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

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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.

Keywords

fast pyrolysis, hydroprocessing, catalytic pyrolysis, techno-economic analysis, Bioeconomy Institute, Mechanical Engineering

Disciplines

Industrial Engineering | Mechanical Engineering | Systems Engineering

Comments

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Technoeconomic Sensitivity of Biobased Hydrocarbon Production via Fast Pyrolysis to Government Incentive Programs

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Guiping Hu[2]

Abstract

Fast pyrolysis and upgrading is a promising thermochemical pathway that produces pyrolysis oil that can be upgraded via hydroprocessing into hydrocarbon-based transportation fuels (drop-in biofuels). The internal rate of return (IRR) of a fast pyrolysis and upgrading facility is a function of feedstock cost and projected revenues. We calculate the IRR of a fast pyrolysis and upgrading facility under six different policy scenarios: [1] a baseline scenario in which the facility receives no government support; [2] a scenario in which cap-and-trade (H.R. 2454) is enacted with both carbon price and offsets; [3] a scenario in which the Volumetric Ethanol Excise Tax Credit (VEETC) is modified to include drop-in biofuels; [4] a scenario in which the VEETC is replaced with a variable VEETC; [5] the revised Renewable Fuel Standard (RFS2); and [6] the Cellulosic Biofuel Producer Tax Credit (CBPTC). Combinations of these policy scenarios are also analyzed. We find that the policies responsible for increasing the value of pyrolysis products increase facility IRR the most, while policies minimizing facility tax burden have an only marginal effect on IRR.

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Keywords: Fast pyrolysis; Technoeconomic analysis; Energy policy; Drop-in biofuels; Corn stover

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Introduction

The last decade has witnessed rapid growth in the development and production of hydrocarbons from renewable biomass feedstocks such as lignocellulose and lipids. Indistinguishable from their petroleum-based counterparts, these biobased hydrocarbons can be used to create a variety of products that have heretofore been the sole domain of the petroleum industry, including gasoline and diesel fuel (Carlson et al. 2008; Jones et al. 2009; Anex et al. 2010), commodity chemicals (Holladay et al. 2007; Bozell 2008; Christensen et al. 2008; Ahmad et al. 2010; Vispute et al. 2010), and plastics (Snell and Peoples 2009). While several pathways within the biochemical and thermochemical routes exist for the production of biobased hydrocarbons, fast pyrolysis is an economically attractive option (Jones and Zhu 2009a; Anex et al. 2010; Wright et al. 2010a). Strictly defined as the thermal decomposition of biomass at high temperatures (400-600°C) for short periods of time (<2s), fast pyrolysis converts biomass feedstock into gas (syngas), solid (char), and liquid (pyrolysis oil) products. Pyrolysis oil is a viscous, oxygenated, and corrosive mixture of polymeric chemical compounds that has little immediate commercial value (McCarl et al. 2009). Pyrolysis oil must be upgraded via a combination of hydrotreating and either hydrocracking or fluid catalytic cracking (FCC) before high-value biobased hydrocarbons can be derived from it. Char can serve as a low-value coal substitute but may have higher value as a carbon sequestration and soil amendment agent (Gaunt and Lehmann 2008; Laird 2008; McCarl et al. 2009; Brown et al. 2011).

Biobased hydrocarbons produced via fast pyrolysis and upgrading can be blended into fuels commonly known as “drop-in biofuels” due to their chemical similarity to petroleum-based fuels such as gasoline and diesel, which allows them to be “dropped into” existing petroleum-based

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transportation fuel infrastructures. The minimum selling price (MSP) of drop-in biofuels produced via fast pyrolysis and upgrading at a 2000 dry metric tons per day (MTPD) facility is estimated to be between $0.46 and $0.82 per liter (Jones et al. 2009b; Brown et al. 2010; Wright et al. 2010a). The upper bound of this range is slightly higher than the sustained pre-tax price of gasoline in the U.S. However, the production of first- and second-generation biofuels (i.e., ethanol from corn and cellulose, respectively) in the U.S. is incentivized by the federal government via a combination of subsidies (the Volumetric Ethanol Excise Tax Credit, or VEETC, and the Cellulosic Biofuel Producer Tax Credit, or CBPTC), a purchase mandate (the Renewable Fuels Standard, or RFS2), a tariff on imported ethanol, and various below-market loans and loan guarantees (while various states offer their own incentives, the wide range of available options exceeds the scope of this paper). Whereas the tariff and VEETC only apply to ethanol, the RFS2 mandates the purchase of 5.11 billion liters of advanced biofuels (defined as biofuels utilizing feedstocks other than corn starch) in 2011, including biobased gasoline if available. The CBPTC also applies to cellulosic biofuels in addition to ethanol. At present there are no technoeconomic analyses (TEAs) in the literature for fast pyrolysis and upgrading that account for these government incentives.

Several additional government programs that would impact the MSP of drop-in biofuels produced via fast pyrolysis have been proposed by U.S. policymakers but not yet implemented at the time of writing. Examples include the cap-and-trade program created by the American Clean Energy and Security Act of 2009 (H.R. 2454), which was passed by the House of Representatives but failed to make it out of the Senate, and regulations on large petroleum refineries and power plants proposed by the Environmental Protection Agency (EPA) (Wald 2010b). One technoeconomic analysis of drop-in biofuel production via fast pyrolysis and

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upgrading at a 2000 dry MTPD facility calculates the MSP with H.R. 2454 enacted to be $0.71

per liter (Brown et al. 2010), with the facility benefiting under H.R. 2454 due to higher costs of production for competing petroleum-based gasoline and diesel due to the carbon price and the receipt of carbon offset credits for biochar production by the pyrolysis facility. This result suggests that government policy can improve the economic feasibility of drop-in biofuel production via fast pyrolysis, although it is unclear whether other programs could have as pronounced an effect.

The objective of this paper is to analyze the technoeconomics of drop-in biofuel production under six national policy scenarios: [1] a baseline scenario in which the fast pyrolysis and upgrading facility receives no government support; [2] a scenario in which H.R. 2454 is enacted with both a carbon price and carbon offsets; [3] a scenario in which the VEETC is modified to include drop-in biofuels as well as ethanol; [4] a scenario in which legislation replacing the existing VEETC with a variable VEETC is enacted (based on S.884 – the Domestic Energy Promotion Act of 2011), also modified to include drop-in biofuels; [5] the RFS2; and [6] the CBPTC. Combinations of these scenarios are also analyzed. The fast pyrolysis and upgrading process is reviewed and the policy scenarios are detailed. The policy scenarios incorporate data from government reports and extrapolate missing data when necessary. The results from the different scenarios are presented and compared, concluding with a discussion of their implications.

