



Techno-economic analysis of biomass fast pyrolysis to transportation fuels

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ABSTRACT

This techno-economic study examines fast pyrolysis of corn stover to bio-oil with subsequent upgrading of the bio-oil to naphtha and diesel range fuels. Two 2000 dry tonne per day scenarios are developed: the first scenario separates a fraction of the bio-oil to generate hydrogen on-site for fuel upgrading, while the second scenario relies on merchant hydrogen.

The modeling effort resulted in liquid fuel production rates of 134 and 220 million liters per year for the hydrogen production and purchase scenarios, respectively. Capital costs for these plants are \$287 and \$200 million. Fuel product value estimates are \$3.09 and \$2.11 per gallon of gasoline equivalent (\$0.82 and \$0.56 per liter). While calculated costs of this biofuel are competitive with other kinds of alternative fuels, further research is required to better determine the effect of feedstock properties and process conditions on the ultimate yield of liquid fuel from bio-oil. Pioneer plant analysis estimates capital costs to be \$911 and \$585 million for construction of a first-of-a-kind fast pyrolysis and upgrading biorefinery with product values of \$6.55 and \$3.41 per gge (\$1.73 and \$0.90 per liter).

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1. Introduction

According to the Energy Information Administration, renewable fuels lead recent increases in primary energy consumption. Biomass energy consumption is projected to increase by 4.4% per year from 2007 to 2030 compared to 0.5% increase in primary energy consumption for end-use markets [1]. By 2030, biomass consumption in primary markets is expected to reach 20% of renewable energy sources. Although ethanol and biodiesel have led the adoption of renewable fuels in the transportation industry, the Energy Independence and Security Act of 2007 mandates production of at least 36 billion gallons of renewable fuels by 2022 with cellulosic biofuels contributing more (16 billion gallons) than corn ethanol (15 billion gallons). Biomass fast pyrolysis and bio-oil upgrading is a cellulosic conversion technology that can contribute to renewable fuels by producing naphtha and diesel range stock fuel.

This study is a techno-economic analysis of naphtha and diesel range stock fuel production from the fast pyrolysis of corn stover

and upgrading of the resulting bio-oil. The focus is on technologies projected to be viable within a 5–8 year timeframe. Based on this timeframe and after considering time for design, construction, and startup, the process would likely have to be based on experimental data available today. Initially, 13 published pyrolysis technologies were reviewed and a matrix was prepared considering economics, technological maturity, environmental aspects, process performance, and technical and economic risks.

Several previous studies report the cost of producing bio-oil via fast pyrolysis [2–8], but very few have explored the cost of upgrading bio-oil to transportation fuel. Furthermore, previous studies apply varying assumptions for biomass cost, plant capacity, reactor technology, and other variables. Results presented in this study are given in terms of the fuel product value (PV) that yields a net present value of zero with an internal rate of return of 10%. Additional economic assumptions are presented in the economics section.

Previous studies have estimated the cost of bio-oil to range between \$0.41 and \$2.46 per gallon (\$0.11 and \$0.65 per liter) [2–9]. Capital cost estimates for these studies range from \$37 million [8] to \$143 million [7] for 1000 tonne per day capacities. A 2006 study by the National Renewable Energy Laboratory for a 550 dry short tons (499 tonne) per day wood fast pyrolysis plant producing 28 million gallons (106 million liters) of bio-oil per year estimated the capital and operating cost to be \$48.2 and \$9.6 million respectively corresponding to a selling price of \$0.62 per gallon (\$0.16 per

Abbreviations: GGE, gallon of gasoline equivalent equal to 115,000 BTU's or 121 MJ's; PV, product value with NPV = 0 and IRR of 10% in 20 years; MACRS, modified accelerated cost recovery system; DTPD, dry tonne per day.

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liter). There are various companies including Dynamotive [10] and NewEarth [11] producing bio-oil commercially.

Although petroleum hydroprocessing is commercially mature, relatively little data is available on bio-oil hydroprocessing. A 2005 study by UOP, Inc. found that gasoline from bio-oil is economically attractive if bio-oil is available at \$18 per barrel (\$0.11 per liter) and crude oil sells for more than \$50 per barrel (\$0.31 per liter) [12]. A 2008 report by UOP, Inc. estimates the cost of naphtha and diesel range fuel from corn stover to be \$1.80 per gallon (\$0.48 per liter) [13]. An independent 2009 report for conversion of woody biomass into liquid fuel employing fast pyrolysis and bio-oil hydroprocessing estimates the cost of naphtha and diesel range stock fuel to be \$2.04 per gallon (\$0.54 per liter) for a stand-alone biorefinery with purchase of electricity and natural gas [14]. There are currently no commercial enterprises producing naphtha and diesel fuel from bio-oil hydroprocessing.

