REGIONAL TECHNO-ECONOMIC AND LIFE CYCLE ANALYSIS OF THE PYROLYSIS-BIOENERGY-BIOCHAR PLATFORM FOR CARBON-NEGATIVE ENERGY

Wenqin Li, Jerome Dumortier, Hamze Dokoohaki, Fernando E. Miguez, Robert C. Brown, David Laird, Mark M. Wright

Abstract

This study investigates the sensitivity of the minimum fuel selling price and greenhouse gas emissions (GHG) for a 2000 Mg day^{-1} integrated pyrolysis-bioenergy-biochar platform with respect to the biorefinery location. The regional techno-economic and life cycle analysis is evaluated in three U.S. counties using representative crops: Rice in Glenn County (California), corn in Hamilton County (Iowa), and peanuts in Jackson County (Florida). We evaluate the biochar selling price considering crop yield increases of 0.6%, 2.9%, and 10% after biochar application over 20 years in Glenn, Hamilton, and Jackson County, respectively. The biochar prices are calculated under low and high commodity prices to determine upper and lower bounds. Jackson County has the most economically beneficial scenario of $1.55/gal of biofuel produced while Hamilton County has the highest average minimum fuel selling price (MFSP) of $3.82/gal. The environmental analysis shows a high potential of carbon-negative energy production for this platform with GHG emission reductions of over 60% for wood, grass and straw biomass.

Introduction

Federal policy has played a crucial role in the development of bio-renewable energy in United States. The Renewable Fuel Standard (RFS) originated with the Energy Policy Act of 2005 and

This is the author's manuscript of the article published in final edited form as:

Li, W., Dumortier, J., Dokoohaki, H., Miguez, F. E., Brown, R. C., Laird, D., & Wright, M. M. (2019). Regional techno-economic and life-cycle analysis of the pyrolysis-bioenergy-biochar platform for carbon-negative energy. Biofuels, Bioproducts and Biorefining, 13(6), 1428–1438. https://doi.org/10.1002/bbb.2043

mandated at least 4 billion gallons of biofuel to be used in 2006 and 7.5 billion in 2012.[1] Biofuel mandated volumes were expanded to a total of 36 billion gallons in 2022 under the 2017 Energy Independence and Security Act (RFS2).[1] Four renewable fuel categories including biomass-based diesel, cellulosic biofuel, advanced biofuel, and total renewable fuel are regulated within volume targets.[2] Blenders are mandated to produce cellulosic biofuel from cellulose, hemicellulose, or lignin meeting at least 60% greenhouse gas (GHG) emission reductions with volumes of 16 billion gallons by 2022.[1]

Fast pyrolysis is a promising cellulosic biofuel production technology because it can thermochemically decompose lignocellulosic biomass into gas, solid, and liquid products. Fast pyrolysis employs a high heating rate, moderate temperature (around 500°C) and short resident times of a few seconds.[3] The solid pyrolysis product biochar mainly consists of aromatic carbon and could be biologically recalcitrant in the soil for many years.[4,5] Biochar application to agricultural land has potentially several advantages such as improving crop yields, increasing soil carbon sequestration resulting in the mitigation of climate change, extending soil nutrient retention after crop harvest, reducing soil bulk density, and increasing soil water retention. [5],[6],

The economic and environmental performance of the pyrolysis-bioenergy-biochar platform is very sensitive to the biorefinery location [Any reference for this claim?]. Feedstock type, availability and cost, capital and operating costs, tax rates, soil types and qualities, biochar types and markets, crop categories and commodity prices, biomass and biofuel logistics vary significantly by region. Brown et al. 2013 have compared the differences in the economic feasibility of fast pyrolysis and hydroprocessing in 30 states.[7] They quantified the internal rate of return (IRR) and net present value (NPV) variances and found values ranging from 7.4% and -$79.5 million in Illinois to 17.2% and $165.5 million in Georgia.[7] Very few subsequent studies have further investigated the economic performance of pyrolysis bioenergy production technology considering the regional effects and this contributes to filling this gap. Our motivation is to assess recent developments in the pyrolysis-bioenergy-biochar platform aiming at producing carbon-negative energy and to better understand the spatial variations of economic and environmental impacts of biochar sequestration. This assessment is necessary to comprehensively assess the carbon-negative energy production potential of the pyrolysis-bioenergy-biochar platform.

Biochar market value varies based on its end use and the method to quantify the impacts of applying it to different soils. Brown et al. 2010 estimated biochar values of \$20 to \$60 Mg^{-1} from 2015 to 2030 when comparing the profitability of biochar production from slow and fast pyrolysis.[8] Granatstein et al. 2009 reported a biochar value of \$114 Mg^{-1} based on energy content only and a break-even selling price of biochar from a fast pyrolysis facility of \$87 Mg^{-1}.[9] Galinato et al. 2011 have evaluated the economic value of biochar sequestration on wheat cropland in Washington State considering the carbon emission reduction and soil amendment properties.[10] They suggest biochar market prices of \$12.14 and \$100.73 Mg^{-1} when the carbon offset price is \$1 Mg^{-1} and \$31 Mg^{-1} CO_2-equivalent (CO_2-e), respectively. These prices could make it profitable for farmers to apply biochar to cropland.[10] The studies mentioned above focus on investigating the biochar as an individual product. However, understanding the biofuel competitiveness within regional-sensitive biochar markets is important to further evaluate the economic and environmental performance of the pyrolysis-bioenergy-biochar platform.

The goal of this study is to investigate the regional economic and environmental performance of the pyrolysis-bioenergy-biochar platform considering the biochar sequestration impacts on the different soils. Three representative counties with different soil types were chosen: Glenn County in Georgia (CA), Hamilton County in Iowa (IA) and Jackson County in Florida (FL). The region-sensitive economic model considers capital cost, feedstock types and cost, soil types and quality, biochar types and price, as well as crop types and commodity prices.

