Estimating Profitability of Two Biochar Production Scenarios: Slow Pyrolysis vs. Fast Pyrolysis

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ABSTRACT

We estimate the profitability of producing biochar from crop residue (corn stover) for two scenarios. The first employs *slow pyrolysis* to generate biochar and pyrolysis gas and has the advantage of high yields of char (as much as 40 wt-%) but the disadvantage of producing a relatively low-value energy product (pyrolysis gas of modest heating value). The second scenario employs *fast pyrolysis* to maximize production of bio-oil with biochar and pyrolysis gas as lower-yielding co-products. The fast pyrolysis scenario produces a substantially higher value energy product than slow pyrolysis but at the cost of higher capital investment.

We calculate the internal rate of return (IRR) for each scenario as functions of cost of feedstock and projected revenues for the pyrolysis facility. The assumed price range for delivered biomass feedstock is $0 to $83 per metric ton. The assumed carbon offset value for biochar ranges from $20 per metric ton of biochar in 2015 to $60 in 2030.

The slow pyrolysis scenario in 2015 is not profitable at an assumed feedstock cost of $83 per metric ton. The fast pyrolysis scenario in 2015 yields 15% IRR with the same feedstock cost because gasoline refined from the bio-oil provides revenues of $2.96 per gallon gasoline equivalent. By 2030, the value of biochar as a carbon offset is projected to increase to $60 per metric ton and the price of gasoline is expected to reach $3.70 per gallon, which would provide investors with an IRR of 26%.

Keywords: fast pyrolysis, slow pyrolysis, biochar, bio-oil, corn stover

1. INTRODUCTION

The proposed American Clean Energy and Security Act (ACESA) would create a program in which parties are eligible to receive carbon offsets for practices resulting in a net sequestration of carbon dioxide or its equivalent (CO_2-e). Of the offset practices found in ACESA, afforestation has the greatest carbon sequestration potential and is expected to experience widespread adoption as a result. Differences in soil carbon amounts will make offsets for converting cropland to forest more valuable than converting pasture or conservation land to forest (see Table 1)[1], potentially causing a significant decrease in U.S. food production and a corresponding increase in food commodity prices (Glauber JW (http://www.usda.gov/oce/forum/2009_Speeches/Speeches/Glauber.pdf); Brown TR, Elobeid A, Dumortier J, Hayes, DJ (http://www.card.iastate.edu/publications/DBS/PDFFiles/10wp502.pdf)).

While landowners will benefit from any increase in rental values resulting from higher commodity prices, renters will experience eroding profit margins and businesses involved in activities that are ancillary to food production (i.e., equipment manufacture, transport, fertilizer production, and farm labor) will be negatively impacted in the face of reduced demand for those services. Globally, the risk of famine and unrest in developing and underdeveloped countries could significantly increase as the breadbasket of the world reduces its exports to satisfy domestic supply shortages (Brown LR (http://www.earth-policy.org/index.php?/press_room/C68/SenateEPW07)).

It is possible to combat greenhouse gas (GHG) emissions and reinvigorate rural and agricultural communities simultaneously through the use of biochar. Biochar is the name given to charcoal produced for agronomic and other ecosystem applications. It is produced by heating biomass in the absence of oxygen, a process known as pyrolysis. In addition to stably sequestering the carbon in the biochar for periods of time estimated to be several hundred to several thousand years,[2,3,4] biochar can be applied to cropland to increase crop yields, decrease runoff, decrease fertilizer and lime use, increase soil fertility and minimize nitrous oxide (N_2O) and methane (CH_4) emissions, which are also potent greenhouse gases.[5,6,7,8,9,10]

Pyrolysis of biomass also produces pyrolysis gas, a flammable mixture of non-condensable gases, and bio-oil, derived from condensable vapors and liquid aerosols released during pyrolysis. Pyrolysis gas can substitute for natural gas in process heat or even power generation applications although the presence of hydrogen and carbon monoxide in the gas mixture makes it unsuitable for long-distance distribution or residential applications. Bio-oil can be refined into “green” gasoline and diesel, which are attractive “drop-in” biofuels. The projected minimum selling prices for these bio-oil derived transportation fuels are in the range of $1.74-$3.09/gallon,[11,12] which are slightly too high to be economically viable today. However, in combination, the sale of pyrolysis products (biochar, pyrolysis gas, and bio-oil) or their derivatives (transportation fuels from bio-oil) might quickly become economically viable in a carbon-regulated economy where biochar qualifies as a carbon offset practice.

This paper discusses the economics of biochar production under a scenario in which ACESA is passed and the value of biochar offsets is pegged to the allowance price under the legislation. This scenario utilizes currently available projections from other studies on the price of allowances and gasoline under ACESA to determine the overall value of biochar. Section 2 contains a review of pyrolysis for production of bio-oil, gas and biochar. Section 3 describes the domestic offset program created by ACESA. Section 4 provides a description of biochar as a soil amendment. Section 5 describes the process model used to evaluate the economics of pyrolysis scenarios evaluated in this study. Section 6 describes the two production scenarios. Section 7 presents the results of this scenario. Section 8 concludes with a discussion of the policy implications of this study.

2. PYROLYSIS

Various researchers have explored the pyrolysis platform’s economic[11,12,13,14,15] and environmental[16,17] performance. These previous studies have explored a wide range of biomass pyrolysis applications including heat and power, liquid fuels, soil amendment, and carbon mitigation strategies.

While there exist substantial bodies of research on biochar production via pyrolysis, studies on the economic feasibility of biochar production are fewer. McCarl et al. completed[18] an economic analysis of pyrolysis from corn stover and found both fast and slow pyrolysis to be economically infeasible. That study used technical data that is now outdated, however, and the authors admitted that the results depended on numerous assumptions not strongly supported by evidence. The primary difference between that study and the current one is that the former considered biochar and bio-oil to be most economically attractive as fuel for electricity generation, a low-value use relative to the value attained from using bio-oil as a feedstock for production of drop-in “green” gasoline.

In addition to agronomic and transportation applications, the products of pyrolysis are suitable for combustion applications. In the National Renewable Energy Laboratory (NREL) 2005 pyrolysis report,[15] pyrolysis non-condensable gases and biochar are employed to provide process heat and power. Similarly, Mullaney et al. (Mullaney H, Farag I, LaClaire C, Barrett C (http://www.unh.edu/p2/biooil/bounhif.pdf)) estimated that pyrolysis products could provide sufficient energy to both heat the pyrolysis process and provide process heat for other applications. Various process designs have been considered that generate heat and power from pyrolysis products. Bridgwater et al.[14] included pyrolysis in a comparison of various biomass power generation pathways. In their study, pyrolysis units were employed to generate bio-oil, which serves as feedstock to power generating diesel engines. Three power generation capacities were considered: 1, 6, and 20 MWe. Biomass pyrolysis electricity costs were estimated to be 0.20, 0.12, and 0.08 Euro/kWh ($0.18, $0.11, and $0.07/kWh), respectively.[*]

Several research groups are investigating the cost of converting bio-oil into transportation fuels including the Pacific Northwest National Laboratory (PNNL)[11] and Iowa State University.[12] Bio-oil conversion to gasoline and diesel involves the procurement of significant quantities of hydrogen. Most of these studies differ by the method employed to acquire the requisite amount of hydrogen. PNNL assumed that hydrogen would be generated by steam reforming of natural gas at a biomass facility. Holmgren et al. investigated various approaches to integrating bio-oil into existing crude oil refineries.[19] Iowa State University assumed that hydrogen could be refined from a fraction of the generated bio-oil or purchased as merchant hydrogen. Each of these groups identified the opportunity to integrate biomass pyrolysis with existing crude oil refineries as an attractive scenario for the production of renewable transportation fuels. Estimates for the production of renewable gasoline and diesel fuel via the fast pyrolysis platform and bio-oil upgrading process range from $1.74 to $3.09 per gallon.[11,12,19]

Biochar from a variety of pyrolysis processes have attractive properties as soil amendment and carbon sequestration agents. Laird recently outlined the opportunities for biochar to simultaneously produce bioenergy, sequester carbon, and improve soil and water quality.[20] A life cycle assessment of biochar's climate change potential estimates the net GHG from stover pyrolysis to heat generation and biochar soil application to –be 864 kg of CO_2 equivalent per metric ton of dry feedstock.[17] This study found that 62 to 66% of the emission reductions were from permanent sequestration of carbon in biochar.