This study models two separate scenarios for procuring hydrogen for bio-oil upgrading. Each of these scenarios is modeled in detail and economic analysis is performed assuming an *n*th plant design, meaning that the technologies used in the design have been employed in previous commercial plants and are relatively well understood. However, cellulosic fast pyrolysis technology has yet to be commercialized, and a pioneer plant is expected to be significantly more expensive than an *n*th plant. To assess the impact of using immature technologies on the PV for a pioneer plant, the potential increase in capital cost and decreased plant performance were estimated using models developed by the RAND Corporation [15]. Various common assumptions were employed to allow simple comparison with biochemical and gasification scenarios explored in companion papers.

2. Material and methods

The biomass conversion plants assumed here process 2000 dry tonnes per day (dtpd) of corn stover. One assumption that distinguishes this study from previous studies is a higher feedstock cost at the plant gate (\$75 per short ton or \$83 per tonne). Major processing steps include biomass pretreatment, fast pyrolysis, solids removal, oil collection, char combustion, and oil upgrading. A schematic of the biomass fast pyrolysis process to produce naphtha and diesel range products is shown in Fig. 1.

Biomass with 25% moisture content is dried to 7% moisture and ground to 3 mm diameter size prior to feeding into a fluid bed pyrolyzer operating at 480 °C and atmospheric pressure. Fluid bed, auger, and drop-tube reactor designs were considered in a down-select process. The fluid bed reactor was selected for its ability to scale, familiarity, and availability of process data. Standard cyclones remove solids consisting mostly of char particles entrained in the vapors exiting the pyrolyzer. Vapors are condensed in indirect contact heat exchangers yielding bio-oil that can be safely stored at ambient conditions prior to upgrading. Pyrolysis solid products are sent to a combustor to provide heat for the drying and pyrolysis process. The hydrogen production scenario employs methane and steam reforming equipment to generate requisite hydrogen. Bio-oil upgrading, which is discussed in the hydroprocessing section, generates fuel compatible with existing infrastructure.

Biomass composition as delivered at the plant gate is an important factor not studied in detail in this analysis. Ash content present in biomass and soil can cause fouling and plugging of high-temperature equipment. Minerals catalyze thermal decomposition reactions that are detrimental to the production of quality bio-oil. Biomass washing using water or acid-removal techniques can reduce alkali content in biomass [16]. Mineral effects were not considered in this study due to the limited knowledge of the mechanisms by which alkali affects pyrolysis yields.

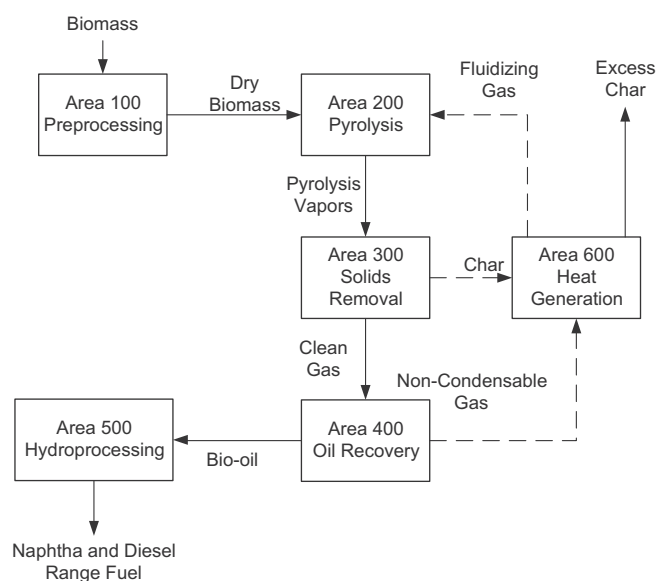


Fig. 1. Biomass fast pyrolysis and bio-oil upgrading diagram.

The upgrading process considered in this study is bio-oil hydrotreating and hydrocracking. Hydrotreating and hydrocracking (both of which fall under the generic term, hydroprocessing) are commonly employed in the petroleum industry to remove undesired compounds such as sulfur from crude oil and break large hydrocarbon molecules to produce clean naphtha and diesel range products. Bio-oil typically contains significant quantities of oxygenated compounds that are undesirable for combustion in vehicle engines. Hydrotreating can convert oxygen found in bio-oil to water and carbon dioxide leaving hydrocarbons that are suitable for internal combustion engines.