Method

Process Modeling

A 2000 Mg day^{-1} biomass fast pyrolysis to gasoline and diesel fuel production facility is modeled in Aspen Plus^{TM}. Figure 1 illustrates the biofuel production process beginning with (cellulosic?) biomass and resulting in gasoline, diesel, and biochar. Biomass is first chopped to a particle size less than 3 millimeters and dried to a moisture content of less than 10 wt% (percentage by mass). The pretreated biomass is sent to a fluidized bed pyrolysis reactor operated at 500°C and 1 atm, and it decomposes into non-condensable gases (NCG), solid biochar, and liquid bio-oil. The heat required for the pyrolysis reactor is provided by NCG and natural gas combustion. A series of cyclones are used to separate out the solid char. The biochar is sequestrated in agricultural lands to improve soil fertility and increase crop yields. Although bio-oil from fast pyrolysis is difficult to efficiently recover due to its complex composition, researchers at Iowa State University have developed a novel five-stage fractionating bio-oil recovery system aiming at recovering bio-oil into five stages fractions with distinctive characteristics and overcoming the fouling problems with conventional condenser.[11,12] Through a series of condensers with different operating conditions and several electrostatic precipitators, bio-oil is recovered into oligomer-rich heavy ends, middle fractions of monomeric phenols & a furans, and light oxygenates-rich aqueous phase.[12] Heavy and middle bio-oil fractions were further sent to a two-step hydroprocessing system to stabilize bio-oil via breaking them into shorter chains and extracting the oxygen. The stable oil is ultimately upgraded and distillated to gasoline and diesel range fuels. The bio-oil aqueous phase consists mainly of water and light oxygenated compounds including acids, ketones, and furans. A steam reforming process composed of steam-reforming and water-gas shift reactors is designed to produce hydrogen from reactions of water, light oxygenates, and merchant natural gas.

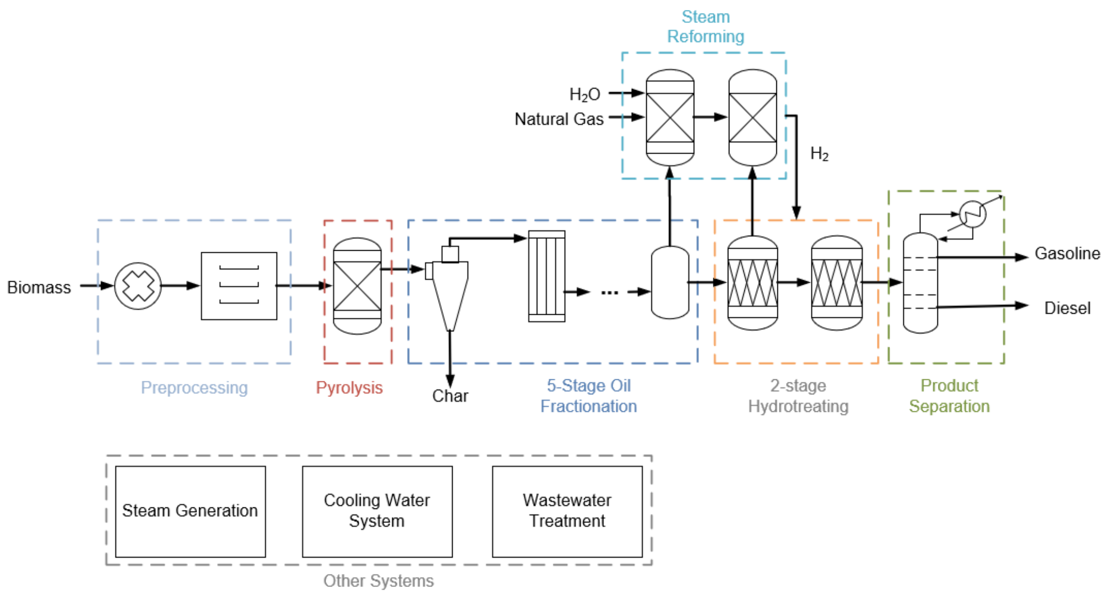

Figure 1. Process flow diagram of biomass fast pyrolysis to gasoline and diesel

Techno-economic Analysis

A region-sensitive economic model to quantify biochar market value based on the crop yield response to biochar application is developed to evaluate the spatial economic performance of the pyrolysis-bioenergy-biochar platform. We use three locations, three crops, and three biochar feedstocks in the United States to compare the economic performance of the platform. Table 1 summarizes the location specific characteristics and biochar properties. Biochar was generated from pyrolyzing the most abundant biomass feedstock in each state and applied to a representative crop in each county. Properties of slow pyrolysis biochar differ from those of biochar obtained via fast pyrolysis but further research is still needed to understand their impacts.[13] The pyrolysis temperature is 500°C for all feedstocks in our analysis.

Table 1. Regional factors for three different counties and chemical properties of biochar and pyrolysis conditions.

Location	Glenn County	Hamilton County	Jackson County
State	California	Iowa	Florida
Crop	Rice	Corn	Peanut
Pyrolysis Feedstock	Wood[31]	Corn Stover[16]	Switchgrass[16]
Feedstock Price	86	101	110
Local Capital Cost Factor	1.36	1.11	0.96
Pyrolysis	Fast	Fast	Slow
pH	9.5	8.4	9.9
Carbon Content (%)	90.5	52.4	71
Nitrogen Content (%)	0.3	0.5	0.9
Ash Content (%)	7.7	37	15.2
C:N (molar)	352	134	94

The biochar market value is predicted based on the crop yield responses to biochar application which occurs due to a complex interaction between soil properties, biochar characteristics, and soil/crop/biochar/climate/management interactions.[14] Dokoohaki et al. 2018[15] have developed an extensive informatics platform for data analysis and large-scale spatial modeling to predict the crop yield responses to biochar application.[16] They use probabilistic graphical models to evaluate crop yield changes to biochar application in different soils at a large spatial scale and to adjust for incomplete datasets and problems arising from high uncertainty. Representative properties of soil such as organic carbon content, sand, silt, clay content, CEC and pH, as well as biochar properties such as carbon, nitrogen, ash, pH, C:N ratio, pyrolysis temperature, and feedstock type are incorporated to predict the crop yield responses to biochar application in the contiguous United States.[16] We use this Bayesian Network model to predict crop yield changes to different biochar application in these three counties.