Background on Fast Pyrolysis

The economic (Cottam and Bridgwater 1994; Bridgwater et al. 2002; Badger and Fransham

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2006; Ringer et al. 2006; Jones and Zhu 2009a; Jones et al. 2009b; McCarl et al. 2009; Brown et

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al. 2010; Trippe et al. 2010; Vispute et al. 2010; Wright et al. 2010a) and environmental (Gaunt and Lehmann 2008; Shoemaker et al. 2008; Laird et al. 2009; Fan et al. 2010; Roberts et al. 2010) aspects of pyrolysis are thoroughly covered in the literature. Heat, power, drop-in biofuels, carbon sequestration, soil amendment agents, and biobased commodity chemicals have all been considered as potential fast pyrolysis products. McCarl et al. (2009) examined the economics of fast pyrolysis as a pathway for heat and power generation and found it to be economically infeasible. Brown et al. (2010) examined the economics of fast pyrolysis and upgrading as a drop-in biofuel and carbon sequestration pathway and found it to be economically infeasible in the near term even with the existence of a high-value carbon offset program. Fast pyrolysis has also been proposed as a pathway for the production of high-value biobased chemicals by Vispute et al. (2010), although the analysis does not account for operating costs and does not provide an answer to the question of the pathway's economic feasibility as a result.

A major advantage to upgrading and refining pyrolysis oil into drop-in biofuels is that the resulting fuels are capable of utilizing the existing fuel infrastructure without any modification (unlike ethanol, which can only be blended with gasoline in quantities of up to 10-15% before necessitating expensive infrastructure upgrades). Drop-in biofuels are identical to petroleum-based hydrocarbons for consumers, giving the fuel a significant advantage in light of recent controversy over increasing the ethanol blend to 15% (Wald 2010a). This also causes fast pyrolysis and upgrading facility income to operate as a function of gasoline prices, as these dictate the value of drop-in biofuels produced by the facility. Raw pyrolysis oil cannot be used as a transportation fuel due to its corrosive and viscous properties, however, and must first be upgraded and refined into drop-in biofuels (Czernik and Bridgwater 2004). Both processes require substantial quantities of hydrogen and existing technoeconomic analyses (TEAs) of the pyrolysis oil upgrading and refining processes highlight the impact that hydrogen procurement strategy has on the project's economic feasibility (Holmgren et al. 2008; Jones et al. 2009b; Wright et al. 2010a). These reports calculate the MSP for drop-in biofuel production via fast pyrolysis and upgrading to range from \$1.74 to \$3.09. All but the highest estimate suggest that these drop-in biofuels are economically feasible over the next 20 years based on the Energy Information Agency's (EIA) projected energy prices (see Table 2) (EIA 2011a).

While the ability to produce drop-in biofuels at costs competitive with those of gasoline and diesel is necessary to ensure receipt of the capital investment required to build and operate a pyrolysis facility, it alone is not sufficient. Communications with biobased industry representatives indicate that capital investors require projected internal rates of return (IRRs) of at least 25% over 20 years for investment consideration (Biobased Industry Center Advisory Board, personal communication, October 2010). Existing TEAs of drop-in biofuel production via pyrolysis assume a 10% IRR (Holmgren et al. 2008; Jones et al. 2009b; Wright et al. 2010a), which falls short of the requisite 25% threshold. Competitiveness with petroleum-based hydrocarbons is of little importance if construction of the pyrolysis facility never commences due to a lack of capital investment and this analysis employs the 25% threshold as the target IRR as a result.

Previous studies have reported a high sensitivity of fast pyrolysis and upgrading facility IRR to factors such as drop-in biofuel market value, pyrolysis oil and biofuel yields, and feedstock costs (Jones et al. 2009b; Wright et al. 2010a; Brown et al. 2011). This suggests that such a facility will benefit most from policies that increase the market value of the drop-in biofuels it produces

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rather than those that decrease its tax liability or labor costs.

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Federal Incentive Programs for Biofuel

Five major government programs incentivizing biofuel production are either in operation or have been considered by Congress. Of those already in existence, the largest historically is the Volumetric Ethanol Excise Tax Credit (VEETC), popularly known as the “blender’s credit.” The VEETC is a tax incentive for gasoline blenders in the amount of $0.12 per liter of pure ethanol (190+ proof) that is blended with gasoline (Department of Energy 2011). The incentive is first taken as a credit against the blender’s income tax liability, with any amount remaining claimed as a direct payment from the Internal Revenue Service (IRS). This can effectively reduce a blender’s tax liability to zero and, if enough ethanol is blended, provide it with additional income of $0.12/liter of additional ethanol blended. This credit is assumed to be passed onto ethanol producers in the form of an increase to product value of $0.12/liter. For analytical purposes it is assumed that the VEETC applies to drop-in biofuels in addition to ethanol, although this is not reality at present.

Controversy regarding the supposed negative impact of U.S. corn ethanol production on global food prices and tropical deforestation has spurred two simultaneous efforts in Congress to remove the VEETC. The first, the “Ethanol Subsidy and Tariff Repeal Act” (S.871), would completely eliminate the VEETC in 2011 if enacted. A competing bill, the “Domestic Energy Production Act of 2011” (S.884), would phase out the VEETC by 2013 and replace it with a variable credit tied to the price of oil if enacted. This “variable VEETC”, which would in turn be phased out in 2016, would effectively have no value as the bill reduces it to $0.00/liter when the price of oil surpasses \$90/bbl, a threshold the EIA expects to be permanently passed by 2014 (EIA 2011a). S.871 is modeled in any scenario that incorporates neither the VEETC nor S.884.

The little sibling to the VEETC (despite its greater value on a per liter basis) is the Cellulosic Biofuel Producer Tax Credit (CBPTC). Whereas the VEETC is a tax incentive to the ethanol blender that is expected to pass through to the ethanol producer, the CBPTC is a tax incentive directly to the biofuel producer in the amount of $0.27 per liter of biofuel produced (Department of Energy 2011). Unlike the VEETC, the CBPTC may only be taken against the producer's income tax liability. This reduces its maximum effective value to an amount equal to the producer's income tax burden.