The plant scenarios are an *n*th plant design meaning significant design, engineering, and operating experience has been achieved. Technical modeling is accomplished by employing Aspen Plus® software to develop mass and energy calculations. Economic analysis is a combination of Aspen Icarus® software equipment cost and sizing, and spreadsheet investment analysis using Peters and Timmerhaus installation factors [17].

Biomass and pyrolysis char have been modeled on a proximate and ultimate analysis basis although there is scarce information found in the literature that is specific to pyrolysis of corn stover. Nonetheless, process feedstock and char composition is modeled using data shown in Table 1. Corn stover pyrolysis analysis is adapted from USDA experimental data [18]. Char composition analysis is based on Iowa State University laboratory results [19].

Table 1
Corn stover and char ultimate and proximate analysis.

Element	Biomass value (wt.%)	Char value (wt.%)
<i>Ultimate analysis (dry basis)</i>		
Ash	6	33.3
Carbon	47.28	51.2
Hydrogen	5.06	2.12
Nitrogen	0.8	0.45
Chlorine	~0	0.471
Sulfur	0.22	0.935
Oxygen	40.63	11.5
<i>Proximate analysis (wet basis)</i>		
Element	Value (wt.%)	Value (ash-free wt.%)
Moisture	25.0	0
Fixed content	17.7	51.21
Volatile matter	52.8	49.79
Ash	4.5	0

Two models have been developed to study the performance of biomass pyrolysis: a hydrogen production scenario that employs bio-oil reforming to generate requisite hydrogen for bio-oil upgrading, and a hydrogen purchase scenario that relies on merchant hydrogen. These scenarios employ a common process design that can be divided into eight distinct sections: chopping and grinding, drying, pyrolysis, solids removal, bio-oil recovery, storage, combustion, and hydroprocessing.

2.1. Chopping and grinding

Delivered feedstock typically requires conditioning prior to feeding into a pyrolysis reactor to avoid penalties that reduce yields and increase heat requirements. Mechanical particle size reduction and drying are commonly used in thermochemical processes.

This model employs a two-step comminution process that reduces mean particle sizes initially to 10 and 3 mm in the final grinding step. The first step allows for improved biomass drying performance. This final size is optimal for fluid bed biomass pyrolysis allowing efficient heat transfer to the biomass particles [20]. Power requirements for biomass grinding are based on research by Mani et al. [21] that correlates the grinder screen size to the energy requirement for a hammer mill.

2.2. Drying

Feedstock drying is very important for thermochemical processes. Moisture embedded in the feed consumes process heat and contributes to lower process yields. This study assumes that biomass is dried to a moisture content of less than 7%, which is recommended for reasonable pyrolysis performance [22]. This model employs a rule-of-thumb estimate for drying energy requirement of 5 MJ per kg (2000 BTU per pound) of water evaporated using a steam rotary dryer.

2.3. Pyrolysis

Biomass fast pyrolysis is a thermal process that requires temperatures near 500 °C, rapid heat transfer, and low residence times. Various reactor designs have been proposed for this process [23]. Due to concerns over the scalability of existing reactor designs, this study assumes that four 500 tonne per day reactors are employed in parallel. This size was selected based on assumptions from a report by the National Renewable Energy Laboratory (NREL) [9]. Commercial units as large as 200 tonne per day are currently in operation [10] and larger units (more than 2000 dtpd) are completing development although the exact nature of their reactor design is unknown [11]. Although the dynamic aspects of this process are very important, there is insufficient information to fully model this process in Aspen Plus® software. Pyrolysis product distribution is adapted from USDA data [18] using bio-oil and non-condensable gas (NCG) composition shown in Table 2. Bio-oil and NCG composition is a modification of NREL analysis [9]. Bio-oil compounds were selected based on available Aspen Plus® software compounds and may not share the same properties as compounds selected by NREL. Organic yields are reported to be 62% by weight of dry corn stover. Char and ash yields account for 17% of the feedstock mass, and the balance consists of non-condensable gases. Bio-oil composition is shown in Table 2. These values have been adjusted from the original analysis to achieve mole balance.

2.4. Cleanup

Gases exiting from the pyrolysis reactor contain entrained particles of various sizes. Compared to particles generated from

Table 2

Assumed pyrolysis bio-oil and non-condensable gas composition.