To calculate the farmers' willingness-to-pay per metric ton of biochar, we compare the net present value (NPV) of the crop revenue over 20 years with and without biochar application. In a first step, we obtained historical crop yields for the counties included in this analysis over the last 20 years from the U.S. Department of Agriculture (USDA) National Statistics Service (NASS).[18] We fit a linear time trend model to the data and projected the county yields over the 2016-2035 period. This implicitly assumes that farmer expects the yields to continue to grow at the same rate (in Mg year^{-1}) over the past 20 years.[19] We create a second yield projection based on the expected yield improvement over the projection period from the Bayesian Network model. This percentage is assumed to be constant over 20 years. In a second step, we calculated the lowest and highest real commodity prices (in 2017 \$) between 1996 and 2017 based on data from USDA NASS. We multiply the minimum and maximum commodity prices by the two yield projections to obtain a series of per hectare revenue streams that differ along two dimensions: biochar application (with and without) and commodity price levels (low and high). Those minimum and maximum commodity prices are creating an upper and lower bound of expected revenue. Assuming a discount rate of 5%, we calculate the NPV assuming an application rate of 5 Mg ha^{-1}. Because biochar is only applied in the first year, the farmer needs to know whether the difference between the NPV of the revenue with and without biochar application (assuming constant commodity prices at one of the two levels) outweighs the cost of biochar. For example, if the NPV over 20 years with and without biochar application is \$6000 and \$5000, respectively, then the maximum willingness-to-pay per ton of biochar is \$200 (\$1000 divided by 5 Mg). If biochar is available at a price below $200, the farmer will purchase and apply biochar.

The economic performance of the pyrolysis-bioenergy-biochar platform is evaluated based on capital and operating costs as well as the minimum fuel selling price (MFSP). The capital cost of this platform refers to the investment to purchase and install all the equipment for the biomass-to-biofuel process. The basis for most of the equipment costs is Aspen Plus Economic Analyzer (APEA).[20] Costs for custom equipment such as the pyrolysis reactor are calculated by applying scaling ratios based on previous literature.[21–24] The installed equipment costs are generated by multiplying equipment purchase costs with the installation factors provided by Peters and Timmerhaus (2003).[25] The operating costs consist of variable (i.e., raw materials, waste disposal, credits from byproducts) and fixed cost (i.e., employee salaries, overhead, insurance, taxes and maintenance).[26] The MFSP is the break-even selling price of the main product using the discounted cash flow rate of return (DFROR) method. The rate of return is assumed as 10% within a 20 years plant life span. All costs are presented on a 2017-year dollar basis.

Table 1 summarizes the regional factors used in this techno-economic analysis. Feedstock costs is obtained from the National Research Council (NRC) which uses the Biofuel Breakeven model (BioBreak) to investigate the minimum willingness-to-pay delivered price per dry ton of various lignocellulosic biomass in different regions. Capital costs for biorefineries vary by locations and we use the Department of Defense's (DOD) area cost factors to account for the capital cost sensitivity to the facility location states.[27] This DOD index covers all U.S. states for both urban and rural areas, with the consideration of the difference in labor jobs, construction materials, equipment types and local climate conditions.[7] The corporate tax rates differ among states but are not discussed in this study since Brown et al. 2013 claim a low sensitivity of biorefineries' NPV with respect to state income tax rate.[7]

Pyrolysis product yields varies by feedstock which further affects the process' economic performance. Therefore, a wide range of feedstocks from Phyllis 2 database created by the Energy Research Center of Netherland (ECN) are used to account for the product yield variances in order to comprehensively investigate the economic performance of the pyrolysis-bioenergy-biochar platform.[29] The ultimate analysis data (on a dry biomass basis) of three types, 304 cases of different biomass including wood, grass and straw were collected. The hydrogen-to-carbon ratio (H/C) and oxygen-to-carbon (O/C) ratio of these feedstock range from 0.09-0.16 and 0.88-1.11, respectively.[29] We incorporated our process model with regression models generated by Li et al. (2017) to quantify the relations between the biomass properties and pyrolysis products,[30] and further evaluate the economic performance of the pyrolysis-bioenergy-biochar platform within a wide range of biomass. The representative biomass properties are chosen as O/C and ash content. The biomass properties are only considered to affect the pyrolysis product yields. The biochar properties are assumed to be the same for pyrolysis of each category of feedstock. Table 1 shows the biochar properties from pyrolysis of pitch pine, switchgrass, and corn stover to represent the biochar from pyrolysis of wood, grass, and straw.

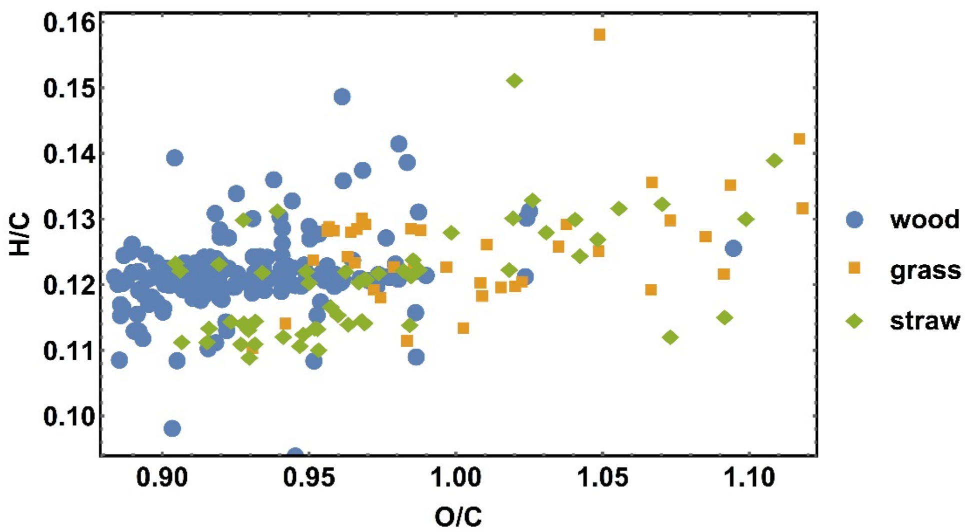

Figure 2. Feedstock types from Phyllis2 ECN database[29]