[*] Euro to dollar 2000 conversion rate: 0.923

3. THE TITLE V OFFSET PROGRAM

The Title V domestic program provides for offsets to be distributed to entities engaged in carbon mitigation or sequestration in the agricultural, forestry, and manure sectors. Specifically, Section 502(b)(1) allows offset credits to be distributed for programs that represent "verifiable" (GHG) emission reductions, avoidance, or increases in sequestration. Section 501(a)(5)(B) includes methane gas in the definition of greenhouse gases. Section 503(b) lists the specific types of practices that are to qualify for offsets under Title V. As shown in Table 2, they are categorized as: agriculture and grassland, land-use change and forestry, and manure management and disposal.

Section 507(b) requires the exchange of one offset credit for each metric ton of CO_2-e equivalent that the USDA determines to have been reduced, avoided, or sequestered during a specified time span. Section 504(e)(2) places this time span at five years for agricultural practices, 20 years for forestry practices, and 10 years for all others (i.e., manure management). The practitioner may reenroll in the offset program within 18 months of the time span's completion provided the practice still qualifies under the program.

Section 503(c) tasks the Secretary of Agriculture with updating the list of qualifying offset practices biannually to include additional programs that meet the requirements of Section 502(b)(1). The public may petition the Secretary to consider adding particular practices. It must be demonstrated that new practices will result in the mitigation or avoidance of CO_2-e emissions in an amount exceeding a pre-existing guideline before they may be added.

Section 504(a)(2)(D) states that, when accounting for carbon leakage resulting from an offset practice, indirect land use changes are to be excluded until such time as the National Academies of Science prepare a report on the accuracy of ILUC calculations, at which point the Environmental Protection Agency (EPA) Administrator and Secretary of Agriculture shall determine whether ILUC may be used as a factor in calculating the effectiveness of domestic offset practices, among other things. The legislation mandates the release of the report within four years of becoming law.

While the House of Representatives has passed the legislation containing the Title V offsets program, the companion legislation is currently stalled in the Senate and is unlikely to be passed before the 2010 midterm elections. With that said, the EPA has pledged to move ahead with regulations designed to reduce domestic GHG emissions in the event that Congress fails to enact its own legislation.

The Title V offsets program (or a similar program) could serve the same function within any future EPA regulations as it is intended to serve within the ACESA.

4. BIOCHAR AS SOIL AMENDMENT

Biochar is produced by heating plant material under oxygen-starved conditions, a process known as pyrolysis. The result is a carbon-rich material capable of resisting chemical and microbial breakdown, allowing the carbon to be sequestered for periods of time approaching hundreds or even thousands of years.[5] Biochar was first used as a soil enhancement agent by pre-Columbian inhabitants of the Amazon Basin to increase the productivity of infertile soils.[21,22] While it is difficult to discern whether char was buried intentionally, the prevalence of the practice well beyond village middens suggests that it was intentional.

In addition to sequestering carbon, field studies have shown that biochar works in conjunction with compost or fertilizers to increase crop productivity. Steiner et al. found that the application of both biochar and chemical fertilizer to test plots improved plant growth and doubled crop yields over those attained by test plots in which just chemical fertilizer was used.[23] Additionally, the biochar/fertilizer plot did not deplete the soil nutrients as much as the fertilizer plot did, despite the increased crop productivity. Other studies have found a combination of biochar and fertilizer to result in productivity increases of 25-50% and 60% over fertilizer alone.[22] A review of studies on the impact of biochar application on crop productivity revealed that the results were by no means uniform, however.[24] The effectiveness of biochar in enhancing plant fertility is a function of soil type, climate, and type of crop. The role of biochar in increasing fertility appears to be manifold including increasing cation exchange capacity and water holding capacity, reducing soil compaction, and fostering the growth of bacteria and fungi that foster symbiotic exchange of water and nutrients with plant roots.[16] The latter phenomenon is not fully understood but may account for much of the beneficial impact of biochar on fertility. For example, biochar is reported to increase nitrogen uptake of the soil by up to 400% as a result of increased microbial activity.[25]

5. PROCESS MODEL DESCRIPTION

Two distinct pyrolysis systems are modeled using Aspen Plus™ software for the daily conversion of 2000 dry metric tons of corn stover to biochar and energy products. Table 3 shows the material flow and consumption rates of the fast and slow pyrolysis processes and Table 4 shows the properties of stover. The fast pyrolysis system yields mostly bio-oil, which is subsequently upgraded to transportation fuels, and smaller quantities of biochar and pyrolysis gas. The slow pyrolysis system yields primarily biochar and pyrolysis gas, the latter substituting for natural gas in process heat applications. Table 5 shows a comparison of the product yields for both processes.

The fast pyrolysis systems employs six distinct steps for conversion of biomass to transportation fuels: pretreatment, pyrolysis, solids removal, oil recovery, heat generation, and hydroprocessing. Pretreatment consists of drying biomass to 7% moisture content and grinding it to a final particle size diameter of 3 mm. The pyrolysis reactor consists of a fluidized bed reactor operating at 450 °C and atmospheric pressure in an oxygen-free environment using a fluid bed reactor. Biochar recovery employs conventional cyclones to separate 90% of solid particles from the vapor stream. The oil recovery section employs indirect heat exchangers and an electro-static precipitator to collect condensable vapors. Non-condensable gases are recycled through the heat generation unit where they are combusted to provide heat for drying; the combustion flue gases are employed as a fluidizing agent in the pyrolysis fluid bed unit. A fraction of the biochar is combusted to provide sufficient energy to dry biomass feedstock and to sustain the pyrolysis process. Hydroprocessing of bio-oil to transportation fuels employs hydrocracking and hydrotreating with cobalt-molybdenum catalysts at 300 °C to 400 °C and 7 MPa to 10 MPa. This study assumes that requisite hydrogen for hydroprocessing is procured from an external source at a cost of $1.50 per kg. A schematic of the fast pyrolysis scenario is shown in Figure 1. Further details of the fast pyrolysis system, including detailed mass and energy balances, are found in Wright et al.[12]

The slow pyrolysis system employs four steps to generate biochar and pyrolysis gas: pretreatment, pyrolysis, solids removal, and heat generation. Slow pyrolysis employs a kiln operating at around 400 °C and atmospheric pressure. Slow pyrolysis of biomass produces mainly biochar and pyrolysis gas because of the slower heating rates and longer process times, which converts most condensable organic compounds to solid carbon, light gases and condensable liquids (mostly water, carboxylic acids, and aldehydes).

The key differences between slow and fast pyrolysis are the heating rates and maximum reaction temperatures. Slow pyrolysis heating rates are typically below 100 K/min whereas fast pyrolysis can achieve rates exceeding 1000 K/min. Reaction temperatures are about 300 °C and 500 °C for slow and fast pyrolysis respectively. Slow pyrolysis requires several minutes or even hours, while fast pyrolysis is complete in as little as two seconds. This difference in time results in dramatic differences in product distributions: slow pyrolysis generates primarily gas while fast pyrolysis generates primarily bio-oil (see). For both pyrolysis systems biochar is the second highest yielding product, typically in the range of 15-40% on a weight basis of the biomass feedstock. Product yields from slow pyrolysis are approximately 35% biochar, 30% condensable liquids and 35% syngas by mass. The condensable liquids from slow pyrolysis are not suitable for upgrading to transportation fuels and should not be confused with the energy-rich bio-oils produced by fast pyrolysis. In fact, condensable liquids from slow pyrolysis are typically burnt with pyrolysis gas without attempts to recover them as liquids.

