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# Economic Analysis of Biomass Torrefaction Plants Integrated with Corn Ethanol Plants and Coal-Fired Power Plants

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## ABSTRACT

Torrefaction technologies convert assorted biomass feedstocks into energy-concentrated, carbon neutral fuel that is economically transported and easily ground for blending with fossil coals at numerous power plants around the world without needs to retrofit. Utilization of torrefied biomass in conventional electric generating units may be an increasingly attractive alternative for electricity generation as aging power plants in the world need to be upgraded or improved. This paper examines the economic feasibility of torrefaction in different scenarios by modeling torrefaction plants producing 136,078 t/year (150,000 ton/year) biocoal from wood and corn stover. The utilization of biocoal blends in existing coal-fired power plants is modeled to determine the demand for this fuel in the context of emerging policies regulating emissions from coal in the U.S. setting. Opportunities to co-locate torrefaction facilities adjacent to corn ethanol plants and coal-fired power plants are explored as means to improve economics for collaborating businesses. Life cycle analysis was conducted in parallel to this economic study and was used to determine environmental impacts of converting biomass to biocoal for blending in coal-fired power plants as well as the use of substantial flows of off-gasses produced in the torrefaction process. Sensitivity analysis of the financial rates of return of the different businesses has been performed to measure impacts of different factors, whether input prices, output prices, or policy measures that render costs or rewards for the businesses.

## 1. INTRODUCTION

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Biomass comes in many forms and is an abundant renewable fuel that can be used for space heating, power generation, or production of biofuels. Estimates of biomass production in the U.S. have been made suggesting approximately 799 million tons of biomass per year by 2030 if biomass is priced at \$66.1/t (\$60/ton) (U.S. DOE, 2011). However, the combustion or gasification of biomass can be challenging due to biomass ash characteristics and the need to control emissions. Biomass fuel requires periodic harvests over varied terrains with transportation required to the site of use. At harvest biomass may have moisture levels that favor deterioration in storage, raise its expense to transport, and reduce its net energy release in combustion. Torrefaction is a process that holds promise of becoming a desirable treatment of biomass to facilitate its use in conjunction with coal at power plants in the U.S. and around the world. Energy to dry the biomass and process heat to drive the torrefaction reactions are generally supplied by the biomass, itself. In addition considerable amounts of energy are released as off-gasses that may be used at co-located ethanol or coal-fired power plants.

The torrefaction process roasts biomass in a limited oxygen environment at temperatures from 200 to 300 ℃ for typically 10 – 30 minutes, to reduce the dry matter of the biomass by approximately 30%. Volatile organic compounds (VOC) representing approximately 20% of initial biomass thermal energy are released that may be used for a variety of processes, such as drying the raw biomass to be torrefied or to serve other purposes of co-located businesses that have a reliable demand for steam. The process of torrefaction decomposes hemicellulose, lignin and cellulose with steps of devolatilization and depolymerization resulting in biocoal with an energy densification that is 130% of raw biomass (Bergman et al., 2005; Boyd et al., 2011; Meyer et al., 2011; Tumuluru et al., 2011). Fig. 1 shows how torrefaction changes the dry matter and energy composition of the original corn stover (Grotheim, 2010; Bepex International, 2012).

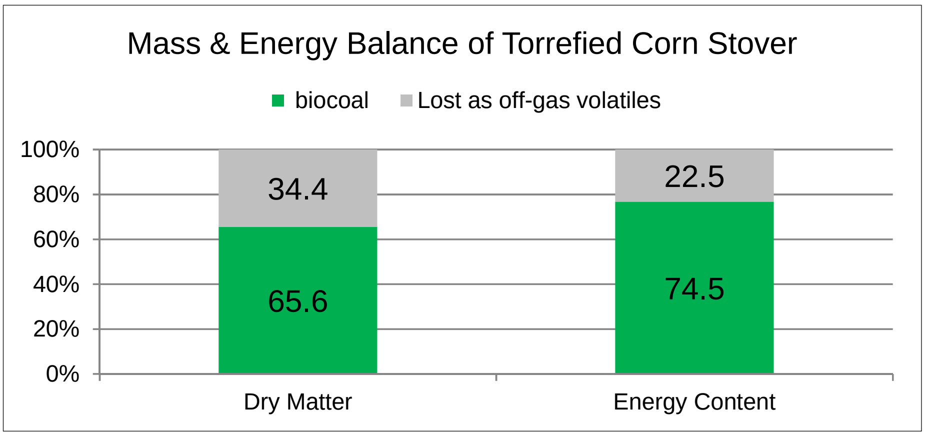


Fig. 1 Mass and energy balances of torrefied corn stover

Biocoal has attributes that make it an attractive fuel to blend with coal. Biocoal is hydrophobic, which keeps it from absorbing moisture and permits transportation in open railcars and stockpiling at outdoor storage sites. Biocoal is brittle and is more easily ground than dry biomass in preparation for combustion in pulverized coal-fired power plants. We analyze technical possibilities of production of biocoal by the torrefaction process and apply economic analysis to learn more about opportunities to co-locate torrefaction plants with ethanol plants or pulverized coal power plants that can utilize steam generated from VOC gasses released by the torrefaction process or directly use the VOCs and the biocoal produced. We have examined the economics of using flue gasses from coal power plants to dry wet wood before torrefaction. We also consider the impact of potential incentives that may prompt users to use biocoal or the steam produced by combustion of off-gasses as well as prices of inputs, outputs or technical factors important for adoption of this technology.

## 2. METHODS

Our efforts to measure financial performance of torrefaction plants and other co-located entities are facilitated by the use of an Excel workbook that contains techno-economic models on individual spreadsheets that state process variables in pro forma budgets, such as Fig. 2, which shows the pro forma of torrefaction plants selling steam. Other spreadsheets represent coal power plants and ethanol plants. Additional spreadsheets in the workbook accept data from the technical spreadsheets and perform financial analysis. The financial worksheets calculate profit and loss, balance sheets, and statements of cash flow for each business entity, including those that are co-located. Potential incentive levels are tested for ethanol plants utilizing steam from torrefaction off-gasses that displace the need to purchase certain amounts of natural gas, which lowers the carbon footprint of the ethanol produced. Because biocoal can replace coal at pulverized coal power plants that are co-located or distant from the torrefaction plant, we can model the economic effect of reduced $CO_2$ emissions as well as the reductions of other emissions that are targeted for reductions. The Life Cycle Analysis (LCA) performed on the material to be torrefied and the use of the off-gasses or steam guide us to economic measures applied to environmental performance.