Life Cycle Analysis

The goal of life cycle analysis (LCA) is to quantify the environmental emissions for each process stage in a product life from "cradle to grave" including all the material and energy consumption from manufacturing, product use, waste disposal, etc.[32] The well-to-wheel analysis is modeled in four steps including goal and scope definition, inventory analysis, impact assessment, and interpretation.[33] Two of the most commonly used software tools to conduct life cycle analysis for are the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model by Argonne National Laboratory and SimaPro.[34,35] To evaluate the environmental performance of the pyrolysis-bioenergy-biochar platform, we modeled the biomass-to-biofuel process via four steps: (1) feedstock production, (2) pyrolysis, stabilization, and upgrading, (3) H_2 production, and (4) fuel transportation.[36] We use GREET to evaluate the greenhouse gas (GHG) emissions of the platform with the functional unit defined as 1 mega joule (MJ) of biofuel produced.

The primary GHG emission sources for this platform are feedstock, natural gas for heat and H_2, utilities, petroleum fuel for feedstock and product transportation, biofuel combustion and credits from biochar sequestration, based on the system boundary. GHG emissions related to biomass production vary by crop management and cultivation methods. The emissions for forest residue, switchgrass, and corn stover are gathered from GREET 2015 and used as representative feedstock emissions for wood, grass and straw respectively. The emissions related to forest residue production (45 g CO_2-e kg^{-1}) mainly came from energy consumption for forest maintenance, harvesting, collection and transportation. No fertilizer or agrochemical inputs are included for forest residue removal. The emissions for forest residue is mass allocated from the total production emission of forest products.[37] Several studies have investigated corn stover production emissions and a common method is using energy or mass allocation of the total emissions of corn production.[38] Argonne National Laboratory evaluates the corn stover emissions from three parts: energy consumed during corn stover harvest, transportation and fertilizer replacement to make up the nutrients loss during corn stover removal. The emissions for corn stover is estimated as 85 g CO_2-e kg^{-1} with a corn stover production assumption of 2.1 dry tons per acre.[37] Switchgrass production emission is estimated at 140 g CO_2-e kg^{-1} for once-per-year harvest with consideration of fertilizer, herbicide, and no irrigation.[39] The emissions related to petroleum energy and pyrolysis product transportation come from GREET.[35]

Biochar coproduct treatment methods can significantly affect the well-to-wheel results for biofuel produced from this platform. Biochar sequestration could not only capture and restore carbon in soils, but also increase the soil quality, such as enhancing the plant nutrients & water, decreasing nitrous oxide loss.[40] Several studies show a positive crop yields response to biochar application. Kauffman et al. 2014 have suggested indirect land use change credits of up to 14.79

t CO_{2e} per hectare annually with 8% crop yield increase in U.S. Midwest over 30 years' time span.[41] In this study, we only focus on the carbon sequestration impacts and chose the displacement method to quantify the GHG credits for biochar sequestration. To evaluate the GHG emission credits from biochar, Han et al.2013 has assumed that 20% of biochar carbon is emitted to the atmosphere over 100 years, while the biochar carbon is defaulted as 51.2%.[42] However, biochar carbon content is highly dependent on biomass type and pyrolysis conditions.[42] Instead of assuming a fixed biochar carbon content, we employ biochar from pyrolysis of pitch pine, switchgrass and corn stover as the representative biochar properties for wood, grass and straw type of feedstock (Table 1). We calculated the total GHG emissions for 304 cases of biomass (3 types) with the consideration of product yields from Aspen Plus, feedstock and biochar emission credits variances. The emissions from biofuel combustion are assumed to be absorbed as the biogenic CO_2 via biomass photosynthesis.

Results

Techno-economic Analysis

Table 3 summarizes the crop yields and biochar willingness-to-pay results for the three counties considered in our analysis. The crop yields responded to biochar application in Glenn (CA), Hamilton (IA) and Jackson (FL) are 0.6%, 2.9% and 10%. With low and high crop commodity price, the minimum willingness-to-pay biochar price for these three counties are calculated as $75, $87, $680 and $248, $250, $1272 respectively. All these three case studies showed a positive response to biochar application. According to Dokoohaki et al. 2018[15], soils of high quality have a lower probability to generate a crop yield increase, and high biochar carbon and low C:N ratio are correlated with a high probability to increase crop yields.[16] That explains why our crop yields increase in Hamilton (IA) and Jackson (FL). We are expecting a higher crop yields increase in Glenn (CA) due to a higher biochar carbon content, however, the crop yields are low which might be due to the trade-off function between a high biochar carbon content and a high C:N ratio. The biochar prices are consistent with the crop yield increases even though there are variances among different crop commodities prices. A higher crop yield increase corresponded to a higher willingness-to-pay biochar price.

Table 2. Results for crop yields and biochar willingness-to-pay prices for three different counties

County	State	Crop Yield	Biochar Price (Low)	Biochar Price (High)
Glenn	CA	0.60%	$75	$248
Hamilton	IA	2.90%	$87	$250
Jackson	FL	10.00%	$680	$1272

We have calculated the minimum fuel selling price (MFSP) incorporating with the willingness-to-pay biochar prices for these 304 different biomasses including three types feedstock of wood, grass and straw, as shown in Figure 3. The average MFSP is presented as the white line in the middle, while the color bar covers 25% to 75% percentile of all possible MFSPs. The mean MFSP in Jackson (FL) is the lowest while Hamilton (IA) has the highest mean MFSP. These represent the integrated interaction among product yields, feedstock price, and the biochar value. A higher biochar selling price leads to a more competitive lower minimum fuel selling price for all three states. The difference between a high and low biochar price could result in up to $1.06/gal (FL case) fuel price variance. Hamilton (IA) covered a wider range of MFSPs compared to the other two counties, and this is mainly due to a wider range of straw feedstock properties.

