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Techno-economic analysis of biomass to transportation fuels and electricity via fast pyrolysis and hydroprocessing

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HIGHLIGHTS

- ▶ We model an updated 2000 metric ton per day fast pyrolysis and hydroprocessing system.
- ▶ We incorporate recent commercialization and literature data on the pathway.
- ▶ We present the results of a techno-economic analysis of this system.
- ▶ We compare these results with those published in a 2010 Iowa State University study.

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ABSTRACT

A previous Iowa State University (ISU) analysis published in 2010 investigated the technical and economic feasibility of the fast pyrolysis and hydroprocessing of biomass, and concluded that the pathway could produce cellulosic biofuels for a minimum fuel selling price (MFSP) of \$2.11/gal. The 2010 ISU study was largely theoretical in that no commercial-scale fast pyrolysis facilities were being constructed at the time of publication.

The present analysis expands upon the 2010 ISU study by performing an updated techno-economic analysis of the fast pyrolysis and hydroprocessing pathway. Recent advances in pathway technology and commercialization and new parameters suggested by the recent literature are accounted for. The MFSP for a 2000 MTPD facility employing fast pyrolysis and hydroprocessing to convert corn stover to gasoline and diesel fuel is calculated to quantify the economic feasibility of the pathway.

The present analysis determines the MFSP of gasoline and diesel fuel produced via fast pyrolysis and hydroprocessing to be \$2.57/gal. This result indicates that the pathway could be competitive with petroleum, although not as competitive as suggested by the 2010 ISU study. The present analysis also demonstrates the sensitivity of the result to process assumptions.

1. Introduction

The Renewable Fuel Standard (RFS) was created in 2005 by Congress to mandate the domestic consumption of ethanol, particularly grain ethanol [1]. Concerns that the use of grains to produce ethanol was causing both rainforest destruction [2] and hunger in the developing world [3] led Congress to direct the Environmental Protection Agency (EPA) to revise the RFS in a manner that placed greater emphasis on cellulosic biofuels [4]. While grain ethanol production has had little difficulty meeting its share of the revised mandate (RFS2), cellulosic biofuels have fallen far short. The RFS2 initially mandated the production of 250 million gallons per year (MGY) of cellulosic biofuels in 2011, although no commercial-scale production occurred [5]. The RFS2 mandates the production of 16,000 MGY of cellulosic biofuels by 2022 [4].

In 2010 Iowa State University (ISU) researchers assessed the technical and economic feasibility of three different cellulosic biofuel pathways (cellulosic ethanol; gasification and Fischer–Tropsch synthesis; and fast pyrolysis and hydroprocessing) and identified fast pyrolysis (FP) and hydroprocessing as being the most economically feasible of the three [6–8]. Specifically, the researchers calculated the minimum fuel selling price (MFSP) of gasoline and diesel fuel produced via the pathway to be as low as \$2.11/gal. FP and hydroprocessing was the only one of the three pathways to attain a MFSP for an *n*th plant below \$4/gal gasoline-equivalent (gge) [9].

FP is a thermochemical pathway that uses heat to rapidly decompose lignocellulosic biomass into solid (char), gas (noncondensable gas, or NCG) and liquid (bio-oil). Char has potential value as both a cropland soil amendment [10] and carbon sequestration

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method [11] while NCG provides process heat to the FP facility. Bio-oil can serve as a feedstock for electricity generation [12] or production of ethanol [13], renewable gasoline and diesel fuel [14], and commodity chemicals [15]. Techno-economic analyses suggest that serving as a feedstock for the production of renewable hydrocarbon fuels and chemicals is the most economically-feasible use of bio-oil despite the substantially higher capital and operating costs involved, although this is sensitive to input costs and output values [8,16,17].

Raw bio-oil is corrosive, viscous, and highly oxygenated, characteristics that make it difficult to store, transport and refine without prior upgrading [18]. Upgrading can be accomplished via either fluid catalytic cracking (FCC) [19] or hydroprocessing [20]. For the purposes of the RFS2, hydroprocessing is more applicable because FCC yields alkenes and aromatics [15] while hydroprocessing yields alkanes and aromatics [20] more suitable for fuel blending. Hydroprocessing employs two steps: hydrotreating and hydrocracking. Hydrotreating reacts bio-oil with hydrogen (1.2–3.5 wt% on a bio-oil basis) in the presence of a catalyst and heat [21], removing heteronuclear atoms such as chlorine, nitrogen, oxygen and sulfur and reducing bio-oil's viscosity and corrosiveness [20]. Hydrocracking reacts the hydrotreated bio-oil with hydrogen in the presence of a catalyst under more severe reaction conditions, with the objective of achieving complete deoxygenation and inducing the depolymerization of the oligomeric species within the bio-oil into monomeric hydrocarbons that can be split and blended into gasoline and diesel fuels.

Transportation fuel yields from hydroprocessing of bio-oil are sensitive to a number of factors such as operating conditions and hydrogen consumption [20]. For this reason the yields reported in the literature vary. The first factor affecting fuel yields is the bio-oil yield from the FP reactor. Yields of 55–70 wt% on a biomass basis are typical [22], although yields above or below this range are not uncommon, depending on the kind of feedstock and reactor employed. The second factor affecting fuel yields is the volume of monomeric hydrocarbons yielded by hydrotreating and hydrocracking. This varies according to pyrolysis feedstock type, reactor operating conditions, and bio-oil fraction. Elliott et al. [20] report a range of 31.6–60.7 wt% (bio-oil basis) for five different bio-oils under identical hydroprocessor operating conditions.