| | | | | | | |
|---|---|---|---|---|---|---|
| **Torrefaction Process** | by Douglas G. Tiffany | | 30-May-13 | **Biomass with Sale of Steam** | | |
| | University of Minnesota | | | Return on Invested Capital | | 16.07% |
| | | | | Return on Invested Capital (No Steam) | | 6.03% |
| **Installed Capital Cost** | | | | | | Total |
| Nameplate Annual Output | 136,078 | Finished Metric Tonnes | 93.2% | Capacity Factor | | |
| Installed Capital Cost | $251.33 | per t of Capacity | | | | $34,200,000 |
| Percent Equity | 40% | | | | | |
| Percent Debt | 60% | | | | | |
| Interest Rate Charged on Debt | 6% | | | | | |
| **Operational Parameters** | | | | | | |
| Dry Matter Remaining | 70% | BDT/BDT | (60-75%) | | | |
| MJ used for drying at rate of | 2.79 | MJ/ kg. of Water Removed | | | | |
| MJ Released by facility per hour | 101,233 | from flow of | 30.3 | Tonnes of 17% Biomass = | 3,342 | Moisture |
| kg.H2O Removed to Give Ton @17% | 0 | | - | MJ to Dry a Ton As Received to 17% | | |
| Feedstock Grinding | 41.67 | kWh/t Biomass | 151,138.0 | $ 0.07 | 440,826.57 | |
| Torrefaction Reactor Electrical | 62.00 | kWh/t BioCoal | 0.0 | $ 0.07 | - | |
| Roll Press Briquetting Electrical | 8.87 | kWh/t BioCoal | 0.0 | $ 0.07 | - | |
| Natural Gas for Volatile Combustion | 52.33 | MJ of NG/t of Bmass | 151,138.0 | $ 5.00 | $ 39,549,003.16 | |
| Water pumping for BioCoal Quenching | 0.07 | kWh/t BioCoal | 0.0 | $ 0.07 | - | |
| Fan Cooling of BioCoal Pellets | 1.20 | kWh/t BioCoal | 0.0 | $ 0.07 | - | |
| **Revenues** | | | | | | |
| Sale of Biocoal (F.O.B.) | $154.32 | at moisture of | 1.10% | Biocoal Production | kg of Steam/hr | $ - |
| MJ Remaining After Drying | 101,233 | 89 | kg. of Steam/hr. | | 724,249 | |
| Steam Price (Per 1,000 kg.) | $ 11.02 | | 8164.32 | Hours of Operation | | $ 3,432,276 |
| Total Revenues | | | | | | $ 3,432,276 |
| | | | (17%-62%) | Wet Tonnes Delivered | | |
| Delivered Cost of Biomass | $77.16 | per Tonne at moist. of | 17.00% | 151,138.04 | | $ 11,662,079 |
| **Gross Margin** | | | | | | $ (8,229,803) |
| **Operating Costs and Depreciation** | | | Costs per Ton Produced | | | |
| Salaries and Benefits | Rate/Fin. Tonne | | $ 4.96 | | | $ 629,100 |
| General & Administrative | Rate/Fin. Tonne | | $ 1.10 | | | $ 139,800 |
| Maintenance Expenses | Rate/Fin. Tonne | | $ 3.53 | | | $ 447,360 |
| Natural Gas Expense | | | | | | $ 37,485 |
| Electrical Expense | | | | | | $ 440,827 |
| Interest | Rate/Fin. Tonne | | $ 10.70 | | | $ 1,231,200 |
| Depreciation (SL) for asset life of | 15 | years | $ 17.98 | | | $ 2,280,000 |
| Total Operating Costs and Depreciation | | | $ 38.27 | $ 41.05 | | $ 5,205,772 |
| Net Margin | | | | Margin Per Finished Tonne | | $ 5,495,883 |
| Return on Invested Capital | | | | $ 39.31 | | 16.07% |
| Return on Invested Capital (No Steam) | | | | $ 14.76 | | 6.03% |

Fig. 2 Technical spreadsheet showing pro forma budget of torrefaction plant co-located with an ethanol plant and selling steam

## 3. DATA

We primarily rely upon reported data of Torrsys, a subsidiary of Bepex International, which closely conforms to reported data of ECN, Topell, and other firms involved in perfecting torrefaction equipment (Grotheim, 2010; Bepex International, 2012). The largest amount of testing by Torrsys was with corn stover. Data characterizing the mass and energy flows at corn dry-grind ethanol plants originated with the Agricultural Research Service (ARS) and was also utilized in previous work by De Kam et al. (2009). The GREET model produced by Argonne National Laboratory and the BESS Model developed by the University of Nebraska were studied to validate ethanol plant life cycle analysis.

Data on coal-fired power plants was gleaned from the Department of Energy (DOE), Energy Information Agency (EIA), the National Renewable Energy Lab (NREL) and Argonne National Laboratory, which contributed to our understanding of coal-fired power plants and emissions from these facilities. Capital and operating costs of a wood dryer using flue gasses were derived in order to model torrefaction plants using wood that are co-located at a coal power plant. (Li et al, 2012).

## 4. POLICY AND ECONOMIC DRIVERS

Economics literature describes causal relationships between policy changes and the price of emission allowances (Benz and Trück, 2009; Boutabba et al., 2012). This section discusses current and pending federal emission reduction regulations that will significantly affect coal-fired power plants in the United States and how use of biocoal in existing coal-fired power plants may become an economically viable strategy for coal-fired power plants.

Both coal-fired power plants and fuel ethanol plants are under scrutiny to reduce greenhouse gases when economically and technically feasible. Coal power plants face increasingly stringent standards in reduction of emissions from regulations enforced by EPA and the states. Similarly, ethanol production is under pressure to comply with the GHG reduction goals of the Renewable Fuels Standard, California and other states. There are federal standards for regular and advanced biofuels based on the feedstocks used as well as the levels of GHG emitted in the process of producing ethanol. GHG standards are constantly evolving and are financially important to ethanol producers when categories of Renewable Identification Numbers (RIN) certificates are created to validate compliance efforts across the country for companies that blend and sell biofuels (Wisner, 2009). The use of steam produced by torrefaction off-gasses in the corn ethanol process can substantially reduce the carbon footprint of corn ethanol and perhaps meet the standards of advanced biofuels.

Coal-fired power plants in the United States provided 320 GW of existing electricity generating capacity, or about 30% of total electrical production capacity in 2010. However, the Electric Power Research Institute (EPRI) projects that coal-fired plants producing a total of 61 GW will become unprofitable by 2020 and close due to poor scale economies and costs of emissions mitigation. If current and pending environmental regulations are implemented, the continued operation of plants producing another 54 GW of coal-fired power would be in question due to projected costs of emissions mitigation (EPRI, 2012). Most of the plants to be retired will be 50–60 years old; however, some plants will refuel with natural gas. Future economic projections for coal-fired power plants as well as the trend in regulatory controls, suggest that coal’s role in the U.S power market is changing dramatically.

Current EPA regulations in U.S, whether pending or active, reflect a trend toward cleaner electricity, by reducing local emissions of toxic compounds and emissions of GHG gasses. The increasing pressure to reduce emissions is expected to result in higher costs of abatement for coal-fired power plants. In this study, various projections are used to estimate the price of compliance for coal-fired power plants. To account for uncertainty in the projections, this study includes sensitivity analysis.

Renewable Portfolio Standards (RPS) established at the state level are another major factor that could influence the U.S. power market. As of October 2012, RPS requirements are established and enforced in 37 states and the District of Columbia. An RPS is a policy designed to encourage the supply of electricity generated from renewable sources often used as a quota requiring generating units and retail providers to supply minimum amounts of electricity from eligible renewable energy sources such as wind, solar, geothermal, landfill gas, tidal energy, and biomass. The states have set minimum amounts ranging from 4-30% (U.S. EPA, 2012d). Power plants can meet an RPS standard either by generating renewable power at their own facilities or by purchasing Renewable Energy Credits (REC) from other parties. RECs are tradable renewable certificates that guarantee 1 MWh of electricity generation from renewable energy sources and demonstrate RPS compliance. RECs offer flexibility in RPS compliance to power utilities and currently vary in price from \$1/MWh to \$60/MWh, the range analyzed in the economic analysis conducted in this study (NREL, 2012).

## 5. BASELINE OPERATING CONDITIONS OF ECONOMIC ENTITIES

Our approach to learn about the feasibility of torrefaction technology is to represent the technology accurately and then model the financial performance of the following business enterprises through sensitivity analysis:

1) Torrefaction plant operating independently
2) Coal power plant operating independently
3) Ethanol plant operating independently
4) Torrefaction plant selling steam from combustion of VOC off-gasses
5) Coal power plant buying and co-firing biocoal
6) Ethanol plant buying steam derived from VOC off-gasses of torrefaction plant
7) Torrefaction plant using power plant flue gasses to dry wood
8) Coal power plant using wood torrefaction VOC off-gasses and biocoal to generate power

To set the stage for these business enterprises, baseline operating conditions were established at reasonable levels for input and output prices, debt/equity levels, costs of debt, depreciation methods, and technical standards such as ethanol yield per bushel, moisture level of biomass, etc. Table 1 contains some of the key economic and policy variables at their baseline levels.