Process economic estimates employ Aspen Icarus™ software for free-on-board equipment costs and Peters and Timmerhaus investment factors[26] to calculate total project investment. The internal rate of return (IRR) is estimated using a modified 20 year discounted cash flow rate of return spreadsheet developed by the National Renewable Energy Laboratory.[27] The spreadsheet is modified to determine the IRR for specified market values of bio-char, pyrolysis gas, and gasoline.

6. ENERGY POLICY SCENARIO

The national energy policy scenario for this analysis assumes that Congress passes ACESA in a slightly modified form. This modified version is identical to the original version with the exception that the application of biochar on cropland is included as a qualified sequestration practice under Section 503(b). Gasoline prices are assumed to experience a slight increase over the baseline under the legislation (see) (Energy Information Agency (http://www.eia.doe.gov/oiaf/servicerpt/hr2454/index.html)). Since retail gasoline prices include taxes that do not contribute to biorefinery revenues, revenues are estimated from projected pre-tax gasoline prices.

The value of domestic offsets per metric ton of CO_2-e sequestered is assumed to be identical to the price of carbon allowances under the legislation (see Table 6). The projected value of the carbon allowances over time is calculated by taking the mean of the price projections found in the currently available reports on the legislation (see Figure 2).

Calculating the value of offsets distributed for the application of biochar on cropland requires a more complex analysis. Several factors determine how much net CO_2-e is sequestered per each metric ton of biochar applied to agricultural lands. In addition to directly sequestering solid carbon, biochar is reported to significantly reduce N_2O emissions associated with the use of nitrogen fertilizers. Since biochar is assumed to be produced from crop residues that would otherwise contribute toward preserving or even building soil carbon if left on the land, the effect of its removal on soil erosion and carbon mineralization must be included in the analysis of net sequestration potential.

Assuming the widely used stover:grain fresh weight ratio of 1:1 and a 1% increase in yield over 2009 figures for northwestern Iowa (Johanns AM (http://www.extension.iastate.edu/agdm/crops/pdf/a1-12.pdf)), we project corn agriculture to yield 4.35 metric tons/acre of corn stover in 2010. Although pyrolysis is more efficient at turning biomass into solid carbon (15-40% yields) than natural decomposition of crop residues left on the field (<5%), some crop residue must be left on the field to prevent soil erosion. The amount depends on soil type, land topography, climate, and tillage practice. It is estimated that about 32% of the stover should be left on the field in northern Iowa to keep soil erosion at acceptable levels.[28] Accordingly, we assume that 68% of each acre's corn stover yield is used for biochar production.

Based on the above data, farmers with high corn yields can produce 3.0 metric tons of stover per acre while ensuring erosion control. It has been estimated that a farmer needs to receive $37-$46 per metric ton of stover to cover logistical costs (harvest, collection, storage, handling, and transportation) and $15-$17 per metric ton for the grower payment, or a total of $52-$63 per metric ton.[29] We have established a baseline feedstock selling price of $83/metric ton to provide farmers a profit of $19-$30 per metric ton or $62-$95 per acre.

In tests with a fast pyrolysis process development unit a ton of stover yielded 0.257 metric ton of biochar containing 50 wt-% ash (Brown RC, 2010, written comm.). The following formula describes the amount of CO_2-e that can be sequestered per acre of corn production based on the assumptions of biochar production via fast pyrolysis:

$$\frac{4.35 \text{ MT stover}}{\text{acre}} \times \frac{0.68 \text{ MT stover harvested}}{1 \text{ MT stover available}} \times \frac{0.257 \text{ MT biochar}}{1 \text{ MT stover}} \times \frac{0.5 \text{ MT carbon}}{1 \text{ MT biochar}} \times \frac{44 \text{ MT CO2}}{12 \text{ MT C}}$$

This equals 0.8 metric tons of biochar/acre of stover/year, or a sequestration rate of 1.4 metric tons CO_2-e/acre of stover/year. In a year in which carbon allowances are valued at $20/metric ton, this represents a nominal value to the farmer of $28/acre of stover/year.

In the case of slow pyrolysis, we estimate the biochar yield to be 0.4 metric ton per ton of stover with 32.5 wt% ash content. The amount of CO_2-e that can be sequestered per acre of corn production via slow pyrolysis is calculated according to the following formula:

$$\frac{4.35 \text{ MT stover}}{\text{acre}} \times \frac{0.68 \text{ MT stover harvested}}{1 \text{ MT stover available}} \times \frac{0.4 \text{ MT biochar}}{1 \text{ MT stover}} \times \frac{0.675 \text{ MT carbon}}{1 \text{ MT biochar}} \times \frac{44 \text{ MT CO2}}{12 \text{ MT C}}$$

This equals 1.2 metric tons of biochar/acre of stover/year, or a sequestration rate of 2.9 metric tons CO_2-e/acre of stover/year. Using the above $20/metric ton scenario, this represents a nominal value to the farmer of $58/acre of stover/year, over twice that of biochar from fast pyrolysis.

Few farmers can afford the cost of the pyrolysis facilities required for biochar production. Very likely, they would participate in larger cooperatives or trade with independently-owned pyrolysis facilities capable of serving numerous farmers. Therefore, an accounting of the real offset value to the farmer requires transportation costs to be factored into the equation. Assuming that most farmers live within 15 miles of a pyrolysis facility and considering transportation costs of $0.71/mile/metric ton stover, total transportation costs of $10.65/metric ton stover must be subtracted from the nominal offset value. The resulting values can be seen in Table 7.

The economics of biochar are likely to be improved by identifying high value applications of the other pyrolysis products. While fast pyrolysis produces 0.257 metric tons of biochar from each metric ton of stover, it also produces 0.53 metric tons of bio-oil from the same ton of stover. This bio-oil can be refined into a drop-in renewable fuel, or “green” gasoline, with 0.42 metric tons of gasoline resulting from each metric ton of bio-oil, or 0.22 metric tons of gasoline from each metric ton of stover. This fuel potential must also be accounted for, with its value increasing as the price of conventional gasoline increases. Fast pyrolysis and upgrading of stover is assumed here to yield 57 gallons of gasoline from each metric ton of stover. At a gasoline price of $3.40 per gallon, stover would be valued at $194 per metric ton.

The above data were used as the inputs in the Aspen Plus™ model to calculate the IRR that a pyrolysis plant will achieve while paying farmers $83 per metric ton of stover. These outputs represent a combination of biochar, which has value as a carbon sequestration agent via the domestic offset program and bio-oil, which can be refined into gasoline and has value as an engine fuel. The value of the stover that is used to create the outputs increases as the value of the outputs increases. Under a cap-and-trade program such as ACESA the price of carbon allowances (and thus the value of offsets) is expected to steadily increase over time as the federal government gradually diminishes the available supply. The value of biochar is directly linked to the allowance value and the value of gasoline is linked indirectly to it, since the price of gasoline is expected to increase in a carbon-regulated economy as the price of allowances (which must be purchased by refiners) increases. As such, the value of stover should also steadily increase over time.

7. RESULTS

Both process designs employ 2000 dry metric tons per day (dtpd) of corn stover. The fast pyrolysis process design generates 45.5 million gallons of transportation fuel, 124,000 metric tons of bio-char per year, and 863,000 million BTU (MMBTU) of fuel gas. The slow pyrolysis design produces 262,000 metric tons of biochar and 2,232,000 MMBTU of fuel gas.

Fixed capital cost estimates can be compared in Figure 3. Capital investment costs are lower in the slow pyrolysis scenario, which does not require systems to recover and upgrade bio-oil to transportation fuels. The only capital cost that is higher for the slow pyrolysis system is storage facilities for biochar, since slow pyrolysis generates more biochar than does fast pyrolysis for the same processing capacity. This does not include the costs of any safety measures potentially made necessary by biochar's combustible nature, as they have not yet been quantified in the existing literature. Total project investment costs are estimated at $200 million and $132 million for the fast and slow pyrolysis scenarios, respectively.

