



# Life cycle analysis of fuel production from fast pyrolysis of biomass



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## HIGHLIGHTS

- ▶ Pyrolysis gasoline can reduce WTW GHG emissions by over 60% to petroleum gasoline.
- ▶ A tradeoff between fuel yields and GHG reductions by H<sub>2</sub> source were observed.
- ▶ Probability distribution functions for key parameters were developed.
- ▶ H<sub>2</sub> source and biochar usage make statistically significant GHG emissions changes.
- ▶ Highly uncertain biochar characteristics affect the WTW results significantly.

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## ABSTRACT

A well-to-wheels (WTW) analysis of pyrolysis-based gasoline was conducted and compared with petroleum gasoline. To address the variation and uncertainty in the pyrolysis pathways, probability distributions for key parameters were developed with data from literature. The impacts of two different hydrogen sources for pyrolysis oil upgrading and of two bio-char co-product applications were investigated. Reforming fuel gas/natural gas for H<sub>2</sub> reduces WTW GHG emissions by 60% (range of 55–64%) compared to the mean of petroleum fuels. Reforming pyrolysis oil for H<sub>2</sub> increases the WTW GHG emissions reduction up to 112% (range of 97–126%), but reduces petroleum savings per unit of biomass used due to the dramatic decline in the liquid fuel yield. Thus, the hydrogen source causes a trade-off between GHG reduction per unit fuel output and petroleum displacement per unit biomass used. Soil application of biochar could provide significant carbon sequestration with large uncertainty.

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## 1. Introduction

As the global population and economy continue to grow, so too, will the demand for energy. According to the Energy Information Administration (EIA) of the US Department of Energy (DOE), the worldwide transportation sector has been relying overwhelmingly on petroleum, consuming more than 50% of global world oil production (US EIA, 2011). In terms of demand, the United States is the top oil-importing country. Two major issues facing the transportation sector in the United States, as well as in other major countries, are energy security and environmental sustainability. The United States imported about 49% of the crude oil and refined petroleum products consumed during 2010 (US EIA, 2012). Moreover, according to the US Environmental Protection Agency (US EPA, 2011), greenhouse gas (GHG) emissions from the transporta-

tion sector represent about 26% of US total GHG emissions. To address these issues, the Energy Independence and Security Act of 2007 (EISA) mandated the production of 79 billion liters of advanced biofuels (whose life-cycle GHG emissions reduction exceeds 50% relative to the total life-cycle emissions of the corresponding baseline petroleum fuel) and the production of 57 billion liters of conventional biofuels (whose life-cycle GHG emissions are no more than 80% that of baseline petroleum fuel) by 2022 (US Congress, 2007).

Liquid fuel from the upgrading of pyrolysis oil is a mixture of naphtha-range products (gasoline blend stock) and diesel-range products (diesel blend stock). Unlike ethanol, pyrolysis-derived diesel and gasoline fuels do not have compatibility issues with existing fuel distribution infrastructure and present-day vehicle technologies. These fuels could play an important role in biofuel production. Fast pyrolysis is performed under a range of temperatures and short residence times in the reactor to maximize the pyrolysis bio-oil yield. This process contrasts with the much slower gasification process, which provides a high yield of synthesis gas that can be converted into liquid fuel (e.g., via the Fischer–Tropsch [FT] process). Liquid fuel production via the fast pyrolysis of biomass is described in numerous sources. Excellent and extensive

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reviews of the fast pyrolysis of biomass and product upgrading are presented by Mohan et al. (2006), Butler et al. (2011) and Bridgwater (2012). Bulushev and Ross (2011) reviewed and compared catalytic conversion processes for biomass, such as pyrolysis, gasification, hydrotreating, hydrocracking, and esterification.

The energy and GHG emissions benefits of the fast-pyrolysis-based liquid fuels compared with those from the use of conventional petroleum fuels can be assessed through a life-cycle analysis (LCA) where energy and emissions burdens in all the stages of a product's life, from the extraction of raw materials through the materials' processing, manufacturing, distribution, use, and disposal or recycling are taken into account. The literature contains several LCA studies on pyrolysis-based pathways. The study of Roberts et al. (2010) was based on slow pyrolysis of various biomasses that did not produce liquid fuels. The process rather produced biochar for soil application with heat and electricity as co-products. The study showed that pyrolysis of 1 tonne of biomass could generate 3.0–4.8 GJ of net energy and sequester 0.0–0.9 tonne of net GHG emissions. The net energy generation resulted from syngas combustion while most of the carbon sequestration resulted from biochar application to soil. On the other hand, the study of Kauffman et al. (2011) relied on a techno-economic analysis of the fast pyrolysis of corn stover to produce liquid fuels conducted by Wright et al. (2010). The study concluded the net GHG emissions from pyrolysis of one tonne of corn stover would be  $-0.5$  tonne  $\text{CO}_2\text{e}$ . Hsu (2011) provided the LCA results per unit output (e.g., MJ of liquid fuel output or vehicle km traveled). His analysis was based on a study of the fast pyrolysis of forest residue (Jones et al., 2009), and found that pyrolysis gasoline can reduce GHG emissions by 53% relative to those from petroleum gasoline. In the design by Jones et al. (2009), all co-produced biochar is consumed to satisfy the process heating requirements and is therefore not used for electricity generation or for soil application. Hsu also conducted an uncertainty analysis with a triangular distribution for liquid fuel yields.