The economic impacts of policy incentives are represented as either costs or increments of added value. For example, the existence of carbon tax at \$16.5/t (\$15/ton) of $CO_2$ equivalent emitted adds value to ethanol produced because life cycle analysis shows energy in ethanol fuel emits substantially less than the fuel that ethanol usually replaces, gasoline. The same carbon tax of \$16.5/t (\$15/ton) applied to the operations of a pulverized coal power plant results in higher costs of production of the electricity due to the emissions from combusting coal.

Debt and equity positions of the businesses modeled differ. Although there is variation in the industry, 80% equity and 20% debt were chosen for the ethanol plants, with 6% interest assumed. Torrefaction plants were assumed to start with 40% equity and 60% debt with 6% interest charged. In the case of the electric power utilities, we selected the equity average of 57% and 43% debt at an assumed lower cost of debt of 4.29% (Damodaran, 2012). The baseline price of biocoal is assumed to be \$154.3/t (\$140/ton) at the torrefaction plant because it provides reasonably attractive ROEs when \$77.2/t corn stover at 17% moisture is delivered to the torrefaction plant. Bituminous coal is priced at the baseline at \$76.1/t (\$69/ton), which is the price listed in 2010 for U.S. utilities using this grade of coal (EIA, 2011). Transportation costs of \$11.0/t (\$10/ton) are assumed for biocoal, because this charge conforms to 2010 rail transportation cost for coal transported from Illinois (EIA, 2012). The baseline selling price of electricity for the bituminous coal power plants is \$0.07 per kWh from plants that are assumed to run at a capacity factor of 90%. We assume the baseline size of the coal power plant is 550 MW, although we also analyze power plants of smaller scales down to 108MW.

Policy incentives are important to this analysis, but in most cases baseline levels are set at zero cost to represent current standards and typical business returns. While carbon taxes are not currently being applied in the U.S., they are part of numerous discussions and analyses conducted by power plants, power regulators, and policy makers. Australia has enacted a carbon tax of \$24.5 US/t of $CO_2$ and the European Union uses the same framework to guide environmental performance in a number of economic sectors. Baseline level for carbon tax is set at \$0/t as are the costs of compliance for $SO_2$, NOx annual, and NOx ozone. State renewable portfolio standards (RPS) are set at 30%, although the costs of these standards vary according to states and circumstances. Renewable Energy Certificates (RECs) are valued at \$0/MWh at baseline, although there may be considerable variability due to state public utility requirements and the availability of alternatives in a particular state.

Table 1. Baseline Conditions

| Ethanol Plants | | Torrefaction Plants | | Coal Power Plants | |
|---|---|---|---|---|---|
| Name Plate Capacity (l/yr) | 378,541,000 | Number of Torrefaction Trains | 2 | Name Plate Capacity (MW) | 550 |
| Factor of Equity | 80% | Capacity of Torref. Train (t/yr) | 136,078 | Factor of Equity | 57% |
| Factor of Debt | 20% | Capacity Factor | 93.20% | Factor of Debt | 43% |
| Interest Rate on Debt | 6% | Factor of Equity | 40% | Interest Rate Charged on Debt | 4.30% |
| Depreciation Method Chosen (SL or DDB) | SL | Factor of Debt | 60% | Co-firing Rate | 10% |
| Depreciation based on asset life (yr) | 15 | Interest Rate Charged on Debt | 6% | Delivered Cost of Coal ($/t) | $75.5 |
| Ethanol Price ($/l) | $0.59 | Loan Duration (yr) | 15 | Delivered Cost of Biocoal ($/t) | $165 |
| DDGS Price ($/t) | $319.70 | Depreciation Method Chosen (SL or DDB) | SL | SO2 Allowance Market ($/t) | $0 |
| CO2 Price sold for Food and Industrial Uses ($/t liq. CO2) | $11.00 | Price of Biocoal - CornStover ($/t) | $154.3 | NOx (Annual)Allowance ($/t) | $0 |
| Corn Price ($/t) | $275.58 | Price of Biocoal - Woody Biomass ($/t) | $177.5 | NOx (Ozone) Allowance ($/t) | $0 |
| Steam Purch. fr. Torre. plant. ($/1000kg) | $11.02 | Delivered Cost of Cornstover ($/t) | $77.2 | CO2 Tax ($/t) | $0 |
| Natural Gas Price Purchased ($/MJ) | $0.0047 | Delivered Cost of Woody Biomass ($/t) | $49.6 | Capacity factor | 90% |
| Electricity Purchase from Grid ($/kWh) | $0.07 | Initial M.C of Cornstover | 17% | RPS requirement | 30% |
| Propane Purchase ($/l) | $0.44 | Initial M.C of Woody Biomass | 50% | REC price ($/MWh) | $0 |
| Denaturant Price ($/l) | $0.53 | Price of VOC ($/MJ) | $0.002 | Loan Duration (yr) | 30 |
| Denaturant kg./100 kg Anhyd. | 2 | | | Deprec Method (SL or DDB) | SL |
| Ethanol Yield (anhydrous liters/t) | 410 | | | Deprec based on asset life for SL (yr) | 35 |
| Carbon Tax ($/t) | $0 | | | Income Tax Rate | 38% |
| | | | | Price of Electricity ($/kWh) | $0.07 |
| | | | | Prod Tax Credit ($/kWh) | $0.01 |
| | | | | Price of FlueGas ($/MJ) | $0.002 |

## 6. RESULTS

Many conditions were applied to the eight business entities by changing values in the menu page to learn about the sensitivities in terms of returns on equity (ROE). Sensitivity analysis is carried out one factor at a time before analysis of multiple factors acting in concert. In reading our results, the actual rates of return aren't nearly as important as the relative changes from baseline and understandings about business viability. The results are represented in two sections with section 6.1 concerned with six entities involving biocoal produced from corn stover and 6.2 reporting results for coal power plant and torrefaction plant co-location case that deals with biocoal produced from wood and drying of wood by flue gasses from the power plant.

### 6.1 Corn-Stover: Baseline financial conditions of the six business entities

Fig. 3 shows the five year average rates of return on equity for the six business entities modeled under baseline conditions. Fig. 3 uses colors and patterns to identify the activities of the business entities. Solid red signifies an independent ethanol plant, while a red striped pattern signifies an ethanol plant using purchased steam from a nearby torrefaction plant. Similarly, solid green signifies an independent torrefaction plant and a striped green pattern signifies a torrefaction plant selling steam. The independent coal-fired power plants are colored grey, while the grey striped patterns represent coal power plants that utilize biocoal produced at torrefaction plants. These color schemes are used in later figures in this paper.

At baseline the ethanol plant using steam from the torrefaction plant has a slightly higher ROE (7.79%) than the independent ethanol plant (7.64%). This relationship is a feature of several assumptions, including the pricing of natural gas and steam as well as the level of carbon tax pricing, which is zero at baseline. The ethanol plant using steam from torrefaction off-gasses produces ethanol with a substantially lower carbon footprint than the typical independent ethanol plant using natural gas, but with $0 price of carbon tax applied to ethanol, that benefit is null. With respect to the torrefaction plants, the one selling steam has a much higher rate of return on equity (11.73%) than one that operates with no opportunity to sell steam (4.22%). When considering the pulverized coal power plants, the power plant blending 10% biocoal has lower returns on equity (ROE) (10.68%) because it uses more expensive biocoal to displace cheaper, more energy-dense, bituminous coal than a conventional pulverized coal plant (12.37%) at baseline conditions. As more costly emissions allowances are applied, as expected in future years, the rates of return on equity will drop for conventional coal power plants. The rates of return are also dependent upon the baseline delivered prices for biocoal and bituminous coal, which are $165.3/t ($150/ton) and $69.4/t ($63/ton), respectively. As the price levels of biocoal and bituminous coal converge, the ROEs of co-firing and "coal only" plants become more equal.