The Environmental Protection Agency's (EPA) revised Renewable Fuels Standard (RFS2) is a regulatory program that mandates the consumption of different biofuels. Obligated parties (i.e., those introducing gasoline into the marketplace) are required by the RFS2 to obtain a percentage of their fuel from renewable sources. Obligated parties that do not produce qualifying biofuels have the alternative of buying Renewable Identification Numbers (RINs) from producers that do so (or other obligated parties that produce more than they are required to under the mandate). This represents an additional source of income for producers, as the upper bound of a RIN's value is the higher of $0.07/liter or the difference between $0.79/liter and the average gasoline price (Miao et al. 2010).

The final policy proposal analyzed is the now-defunct H.R. 2454. H.R. 2454 was passed by the House of Representatives in June 2009 but failed in the Senate the following fall. Nonetheless, it is a useful policy scenario to analyze due to its incorporation of both a carbon price and carbon offsets and the availability of price data from government analyses of the legislation (see Table 1). Further information on H.R.2454 and its offsets program is provided by Brown et al. (2011).

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Finally, a baseline scenario is constructed using data from the EIA's 2011 Annual Energy Outlook (EIA 2011a) (see Table 2). The purpose of the baseline is to provide an IRR based solely on current macroeconomic forecasts rather than policy scenarios, whether existing or proposed.

Process Model Description

A fast pyrolysis and upgrading system converting 2000 dry MTPD of stover to energy products and biochar is modeled using Aspen Plus$^{\text{TM}}$ process model software. A schematic of the system is shown in Figure 1. Table 3 provides the ultimate and proximate analyses of the stover feedstock. The feedstock cost at the pyrolysis facility gate is assumed to be $83 per dry MT, which includes collection, storage, and transportation (Atchison and Hettenhaus 2004; Graham et al. 2007; Petrolia 2008). The six major processing steps are: pretreatment, pyrolysis, solids removal, pyrolysis oil recovery, heat generation from fractions of co-products syngas and char, and hydroprocessing of the pyrolysis oil.

Pretreatment involves grinding the stover into fine particles of 3mm in diameter before drying to 7% moisture content. The particles are then fed into a fluidized bed reactor where pyrolysis occurs at 480°C and atmospheric pressure in the absence of oxygen. The reactor yields 62 wt% pyrolysis oil, 21 wt% syngas, and 17 wt% char (Wright et al. 2010a). The solids removal stage employs cyclones to separate up to 90% of the solid particles (i.e., char) from the vapor stream. Cyclones are also used to remove ash from the non-condensable vapors (i.e., syngas), which is disposed of at a cost of $18/MT. Approximately 80% of the syngas and 33% of the char collected during the solids removal stage are combusted for heat and power generation. The remaining syngas is sold as fuel gas for $5.44/GJ and the char is sold as a cheap coal substitute ($20/MT).

Pyrolysis oil recovery is achieved via indirect heat exchangers and an electrostatic precipitator for vapor condensation and collection.

The raw pyrolysis oil contains heavy, oxygenated compounds (see Table 4) that must be upgraded before significant amounts of high-value hydrocarbons can be derived from it. Upgrading is achieved via hydroprocessing, which is split into two steps. The first step is hydrotreating the raw pyrolysis oil to remove oxygen impurities. This is accomplished by reacting the pyrolysis oil with hydrogen over a cobalt-molybdenum catalyst at 300°C-400°C and 7-10 MPa. The hydrotreated oil contains heavy hydrocarbons that must be depolymerized into lighter gasoline- and diesel-range hydrocarbons, a task accomplished via hydrocracking. Hydrocracking consists of reacting pyrolysis oil with hydrogen over a nickel-molybdenum catalyst at severe conditions (400°C-450°C and 10-14 MPa). The upgraded pyrolysis oil is then sent to a refinery where it is refined via distillation and blending into drop-in biofuels. 1.5 MT/hour of hydrogen is necessary for hydroprocessing and this is produced at the facility by steam reforming 38% of the pyrolysis oil produced. Additional details on the fast pyrolysis system, including mass and energy balances, are provided by Wright et al. (2010).

Process economic estimates are based on equipment costing data generated with the Aspen In-Plant Cost Estimator software for free-on-board equipment costs by (Wright, Satrio et al. 2010). Total project investment estimates are generated via Peters and Timmerhaus investment factors (Peters et al. 2003) and literature sources (Wright et al. 2010a; Brown et al. 2011). Plant design is based on the current state of technology and the facility is assumed to be the n^{th} of its kind. Facility online time is 7900 hours/year and investment capital is 100% equity financed. The cost year for the analysis is 2007.

Installed equipment cost for the fast pyrolysis and upgrading facility is $159M (see Figure 2) and total investment is $287M. Annual operating costs, excluding capital charges, are $101M (see Figure 3). Facility IRR is calculated using a modified and updated 20-year discounted cash flow spreadsheet developed by the National Renewable Energy Laboratory (Aden et al. 2002). The spreadsheet calculates facility IRR as a function of facility income, total project investment, variable operating costs, and fixed operating costs. The modifications enable the spreadsheet to calculate facility IRR based on specified market values for the product and co-products. The updates ensure that the most accurate and recent data is used when possible.

Important assumptions used to calculate the baseline scenario are found in the sensitivity analysis presented in Figure 4. The 20-year average pre-tax gasoline and industrial NG prices ($0.76/liter and $5.44/GJ, respectively) are based on EIA projections (EIA 2011a). The income tax rate of 35% is based on the 2010 tax rate schedule (IRS 2010) for corporations earning more than $18.3M in annual taxable income (the fast pyrolysis and upgrading facility simulated here is projected to have maximum annual taxable income of $38.8M). The sensitivity analysis also illustrates the factors that have the greatest impact on the IRR of a fast pyrolysis and upgrading facility. IRR is strongly affected by drop-in fuel value and yield. At the other end of the spectrum are income tax rate, catalyst cost, and labor costs, which have only a marginal impact on facility IRR. The results of the sensitivity analysis are indicative of which factors a particular policy will need to impact if it is to substantially influence facility IRR.

Methodology

Five federal incentive programs are simulated: the VEETC, S.884 (variable VEETC) the CBPTC, RINs, and H.R. 2454 (cap-and-trade). The following combinations of policies are also simulated: the CBPTC + RINs, the CBPTC + the VEETC, the VEETC + H.R. 2454, the CBPTC + the VEETC+ RINs, the CBPTC + VEETC + H.R. 2454, and the CBPTC + the VEETC + H.R. 2454 + RINs. Finally, a "business-as-usual" scenario is simulated to provide a comparative baseline.