Figure 4 presents the average MFSPs distribution for all these three counties with two biochar prices. Jackson (FL) has the lowest while Hamilton (IA) has the highest average MFSP. Average biofuel yields for Glenn (CA), Hamilton (IA) and Jackson (FL) are 57, 55 and 50 million gallons per year respectively, while biochar yields are 0.09, 0.11 and 0.1 million tons annually. Feedstock costs play a significant role on the total MFSP for all six cases. The capital cost differences among these three regions are negligible compared to other region-sensitive factors.

The impacts of biomass properties on the MFSP are shown in Figure 5. The MFSPs for wood, grass and straw biomass range from $1.23 to $5.16 per gallon of biofuel. There is a negative correlation of O/C and a positive correlation of ash content on the MFSP for woody biomass. The trend of the impacts of biomass O/C on the economic performance is less obvious for grass and straw due to a small and widespread biomass sample. Biomass properties impacts on the process economics for wood and straw feedstock are consistent with the impacts on the pyrolysis fuel yields, as predicted by Li et al. 2017.[30] However, the biomass O/C impact on biochar yields overrides the impact on fuel output for grass type of feedstock due to a high willingness-to-pay biochar price is predicted for grass type feedstock in Jackson (FL). A higher O/C ratio of biomass has the potential to increase fuel yields but decrease the biochar yields, but a high biochar willingness-to-pay price will further lead to an increasing MFSP with higher O/C.

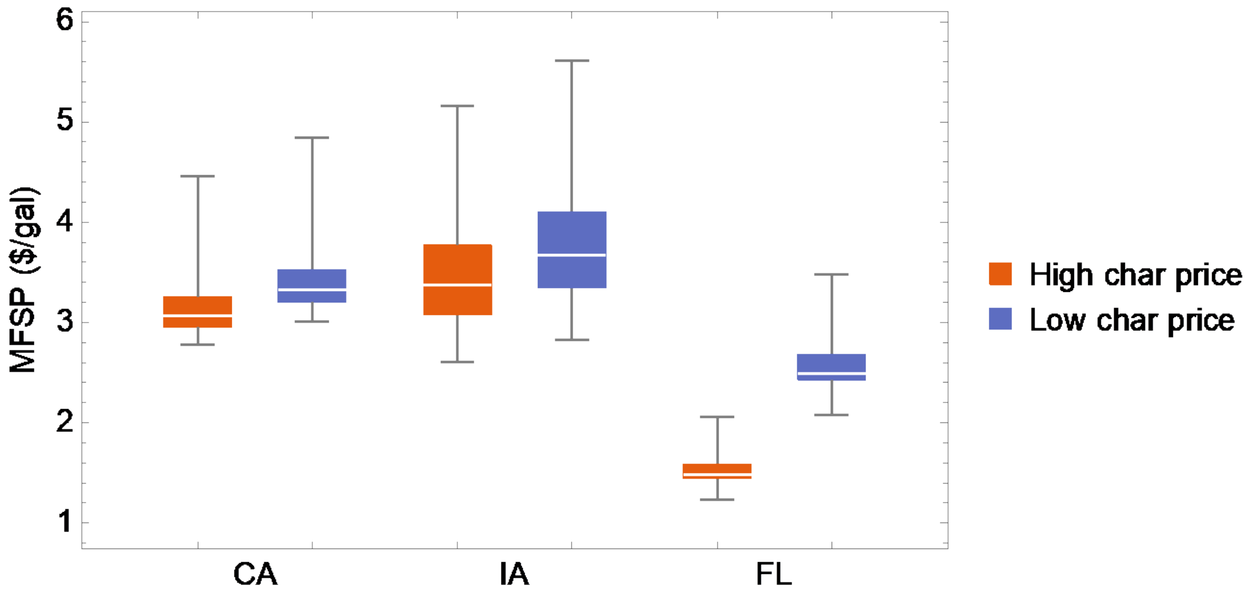

Figure 3. Mean minimum fuel-selling price (MFSP) with standard errors for two different biochar price scenarios in Hamilton (IA), Glenn (CA) and Jackson (FL)

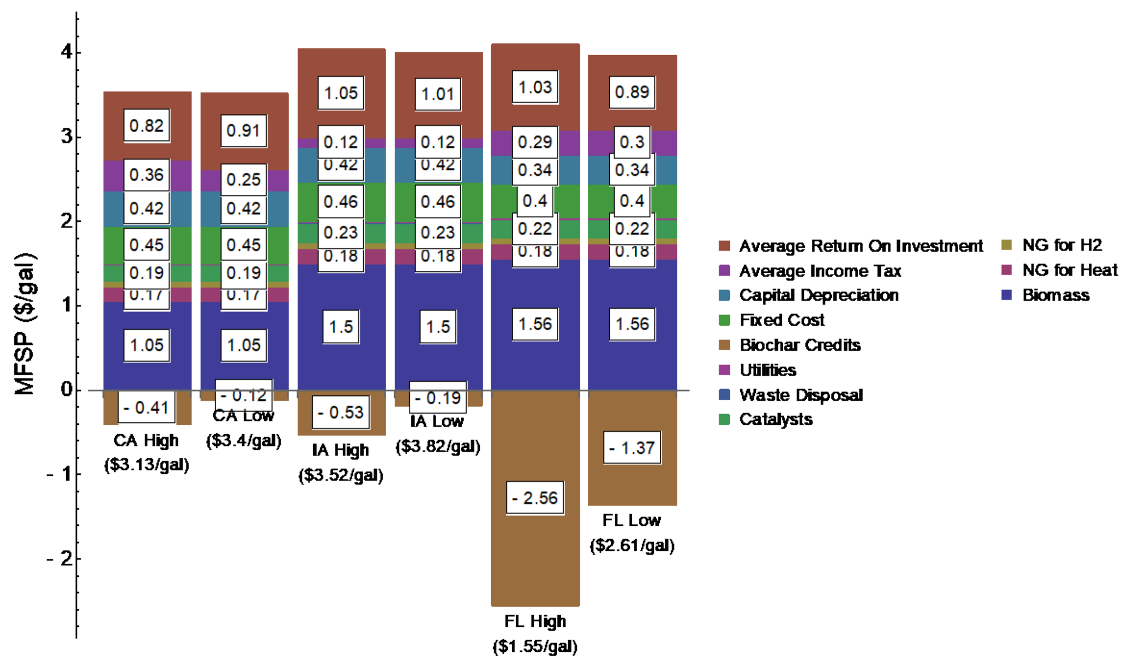

Figure 4. Average minimum fuel selling price distribution for three counties from three states with low and high biochar price