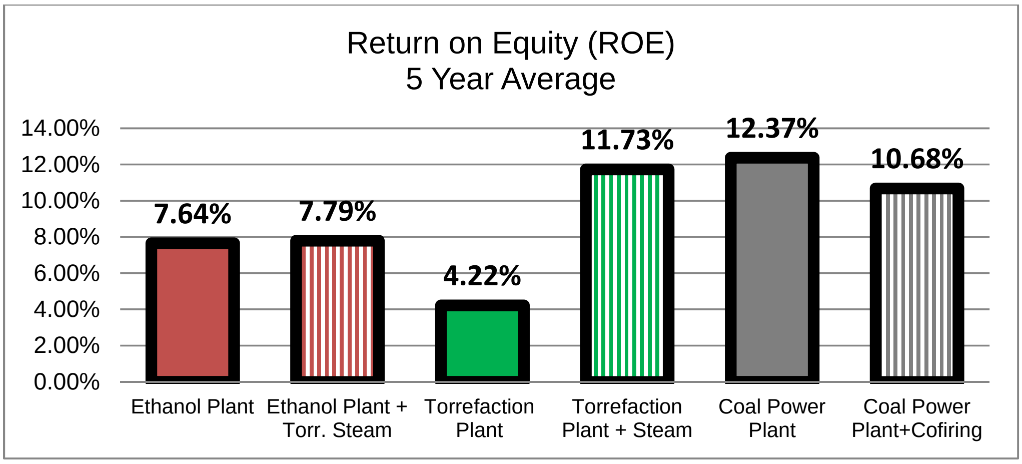


Fig. 3 Baseline Returns on Equity (ROE) of business entities analyzed.

### 6.1.a Factors primarily affecting torrefaction plants

Since the focus of our study is the economics of torrefaction, we will continue with the effects that the price of corn stover exerts on ROE of the torrefaction enterprise. Fig. 4 shows how cheaper delivered corn stover can enhance the returns on equity of the torrefaction plants, whether selling steam from off-gasses or not. Whenever possible, there is a substantial competitive advantage for a torrefaction plant that is able to be co-located so that it is able to sell steam to another business. The range of delivered corn stover price ranges from \$33.1/t to \$99.2/t (\$30/ton to \$90/ton). While the lower costs of \$33.1/t and \$44.1/t (\$30/ton and \$40/ton) seem extreme, they point out the advantages of using enhanced mechanization and the potential use of by-products as feedstocks.

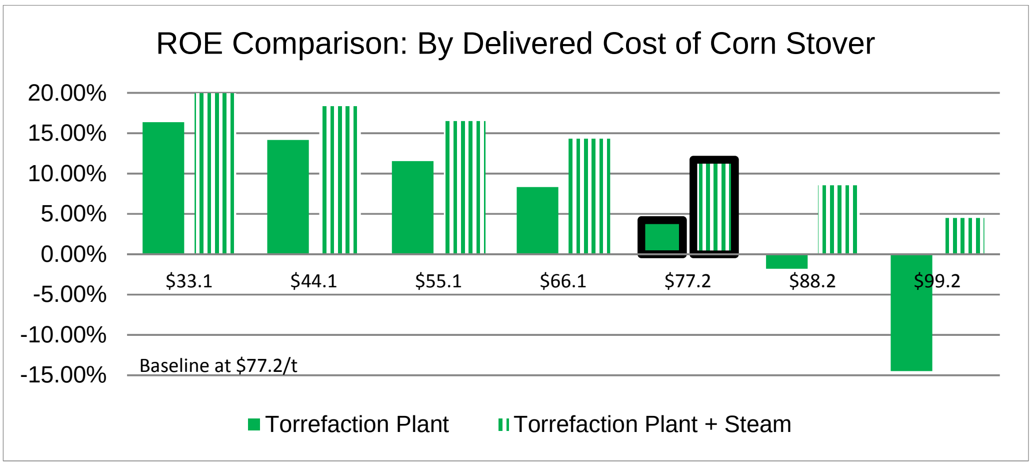


Fig. 4 Effect of stover cost on ROE of torrefaction plants.

Fig. 5 shows the effects of higher moisture content on the economics of torrefying corn stover for plants with and without the opportunity to sell steam. This graph shows the rapid decline in ROE that occurs as moisture levels exceed 20%. This figure represents valuation of corn stover on an "as received" basis, meaning that the buyer pays more per unit of dry matter when receiving wetter material.  There are two effects shown in Figure 6. Wetter corn stover costs more per unit of dry matter, and it requires more energy from the off-gasses to dry the stover before it can be torrefied.  This reduces the amount of energy that can be converted to steam and sold.  Fortunately, corn stover is typically available at moistures levels of 17% or less. The sale of steam from combustion of off-gases permit steam-selling torrefaction plants to stay profitable even at higher moisture contents of corn stover.

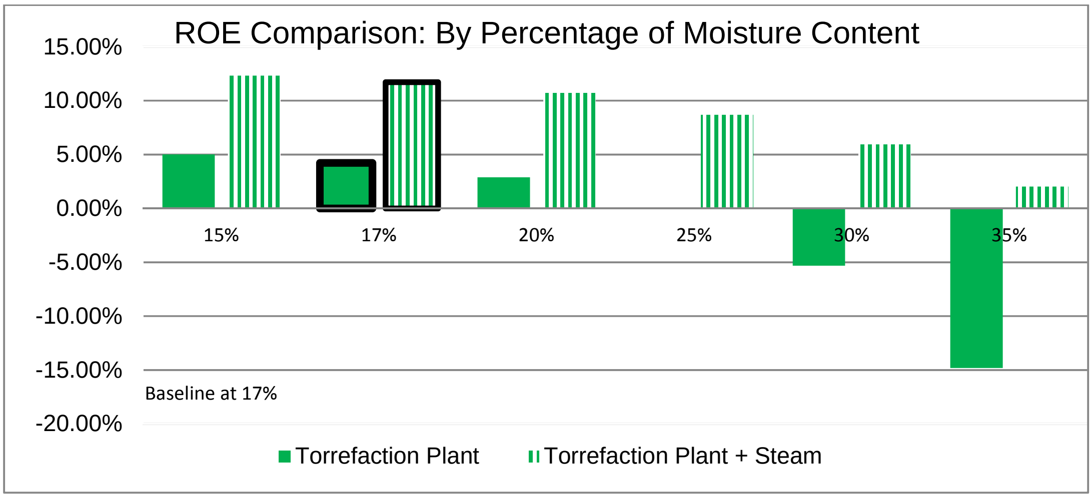


Fig. 5  Effects of stover moisture on ROE of torrefaction plants.

The sale price of biocoal leaving the torrefaction plant affects ROE on torrefaction plants as well as co-firing coal power plants using 10% biocoal on a mass basis. Fig. 6 shows the favorable situation of the torrefaction plants that sell steam over those that do not sell steam. The ROEs of co-firing power plants using 10% biocoal are only gradually diminished as biocoal prices rise, while small incremental price increases in the sale price of biocoal substantially increase ROE levels of torrefaction plants. With biocoal prices at \$143.3/t, independent torrefaction plants do not generate positive five year average rates of return on equity. A steam-selling torrefaction plant is profitable at \$121.3/t biocoal, but an independent torrefaction plant requires \$154.3/t with other conditions at baseline to be profitable.