Fast pyrolysis and upgrading facility IRR is a function of input costs, output value, and capital and operating expenses. Each scenario is modeled by identifying and quantifying its impact on each factor and then adjusting the DCF spreadsheet to reflect the results of this assessment. For example, if a scenario is determined to increase the value of drop-in biofuels produced at the facility by making petroleum-based fuels more expensive, the change in value is quantified and the spreadsheet adjusted to reflect this change. Similarly, if a scenario is determined to reduce the income tax rate for a facility (with the tax burden treated as an operating expense), the rate change is quantified and the original income tax rate in the spreadsheet adjusted to reflect the new rate. The spreadsheet is then run to calculate a new IRR based on the new factor(s).

The baseline scenario uses EIA (2011a) projected prices for natural gas and gasoline (2010 dollars) to calculate the IRR of a fast pyrolysis and upgrading facility for the years 2011-2030 (see Table 2). 20-year averages for each commodity are taken so as to account for future fluctuations in price and used to determine the value of facility outputs in the DCFROR spreadsheet. The pre-tax price of gasoline is used so as not to artificially inflate the value of drop-in biofuels produced by the facility. Under the baseline assumptions, the 20-year IRR for a fast pyrolysis and upgrading facility is 8.15%.

The CBPTC serves as a tax credit to qualified cellulosic biofuel producers and can eliminate a producer's income tax burden for a particular year if enough biofuel is produced. It is simulated by adopting the baseline scenario's assumptions but reducing the fast pyrolysis and upgrading facility's income tax rate from 35% to 0%.

The VEETC also serves as a tax credit but can also generate facility income if enough biofuel is blended by a qualifying party. It is simulated by adopting the baseline scenario's assumptions but reducing the facility's income tax rate from 35% to 0% and increasing the 20-year average pre-tax gasoline price from the baseline of $0.76/liter to $0.87. This $0.12/liter difference is the value of the tax credit per liter of biofuel blended.

S.884 is a short-term, declining tax credit that is phased out completely by 2014 based on the credit's inverted peg to petroleum prices and the EIA's projected petroleum prices. It is simulated here as an increase to drop-in biofuel value of $0.12/liter in 2011, $0.08/liter in 2012, $0.04/liter in 2013, and $0.00/liter thereafter, which over a 20-year average represents a $0.01/liter increase to the baseline pre-tax gasoline price. Other baseline assumptions remain the same.

The RIN mechanism of the RFS2 represents a $0.07/liter premium to the value of qualifying biofuels. It is simulated here as an increase to the baseline 20-year average pre-tax gasoline price of $0.07/liter, raising it to $82/liter. Other baseline assumptions remain the same.

The implementation of H.R. 2454 was projected to increase the prices of NG and gasoline above the baseline. Additionally, it would have added value to each MT of CO_2 sequestered or mitigated in the form of carbon offsets pegged to an annual carbon price (see Table 1). H.R. 2454 is simulated here as an increase to the value of all of fast pyrolysis and upgrading facility's products. It is simulated by increasing the 20-year average prices of gasoline (pre-tax), NG, and char to $0.86/liter, $12.81/GJ, and $38.55/MT, respectively. Other baseline assumptions remain the same.

Various combinations of the above policies are also simulated when not mutually exclusive (i.e., the VEETC and S.884 cannot be combined). This is done by combining the practical effects of each policy; for example, in the CBPTC + RIN scenario the income tax rate is reduced from 35% to 0% and the 20-year average pre-tax gasoline price is increased by $0.07/liter to $0.82/liter. Table 5 presents the primary assumptions under each individual scenario and scenario combination.

Numerical Results

The fast pyrolysis process design converts 2000 dry MTPD of stover into annual yields of 134 million liters of drop-in biofuel, 124,000 MT of biochar, and 818,009 gigajoules (GJ) of fuel gas. Total fixed capital investment is $247 million, of which $53 million is for equipment costs and $159 million for installation costs. The annual product cost is $74 million, or $0.55/liter of transportation fuel produced.

Table 5 presents the IRRs for the scenarios analyzed, as well as the change over the baseline and the pre-tax gasoline price for each. The baseline scenario incorporating the EIA (2011a) price data produces a facility IRR of 8.15%. While too low to merit capital investment, this number nonetheless demonstrates that the fast pyrolysis facility is economically feasible over a 20 year period without government support. The implementation of S.884 only marginally increases facility IRR to 8.53%, primarily due to the variable credit's short life and low value.

The CBPTC IRR of 10.41% is an improvement over the baseline and S.884 scenarios but its impact is limited by the fact that the pyrolysis facility has no tax liability until 2017, meaning that the CBPTC only has value for part of the facility's 20 year life. It effectively reduces the facility's tax liability to zero for the duration. The RIN scenario results in a virtually identical IRR of 10.47%; while it benefits the facility for a greater number of years than the CBPTC it has reduced value on a volumetric basis of $0.07/liter.

Expansion of the VEETC to include drop-in biofuels results in an IRR of 12.18%, an increase of nearly 50% over the baseline, due to the significant increase to the product value that it provides. This is in turn surpassed by the H.R. 2454 scenario, which results in a lower drop-in biofuel value than the VEETC scenario (albeit still higher than the other individual policy scenarios) but greater co-product value, resulting in an IRR of 12.88%. The value of natural gas is significantly higher under the H.R. 2454 (EIA 2009) scenario than the EIA (2011a) scenario, particularly in the later years. Furthermore, biochar has value as a CO_2 sequestration agent in the H.R. 2454 scenario, whereas it has zero value under the EIA (2011a) scenario. The combined increase in value to these co-products is greater than the reduced product value relative to the VEETC scenario.

Finally, multiple combinations of policy scenarios are analyzed to determine which grouping can achieve the 25% IRR threshold. Of these, that with the lowest IRR is the CBPTC + RIN scenario, which produces an IRR of 13.22%. This scenario also most closely resembles present politico-economic conditions. Expanding the VEETC to include drop-in biofuels results in an IRR of 17.79%. Finally, the combination of all policy scenarios (with the exception of S.884) results in an IRR of 22.69%, which comes closest out of all of the scenarios to attaining the 25% threshold but still falls short. As

Figure 5 shows, IRR is largely (but not entirely) driven by the product value, suggesting that a combination of government incentive programs and higher-than-projected gasoline prices could be sufficient to meet the threshold (worth noting at a time when the average U.S. gasoline price is 50% higher (EIA 2011b) than that projected by the EIA for 2011 (2011a).