Composition (kg/100 kg of dry biomass)	
<i>Gas compounds</i>	
Carbon dioxide	5.42
Carbon monoxide	6.56
Methane	0.035
Ethane	0.142
Hydrogen	0.588 ^a
Propene	0.152
Ammonia	0.0121
<i>Bio-oil compounds</i>	
Acetic acid	5.93
Propionic acid	7.31
Methoxyphenol	0.61
Ethylphenol	3.80
Formic acid	3.41
propyl-benzoate	16.36
Phenol	0.46
Toluene	2.27
Furfural	18.98
Benzene	0.77
<i>Other compounds</i>	
Water	10.8
Char/ASH	16.39

^a Corrected to 0.02 kg/kg of biomass based on engineering judgment.

gasification, pyrolysis particles can be much smaller with sizes of less than 25 microns. The particle size is important because it affects the design and performance of cleaning equipment such as cyclones and filters. This model assumes that a set of parallel cyclones remove 90% of entrained char particles. Char collected from the cleanup section is sent to the combustion section where it is employed to provide process heat. A portion of the char is burned while the rest is collected and sold as a by-product. If bio-oil is fed into a gasifier, char could be mixed with this bio-oil to form a slurry with attractive thermal properties. Dynamotive® employs the name BioOil Plus [10] to differentiate their bio-oil and char mixture.

2.5. Bio-oil collection

There are various possible approaches to the collection of pyrolysis oil. To collect high quality bio-oil, and maintain high yields, vapors should be condensed within fractions of a second of exiting the pyrolysis reactor. Longer residence times favor secondary reactions that reduce the quantity and quality of bio-oil collected [23].

To accomplish rapid condensation of pyrolysis vapors, this model employs an indirect heat exchanger to transfer heat from hot vapors at 480 °C to a water stream. Cool vapors exit the condenser unit at 150 °C raising about 8000 tonne of saturated steam. After most of the bio-oil has been condensed, an Electro-Static Precipitator (ESP) unit collects remaining droplets known as aerosols by using high voltage charges. The formation of aerosols is a complex process with scarce information on the mechanism involved. This model assumes that remaining char, representing less than 10% of the initial char produced, entrained in the vapors is collected in the ESP unit. Condensable vapors coalesce on the surface of these fine char particles and therefore act as a collection mechanism of entrained char.

Non-condensable gases (NCGs) include significant amounts of methane and other combustible gases. NCGs are sent to the combustor to provide heat for biomass drying and the pyrolysis reaction, and later recycled to the reactor on a 1.6 kg of gas per kg of dry biomass ratio to provide process heat and aid in fluidizing the reactor.

2.6. Storage

Bio-oil and char are collected in the storage section, which can store up to 4 weeks of liquid product. Bio-oil storage is provided as a buffer to the upgrading section. Under typical conditions, bio-oil would be continuously upgraded requiring minimal storage time. Although there have been concerns regarding the long-term stability of bio-oil, NREL reports that bio-oil can remain stable over a period of months [9], and Dynamotive® suggests that bio-oil should be stored in an air-free environment in stainless steel material to prevent corrosion [24]. Storage for the naphtha and diesel range products is similarly sized for 4 weeks of capacity in case there is a delay in getting the product to market.

2.7. Combustion

Non-condensable gases and a fraction of pyrolysis char are combusted to provide the necessary process heat for the pyrolysis process and steam generation. Combustion air, at 20% excess, is sent to the combustion reactor. Combustion gases are cooled to provide additional heat to generate steam. Finally, cyclones collect ash from the combustion gases, which is land filled with a solids disposal cost of \$18 per short ton (\$16 per tonne) [25]. Only 100 tonnes per day of char (about a third of total char produced) need to be combusted to provide process heat in addition to the combustion of NCGs.

2.8. Hydroprocessing

Hydrotreating is an exothermic process commonly used in the oil industry to selectively remove impurities such as sulfur, nitrogen, and metals. This study targets typical hydrotreating conditions such as a hydrogen rich environment (about 95 mol% or 5% by weight), 7–10 MPa (1000–1500 psi) pressure, and temperatures of 300–400 °C using a cobalt-molybdenum catalyst. Hydrotreating is followed by hydrocracking, which breaks down heavy molecules into shorter chains. For example, heavy hydrocarbons with 30 or more carbon atoms can be split into chains within the diesel (C₁₂) or naphtha (C₈) range. Process conditions are more severe than hydrotreating with pressures of 10–14 MPa (1500–2000 psi) and temperatures of 400–450 °C using a nickel-molybdenum catalyst.