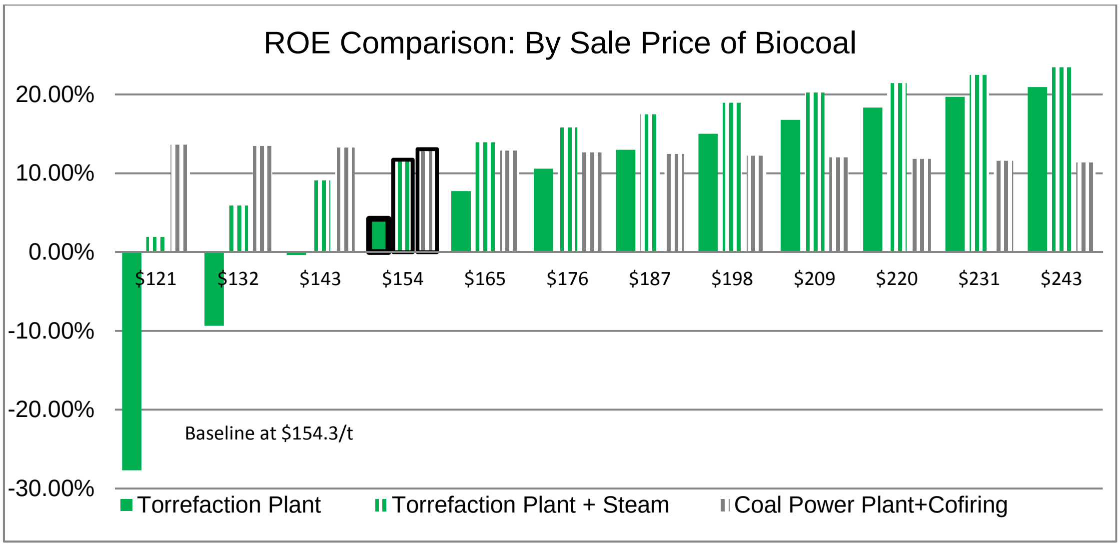


Fig. 6 Effect of the price of biocoal on ROEs of torrefaction plants, with and without steam sales, and coal power plants co-firing with 10% biocoal.

### 6.1.b Factors primarily affecting ethanol plants

Our analysis was designed to determine the extent and sources of economic advantages that ethanol plants or other businesses with a steady demand for steam throughout the year would enjoy if co-located at the torrefaction plants. There are several potential advantages for co-located ethanol plants, some immediate and some with potential in the future. Immediate advantages arise when the price of steam sold by a torrefaction plant is less than the price of buying natural gas and using one's own boiler to produce steam. Fig. 7 shows how the ROEs of ethanol plants are affected when buying steam from torrefaction plants at a range of steam prices versus a set price for natural gas, which is $0.002/MJ ($5.00/mmbtu). When steam sells for $6.6/1000kg and natural gas sells at $0.002/MJ, torrefaction and ethanol plants doing business together have virtually the same ROEs with the ethanol plant at 9.03% and the torrefaction plant at 9.16%. At baseline conditions of $11.02/1000kg of steam ($5.00/1000lb of steam) and $0.002/MJ of natural gas, the ROEs are 7.79% and 11.73% for the collaborating ethanol plant and torrefaction plant, respectively.

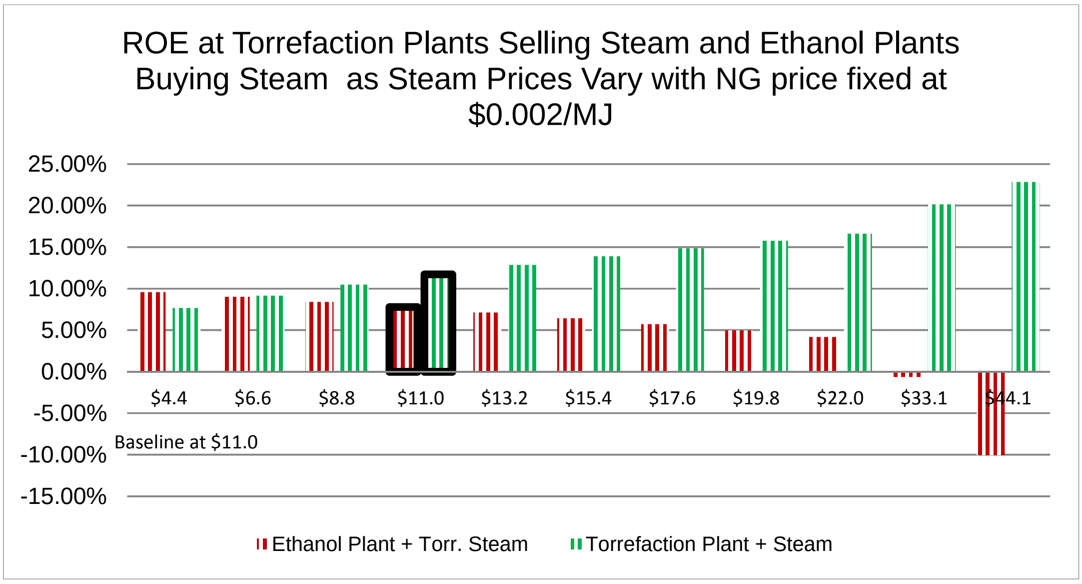


Fig. 7 Effect of pricing steam from torrefaction plant versus natural gas cost on ROEs of co-located ethanol plants and torrefaction plants.

The imposition of carbon taxes has a favorable impact on renewable fuels, especially on ethanol plant ROEs, as shown in Fig. 8. As carbon tax rates increase, the ROEs of ethanol plants increase. Evident are the effects on the four business entities (two ethanol plant cases and two pulverized coal power plants) as carbon taxes rise from $5.5/t to $33.1/t ($5/ton to $30/ton) of $CO_2$ equivalent gases emitted. The coal-fired power plants become unprofitable at baseline conditions as carbon taxes rise from $22.0/t to $27.6/t ($20/ton to $25/ton). Higher carbon taxes deliver more advantage in ROEs to the ethanol plants that purchase renewable steam from a co-located torrefaction plant. The improvement in ROEs for ethanol plants is in contrast to the pulverized coal power plants, whether co-firing with expensive biocoal or not. Every gallon of ethanol produced represents a valuable reduction in $CO_2$ tax liability versus gasoline, while every kilowatt-hour of electricity produced by coal will be required to pay more carbon tax.

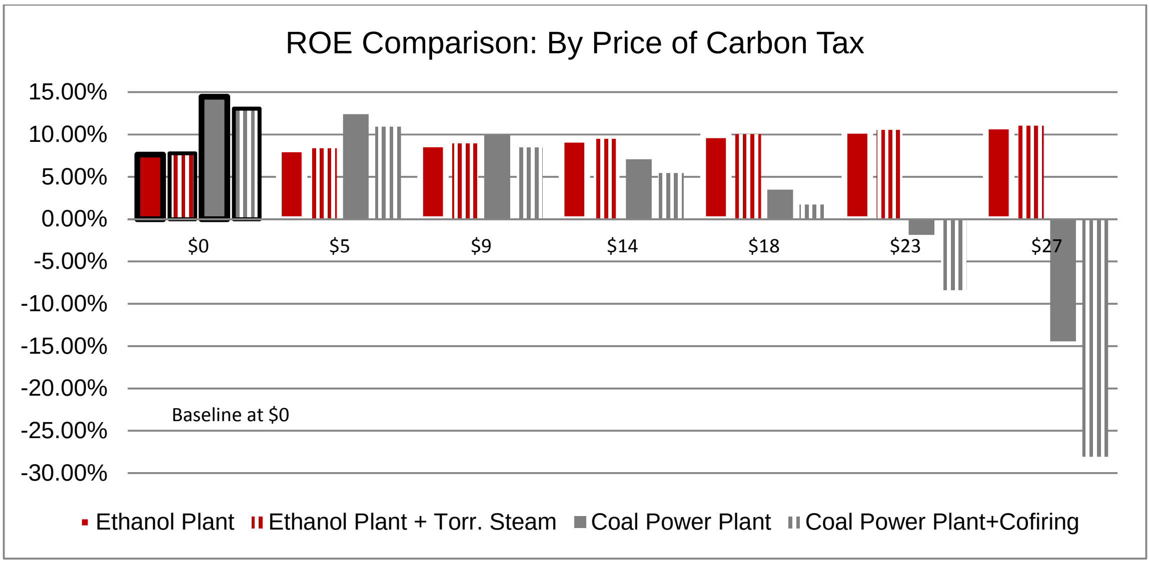


Fig. 8 Effect of $CO_2$ taxes on ROE of ethanol plants and co-firing coal plants at 10% levels as $CO_2$ taxes are imposed at various prices.

