distribution is represented by a blue dashed line and the median is represented by a solid line within the box.

Conclusions

An LCA of gasoline and diesel produced through fast pyrolysis of forest residues followed by hydrotreating and hydrocracking results in GHG emissions of 0.142 kg CO_2-equiv. per km and an NEV of 1.00 MJ per km for a process using grid electricity based on the PNNL design report. Monte Carlo uncertainty analysis shows a range of results, with all values better than those of conventional gasoline in 2005. The median values are higher than the reference case values as a result of the skewed input distribution used for fuel yield. Further research to achieve the targeted fuel yields is needed to reduce the uncertainty of the GHG and NEV results.

Although pyrolysis-derived gasoline and diesel have lower GHG emissions and higher NEV than conventional gasoline does in 2005, they underperform ethanol produced via gasification from the same feedstock. GHG emissions for pyrolysis could be lowered further if electricity and hydrogen are produced from biomass instead of from fossil sources, as long as the fuel yield does not fall to offset the GHG savings. Based on a pyrolysis process using biomass-derived electricity, the GHG emissions are 0.104 kg CO_2-equiv. per km traveled coming from the mix of

renewable gasoline and diesel produced through pyrolysis and the NEV is 1.60 MJ per km traveled. Future revisions to the pyrolysis and upgrading design report scheduled for the 2012/2013 time frame (per the MYPP) will benefit from techno-economics coupled with life cycle analysis.

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Appendix

Table A-1. Distributional Characteristics of Monte Carlo Uncertainty Analysis Results
Field-to-wheels projected greenhouse gas emissions and net energy value for a U.S. passenger car in 2022 using fuels produced via pyrolysis and hydroprocessing

	Greenhouse gas emissions (kg CO_2-eq per km)			Net energy value (MJ per km)		
	Gasoline and diesel	Gasoline	Diesel	Gasoline and diesel	Gasoline	Diesel
Reference case	0.142	0.151	0.136	1.00	1.12	0.93
Mean	0.156	0.166	0.149	0.84	0.94	0.78
Standard deviation	0.022	0.025	0.020	0.13	0.15	0.12
Median	0.156	0.167	0.150	0.87	0.97	0.81
5%	0.122	0.128	0.117	0.58	0.66	0.55
10%	0.129	0.136	0.124	0.64	0.72	0.60
25%	0.141	0.149	0.135	0.75	0.84	0.70
75%	0.171	0.183	0.163	0.94	1.05	0.88
90%	0.185	0.198	0.175	0.99	1.10	0.92
95%	0.193	0.207	0.183	1.01	1.12	0.94

Scenarios run for fast pyrolysis and hydroprocessing in order to determine regression equations

Percentages displayed show the difference from the default value used in the Jones et al. design report [10]. Linear regressions are developed for the results of these runs to facilitate Monte Carlo uncertainty analysis.

Fast pyrolysis
Bio-oil yield: -10%, -20%

Water yield: -20%, +20%

Char yield: +20%

Gas yield: +20%

Hydroprocessing
Gas yield: -50%, -20%, +20%, +50%

Oil yield: -20%, +10%

Table A-2. Fast Pyrolysis Input-Output Table
Functional unit: Mass of bio-oil produced

Name	Amount	Unit	Reference
Outputs: products and coproducts			
Bio-oil (from wood via pyrolysis)	152,000	lb	
Resources			
Water, process, unspecified natural origin/kg	6,000	lb	Quench water (Stream 160)
Air	350,000	lb	Stream 120
Water, cooling, unspecified natural origin/kg	180,000	lb	Cooling water makeup. Sum of losses from Stream 1810. Result based on regression from several CHEMCAD runs.
Water, unspecified natural origin/kg	84,800	lb	This is not "real" water, but included to make the simulation correct. Basically this is the moisture content of the feed difference between the design report and what we use here.
Materials and fuels			
Preprocessed residue, at conversion facility (inc)	283,000	lb	Stream 100. Adjusted for the difference in moisture content compared to the design report value of 50%.
Electricity, medium voltage, at grid/US with US electricity U	12,000	kWh	
Hydrochloric acid, 30% in H_2O, at plant/RER with US electricity U	0.667	lb	Boiler chemicals
Sodium hydroxide, 50% in H_2O, production mix, at plant/RER with US electricity U	0.667	lb	Boiler chemicals
Sulphite, at plant/RER with US electricity U	0.667	lb	Boiler chemicals
Chemicals, inorganic, at plant/GLO with US electricity U	1	lb	Cooling tower chemicals
Thermochemical conversion plant	5.95E-06	p	
Indirect heated, heated zones, softwood, plywood veneer drying, AP-42	184,000	lb	Stream 106. Use plywood drying as approximation. Mass is oven-dried wood mass.
Lignite combustion, cyclone, uncontrolled, AP-42	14,800	lb	No non-CO_2 GHGs. Just PM and criteria air pollutants. This is what's sent to char combustion.
Emissions to air			
Oxygen	24,400	lb	Stream 105. Based on regression from CHEMCAD runs.