Bio-oil contains a large variety of heavy and light compounds. It also includes a water-soluble aqueous phase that can be reformed to produce the required hydrogen. Heavy molecules present in bio-oil can be hydrocracked to lighter molecules. Bio-oil may be suitable for both hydrotreating at an oil refinery where hydrogen can be provided separately and stand-alone processing that employs the bio-oil aqueous phase to generate hydrogen. In 2005 UOP published [26] one of the few publically available reports on bio-oil hydroprocessing. Their initial report employed bio-oil's aqueous phase to generate hydrogen to upgrade the pyrolysis lignin (heavy) phase. This process employs gravity separation to separate pyrolysis lignin from the water-soluble bio-oil compounds (aqueous phase bio-oil). Aqueous phase bio-oil is mixed with steam and sent to a high-temperature pre-reformer and converted into syngas. This syngas is then fed into a reformer with methane to produce hydrogen. Various reactions including water-gas-shift take place in the reformer to produce hydrogen. Analysis from Markevich et al. [27] is employed in this study to model the reforming reaction mechanism.

The hydrogen production scenario developed for this study differs from the original UOP analysis by employing a smaller fraction of oil for reforming purposes. Bio-oil's aqueous phase can account for up to 70% of the bio-oil weight, which leaves only 30% available for upgrading. In this project, just a bit more than a third of bio-oil

is required to produce the requisite hydrogen. Published studies on bio-oil reforming indicate that this is a valid assumption for the current state of technology [27]. This study calculates that 38% of the single-phase bio-oil needs to be reformed into hydrogen to upgrade the remaining bio-oil.

UOP updated their bio-oil hydrotreating analysis in 2008 [13]. Their most recent study explores converting all bio-oil components to transportation fuels therefore maximizing yields from pyrolysis oils. This approach requires a remote source of hydrogen such as an oil refinery. Published yields for this scenario estimate that up to 42% of the upgrading feed can be converted to equal fractions of naphtha and diesel range fuel.

Hydrocracking typically processes hydrocarbons of long (+30) carbon chain lengths. The longest carbon chain for a compound used in this model has 10 carbon atoms, and therefore the hydrocracking model could be improved with better knowledge of bio-oil composition. Nevertheless, a hydrocracking unit is included because this is an important component in the conversion of bio-oil to transportation fuels. Hydrocracking fuel yields are based on Aspen Plus® software stoichiometric calculations. It is known that metals (phosphorous, potassium, sodium, calcium and others) originating from corn stover will be contained in bio-oil. Traditionally, concentration of metals has to be lowered to 10 ppm or less by utilizing a guard bed with sacrificial catalyst in order to prevent significant poisoning of the hydrotreating catalyst. Typical levels of total metal content in bio-oil can be as high as 500 ppm. Technology to remove metals specifically found in bio-oil is not well understood and is under current development. Therefore, in this model a placeholder component for the guard bed has been included. Capital costs for the guard bed were estimated as 15% of the hydroprocessing capital expenditure, which is its typical capital cost contribution in petroleum refineries. Sensitivity analysis associated with the cost of operating and replacing catalysts are considered in the results section, and this analysis provides some insight into the implications of this assumption.

2.9. Economics

This project employs Aspen Icarus® software to estimate free-on-board (FOB) equipment costs and Peters and Timmerhaus investment factors to calculate project capital expenditures [17]. Estimates based on this methodology are typically accurate within 30%. The profitability of a given process can be determined from the operating costs and profitability analysis. A modified NREL discounted cash flow rate of return (DCFROR) analysis spreadsheet is employed in this study to calculate the PV.

The plant is designed based on the current state of technology, and is assumed to be the *n*th plant of its kind. Economic analysis for a pioneer plant is developed using risk analysis formulas that take into account the maturity of the technology and accuracy of the simulation. The online time is 329 days per year (equivalent capacity factor of 90%). Construction time of less than 24 months is considered. The startup period is 25% of the construction time (6 months), and during this period, an average of 50% production is achieved with expenditures of about 75% of variable expenses and 100% of fixed expenses. Equipment costing data, and installation factors, are collected from direct quotation, published data, and Aspen Icarus® software evaluation with preference given in the order shown here.

Feedstock cost is assumed to be \$75 per dry short ton (\$83 per dry tonne) and includes delivery cost. Electricity cost is assumed to be \$0.054 per kWh. Catalyst replacement costs are estimated at \$1.77 million per year based on costs for crude oil processing [28]. Actual costs will strongly depend on the quality of the bio-oil produced, and sensitivities are employed here to understand the potential impact of increased catalyst fouling.