### 6.1.c Factors primarily affecting pulverized coal power plants

This portion of the analysis is concerned with the primary market for biocoal, which includes the many pulverized coal power plants in the U.S., especially those east of the Mississippi River that use bituminous coal. Baseline conditions assume that 10% blends of biocoal are made with bituminous coal, which will have the effect of lowering $CO_2$ emissions as well as $SO_2$, and NOx. Because biocoal contains less energy than bituminous coal, the favorable effects of lower emissions are less on an energy basis.

Data from the Energy Information Agency identifies our baseline price for bituminous coal at a delivered price of $75.5/t ($68.5/ton) (EIA, 2011). Fig. 9 shows the impact of bituminous coal price on the ROE of the coal-fired plants, whether independent or practicing co-firing 10% biocoal with the baseline levels noted on the graph. The baseline levels reflect the scale economies of the 550 MW power plants and the selling price of electricity of $0.07 per kWh. An independent bituminous coal power plant can still be profitable using up to $132.3/t ($120/ton) of bituminous coal, while a power plant co-firing using $121.3/t ($110/ton) bituminous coal is not profitable.

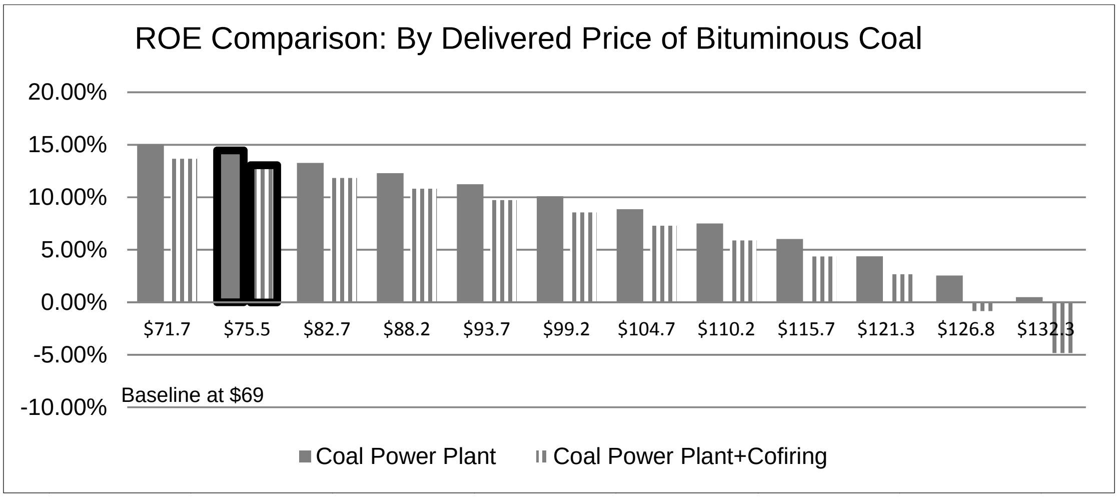


Fig. 9 Effects on ROE of delivered bituminous coal prices on power plants

The combined effects on ROE of the cost of $CO_2$ taxes and the price of biocoal are shown in Fig. 10. The range shown on this graph has carbon taxes centered on $16.5/t ($15/ton) and reduced by approximately 20% and increased by approximately 20%. Similarly, biocoal prices are centered on our baseline delivered cost of $165.3/t ($150/ton) ranging plus 20% to minus 20%. Observation of the gradients of the tops of the columns shows that carbon taxes exert a more powerful effect than biocoal prices at these levels.

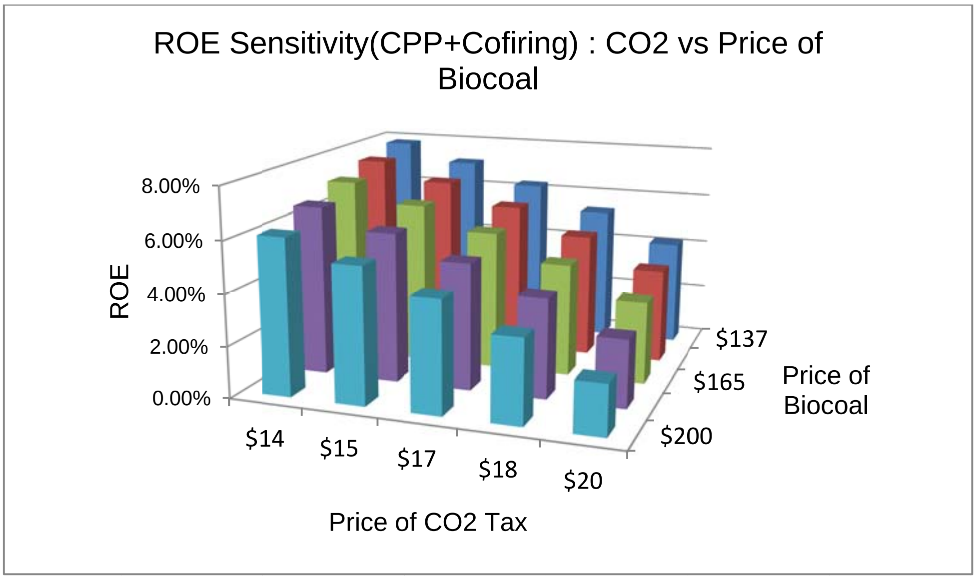


Fig. 10 Combined effects of $CO_2$ taxation and the cost of biocoal on ROE of power plants co-firing 10% biocoal.

### 6.1.d ADDITIONAL SENSITIVITIES

Table 2 contains ROEs of the six business entities that can be modeled by applying single or multiple factors affecting the different businesses. Discussion of the modeled results occurs below based on the principal factors tested. Baseline ROE levels are shown at the top of the table for all six businesses, and shaded cells signify that a particular treatment left the baseline ROEs unaffected.

#### 6.1.d.1 Sensitivities involving coal emissions pricing

Some additional sensitvities beyond those that are so readily graphed were performed and are shown in Table 2. Treatment 1 conforms to the conditions projected for 2015 with carbon dioxide tax applied at \$16.5/t (\$15/ton) with emissions allowances for $SO_2$ at \$1242.3/t (\$1127/ton), NOx annual at \$628.3/t (\$570/ton) and NOx ozone at \$1688.7/t (\$1532/ton). This combination had the effect of raising ethanol plant ROEs substantially above baseline levels while reducing ROEs of coal power plants to just 1.45% and -2.95% for independent and co-firing plants (using 10% biocoal), respectively. Treatment 2 conforms to the conditions projected for 2020 with $CO_2$ taxes raised to \$23.1/t (\$21/ton), \$1710.8/t (\$1552/ton) for $SO_2$, \$875.2/t (\$794/ton) NOx annual, and NOx ozone at \$2326.9/t (\$2,111/ton). The effect of Treatment 2 reduces ROEs for independent and co-firing coal plants to -19.3% and -38.2%, respectively. Ethanol plant ROEs are improved by Treatment 2, with the independent ethanol plant and steam-buying plant posting ROEs of 10.0% and 10.2%, respectively.

#### 6.1.d.2 Sensitivities involving renewalable energy credit pricing

In Treatment 3, Renewable Electricity Credits are priced at \$30/MWh and had the effect of driving down the ROEs of both the independent and co-firing coal power plants from baseline, making both about equal at 10.4% and 10.2%, respectively. In Treatment 4, RECs priced higher at \$50/MWh had the effects of driving ROEs even lower for independent and co-firing coal power plants to 6.8% and 7.8%, respectively. Treatment 5 prices RECs at \$60/MWh and has the effect of reducing the independent and co-firing coal plants ROEs to 4.6% and 6.5%, respectively. Treatment 6 applies a REC price of \$30/MWh and a biocoal price that is \$20 lower than baseline levels for both the torrefaction plant and power plant. This has the effect of reducing ROE for the independent torrefaction plant to -9.3% and the steam-selling torrefaction plant to 5.9% from the baseline levels of 4.2% and 11.7%, respectively. The ROEs for the independent and co-firing coal plants are close in magnitude at 10.4% and 10.6%, respectively.