Total annual operating costs for the slow and fast pyrolysis scenarios are shown in Figure 4, assuming corn stover feedstock cost of $83 per metric ton ($75 per short ton). Total annual operating costs exclusive of feedstock costs are $11.1 million and $18.8 million for the slow and fast pyrolysis scenarios respectively, which include product credits for fuel gas of $11.2 million, and $7.1 million for char and fuel gas. Product credits can compensate for almost half of the non-feedstock operating expenditures of the slow pyrolysis design at fuel gas prices of $5/MMBTU. Fast pyrolysis product credits consist of fuel gas and bio-char valued at $20/ton. Minimum product selling prices are estimated at $346 per metric ton of bio-char for slow pyrolysis and $2.68 per gallon of transportation fuel for fast pyrolysis.

The IRR for a pyrolysis facility will be strongly dependent upon the cost of delivered biomass feedstock and the market prices for the biochar and energy products, all of which are likely to fluctuate dramatically as national policy evolves on agriculture, energy, and climate. Thus, it is important that IRR is sufficiently high under the best estimate of future prices of feedstocks and pyrolysis products that investors will be willing to support a new pyrolysis facility. Figure 5 plots estimated IRR between 2015 and 2030 for fast pyrolysis and slow pyrolysis systems that produce both biochar and energy products based on projected prices for carbon credits, gasoline and natural gas over that time frame. Two delivered costs for feedstock are assumed: $0 per metric ton for a hypothetical waste feedstock and $83 per metric ton for stover.

Slow pyrolysis has a projected IRR that is negative during the whole time period for feedstock costing $83 per metric ton. Even if the feedstock were free, the IRR would only range between 8% and 17%, which is usually not considered sufficiently profitable for new technology enterprises. Although slow pyrolysis produces more biochar than fast pyrolysis, the profitability of either biochar enterprise rests on the value of its energy product. For slow pyrolysis this energy product is pyrolysis gas, which can serve as a substitute for natural gas based on energy content ($/MMBtu). The price of natural gas is not projected to be high enough to make the slow pyrolysis system economically attractive.

Fast pyrolysis is projected to have an IRR of 29%-37% for zero-cost feedstock and 15-26% for $83 per metric ton feedstock. Although these returns are significantly higher than for slow pyrolysis, they may still be marginal for large capital investment projects. On the other hand, these could be attractive returns if the fast pyrolysis plants can be gradually introduced as small, distributed installations that ship bio-oil to existing petroleum refineries for refinement. Although the fast pyrolysis scenario sequesters less carbon than does the slow pyrolysis scenario, the ultimate energy products produced by the fast pyrolysis system (transportation fuels) have significantly more value than the products from the slow pyrolysis system (biochar and pyrolysis gas), making fast pyrolysis a more attractive scenario for profitable biochar production.

8. SENSITIVITY ANALYSIS

There are various key variables that can have a significant impact on the cost of producing biobased products. This study considered the impact of process performance (bio-oil and fuel yield), product values (corn stover, pyrolysis gas, biochar, hydrogen, and catalyst), and capital costs. The impact of varying the assumed values of these variables can be seen in Figure 6 and Figure 7.

Figure 6 includes the sensitivity analysis results for the corn stover fast pyrolysis scenario. To achieve a baseline IRR of 10%, the selling price of renewable transportation fuel is set at $2.68 per gallon gasoline equivalent. Negative IRR values indicate that investors would not recuperate their initial investment. The most significant parameters affecting IRR are bio-oil yield, biomass cost, fuel yield, fixed capital cost, hydrogen price, gas credit value, char value, and catalyst cost, in that order. Bio-oil yield within the range of 55 to 70 wt% changed profitability of gasoline from corn stover from -5.8% to 19%. Biomass costs of $110 to $55 per metric ton varied the IRR from 2.7% to 16%. On the other hand, the selling prices of co-products bio-oil and pyrolysis gas had relatively little impact on profitability of the fast pyrolysis scenario.

Figure 7 shows the results of sensitivity analysis for the slow pyrolysis scenario. To achieve a baseline IRR of 10%, the selling price of biochar is set at $346 per ton. The most significant parameters affecting IRR are char yield, biomass cost, gas credit value, fixed capital cost, and fuel gas yield in that order. Biochar yields ranging between 27 and 45 wt% increased IRR of the slow pyrolysis scenario from -6% and 19%. Biomass costs ranging from $110 to $55 increased IRR from -3% to 18%. Gas credit value ranging from $0 to $16.5/MMBTU increased IRR from 3% to 21%. Capital costs and fuel gas yield had relatively small effects on the profitability of the slow pyrolysis scenario.

9. POLICY IMPLICATIONS

The pyrolysis of corn stover has the ability to sequester carbon from the atmosphere, improve U.S. energy security and provide additional income to rural communities. These advantages will only arise if pyrolysis facility are sufficiently profitable to attract investment capital. Shrinking credit markets following the 2008 banking crisis have made start-up capital more difficult to acquire and anecdotal evidence suggests that potential investors and creditors will demand minimum facility IRRs on the order of 25% before investing or loaning the necessary capital. Without such guarantees the commercialization of pyrolysis and the subsequent environmental and economic benefits are unlikely to occur.

While significant emphasis[30,31,32] has been placed on increasing the commercial attractiveness of pyrolysis facilities through technological developments, policy can also play a significant role in encouraging investment in this promising technology. One method would be the creation of a cap-and-trade program with an offset program including biochar as an offset practice, as envisioned in this paper. Pyrolysis would experience a twofold benefit under such a program: owners of pyrolysis facilities and farmers would receive offset credits for biochar-related GHG sequestration and mitigation while biobased gasoline would attain a cost advantage over petroleum-based gasoline, increasing the profitability of pyrolysis facilities. While assigning biochar an offset value will make fast pyrolysis slightly more profitable, increasing the bio-oil yield per metric ton of feedstock will result in a significant improvement to facility profitability. As this paper shows, the adoption of fast pyrolysis will encourage biochar production even when biochar alone is not profitable.

State programs could also improve the profitability of pyrolysis facilities in the absence of a national cap-and-trade program. As illustrated in Figure 4, feedstock costs comprise the majority of the operating costs for both slow and fast pyrolysis facilities. Feedstock costs are in turn largely influenced by transportation costs. In the Midwest an average of $0.28 per gallon is added to the price of diesel (which is commonly used by individuals transporting in bulk) in the form of state taxes (API (http://www.api.org/statistics/fueltaxes/)). State governments could reduce stover transportation costs by providing tax credits to farmers transporting corn stover in the amount of the state diesel tax paid while doing so. This would also increase the effective supply radius of pyrolysis facilities, enabling the construction of large facilities and the advantages resulting from their economies of scale, further decreasing pyrolysis costs.

10. CONCLUSIONS

The profitability of two biochar production scenarios was investigated: fast pyrolysis of corn stover to produce fuel gas, biochar, and transportation fuel and slow pyrolysis of corn stover to produce fuel gas and biochar. Capital costs for biorefineries producing 2000 metric tons per day are estimated to be $132 and $200 million for the slow and fast pyrolysis scenarios respectively.

Projected carbon prices under the ACESA legislation indicate that biochar sequestration could receive credits of $20 per metric ton biochar in 2015 and up to $60 per metric ton by 2030. The impact of projected carbon and energy prices was determined by estimating IRRs based on corn stover in the price range of zero to $83 per metric ton. The fast pyrolysis scenario has an IRR ranging between 29% and 37% for zero-cost feedstock and between 15% and 26% for a more realistic corn stover price of $83 per metric ton. The slow pyrolysis IRR ranges between 8% and 17% at a $0 per ton feedstock price, but is not profitable when corn stover costs a more realistic $83 per metric ton.

The value of biochar is relatively low even when sequestered carbon is valued as $20-$55 per metric ton CO_2-e. Thus, a pyrolysis facility that operates primarily to generate biochar as an ACESA carbon offset is unlikely to be profitable for the foreseeable future. On the other hand, a pyrolysis facility that co-produces biochar for carbon sequestration and bio-oil for transportation fuel has relatively attractive economics based on projected future prices for gasoline and sequestered carbon.