Previous studies have examined several process options in the fast pyrolysis of biomass such as biomass type, pyrolysis oil yield, hydrogen demand and sources, and liquid fuel yield. However, the impacts of these options on LCA results have yet to be addressed systematically and quantitatively. In particular, uncertainty and variability in these parameters are largely unaddressed in the literature and merit exploration. Since these parametric uncertainties propagate through LCA calculations, stochastic modeling and analysis are critical to assess the bounds of potential energy and emissions benefits of pyrolysis-based fuels on a life-cycle basis. To this end, this study develops distribution functions for the key parameters in the pyrolysis pathways based on an extensive review of the literature. Then, we use the Greenhouse gases, Regulated Emissions and Energy use in Transportation (GREET) model and its stochastic simulation toolkit to examine the upper- and lower-bounds of the life-cycle energy and GHG emissions of pyrolysis-based fuels, which are subsequently compared with petroleum fuels. GREET, developed by Argonne National Laboratory with the support of several programs in DOE's Office of Energy Efficiency and Renewable Energy (EERE), is structured to systematically examine the life-cycle energy use and emissions associated with a wide range of vehicle technologies and feedstock sources for producing alternative fuels (Argonne National Laboratory, 2012).

## 2. Methods

### 2.1. Pyrolysis-based pathway description

Well-to-Wheels (WTW) analysis is an LCA applied to transportation fuels for use in vehicles covering feedstock recovery and

transportation, fuel production and transportation, and fuel consumption by vehicles. For example, the WTW pathway for pyrolysis-based gasoline and diesel (shown in Fig. 1) includes fertilizer production, biomass collection and transportation, pyrolysis of biomass, hydrotreating and upgrading of pyrolysis oil to gasoline and diesel, and transportation and distribution of gasoline and diesel to refueling stations (pump) as well as fuel consumption during vehicle operation. The feedstock development activities leading to the fuel production and transportation activities constitute the well-to-pump (WTP) stage. The combustion of fuel for vehicle operation constitutes the pump-to-wheels (PTW) stage. The combination of these two stages constitutes the WTW cycle.

To develop the baseline pathways for pyrolysis-based fuels, we relied on two process design cases characterizing the pyrolysis reaction and the subsequent stabilization and upgrading (Jones et al., 2009; Wright et al., 2010). The fast pyrolysis processes designed by Wright et al. (2010) and Jones et al. (2009) used corn stover and forest residue, respectively, as feedstock for liquid fuel production. The feedstock type and reactor design influence the pyrolysis product yields and composition. Another major difference between the two studies is the  $\text{H}_2$  source: the process by Wright et al. (2010) reformed pyrolysis oil while that by Jones et al. (2009) reformed fuel gas and natural gas (NG) for  $\text{H}_2$  production. The  $\text{H}_2$  source impacts liquid fuel yields, fossil fuel demand and co-product yields (Han et al., 2011). The co-product yield and usage in the above two design cases are also different. All co-products (biochar and fuel gas) in Jones et al. (2009) are consumed internally to provide process heat and  $\text{H}_2$  while a fraction of fuel gas and biochar are available for export in Wright et al. (2010).

This study develops and investigates three pathways: (1) a pathway with fuel gas/NG reforming for  $\text{H}_2$  (denoted as FN), (2) a pathway with pyrolysis oil reforming for  $\text{H}_2$  and biochar combustion for electricity generation (denoted as PO-Elec), and (3) a pathway with pyrolysis oil reforming for  $\text{H}_2$  and biochar application to soil (denoted as PO-Soil). The FN pathway is based on the design case in Jones et al. (2009) while the two PO pathways are based on that in Wright et al. (2010). Following the original design cases, FN uses forest residue as feedstock while the two PO pathways use corn stover. Details of the scenarios are summarized in Table 1.

The design cases by Wright et al. (2010) and Jones et al. (2009) are intended for an integrated refinery scenario where pyrolysis, stabilization and upgrading processes are collocated. In addition to the integrated refinery scenario, Han et al. (2011) investigated a distributed pyrolysis scenarios (under which pyrolysis oil from distributed pyrolyzers is sent to a central refinery), and concluded that the difference between these two refinery scenarios had an insignificant impact on LCA results. Therefore, this study focuses on the integrated refinery scenario.

### 2.2. Biomass collection and transportation

Corn stover collection consumes diesel for windrowing, baling and transporting the stover to a roadside location in the field (Hess et al., 2009). On the other hand, forest residue collection includes separation of the residues from main forestry products (small round wood and saw logs), their removal residues from the forest, and their chipping, which also consume diesel (Elsayed et al., 2003). In our analysis, we assume that farmers replenish the nutrient content of harvested corn stover kg-per-kg with fertilizers (N,  $\text{P}_2\text{O}_5$ , and  $\text{K}_2\text{O}$ ) (Han et al., 2011). Whether the removal of forest residue adversely affects soil is an open question (Whittaker et al., 2011). We assume no supplemental nutrients are added to forests from which residue is removed. Biomass transportation includes both transporting biomass to pyrolysis facilities by truck and a backhaul travel.

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