Nitrogen	270,000	lb	Stream 105. Based on regression. Low R squared.
Water	180,000	lb	Stream 105. Based on regression from CHEMCAD runs.
Hydrogen	2.01	lb	Stream 105. Based on regression.
Carbon monoxide, biogenic	504	lb	Stream 105. Based on regression.
Carbon dioxide, biogenic	88,100	lb	Stream 105. Based on regression from CHEMCAD runs.
Water	128,000	lb	CWS evaporation rate. Based on design case spreadsheet from PNNL. 15 degree temperature rise * 0.085% evap loss in circulation rate.
Water	20,100	lb	CWS drift loss. Based on design case spreadsheet from PNNL. 0.20% drift loss.
Water	32,000	lb	CWS blowdown. Based on design case spreadsheet from PNNL. Evaporative loss divided by one less than the number of cycles (5).
Water	1,200	lb	Stream 161 (water fraction evaporated, not to treatment)
Waste to treatment			
Disposal, wood ash mixture, pure, 0% water, to sanitary landfill/CH with US electricity U	3,600	lb	Stream 161 (ash)
Treatment, sewage, unpolluted, to wastewater treatment, class 3/CH with US electricity U	2.18	m^3	Stream 161 (Assumes water and ash separated and treated. No separation energy, but not all of the water would necessarily need to go to treatment.)

Table A-3. Hydroprocessing and Steam Reforming Input-Output Table
Functional unit: Mass of gasoline and diesel produced

Name	Amount	Unit	Reference
Outputs: products and coproducts			
Gasoline (from bio-oil via upgrading)	28,600	lb	
Diesel (from bio-oil via upgrading)	38,400	lb	
Resources			
Water, cooling, unspecified natural origin/kg	6,070	lb	Cooling tower makeup water. Sum of all the losses from streams 1820, 1850, 790.
Water, unspecified natural origin/kg	56,400	lb	Boiler feed water makeup. Stream 700.
Air	230,000	lb	Air in upgrading. Stream 610.
Materials and fuels			
Natural gas, high pressure, at consumer/RER with US electricity U	374,000	MJ	Calculating the MJ from lb of natural gas based on the SimaPro process (natural gas, production mix, at service station). Calculation converts the natural gas to kg then multiplies by the MJ/kg just for high pressure.
Zeolite, powder, at plant/RER with US electricity U	85	lb	Hydrogenation catalyst
Zeolite, powder, at plant/RER with US electricity U	0.371	lb	Hydrocracking catalyst
Zeolite, powder, at plant/RER with US electricity U	3.27	lb	Hydrogen catalyst
Electricity, medium voltage, at grid/US U	12,600	kWh	
Bio-oil (from wood via pyrolysis)	152,000	lb	Stream 200
Refinery/RER/I with US electricity U	3.3E-06	p	
Emissions to air			
Water	29,000	lb	Stream 630. Most numbers are around design report value. For regression, had to use bio-oil, fuel LHV, cross term, and gasoline to get a decent regression fit.
Nitrogen	176,000	lb	Stream 630
Oxygen	9,740	lb	Stream 630. Used design report value. Regression fit was not very good.
Water	68.3	lb	Stream 602. Equation based on regression of several CHEMCAD runs.
Hydrogen	123	lb	Stream 602. Equation based on regression of several CHEMCAD runs.
Carbon dioxide,	1,750	lb	Stream 602. Equation based on regression of several

biogenic			CHEMCAD runs.
Methane, biogenic	671	lb	Stream 602. Equation based on regression of several CHEMCAD runs.
Ethane	402	lb	Stream 602. Equation based on regression of several CHEMCAD runs.
Propane	339	lb	Stream 602. Equation based on regression of several CHEMCAD runs.
Isobutane	301	lb	Stream 602. Equation based on regression of several CHEMCAD runs.
Heptane	376	lb	Stream 602. Equation based on regression of several CHEMCAD runs.
Cyclohexane, propyl-	7.24	lb	Stream 602, 1-ts-35-3C1cycC6 in CHEMCAD. Equation based on regression of several CHEMCAD runs.
Hydrocarbons, aliphatic, alkanes, unspecified	1.52	lb	Stream 602, 3,3,5-TriMth-C7 in CHEMCAD. Equation based on regression of several CHEMCAD runs.
Hydrocarbons, alkanes, cyclo-, C6	2.87	lb	Stream 602, N-PropylCyc-C6 in CHEMCAD. Equation based on regression of several CHEMCAD runs.
Xylene	1.08	lb	Stream 602
Water	6,070	lb	Cooling water losses from stream 1820
Water	341	lb	Cooling water losses from stream 1850
Water	-345	lb	Stream 790 (blowdown). This is negative because it's being condensed and used as cooling water.
Carbon dioxide, biogenic	83,900	lb	Stream 630. Done by difference.