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Table 1 Carbon Sequestration Rates by Region and Practice (metric tons CO_2-e/acre/year)*

Region	From cropland to forest	From pasture to forest	From CAC to grassland	From conventional till to conservation till
Appalachia	5.75	3.43	1.40	0.49
Corn Belt	3.43	3.10	1.79	0.62
Delta States	6.30	3.76	1.85	0.65
Lakes States	4.87	4.54	1.55	0.55
Mountain States	0.00	0.00	0.91	0.31
Northeast	4.42	4.09	1.41	0.49
Northern Plains	0.00	0.00	1.38	0.49
Pacific States	2.93	2.93	1.14	0.40
Southeast	5.75	3.43	1.20	0.41
Southern Plains	2.66	2.65	1.44	0.51

Sources: Birdsey[1]; Lewandrowski J, Peters M, Jones C, House R, Sperow M, Eve M, *et al.* (http://www.ers.usda.gov/Publications/TB1909/)

* Includes data for Southern Plains that was found in Birdsey but was not included in the original Lewandrowski study.

Table 2 Specific Practices that Qualify for Offsets under Title V (http://energycommerce.house.gov/Press_111/20090720/hr2454_sectionsummary.pdf)

Agricultural	Forestry	Manure Management
• Altered tillage practices • Winter cover cropping • Reduced N fertilizer use • Reduced GHG emissions from manure • Reduced GHG emissions from animals • Reduced flooding of rice paddies • Reduced C emissions from organic soils	• Afforestation/reforestation • Increased forest carbon stores • Management of peatland/wetland • Conservation of grassland/forest • Reduced deforestation • Urban tree-planting • Agro-forestry • Increased forest sequestration via gen. eng.	• Waste aeration • Biogas capture and combustion • Replacing commercial fertilizer with manure

Table 3 Material flow and consumption rates for slow and fast pyrolysis on a dry basis

Input (dry basis)	Slow Pyrolysis [metric ton/day]	Fast Pyrolysis [metric ton/day]
Biomass	2000	2000
Output (dry basis)		
Biochar	723	567 (~150 consumed)
Bio-oil	0	1168
Pyrolysis Gas	1277 (~425 consumed)	265 (265 consumed)

Source: Wright MM, Daugaard DE, Satrio JA, and Brown RC (2010)[12]

Table 4 Properties of Corn Stover

Ultimate Analysis (dry basis)	
Element	**Value (wt %)**
Ash	6
Carbon	47.28
Hydrogen	5.06
Nitrogen	0.8
Chlorine	0
Sulfur	0.22
Oxygen	40.63
Proximate Analysis (wet basis)	
Element	**Value (wt %)**
Moisture	25.0
Fixed Content	17.7
Volatile Matter	52.8
Ash	4.5

Source: Wright MM, Daugaard DE, Satrio JA, and Brown RC (2010)[12]

Table 5 Product Yields (wt%) for Corn Stover Pyrolysis (dry basis)

Product Yields	Slow Pyrolysis	Fast Pyrolysis
Pyrolysis Gas	64	21
Pyrolysis Char	36	26
Pyrolysis Oil	<1	53

Source: Laird DA, Brown RC, Amonette JE, and Lehmann J (2009)[16]; Brown RC, 2010, written comm.

Table 6 Projected Price of Gasoline, Natural Gas, and Carbon Offset Values (from EIA) under ACESA between 2015 and 2030

Year	Gasoline Pump Price ($/gal)*	Gasoline Pre-tax Price ($/gal.)†	Natural Gas Price ($/MMBTU)	Carbon Offset Value ($/metric ton CO_2-e)
2015	3.44	2.96	12.78	17.33
2016	3.51	3.04	12.79	18.59
2017	3.59	3.12	12.81	19.85
2018	3.67	3.19	12.83	21.10
2019	3.74	3.27	12.84	22.36
2020	3.82	3.35	12.86	23.62
2021	3.86	3.38	13.20	25.17
2022	3.89	3.42	13.54	26.73
2023	3.93	3.45	13.89	28.28
2024	3.96	3.49	14.23	29.84
2025	4.00	3.52	14.57	31.39
2026	4.03	3.56	14.92	32.94
2027	4.07	3.59	15.26	34.50
2028	4.10	3.63	15.60	36.05
2029	4.14	3.66	15.95	37.61
2030	4.17	3.70	16.29	39.16

* Annual gasoline price projections are not available in EIA (2009). Data was collected for the years available and assumed to move on a linear progression during the missing years.

† Assumes the average gasoline tax in the U.S. remains unchanged from the 2010 amount (API 2010).

Table 7 Biochar Offset Value Under ACESA

Year	Biochar Offset Value ($/metric ton)
2015	20
2016	22
2017	25
2018	27
2019	29
2020	32
2021	34
2022	37
2023	40
2024	43
2025	46
2026	49
2027	52
2028	54
2029	57
2030	60