#### 6.1.d.3 Sensitivities involving blend percentages

Treatment 7 shows the effect of applying a \$16.5/t (\$15/ton) of $CO_2$ on ethanol plants and the coal power plants. The effect of the \$16.5/t (\$15/ton) $CO_2$ tax raises the typical ethanol plant's ROE from 7.6% at baseline to 9.4%. The ethanol plant buying steam for \$11.0/1000kg (\$5.00/1000lb)versus \$0.002/MJ natural gas, goes from baseline level of 7.8% to 9.5% with its ROE. Treatment 8 raises the co-firing rate of a co-firing power plant from 10% to 20% and lowers its ROE from 10.7% to 8.7%, using baseline pricing of biocoal. Treatment 9 applies the 20% blend rate to the biocoal blending power plant and also imposes a \$30/MWh REC. This has the effect of maintaining the differential in the ROEs of the independent and co-firing power plants at 7.5% and 6.8%, respectively. A 30% biocoal blend rate applied in treatment 10 has the effect of driving the ROE of the co-firing power plant down to 6.3%, when it had been 10.7% at the baseline 10% co-firng rate. Treatment 11 applies the 30% co-firing rate and also \$30/MWh RECs, and has the effect of driving the ROEs down by the same factor, resulting in ROEs for the independent and co-firing power plant at 7.5% and 5.3%, respectively.

Table. 2 ROE for additional sensitivities. Rates of return on equity in shaded cells equal baseline levels.

| Treatments Applied to Model | Treatment Number | Ethanol Plant | Ethanol Plant + Torr. Steam | Torrefaction Plant | Torrefaction Plant + Steam | Coal Power Plant | Coal Power Plant + Cofiring |
|---|---|---|---|---|---|---|---|
| Baseline Returns on Equity | Baseline | 7.6% | 7.8% | 4.2% | 11.7% | 12.4% | 10.7% |
| Coal Emissions Allowances at $CO_2$ at \$16.5/t. $SO_2$ at \$1242/t., NOx Annual at \$628/t., and NOx Ozone at \$1688/t. | 1 | 9.4% | 9.5% | 4.2% | 11.7% | 1.4% | -2.9% |
| Coal Emissions Allowances: $CO_2$ at \$23.1/t., $SO_2$ at \$1710/t. NOx Annual at \$875/t. , NOx Ozone at \$2326/t. | 2 | 10.0% | 10.2% | 4.2% | 11.7% | -19.3% | -38.2% |
| Applying REC Price of \$30/MWh | 3 | 7.6% | 7.8% | 4.2% | 11.7% | 10.4% | 10.2% |
| Applying REC Price of \$50/MWh | 4 | 7.6% | 7.8% | 4.2% | 11.7% | 6.8% | 7.8% |
| Applying REC Price of \$60/MWh | 5 | 7.6% | 7.8% | 4.2% | 11.7% | 4.6% | 6.5% |
| REC Price of \$30/MWh; Biocoal Price of \$143.3/t. | 6 | 7.6% | 7.8% | -9.3% | 5.9% | 10.4% | 10.6% |
| \$16.5/t of $CO_2$ Carbon Tax Applied | 7 | 9.4% | 9.5% | 4.2% | 11.7% | 7.1% | 5.4% |
| 20% Biocoal Blend | 8 | 7.6% | 7.8% | 4.2% | 11.7% | 12.4% | 8.7% |
| 20% Biocoal Blend; \$30 REC | 9 | 7.6% | 7.8% | 4.2% | 11.7% | 7.5% | 6.8% |
| 30% Biocoal Blend | 10 | 7.6% | 7.8% | 4.2% | 11.7% | 12.4% | 6.3% |
| 30% Biocoal Blend; \$30 REC | 11 | 7.6% | 7.8% | 4.2% | 11.7% | 7.5% | 5.3% |

### 6.2 Wood: Baseline financial conditions of the co-located torrefaction and coal-fired power plant.

Co-location of the two entities give mutual advantages in terms of economic performance. The modelling of the co-location shows that two lines of 136,078 t/year (150,000 ton/year) torrefaction plants can meet the 10% cofiring requirement at a 550 MW coal-fired power plant. Two lines of torrefaction plants can generate 1,653,079,575 MJ/yr from VOC, which can be utilized at the coal-fired power plant in electricity generation. The energy contribution of VOC to the required input energy at the 550MW coal-fired power plant is 3.62%, which results in the reduction of 66,245 t/yr coal used in the power plant. This is equivalent to $1,606,307 worth of $CO_2$ tax abatement if $10/t carbon tax is assumed. In the co-location scenario, the coal-fired power plant provides flue gas energy to dry wet wood for the torrefaction plant. In our model, 50% M.C wet wood is pre-dried to 17%, prior to the torrefaction process. The pre-drying process requires 557,212,163 MJ/yr, while the 550MW coal power plant is capable of providing 1,411,672,849 MJ/yr from flue gas.

Fig.11 compares the five year average rates of ROE levels for torrefaction plants and coal power plants under different situations at baseline assumptions. From left to the middle the ROEs reflect the independent, steam selling, and co-located (wood) torrefaction plants with ROEs of 4.22%, 11.73% and 13.25%, respectively. Results for the coal power plants from the middle to the right reflect ROEs for independent, co-firing with biocoal, and co-located using biocoal and VOCs from wood of 12.37%, 10.68% and 9.45%, respectively. The results could change due to negotiations between the parties for pricing of biocoal, flue gasses, and VOCs.

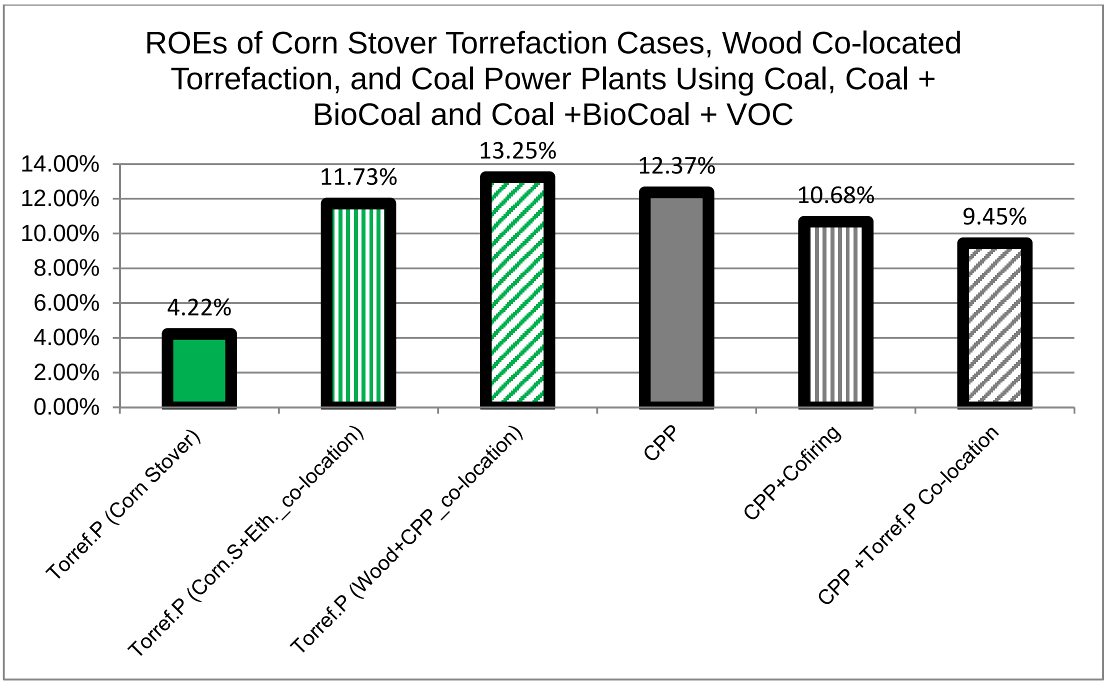


Fig. 11 Co-located wood torrefaction plant and coal power plant compared to baseline ROE of corn stover torrefaction and biocoal using coal power plants