Discussion

The results of this analysis demonstrate that while existing and proposed federal government policies can improve the economic feasibility of fast pyrolysis and upgrading as a drop-in biofuel pathway, they are not all equal. This study finds that, to be effective at increasing fast pyrolysis and upgrading facility IRR, policy must focus on increasing the value of facility products and co-products. Only when facility IRR is positive based on product value should additional policies minimizing the facility income tax rate be considered as a means of aiding IRR in passing the 25% threshold necessary to gain capital investment for commercial scale facilities. Policies such as the CBPTC will do little to benefit fast pyrolysis and upgrading facilities. The VEETC, RIN, and H.R. 2454 will do significantly more, especially when stacked with one another.

Those policies currently in existence (CBPTC and RIN) are unable to push facility IRR within striking distance of the 25% IRR threshold. Pre-tax gasoline prices will need to reach $1.15/liter under the existing present policy scenario (CBPTC + RIN) in order for the pyrolysis facility to attain a 25% IRR. This represents sustained gasoline prices that are substantially higher than those forecast by the EIA (2011a). Sustained high oil prices should not be depended on to move the fast pyrolysis pathway past the 25% IRR threshold. Significant emphasis has also been placed on decreasing pyrolysis costs via mechanical (Atchison and Hettenhaus 2004; Badger and

Fransham 2006; Wright et al. 2008) and technological (Das et al. 2004; Uslu et al. 2008; Pootakham and Kumar 2010; Venderbosch et al. 2010) advances over the last decade and it is unwise to assume that a breakthrough will occur in one of those areas in the immediate future.

A combination of existing and proposed (H.R. 2454 and an expanded VEETC) policies, on the other hand, comes very close to the threshold, attaining an IRR of 22.69%. This may be high enough to merit capital investment at a time when interest rates are at historic lows. For commercial investment in the pyrolytic pathway to occur, therefore, additional policy is needed. While this can take the form of the aforementioned H.R. 2454 and VEETC national policy scenarios, state and local governments can also play a role. One drawback of analyses examining federal policy is that most of the 50 state governments offer their own incentives for biofuel production in addition to those provided by the federal government. These range from additional tax deductions to renewable portfolio standards (RPS), the latter which can increase the value of pyrolysis co-products such as biochar and syngas. A comparison of the RPSs in the states of New York and Iowa is illustrative of how different state policies can result in different IRRs, other factors being equal. New York's RPS is limited to a very detailed list of electricity generation feedstocks, including syngas produced via gasification of biomass and liquid biofuels produced via fast pyrolysis of biomass but with no mention of char or syngas produced via fast pyrolysis of biomass (Flynn et al. 2004). This raises the questions of whether a New York-based fast pyrolysis and upgrading facility combusting char and syngas for heat and power generation qualifies under the RPS and whether it can sell either co-product to power plants as RPS-qualifying electricity feedstocks. At first glance it appears that neither co-product qualifies under the RPS regardless of where it is combusted, although pyrolysis oil does. Iowa, on the other hand, defines qualifying facilities under its RPS as "a…refuse-derived fuel, agricultural crops or residues, or woodburning facility" (Iowa Code § 476:42), suggesting both char and syngas, whether combusted at the fast pyrolysis and upgrading facility or sold to a power plant as electricity feedstocks ("refuse-derived fuels"), qualify under the Iowa RPS. While Wright et al. (2010a) and Brown et al. (2011) indicate that any improvement to facility IRR by inclusion of syngas and char under an RPS would be marginal, this is one example of a novel state policy impacting a facility's IRR.

Similarly, the diversity of state policies also reflects a diversity of relevant factors among the states. Feedstock types, feedstock prices, labor costs, operating costs, production rates, and capital costs all vary according to regional differences and particularities. A stover pyrolysis facility in Minnesota encounters a different set of biochemical, operating, and politico-economic conditions than a dedicated energy crop pyrolysis facility in Georgia or a hardwood pyrolysis facility in Oregon. Feedstock type may play a significant role in determining the yields of high-value hydrocarbons derived via fast pyrolysis and upgrading (Zhang et al. 2011), in which case regions producing feedstocks with naturally high potential hydrocarbon yields will have a significant advantage over those that do not.

This analysis merely addresses the operation of a stover pyrolysis facility in a generic U.S. region based on averaged national data. Additional research into the operation of different types of pyrolysis facilities with different feedstocks in different regions is necessary before determining whether pyrolysis facilities can attain the 25% IRR threshold, and under which conditions it is necessary to operate.

Conclusions

The economic feasibility of a fast pyrolysis and upgrading facility producing drop-in biofuels, biochar, and fuel gas from stover is investigated. In addition to a baseline scenario constructed using data from the EIA (2011a), five different policy scenarios based on existing and proposed energy policy at the federal level are also constructed. The IRRs of the pyrolysis facility are calculated under each policy scenario individually and then under combinations of scenarios. The scenario that most accurately reflects current politico-economic conditions is the combined Cellulosic Biofuel Producer Tax Credit and RFS2 (RIN) scenario, which results in an IRR of 13.22%, approximately half of what is necessary to receive capital investment. A combination of the existing policies and proposed conditions (an expanded VEETC + the H.R. 2454 cap-and-trade program) generates an IRR of 22.69%, the highest among the policy scenarios analyzed.

This study finds that those policy proposals under which a fast pyrolysis and upgrading facility's income tax burden is minimized contribute little to facility IRR. Besides benefiting only those facilities already generating a positive IRR (those with negative IRRs have no net income on which to be taxed), the impact of such a policy on facility IRR is marginal. Far more effective are policies that increase the value of facility products and co-products, particularly of drop-in biofuels produced. The simplest method of doing so is by increasing the price of petroleum-based transportation fuels such as gasoline and diesel, which the value of drop-in biofuels is a function of. While minimizing the income tax rate does benefit a facility already generating a significant IRR, increasing the value of drop-in biofuels has the same impact on a facility whether its initial IRR is positive or negative. Therefore, policymakers interested in fostering favorable economic conditions for advanced biofuel producers such as fast pyrolysis and upgrading facilities should design policy that is more like the VEETC, RIN, or H.R. 2454 and less like the CBPTC. These policies, when combined with additional state and local incentives, may ensure that fast pyrolysis is a competitive candidate to help achieve the goal of energy independency and security in the future.