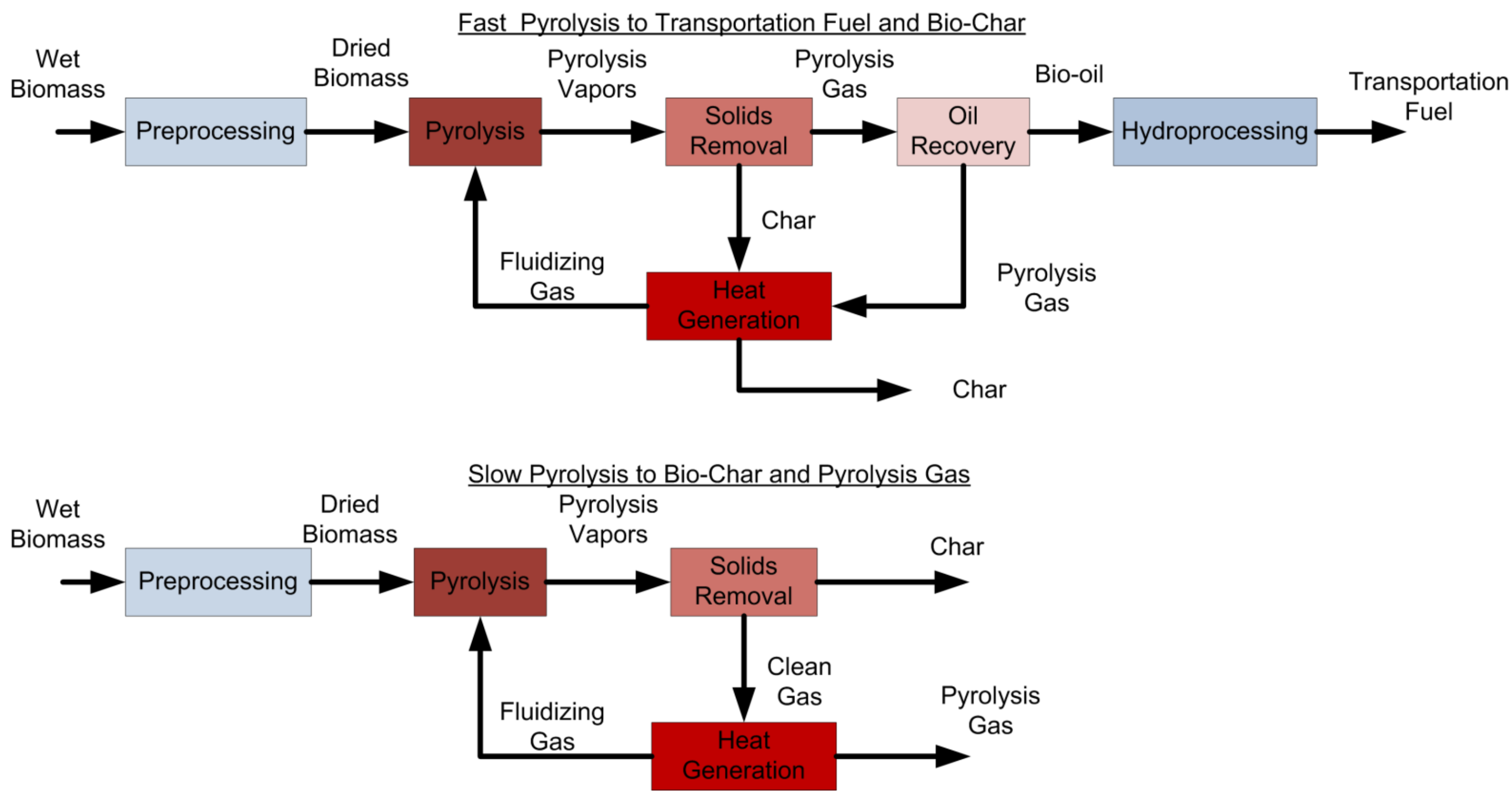

Figure 1 Biomass Pyrolysis Pathways to Biochar and Energy Product

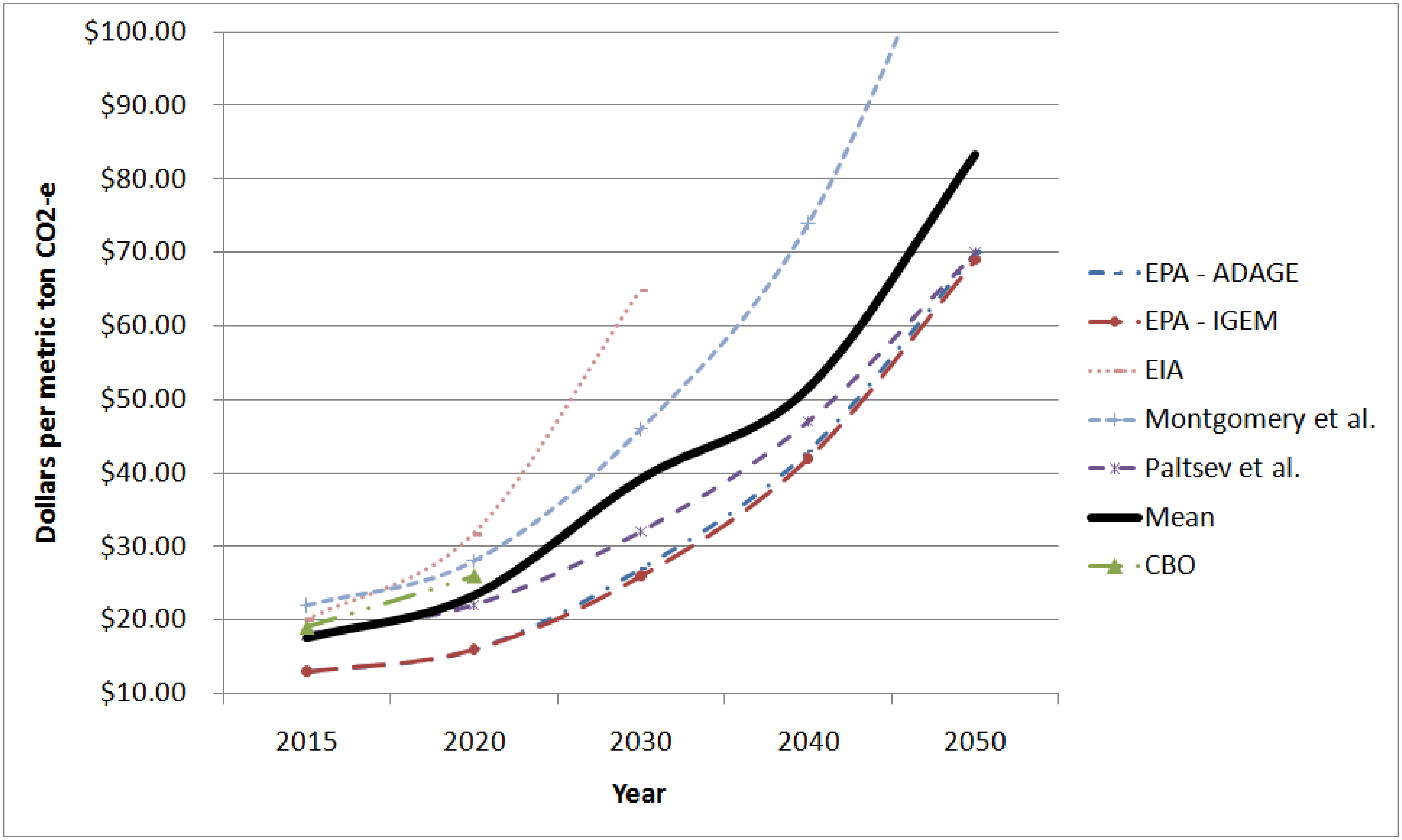

Figure 2 Survey of projected carbon prices ($ per metric ton) (Source: (Brown, Elobeid et al. 2010))

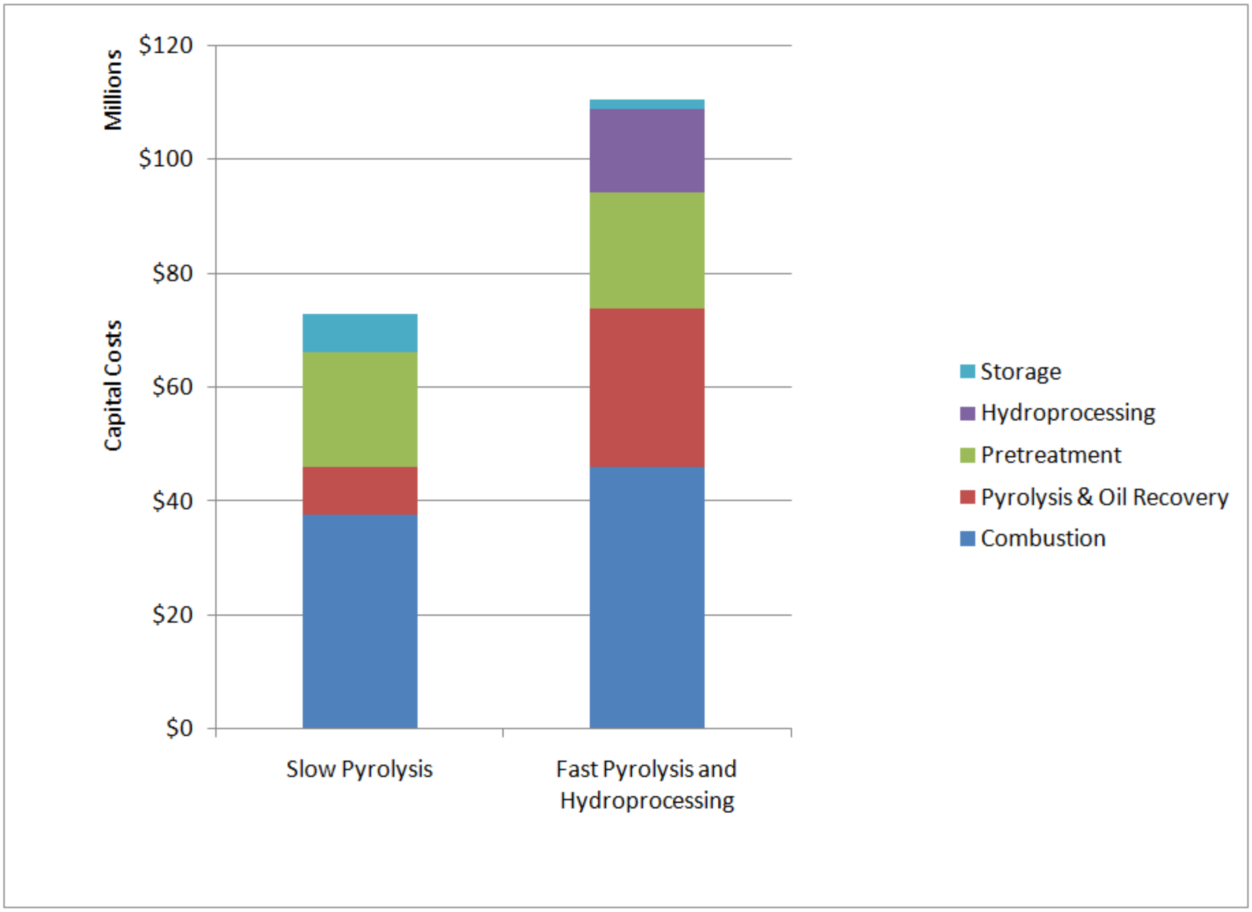

Figure 3 Fixed Capital Investment for Corn Stover Pyrolysis to Transportation Fuels/Bio-Char/Pyrolysis Gas Scenarios (Indirect Costs, Working Capital, and Land Costs Not Included)