Working capital is assumed to be 15% of the total capital investment. It is assumed that the product, naphtha and diesel range fuel, will be made, shipped and paid for in 30 days. Annual maintenance materials are 2% of the total installed equipment cost.

General overhead is a factor of 60% applied to the total salaries and covers items such as safety, general engineering, general plant maintenance, payroll overhead (including benefits), plant security, janitorial and similar services, phone, light, heat, and plant communications.

The total plant investment cost is determined by applying overhead and contingency factors to installed equipment costs. A 20% contingency factor is employed for the base cases, and pioneer plant calculations assume 30% contingency. Insurance and taxes are considered as 1.5% of the total installed equipment cost.

To determine the PV per gallon of naphtha and diesel range fuel, a discounted cash flow analysis is used (after knowing the major three costs areas: total project investment, variable operating costs, and fixed operating cost). A 10% discounted cash flow rate of return is used over a 20 year plant life. The plant is considered 100% equity financed. The IRS Modified Accelerated Cost Recovery System (MACRS) is employed to calculate the federal tax return, with depreciation based on a Declining Balance (DB) method. This allows for the shortest recovery period and largest deductions. The general plant depreciation period is assumed to be 7 years and employs a 200% DB depreciation method. State tax is not considered for these calculations because the location of the plant is not specified. Equipment, chemical and labor costs are indexed to 2007 dollars. Return on investment is calculated on a per gallon basis, and income tax is averaged over the plant life.

In the hydrogen purchase scenario explored for this project, bio-oil is upgraded employing hydrogen from an external source. The purchase price of hydrogen considered here is \$1.50 per gallon of gasoline equivalent (GGE) (\$0.40 per liter) or nearly \$1.50 per kg.

2.10. Sensitivity analysis

Key variables are selected based on their potential impact on the fuel value. Capital cost is a particularly important sensitivity variable due to the uncertainties associated with the estimate in this study. Similarly, upgrading of bio-oil to naphtha and diesel range products is a developing technology with scarce public information about the system performance. Upgrading yields can be strongly affected by bio-oil quality and catalyst performance. Further research is required to improve bio-oil properties and reduce catalyst deactivation.

2.11. Pioneer plant analysis

Pioneer plant analysis is based on multi-factor linear regressions developed by RAND Corporation for estimating production shortfalls and capital growth of chemical pioneer process plants [15]. The regressions were developed using data collected from 44 process plants. Although fast pyrolysis technology was not included in the pioneer regressions, this study assumes that the linear regressions represent reasonable data to estimate fast pyrolysis pioneer plant costs. The production shortfalls are accounted for in the regression equation for “plant performance”, which is the production in the second 6 months after initial operation as a percentage of nameplate capacity. Parameters used to estimate plant performance are based on the number of process steps that have not been demonstrated commercially, the mass and energy balance equations that are validated with commercial-scale data, the potential for waste handling issues, and whether the plant handles solids. A summary of the pioneer plant parameter ranges and values is included in Table 3.

For biomass fast pyrolysis and bio-oil upgrading, pioneer plant performance values of 8.5%, 22.3% and 36.1% were calculated assuming a range of 2–4 new steps; 0% mass and energy balance equations; 3–5 range for solids waste handling, and 1 for solids handling. The number of new process steps has the largest impact on plant performance. Although bio-oil upgrading employs technology similar to crude oil refining equipment, this technology has not been commercially employed to process bio-oil. The average plant performance value for a solids-processing plant in the RAND survey was 50% [29]. This underscores the difficulty for commercial plants to manage solid feedstock. It is not unusual that pioneer plants employing solid feedstock fail to achieve higher than 40% of their nameplate performance resulting in significant losses.

The second regression equation (“cost growth”) estimates the increase in actual capital cost over the original estimate. Parameters for cost growth are based on the cost estimate for equipment not demonstrated at a commercial scale, the potential for buildup of impurities, the number of continuously linked steps, and the inclusiveness of pre-startup and land costs, and the level of site specific information that is included in the cost estimate.

For biomass fast pyrolysis and bio-oil upgrading, cost growth values of 0.56, 0.29, and 0.22 were calculated based on 25%, 60%, and 75% of equipment not demonstrated at commercial scale; 3–5 potential of impurity buildup; 4, 5, and 6 consecutively linked steps; 66%, and 0% inclusiveness of pre-startup and land costs, and 6 and 8 level of site specific information with 8 representing the minimum level of site information included in the estimate. The percent of equipment not demonstrated at commercial scale has the largest impact on the cost growth factor. The amount of knowledge regarding the performance of commercial technology is strongly related to the success of building a plant that employs new technology.