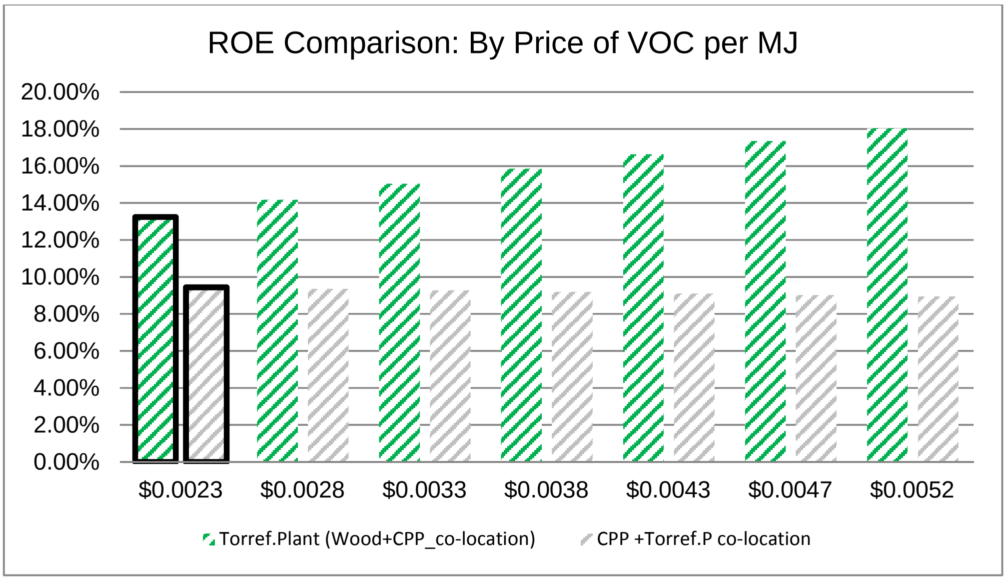


Fig. 12  Effect of price of VOC on ROE of co-located wood torrefaction plant and its adjacent coal power plant that buys VOCs and sells flue gasses

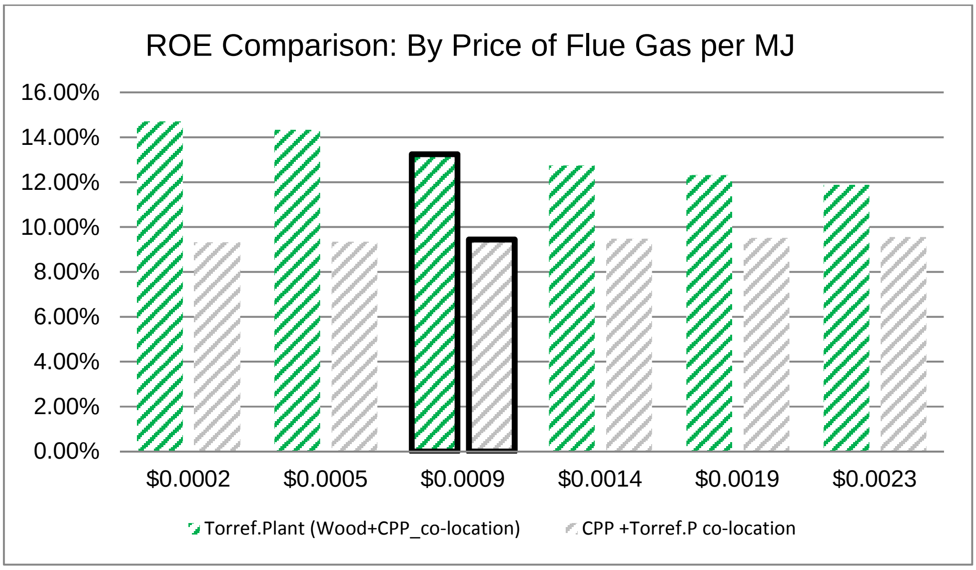


Fig. 13 Effect of flue gas pricing on ROE of co-located wood torrefaction plants and coal power plants buying VOC and selling flue gasses.

## 7. DISCUSSION

Single factor sensitivities helped quantify some basic relationships affecting the ROEs of ethanol plants and torrefaction plants. Torrefaction plants that are co-located with an ethanol plant have a competitive advantage by being able to tolerate lower prices of biocoal or higher costs of biomass. The torrefaction plant is not directly affected by policy initiatives, although these measures may have huge effects on the value of biocoal and the willingness of ethanol plants to purchase steam from the renewable source, torrefaction off-gasses.

The ethanol plants are affected by the pricing of renewable steam from torrefaction plants versus the market price for natural gas and the volatility that may return for that fuel. Dry-grind ethanol plants using steam from torrefaction VOC will be rewarded by the future enactment of $CO_2$ taxes due the lower carbon footprint of ethanol versus gasoline. If dry-grind ethanol plants that buy renewable steam from torrefaction plants qualify as advanced biofuel producers, the higher ROEs of ethanol plants using steam made from torrefaction off-gases will be well rewarded.

The situation faced by coal-fired power plants, particularly those using bituminous coal is challenging because of potential $CO_2$ taxes and additional emissions costs or allowances that may need to be purchased to emit $SO_2$ and NOx in future years. Analysis shows that the most powerful potential impact is that of $CO_2$ taxes. Emissions costs were modeled using projections for 2015 and 2020 and show that the coal-fired power plants will suffer much diminished ROEs. The price of biocoal is generally more powerful than emissions costs or allowances. The cost of Renewable Electricity Credits (REC) have the effect of lowering the ROEs of typical coal power plants, especially at levels of $30 per MWh or higher. As biocoal blend rates rise above 10%, they impose downward pressure on ROEs of the co-firing power plants. However, the simultaneous imposition of REC requirements at $30 has the effect of equalizing the ROEs of coal power plants, both independent and those that co-fire with biocoal.

The co-located wood torrefaction plant and the adjacent coal power plant that supplies ample flue gasses for drying wet wood comprise a special example we chose to analyze.

The co-location case of the torrefaction plants and the coal power plants introduces two different commodities to our analysis. Flue gasses are bought by the torrefaction plant from the coal power plant and used to pre-dry the wet wood. VOC emissions of the torrefaction plants supply energy to the coal-fired power plant and displace coal. The sale of VOC to the coal power plant is a more important revenue stream to the torrefaction plants and a minor expense for the coal plants as demonstrated in Fig. 12. The sale of the flue gasses by the coal power plant represents a minor revenue stream for coal plants, but the price of flue gasses has a greater effect on the ROE of the torrefaction plants as shown in Fig. 13.

## 8. CONCLUSION

Independent torrefaction plants can produce a ton of biocoal for $46.3/t ($42/ton) of biocoal in overhead and operating costs, while co-located torrefaction plants that can sell steam generated from off-gasses operate with net costs of just $18.7/t ($17/ton) of biocoal produced. This differential represents a significant competitive advantage to torrefaction businesses when co-location opportunities exist.

Our sensitivity analyses show us the conditions necessary for a torrefaction plant to be profitable and readily show favorable financial effects from torrefying corn stover on ethanol plants buying steam from off-gasses. Policy changes such as enactment of $CO_2$ taxes and/or designation of advanced biofuel status for ethanol produced with the benefit of renewable steam sources will enhance the appeal of steam purchases when generated by combusting off-gasses from torrefaction plants. Our hypothesis that bituminous coal power plants are the main market for biocoal is logical. However, we recognize the challenges in finding favorable ROEs for traditional bituminous coal and co-firing power plants in the face of more restrictive emissions controls, including $CO_2$ taxes in the U.S. Co-firing plants using biocoal have challenges for four reasons:

1) Biocoal is less energy dense and more expensive than bituminous coal per unit of energy.
2) The price of biocoal has greater impact on cost of electricity than emissions costs or proposed allowances.
3) Higher biocoal blend rates impose downward pressure on ROEs of co-firing power plants.
4) Although biocoal has favorable attributes in reducing $CO_2$ and other costly emissions, it is usually too expensive for the amount of emissions reductions it can deliver.

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