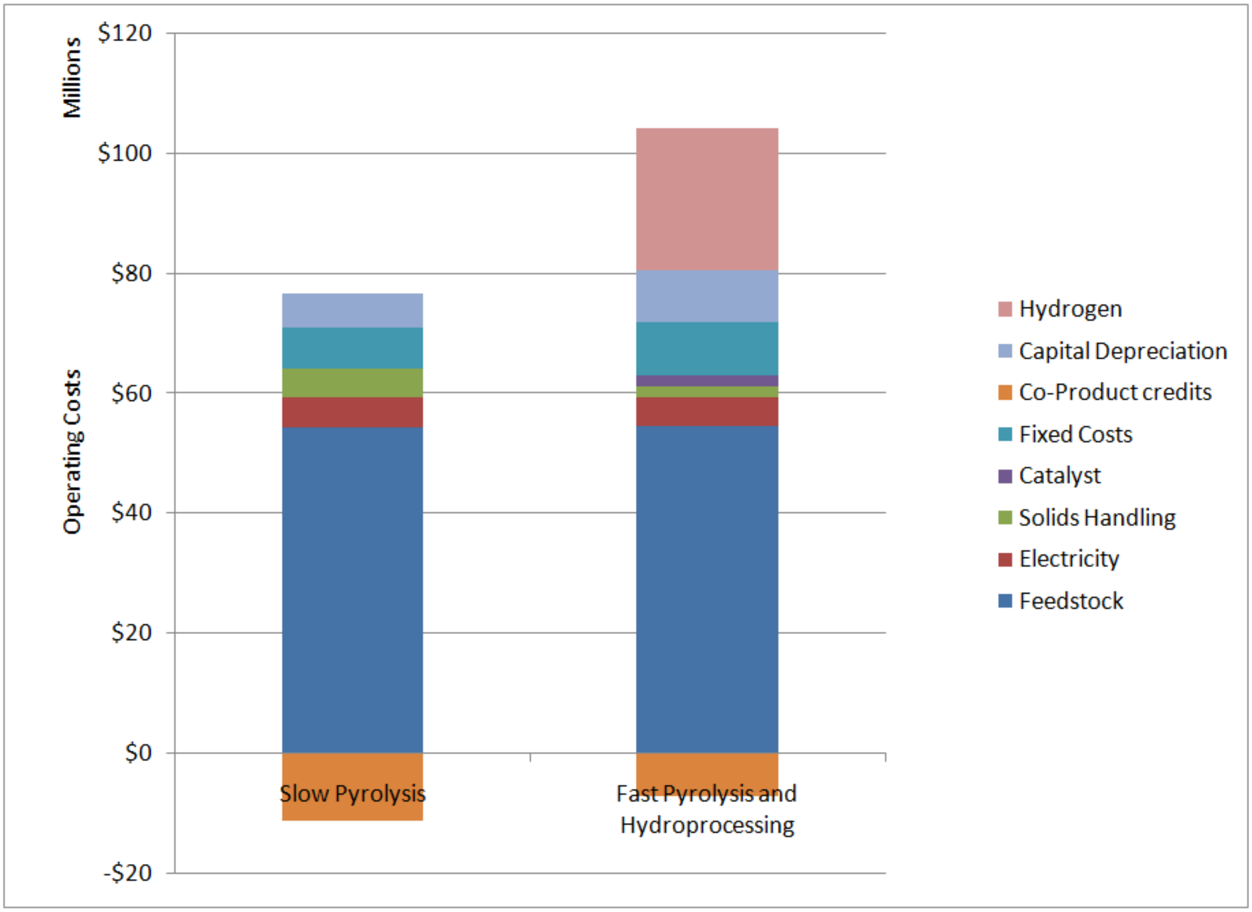

Figure 4 Operating Costs for 2000 Dry Ton per Day Corn Stover Pyrolysis-to-Transportation Fuels/Bio-Char/Fuel Gas Scenarios Assuming Feedstock Cost of $83 per Dry Metric Ton

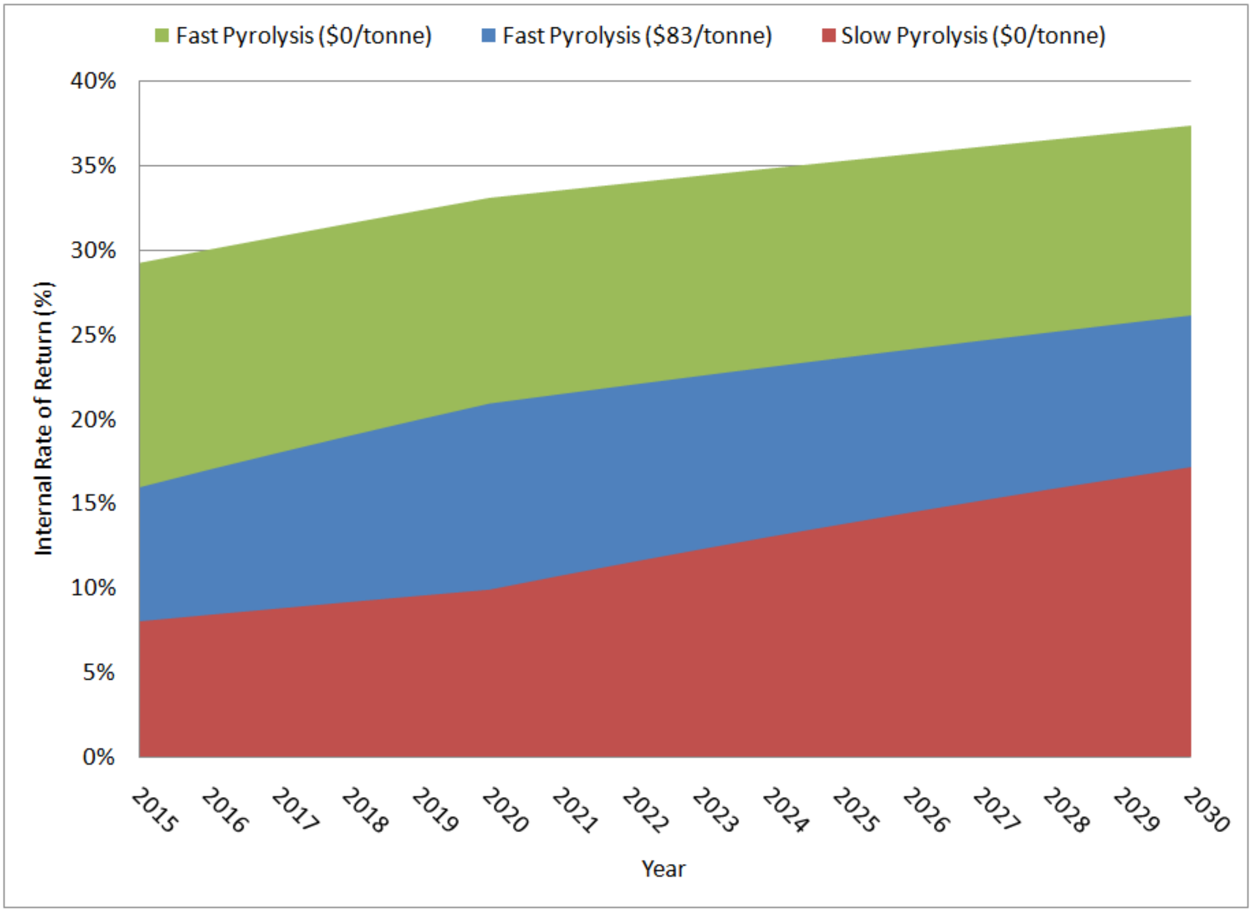

Figure 5 IRR Ranges for Corn Stover Pyrolysis to Fuels and Bio-Char Based on Projections for the Value of Bio-Char (Carbon Credits from ACESA) and Fuel Prices (Natural Gas and Gasoline from EIA)