Table 1. Prices of gasoline, carbon permits, natural gas, and biochar offset credits under H.R.2454 (italics denote extrapolation) (Sources: EIA 2009; Brown et al. 2010)

Year	Pretax gasoline price ($/liter)	Carbon price ($/MT)	Natural gas price ($/GJ)	Biochar offset value ($/MT)
2011	*0.70*	*10.8*	*10.52*	*20.00*
2012	*0.72*	*12.3*	*10.76*	*20.00*
2013	*0.74*	*13.8*	*11.00*	*20.00*
2014	*0.76*	*15.3*	*11.24*	*20.00*
2015	0.78	17.3	12.11	22.04
2016	0.80	18.6	12.12	24.24
2017	0.82	19.9	12.14	27.55
2018	0.84	21.1	12.16	29.75
2019	0.86	22.4	12.17	31.96
2020	0.89	23.6	12.19	35.26
2021	0.89	25.2	12.51	37.47
2022	0.90	26.7	12.83	40.77
2023	0.91	28.3	13.17	44.08
2024	0.92	29.8	13.49	47.39
2025	0.93	31.4	13.81	50.69
2026	0.94	32.9	14.14	54.00
2027	0.95	34.5	14.46	57.30
2028	0.96	36.1	14.79	59.51
2029	0.97	37.6	15.12	62.81
2030	0.98	39.2	15.44	66.12
20 yr avg	**0.86**	**24.84**	**12.81**	**38.55**

Table 2. Forecasted prices for oil, natural gas, and gasoline (Source: EIA 2011a)

Year	Oil price ($/bbl)	Industrial NG price ($/GJ)	Pretax gasoline price ($/gal)
2011	83.21	4.73	0.61
2012	85.73	4.73	0.62
2013	88.03	4.77	0.66
2014	91.38	4.78	0.68
2015	94.58	4.83	0.70
2016	97.62	4.89	0.71
2017	100.50	4.92	0.73
2018	103.15	4.97	0.75
2019	105.71	5.04	0.76
2020	108.10	5.21	0.77
2021	110.30	5.37	0.77
2022	112.36	5.52	0.78
2023	114.21	5.67	0.79
2024	115.96	5.85	0.80
2025	117.54	6.00	0.81
2026	118.99	6.12	0.81
2027	120.25	6.26	0.83
2028	121.34	6.33	0.83
2029	122.30	6.37	0.85
2030	123.09	6.41	0.83
20 yr avg	**106.72**	**5.44**	**0.75**

Table 3. Properties of corn stover

(Source: Wright et al. 2010a).

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

Table 4. Pyrolysis oil composition (dry basis) (Source: Wright et al. 2010a)

Pyrolysis oil composition	**Wt%**
Acetic acid	5.93
Benzene	0.77
Ethylphenol	3.80
Formic acid	3.41
Furfural	18.98
Methoxyphenol	0.61
Phenol	0.46
Propionic acid	7.31
Propyl benzoate	16.36
Toluene	2.27

Table 5. IRRs for a 2000 dry MTPD stover pyrolysis facility with upgrading under individual and combined policy scenarios

Scenario	**IRR**	**+/- baseline**	**Drop-in biofuel value ($/liter)**	**Income tax rate**
Baseline	8.15%	0	0.76	35%
S.884	8.53%	+0.38	0.80	35%
CBPTC	10.41%	+2.26	0.76	0%
RIN	10.47%	+2.32	0.82	35%
VEETC	12.18%	+4.03	1.21	35%
H.R. 2454	12.88%	+4.73	0.83	35%
CBPTC + RIN	13.22%	+5.07	0.82	0%
CBPTC + VEETC	15.32%	+7.17	0.87	0%
VEETC + H.R. 2454	16.33%	+8.18	0.95	35%
CBPTC + VEETC + RIN	17.79%	+9.64	0.94	0%
CBPTC + VEETC + H.R. 2454	20.46%	+12.31	0.95	0%
CBPTC + VEETC + H.R. 2454 + RIN	22.69%	+14.54	1.02	0%

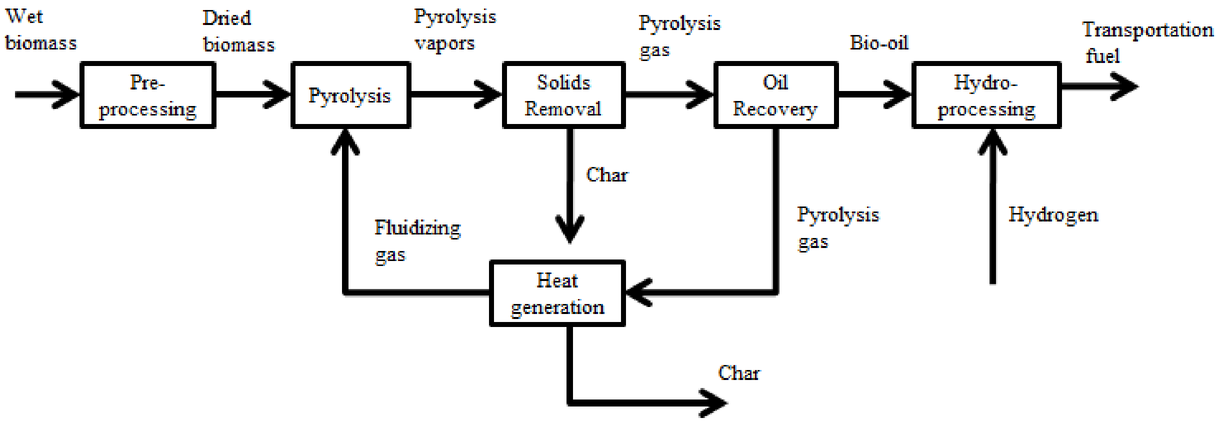

Figure 1. Biomass to transportation fuel via fast pyrolysis (Source: Brown et al. 2011)