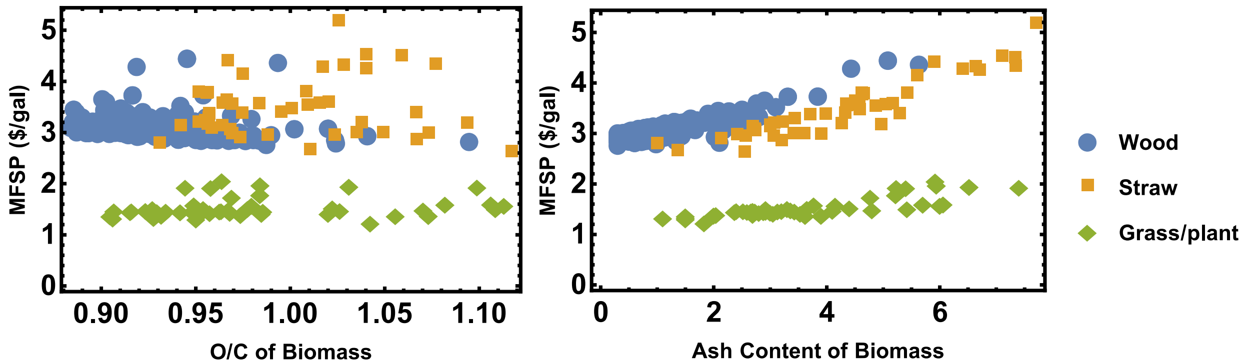

Figure 5. The impact of biomass properties (O/C and ash) on minimum fuel selling price with high biochar price

Life Cycle Analysis

Figure 6 presents how biomass O/C ratio and ash content affect the total GHG emissions for biofuel production from these three types of feedstock. The GHG emissions are positively correlated with the O/C ratio for wood and negative correlated with ash content of biomass for wood, grass, and straw. The ash content impacts on GHG emissions are consistent with the biochar yields. Higher ash content leads to a higher biochar yields which results in a larger GHG emission reduction. The impacts of O/C of biomass on the GHG emissions for grass and straw are relatively scattered due to the coherent impacts of a wide range of biomass ash content. One of the major findings from the GHG emissions in this study is over 64% of the 304 cases of feedstock could have the potential to produce carbon-negative energy, compared to Li et al. 2017 of less than 1% of the 346 cases.[30] This is due to changes in the biorefinery configuration and system management. The majority of negative GHG scenarios result from consideration of biochar carbon content variances.

We randomly chose one feedstock from each type of biomass and investigated the GHG emissions distributions. As shown in Figure 7, GHG emissions for all three biomass have the potential to achieve a GHG emission reduction up to 60%, which would meet the RFSs target for cellulosic biofuels. GHG emission credits from biochar application play a significant role in the total GHG emissions. The biochar yields and biochar carbon content interact together to determine the biochar GHG emission reduction potentials. Feedstock-related GHG emissions vary by feedstock types, it could take up to 70% of the total emissions without considering biochar emission credits. The consumed energy related emissions are also different due to biofuel production variances among different feedstock.