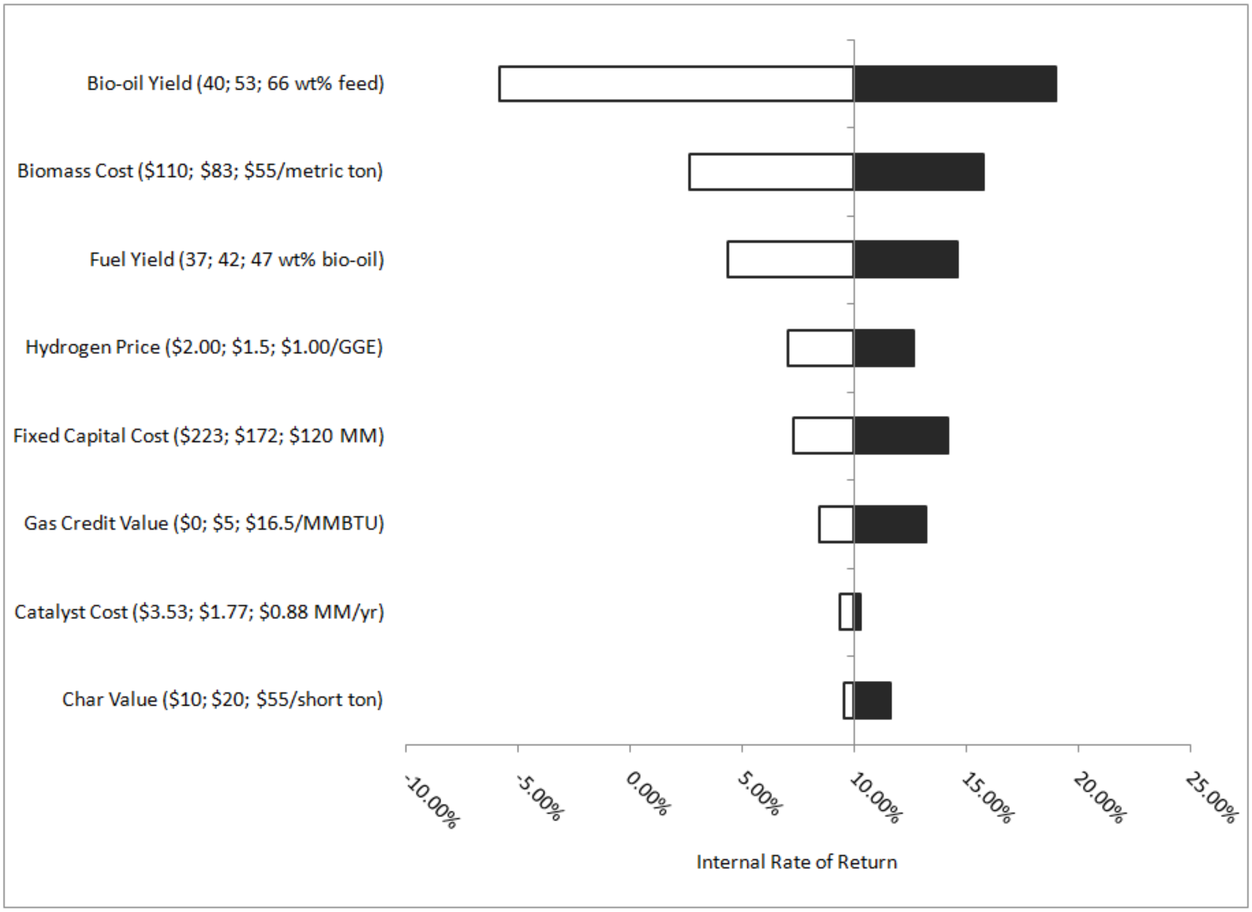

Figure 6 Sensitivity Analysis for 2000 Dry Metric Tons per Day Corn Stover Fast Pyrolysis to Transportation Fuels/Bio-char/Fuel Gas. To Achieve the Baseline IRR of 10%, Renewable Transportation Fuel is Assumed to Sell for $2.68 Per Gallon Gasoline Equivalent

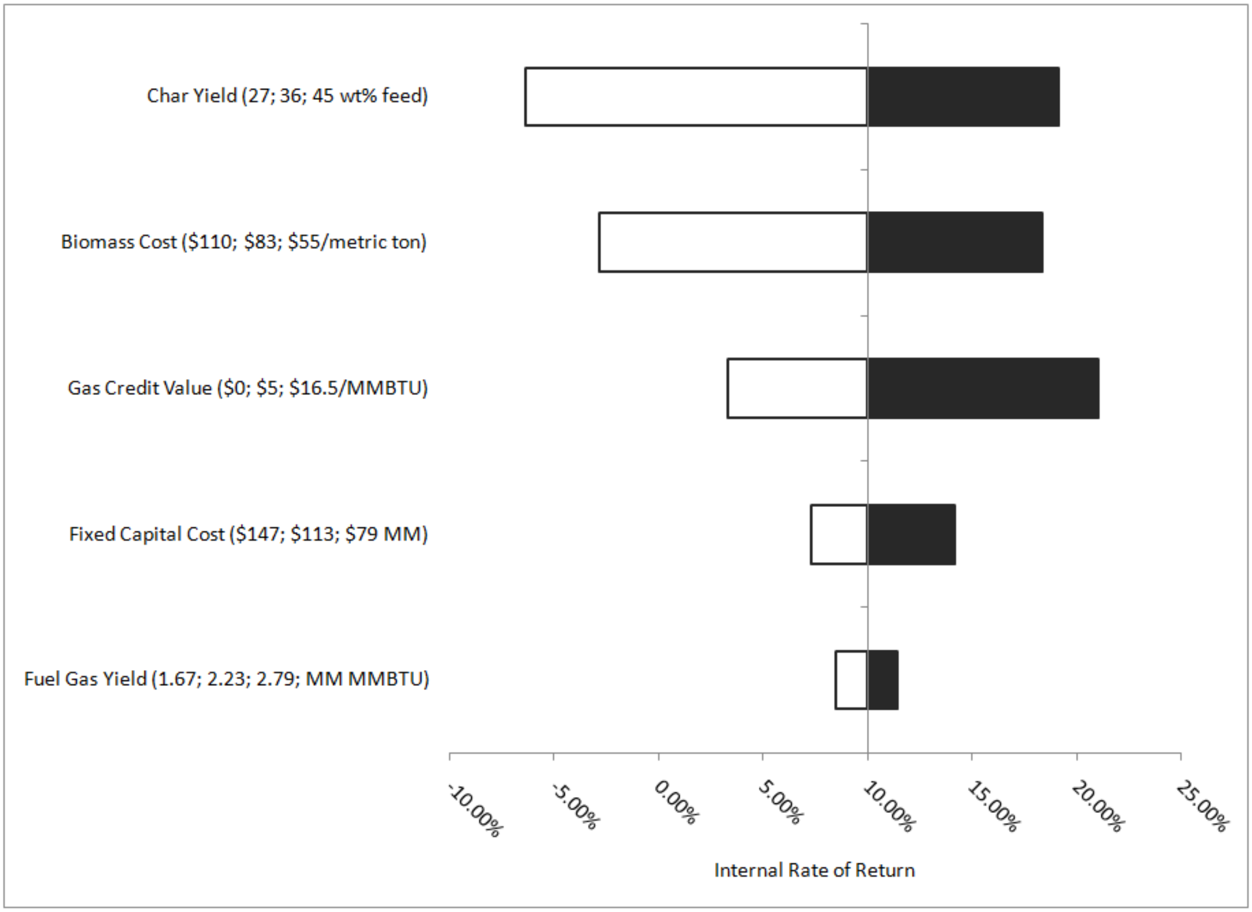

Figure 7 Sensitivity Analysis for 2000 Dry Metric Tons per Day Slow Pyrolysis- to-Biochar and Fuel Gas. To Achieve the Baseline IRR of 10%, Biochar is assumed to Sell for $346 per Metric Ton