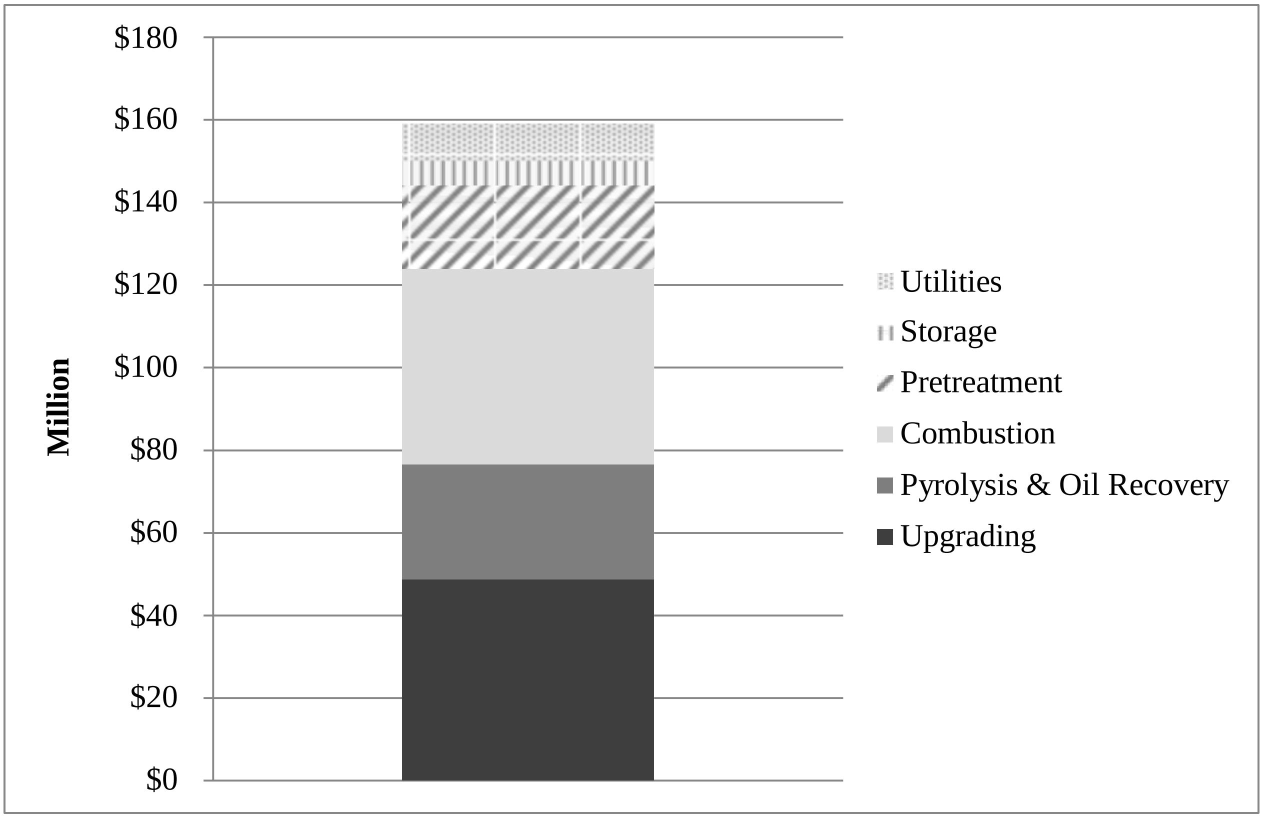

Figure 2. Installed equipment costs for 2000 dry MTPD stover fast pyrolysis and upgrading facility (Source: Wright et al. 2010a).

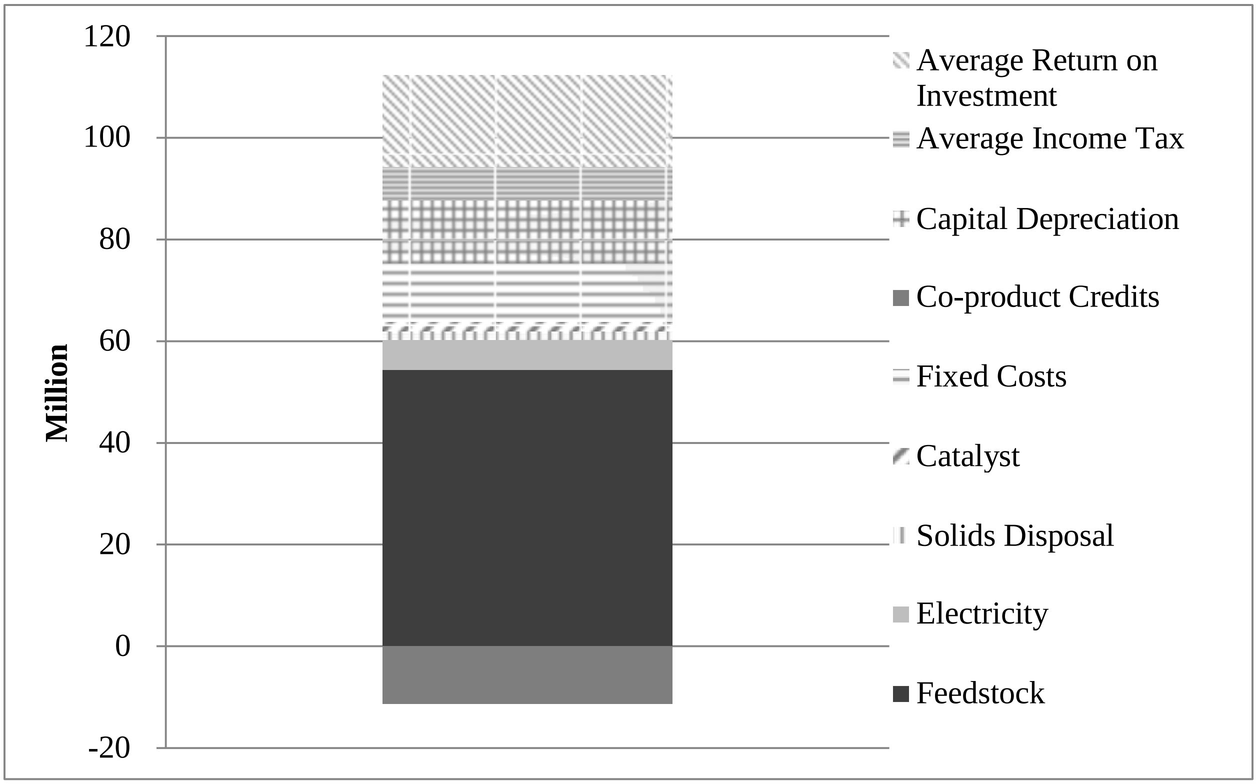

Figure 3. Annual operating costs for 2000 dry MTPD stover fast pyrolysis and upgrading facility

(Source: Wright et al. 2010a)