Catalytic FP (CFP) combines FP and FCC upgrading processes into an integrated pathway. Pyrolysis occurs in the presence of a FCC or pure zeolite catalyst at moderate temperatures and high heating rates [23]. Bio-oil produced via CFP has a lower oxygen and higher aromatics content than that produced via FP as well as lower liquid and higher coke yields [24]. Bio-oil produced via CFP still contains oxygen requiring further upgrading via hydroprocessing to maximize transportation fuel yields. The advantage of CFP over FP as a step in the production of transportation fuels is that the resulting bio-oil is reported to have a lower oxygen content following hydroprocessing (5 wt%) than FP bio-oil following the same treatment (12.4 wt%) [25]. This suggests that the hydroprocessing of bio-oil produced via CFP will consume less hydrogen than bio-oil produced via FP.

CFP is being commercialized by KiOR, which completed an initial public offering in 2011 [26]. The company is currently constructing a 454 metric ton per day (MTPD) CFP and hydroprocessing facility in Columbus, Mississippi and plans to construct four 1361 MTPD facilities in Georgia, Mississippi, and Texas in the coming years [26]. The Columbus facility represents the largest pyrolysis project to date in the US, making it an important bellwether for the future economic feasibility of the CFP pathway. KiOR published detailed information on the expected capital and operating costs for its CFP facilities as part of its initial public offering that is particularly useful for estimating the commercial prospects for catalytic and fast pyrolysis, and identifying facility specifications.

The objective of this paper is to quantify the economic feasibility of gasoline and diesel fuel production from stover via FP and hydroprocessing using updated information that has become available as a result of the successful construction of the KiOR Columbus facility. KiOR data on equipment requirements and facility capital costs that are similar for both FP and CFP are incorporated into this analysis. A 2000 MTPD FP and hydroprocessing facility is modeled, and the total project investment (TPI) and operating costs are estimated to determine a MFSP for the gasoline and diesel fuel under a 10% internal rate of return (IRR). The results of this analysis are compared to the results of the 2010 ISU study, and a sensitivity analysis is employed to identify the impact of the updated assumptions on facility MFSP.

2. Materials and methods

The following steps are employed by the FP system to convert biomass feedstock to bio-oil: pre-processing, pyrolysis reaction, solids removal, bio-oil recovery, heat generation, hydrotreating, hydrocracking, and refining (see Fig. 1) [8]. During the pre-processing step the stover feedstock is dried to 7% moisture content, chopped, and ground to 3 mm particles. The feedstock is then sent to the fluidized bed reactor where it is rapidly heated at atmospheric pressure to 480 °C to obtain yields of 63 wt% bio-oil, 17 wt% char, and 20 wt% NCG (see Table 1). Cyclones with an assumed efficiency of 90% separate most of the char and ash from the pyrolysis vapors, which are then cooled, condensed and sent to an electrostatic precipitator (ESP) for separation of aerosols from the NCG. A small fraction of flue gas is recycled as carrier gas for the pyrolysis reactor. The char and NCG are combusted in a waste heat boiler at 450 °C to generate high pressure (50 MPa) steam, which enters a staged turbine system to provide process heat and facility electricity. Excess electricity is assumed to be sold into the grid for \$0.054/kWh. Tables 2 and 3 provide the properties of the stover feedstock and compositions of the product bio-oil and NCG.

Hydroprocessing employs a mild hydrotreating stage followed by a more severe hydrocracking stage. Both stages use fixed-bed jacketed reactors. Hydrotreating occurs in a hydrogen-rich environment (4 wt% hydrogen), 7–10 MPa pressure, and temperatures of 300–400 °C in the presence of a cobalt-molybdenum catalyst. A hydrogen compressor and pressure swing adsorption unit (PSA) are employed to recycle any excess hydrogen. This scenario assumes that the hydrogen is purchased from an external source for \$1.33/kg, the same value used by the 2010 ISU study [8].[1] Hydrotreating removes impurities such as sulfur and nitrogen from the bio-oil while also partially deoxygenating it. Off-gas produced during the hydrotreating stage is combusted to provide process heat and to fuel the boiler and turbogenerator system for co-generation of steam and electricity. The hydrocracking stage occurs at higher pressures (10–14 MPa) and temperatures (400–500 °C), also in the presence of a cobalt-molybdenum catalyst. Hydrocracking completes the deoxygenation and depolymerization of the heavy molecules found in bio-oil to produce lighter molecules within the diesel fuel and gasoline ranges (C_8–C_{12}). These molecules are then split according to respective ranges for blending into gasoline and diesel fuel. While similar to the system modeled in the 2010 ISU study [8], the fuel yield is reduced to 57.4 MGY to reflect the hydroprocessing results presented in Elliott et al. [20]. The fuel yield is assumed to be split evenly between gasoline and diesel fuel [28].

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[1] While the 2010 ISU study reports the use of \$1.50/kg for the hydrogen price, the tables in Appendix D of the companion NREL study indicate that a value of \$1.33/kg was actually used in the analysis [27].