Table A-4. Operation of a Car, Fueled by Gasoline from Pyrolysis, Input-Output Table
Functional unit: 1 mile traveled

Name	Amount	Unit	Reference
Outputs: products and coproducts			
Car operation, gasoline from pyrolysis, 2022	1	mile	Passenger car, as defined by GREET1.8c; 2020 is the simulation year.
Materials and fuels			
Gasoline, from pyrolysis, at regional storage/US U	0.112	kg	kg conventional gasoline per mile traveled. Fuel economy per GREET 1.8c MPG (25.4 mile per gallon in 2022), converted to kg using 2.835 kg per gallon, which itself is based on density of gasoline as 6.25 lb per gallon (mid point of range from here: Table 6.6, Transportation Energy Data Book, http://cta.ornl.gov/data/tedb27/Edition27_Chapter06.pdf).
Emissions to air			
Carbon dioxide, biogenic	343	g	g/mile based on GREET 1.8c results in 2020, which include accounting for new CAFE. Gasoline vehicles: CG and RFG
Methane, biogenic	0.01	g	g/mile based on GREET 1.8c results, which include accounting for new CAFE.
Dinitrogen monoxide	0.012	g	g/mile based on GREET 1.8c results, which include accounting for new CAFE.
VOC, volatile organic compounds	0.151	g	g/mile based on GREET 1.8c results, which include accounting for new CAFE.
Carbon monoxide, biogenic	3.482	g	g/mile based on GREET 1.8c results, which include accounting for new CAFE.
Nitrogen oxides	0.069	g	g/mile based on GREET 1.8c results, which include accounting for new CAFE.
Particulates, < 10 µm	0.029	g	g/mile based on GREET 1.8c results, which include accounting for new CAFE.
Particulates, < 2.5 µm	0.014	g	g/mile based on GREET 1.8c results, which include accounting for new CAFE.
Sulfur oxides	0.006	g	g/mile based on GREET 1.8c results, which include accounting for new CAFE.

Table A-5. Operation of a Car, Fueled by Diesel from Pyrolysis, Input-Output Table
Functional unit: 1 mile traveled

Name	Amount	Unit	Reference
Outputs: products and coproducts			
Car operation, diesel from pyrolysis, 2022	1	mile	Passenger car, as defined by GREET 1.8c; 2020 is the simulation year.
Materials and fuels			
Diesel, from pyrolysis, at regional storage with US electricity U	0.0944	kg	kg conventional diesel per mile traveled. Fuel economy per GREET 1.8c MPG (30.5 mile per gallon gasoline equivalent in 2022, scaled to gallons of diesel) converted to kg using 3.167 kg per gallon.
Emissions to air			
Carbon dioxide, biogenic	302	g	g/mile based on GREET 1.8c results in 2020, which include accounting for new CAFE. Vehicles tab. CIDI vehicle: conventional and LS diesel.
Methane, biogenic	0.00308	g	g/mile based on GREET 1.8c results, which include accounting for new CAFE.
Dinitrogen monoxide	0.0123	g	g/mile based on GREET 1.8c results, which include accounting for new CAFE.
VOC, volatile organic compounds	0.0616	g	g/mile based on GREET 1.8c results, which include accounting for new CAFE.
Carbon monoxide, biogenic	0.548	g	g/mile based on GREET 1.8c results, which include accounting for new CAFE.
Nitrogen oxides	0.0822	g	g/mile based on GREET 1.8c results, which include accounting for new CAFE.
Particulates, < 10 µm	0.0308	g	g/mile based on GREET 1.8c results, which include accounting for new CAFE.
Particulates, < 2.5 µm	0.0154	g	g/mile based on GREET 1.8c results, which include accounting for new CAFE.
Sulfur oxides	0.00205	g	g/mile based on GREET 1.8c results, which include accounting for new CAFE.

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14. ABSTRACT (Maximum 200 Words)
In this work, a life cycle assessment (LCA) estimating greenhouse gas (GHG) emissions and net energy value (NEV) of the production of gasoline and diesel from forest residues via fast pyrolysis and hydroprocessing, from production of the feedstock to end use of the fuel in a vehicle, is performed. The fast pyrolysis and hydrotreating and hydrocracking processes are based on a Pacific Northwest National Laboratory (PNNL) design report. The LCA results show GHG emissions of 0.142 kg CO2-equiv. per km traveled and NEV of 1.00 MJ per km traveled for a process using grid electricity. Monte Carlo uncertainty analysis shows a range of results, with all values better than those of conventional gasoline in 2005. Results for GHG emissions and NEV of gasoline and diesel from pyrolysis are also reported on a per MJ fuel basis for comparison with ethanol produced via gasification. Although pyrolysis-derived gasoline and diesel have lower GHG emissions and higher NEV than conventional gasoline does in 2005, they underperform ethanol produced via gasification from the same feedstock. GHG emissions for pyrolysis could be lowered further if electricity and hydrogen are produced from biomass instead of from fossil sources.

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