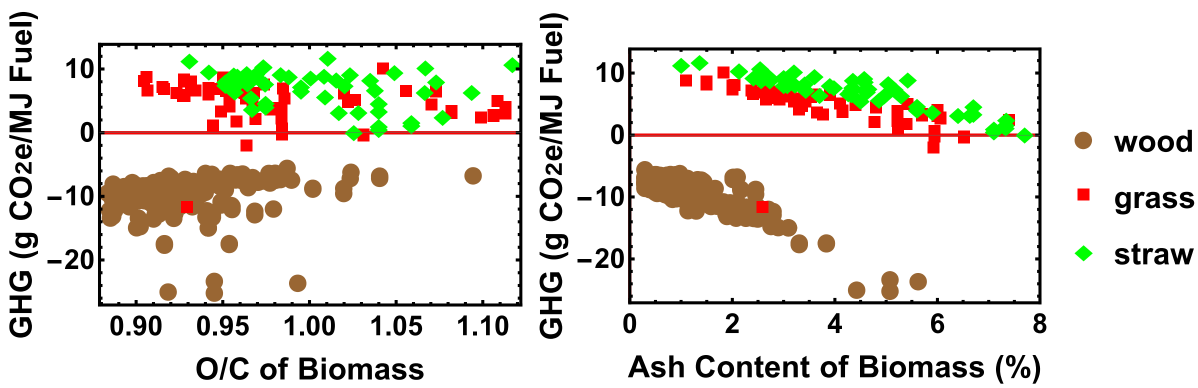

Figure 6. The impact of biomass properties (O/C and ash) on GHG emissions

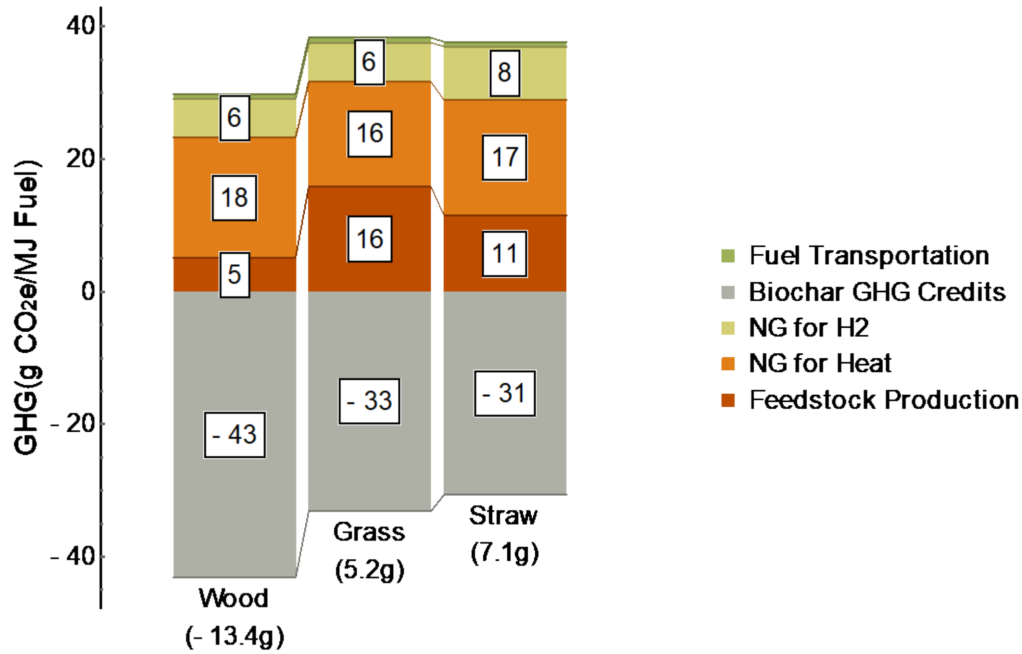

Figure 7. GHG emission distribution for three types of feedstock (The representative feedstock of each category is randomly chosen by Mathematica)

Conclusion

This study evaluates the techno-economic and environmental impacts of a pyrolysis-bioenergy-biochar platform considering regional characteristics of biomass supply and cost. It advances previous research by incorporating a regional-specific capital cost estimations, a model calculating the willingness-to-pay for biochar price model based on crop yields responses, and current biochar GHG emission credits estimation covering variances in feedstock. This study further reveals the potential to produce carbon-negative energy via this pyrolysis-bioenergy-biochar platform. A more rigorous life cycle and economic model to quantify the correlation between biomass properties and biochar properties, to incorporate other biochar impacts on soils, and to convert the environmental benefits into economic values could help more comprehensively understand the economic and environmental performance of this pyrolysis-bioenergy-biochar platform.

Acknowledgments

We would like to thank the Bioeconomy Institute,

References

1. McMinimy, M. A. & Bracmort, K. Renewable fuel standard (RFS): Overview and Issues. *Congr. Res. Serv. Rep.* (2013).

2. US EPA, O. Overview for Renewable Fuel Standard.

3. Gómez, N., Banks, S. W., Nowakowski, D. J., Rosas, J. G., Cara, J., Sánchez, M. E. & Bridgwater, A. V. Effect of temperature on product performance of a high ash biomass during fast pyrolysis and its bio-oil storage evaluation. *Fuel Process. Technol.* **172,** 97–105 (2018). DOI:10.1016/j.fuproc.2017.11.021

4. Keiluweit, M., Nico, P. S. & Johnson, M. G. Dynamic Molecular Structure of Plant Biomass-Derived Black Carbon (Biochar). *Environ. Sci. Technol.* **44,** 1247–1253 (2010). DOI:10.1021/es9031419

5. Fidel, R. B., Laird, D. A. & Parkin, T. B. Impact of six lignocellulosic biochars on C and N dynamics of two contrasting soils. *GCB Bioenergy* **9,** 1279–1291 (2017). DOI:10.1111/gcbb.12414

6. Lehmann, J., Gaunt, J. & Rondon, M. Bio-char sequestration in terrestrial ecosystems - A review. *Mitig. Adapt. Strateg. Glob. Chang.* **11,** 403–427 (2006). DOI:10.1007/s11027-005-9006-5

7. Brown, T. R., Thilakaratne, R., Brown, R. C. & Hu, G. Regional differences in the economic feasibility of advanced biorefineries: Fast pyrolysis and hydroprocessing. *Energy Policy* **57,** 234–243 (2013). DOI:10.1016/j.enpol.2013.01.058

8. Brown, T. R., Wright, M. M. & Brown, R. C. Estimating profi tability of two biochar production scenarios : slow pyrolysis vs fast pyrolysis. 54–68 (2011). DOI:10.1002/bbb

9. Granatstein, D., Kruger, C., Collins, H., Galinato, S., Garcia-Perez, M. & Yoder, J. *Use of Biochar from the Pyrolysis of Waste Organic Material as a Soil Amendment*. *Program* (2009). DOI:09-07-062

10. Galinato, S. P., Yoder, J. K. & Granatstein, D. The economic value of biochar in crop production and carbon sequestration. *Energy Policy* **39,** 6344–6350 (2011). DOI:10.1016/j.enpol.2011.07.035

11. Czernik, S. & Bridgwater, A. V. Overview of Applications of Biomass Fast Pyrolysis Oil.

590–598 (2004).

12. Pollard, A. S., Rover, M. R. & Brown, R. C. Characterization of bio-oil recovered as stage fractions with unique chemical and physical properties. *J. Anal. Appl. Pyrolysis* **93,** 129–138 (2012). DOI:10.1016/j.jaap.2011.10.007

13. Brewer, C. E. & Brown, R. C. L. D. a. Biochar characterization and engineering. *Grad. Teses Diss.* 12284 (2012). DOI:12284

14. Jeffery, Simon, Meinders, Marcel B. J., Stoof, Cathelijne, Bezemer, T. Martijn, vande Voorde, Tess F. J., Mommer, Liesje & Willem van Groenigen, Jan. Why biochar application did not improve the soil water retention of a sandy soil: An investigation into the underlying mechanisms. *EGU Gen. Assem. 2015* **17,** 10226 (2015).

15. Hamze Dokoohaki, Fernando E. Miguez, David Laird, Dumortier, J. Where should we apply biochar? To. *Environ. Res. Lett. Accept.* (2019). DOI:10.1088/1748-9326/aafcf0

16. Dokoohaki, H. The promise of biochar: From lab experiment to national scale impacts. *Diss. Crop Prod. Physiol. Iowa State Univ.* (2018).