Three scenarios are considered in the pioneer plant analysis – most probable, optimistic and pessimistic – representing the range of estimates for variables used in the regression equations for cost growth and plant performance. However, only a comparison of the *n*th plant numbers and the most probable case is discussed in the paper.

In the discounted cash flow spreadsheet the Total Capital Investment (TCI) of the base case *n*th plant is divided by the percentage cost growth to estimate the TCI of the pioneer plant. The first year fuel sales, variable operating costs and electricity export of the *n*th plant is multiplied by the percentage of plant performance to account for the reduced production of a pioneer plant. For the discounted cash flow analysis the plant performance is

Table 3
Description of pioneer plant analysis parameters.

Parameters	Range	Definition
Newsteps	≥ 0	Number of new process areas
Baleqs	0–100	Percentage of M&E balance equations based on commercial plant data
Solids	0 or 1	A factor based on the presence of solids
Waste	0–5	A factor of waste disposal
Plant performance	0–100	Percentage of nameplate capacity operation during the first year
Pctnew	0–100	Percentage of equipment cost for new (under-developed) equipment
Impurities	0–5	A factor of impurities present in the process
Complexity	0–5	Number of consecutively linked plant areas
Inclusiveness	0–100	Percentage of land purchase/lease, initial plant inventory/parts/catalysts, and pre-operating personnel costs included in the analysis
Project definition	2–8	A factor of level of detail in the analysis
Cost growth	N/A	Increase in capital cost expenditure required for pioneer plant

increased by 20% per year until nameplate capacity is reached. The contingency is increased to 30% from 20% used in the n th plant analysis in order to account for greater uncertainty in equipment and other costs related solely to the n th plant design, even before considering cost growth or plant performance.

3. Results and discussion

Table 4 includes a summary comparison of key results from this study. The hydrogen production scenario has higher capital costs due to additional equipment required for bio-oil upgrading compared to the hydrogen purchase scenario. Annual operating costs are higher for the hydrogen purchase scenario at a hydrogen price of \$1.50 per gallon of gasoline equivalent (\$0.40 per liter). Higher fuel yields from upgrading all available bio-oil offset the increase in costs resulting in an improved PV for the hydrogen purchase scenario. Hydrogen availability could impact the economics of this scenario as explored in the sensitivity analysis.

Combined hydrogen production and purchase scenario material results are shown in Fig. 2. For both scenarios, bio-oil yield for 2000 tonne per day corn stover pyrolysis is estimated at 104 million gallons (394 million liters) per year representing 72% by weight of the dry biomass input and includes water content of about 15 wt.%. For the hydrogen production scenario, 38% of the bio-oil is reformed to produce 1500 kg per hour of hydrogen. Biomass to liquid fuel efficiency for the hydrogen production scenario is estimated at 36%.

Table 4
Summary of key results.

	Hydrogen production	Hydrogen purchase
Capital cost (millions \$)	\$287	\$200
Annual operating cost (millions \$)	\$109	\$123
Fuel yield (million L/year)	134	220
PV (\$/gallon gasoline equivalent)	\$3.09 (\$0.82/L)	\$2.11 (\$0.56/L)
Pioneer plant capital cost (million \$)	\$911	\$585
Pioneer PV (\$/gge)	\$6.55 (\$1.73/L)	\$3.41 (\$0.90/L)

Fuel yield for the hydrogen production scenario is 35.4 million gallons (134 million liters) of fuel per year. The hydrogen purchase scenario employs 2040 kg per hour of hydrogen to upgrade 60,000 kg per hour of bio-oil. Feedstock to liquid fuel energy conversion efficiency for the hydrogen purchase scenario is estimated at 50% and includes the hydrogen energy input (120 MJ) per kg or 0.98 gallons of gasoline equivalent per kg of hydrogen). Fuel production for the hydrogen purchase scenario is 58.2 million gallons (220 million liters) of fuel per year.