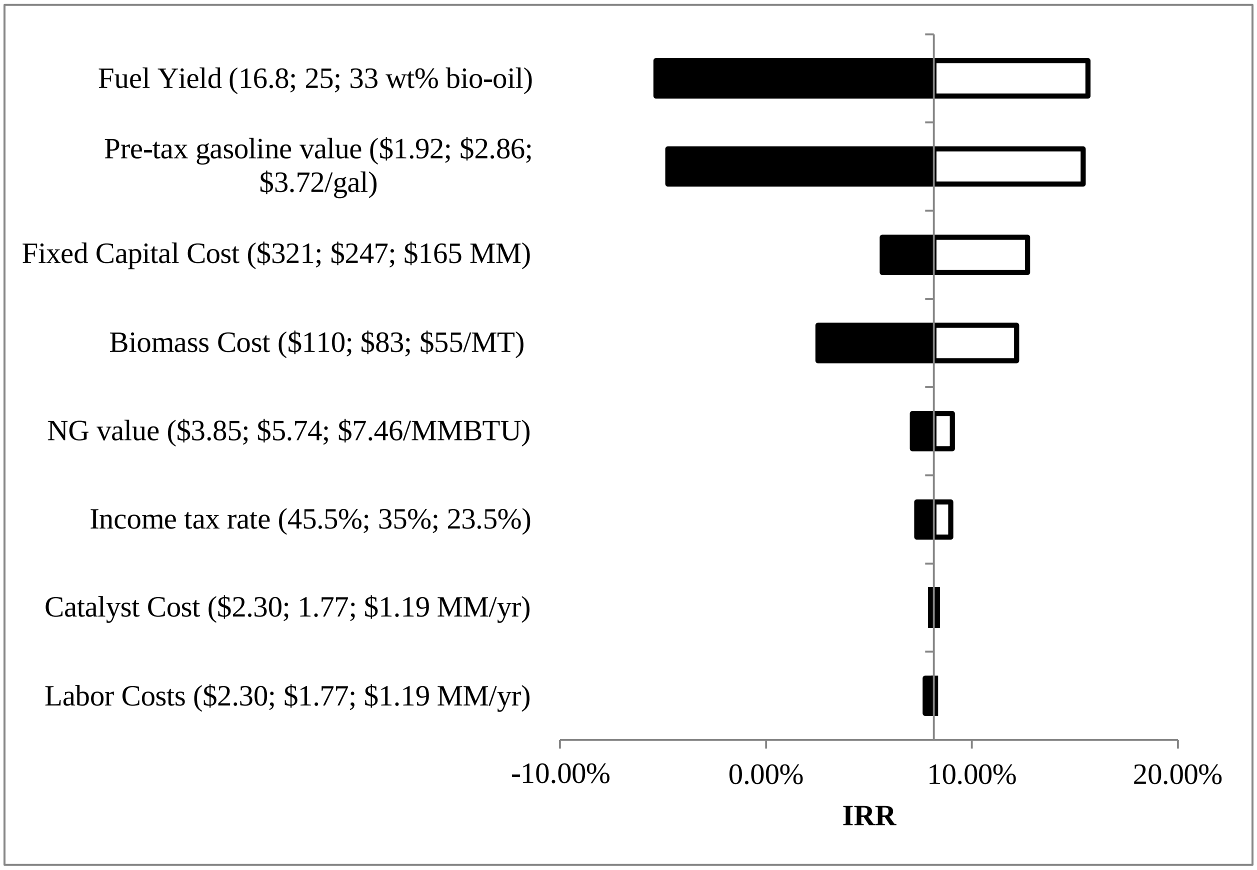

Figure 4. Sensitivity analysis for a 2000 dry MTPD stover fast pyrolysis and upgrading facility (unfavorable, baseline, favorable)

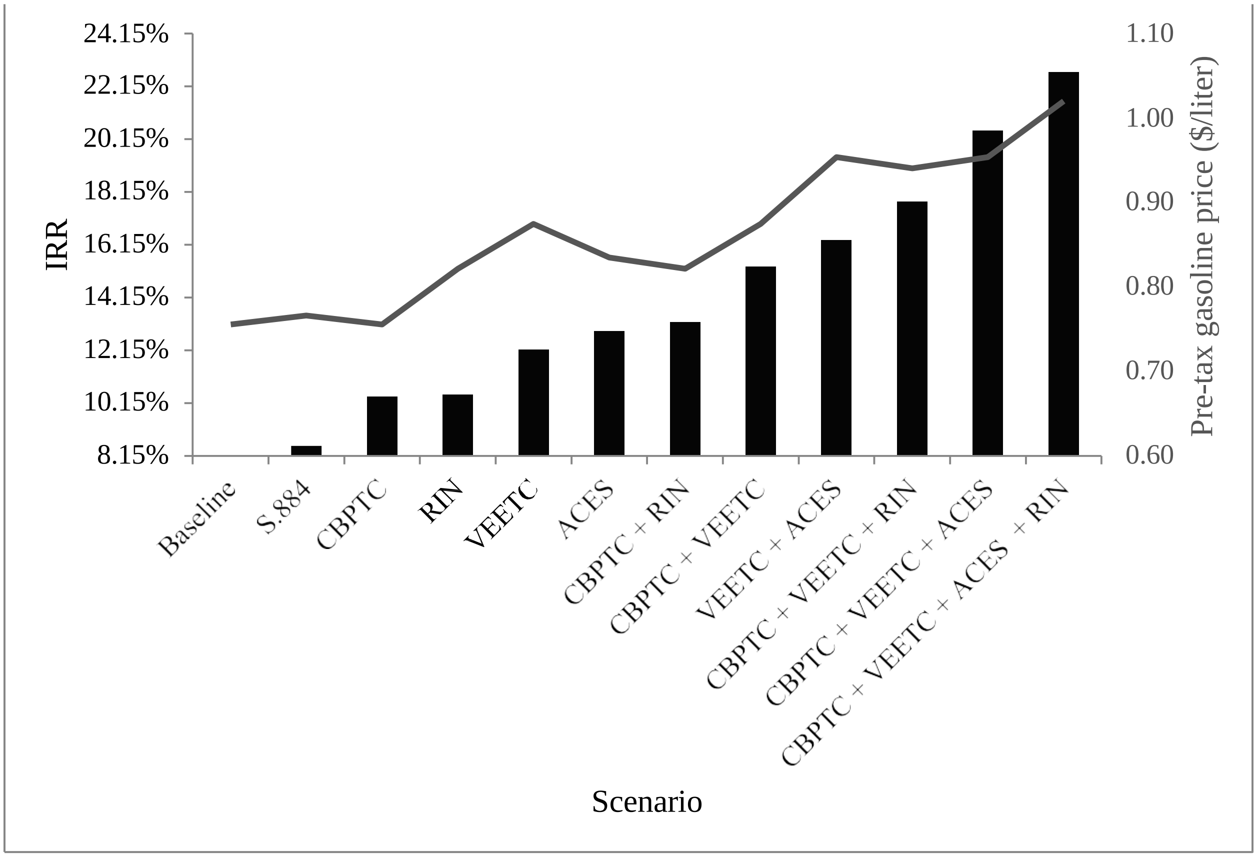

Figure 5. IRRs for 2000 dry MTPD fast pyrolysis and upgrading facility under different policy scenarios (Sources: EIA 2009; EIA 2011a)

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