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Life cycle assessment of gasoline and diesel produced via fast pyrolysis and hydroprocessing

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ABSTRACT

Pyrolysis of biomass followed by hydroprocessing may provide infrastructure-compatible transportation fuels. In this work, a life cycle assessment (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 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 are assumed for parameters involved in the pyrolysis process for Monte Carlo uncertainty analysis.

This 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. Gasoline and diesel produced via pyrolysis are estimated to have greenhouse gas (GHG) emissions of CO_2 equivalent of 117 g km^{-1} and 98 g km^{-1}, respectively, and net energy value (NEV) of 1.09 MJ km^{-1} and 0.92 MJ km^{-1}, respectively. All values from the uncertainty analysis have lower GHG emissions and higher NEV than conventional gasoline in 2005. Grid electricity and natural gas used account for 81% of the net GHG emissions in the base case. An evaluation of a case with biomass-derived electricity shows significant improvement in GHG emissions.

1. Introduction

Because of recent efforts of nations to increase energy independence and curb climate change, more attention and resources have been devoted to the research and production of cellulosic biofuels. For example, in the United States, the Energy Independence and Security Act (EISA) of 2007 mandated a renewable fuel standard that set a production target of 136 hm^3 of biofuels by 2022 [1]. Of that total in 2022, 76 hm^3 are not restricted to a specific type of fuel such as ethanol or biodiesel.

Ethanol currently is produced commercially from sugar cane or starch sources such as corn grain and blended into gasoline. According to the U.S. Congressional Budget Office,

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Abbreviations: CO_2, carbon dioxide; CIDI, compression ignition direct injection; d, day; DOE OBP, U.S. Department of Energy Office of the Biomass Program; EISA, Energy Independence and Security Act of 2007; EPA, U.S. Environmental Protection Agency; FFV, flexible-fuel vehicle; GHG, greenhouse gas; h, hour; HHV, higher heating value; LCA, life cycle assessment; NEV, net energy value; NREL, National Renewable Energy Laboratory; PDF, probability distribution function; PNNL, Pacific Northwest National Laboratory; LCI, life cycle inventory.

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40.9 hm^3 of corn ethanol were produced in the United States in 2009 [2]. Ethanol production, from both corn and cellulosic sources, emits fewer greenhouse gases (GHGs) and has a higher net energy value (NEV) than gasoline [3–7]. However, ethanol suffers from several disadvantages. Ethanol in the United States can be blended at levels of up to a volume fraction of 85% 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 U.S. Environmental Protection Agency (EPA) is a volume fraction of 10%. The EPA recently granted a waiver to approve raising the maximum blend level of ethanol to a volume fraction of 15% 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 citing possible engine damage [9]. An infrastructure-compatible biofuel that is fungible with 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–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 (PNNL) has shown that for an “nth plant,” the minimum fuel selling price is \$0.53 l^{-1} of fuel (2007 dollar basis) [10]. A similar study by ConocoPhillips, Iowa State University, and the National Renewable Energy Laboratory (NREL) showed that an “nth 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 \$0.5 l^{-1} of gasoline equivalent (2007 dollar basis) [11,12], which is lower than fuel product values from comparable studies on cellulosic ethanol via a biochemical pathway [13] and gasoline/diesel via biomass gasification followed by Fischer-Tropsch catalysis [14]. In addition to the competitive fuel prices, pyrolysis may have additional capital cost savings by potentially using existing petroleum refinery infrastructure for hydrotreating and hydrocracking [15].

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. In order to improve energy independence and reduce climate change, biofuels will have to reduce GHG emissions compared to gasoline and generate a positive NEV. EISA legislation set biofuel GHG emissions requirements in comparison to conventional fuel emissions in 2005 [1]. In addition, the European Union set GHG emissions requirements for biofuels to qualify under its Renewable Energy Directive [17]. 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, results from Monte Carlo uncertainty analysis are presented.

2. Methods

The LCA modeling approach follows the methodology described in Hsu et al. [3]. SimaPro v.7.3 LCA modeling software [18] is used to develop and link primary unit processes. Ecoinvent v.2.2 [19] provides most of the life cycle inventories (LCIs) for secondary materials and energy required in those primary unit processes. This study follows the International Organization for Standardization standards for LCAs [20,21].

This study is based in the year 2022, and 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 the results are not indicative of any region of the United States, 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 [3,22], 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 [23]. The forest residues are chipped at the landing using standard industrial chipping equipment and then transported to the biorefinery.

2.1. *Pyrolysis and hydroprocessing*

The pyrolysis of biomass to bio-oil and the subsequent hydroprocessing of bio-oil to transportation fuel are based on the PNNL design report by Jones et al. [10] and the associated CHEMCAD [24] models and spreadsheets. The design report describes an “nth plant” with the capacity to process 2 kt d^{-1} of bone dry hybrid poplar, and the report targets a case demonstrated in 2015–2017. This design case is assumed to be the average plant commercially available in 2022. The design case uses electricity from the U.S. grid. A scenario based on biomass-derived electricity is not run explicitly in CHEMCAD,