18. USDA - National Agricultural Statistics Service Homepage.

19. Mohan, D., Pittman, C. U. & Steele, P. H. Pyrolysis of wood/biomass for bio-oil: A critical review. *Energy and Fuels* **20,** 848–889 (2006). DOI:10.1021/ef0502397

20. Aspen Plus - Process Simulation for Chemicals.

21. Wright, M. M. M., Daugaard, D. D. E., Satrio, J. a. J., Brown, R. R. C. & Hsu, D. D. Techno-economic analysis of biomass fast pyrolysis to transportation fuels. *Fuel* **89,** S2–S10 (2010). DOI:10.1016/j.fuel.2010.07.029

22. Biddy, M. & Dutta, A. In-Situ Catalytic Fast Pyrolysis Technology Pathway In-Situ Catalytic Fast Pyrolysis Technology Pathway. (2013).

23. Jones, S., Snowden-Swan, L., Meyer, P., Zacher, A., Olarte, M., Wang, H. & Drennan, C. Fast Pyrolysis and Hydrotreating: 2014 State of Technology R & D and Projections to 2017. 18 (2016). DOI:DE-AC05-76RL01830

24. Pathway, B., Jones, S., Meyer, P., Snowden-swan, L., Tan, E., Dutta, A., Jacobson, J. & Cafferty, K. Process Design and Economics for the Conversion of Lignocellulosic Biomass to Hydrocarbon Fuels Fast Pyrolysis and Hydrotreating. (2013).

25. Peters, M. S., Timmerhaus, K. D. & West, R. E. *Plant design and economics for chemical engineers*. (McGraw-Hill Science/Engineering/Math, 2003).

26. Dutta, A. *et al.* Process Design and Economics for the Conversion of Lignocellulosic Biomass to Hydrocarbon Fuels Thermochemical Research Pathways with In Situ and Ex Situ Upgrading of Fast Pyrolysis Vapors. 275 (2015). DOI:10.2172/1215007

27. UNIFIED FACILITIES CRITERIA (UFC) - DoD FACILITIES PRICING GUIDE. (2018).

28. National Research Council (U.S.). Committee on Economic and Environmental Impacts of Increasing Biofuels. *Renewable Fuel Standard: Potential Economic and Environmental Effects of U.S. Biofuel Policy*. (Washington, D.C. : National Academies Press, 2011).

29. Phyllis2 - ECN Phyllis classification.

30. Li, W., Dang, Q., Brown, R. C., Laird, D. & Wright, M. M. The impacts of biomass properties on pyrolysis yields, economic and environmental performance of the pyrolysis-bioenergy-biochar platform to carbon-negative energy. *Bioresour. Technol.* **241,** 959–968 (2017). DOI:10.1016/j.biortech.2017.06.049

31. Kim, K. H., Kim, J. Y., Cho, T. S. & Choi, J. W. Influence of pyrolysis temperature on physicochemical properties of biochar obtained from the fast pyrolysis of pitch pine (Pinus rigida). *Bioresour. Technol.* **118,** 158–162 (2012). DOI:10.1016/j.biortech.2012.04.094

32. Rebitzer, G., Ekvall, T., Frischknecht, R., Hunkeler, D., Norris, G., Rydberg, T., Schmidt, W.-P., Suh, S., Weidema, B. P. & Pennington, D. W. Life cycle assessment. *Environ. Int.* **30,** 701–720 (2004). DOI:10.1016/j.envint.2003.11.005

33. Roberts, K. G., Gloy, B. A., Joseph, S., Scott, N. R. & Lehmann, J. Life cycle assessment of biochar systems: Estimating the energetic, economic, and climate change potential. *Environ. Sci. Technol.* **44,** 827–833 (2010). DOI:10.1021/es902266r

34. SimaPro for business - for fact-based sustainability in business.

35. Argonne GREET Model. *(https://greet.es.anl.gov/ Accessed 2018-05-30)*

36. Li, W., Dang, Q., Smith, R., Brown, R. C. & Wright, M. M. Techno-Economic Analysis of the Stabilization of Bio-Oil Fractions for Insertion into Petroleum Refineries. *ACS Sustain. Chem. Eng.* (2017). DOI:10.1021/acssuschemeng.6b02222

37. Han, J., Elgowainy, A., Palou-Rivera, I., Dunn, J. B. & Wang, M. Q. Well-to-Wheels Analysis of Fast Pyrolysis Pathways with GREET.Argonne National Laboratory: Lemont, IL. *ANL/ESD/11-8* 76 (2011).

38. Murphy, C. W. & Kendall, A. Life cycle inventory development for corn and stover production systems under different allocation methods. *Biomass and Bioenergy* **58,** 67–75 (2013). DOI:10.1016/j.biombioe.2013.08.008

39. Wang, M., Han, J., Dunn, J. B., Cai, H. & Elgowainy, A. Well-to-wheels energy use and greenhouse gas emissions of ethanol from corn, sugarcane and cellulosic biomass for US use. *Environ. Res. Lett.* **7,** 045905 (2012). DOI:10.1088/1748-9326/7/4/045905

40. Laird, D. A. The charcoal vision: A win-win-win scenario for simultaneously producing

bioenergy, permanently sequestering carbon, while improving soil and water quality. *Agron. J.* **100,** 178–181 (2008). DOI:10.2134/agronj2007.0161

41. Kauffman, N., Dumortier, J., Hayes, D. J., Brown, R. C. & Laird, D. A. Producing energy while sequestering carbon? The relationship between biochar and agricultural productivity. *Biomass and Bioenergy* **63,** 167–176 (2014). DOI:10.1016/j.biombioe.2014.01.049

42. Han, J., Elgowainy, A., Dunn, J. B. & Wang, M. Q. Life cycle analysis of fuel production from fast pyrolysis of biomass. *Bioresour. Technol.* **133,** 421–428 (2013). DOI:10.1016/j.biortech.2013.01.141