The PV for a 2000 tonne per day corn stover hydrogen production scenario is \$3.09 per gallon (\$0.82 per liter) of gasoline equivalent fuel. This corresponds to a bio-oil production cost of \$0.83 per gallon of bio-oil (\$0.22 per liter). Capital expenditures for this plant are estimated at \$287 million. The PV for a 2000 tonne per day fast pyrolysis and upgrading plant with external hydrogen purchase is \$2.11 per gallon of fuel (\$0.56 per liter). Capital expenditures for the hydrogen purchase plant are estimated at \$200 million. Fig. 3 includes a breakdown of installed equipment cost components,

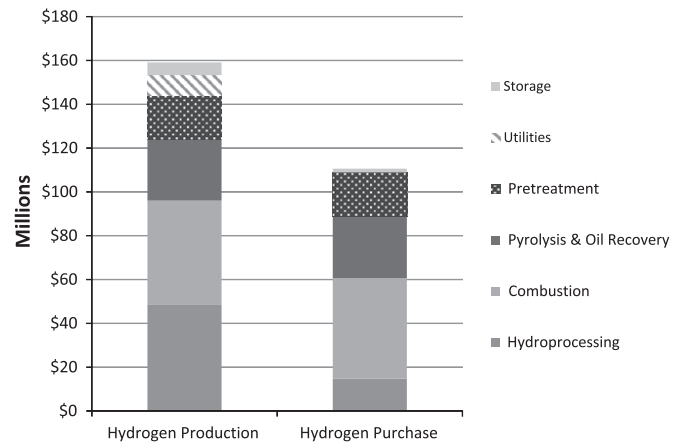


Fig. 3. Corn stover fast pyrolysis and bio-oil upgrading installed equipment costs for 2000 tpd.

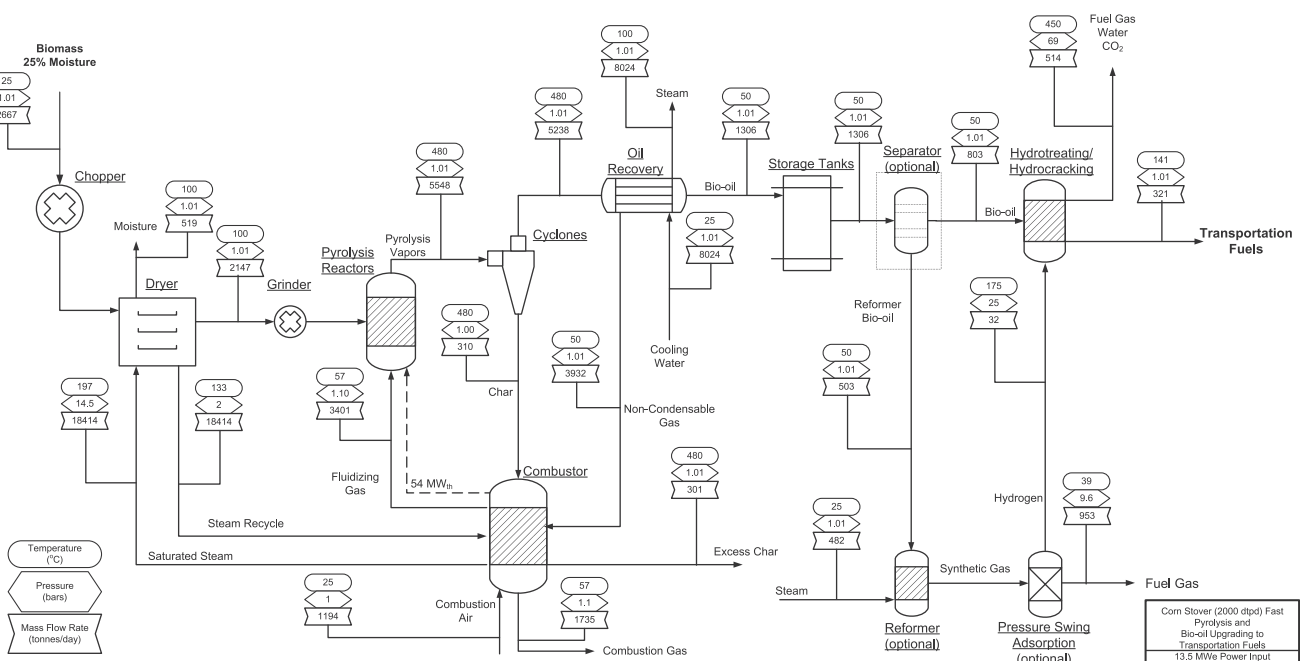


Fig. 2. Combined hydrogen production (optional equipment) and purchase scenario diagram with temperature, pressure, and mass flow rate results.

and Fig. 4 shows the operating costs components for the production and upgrading scenarios. Pioneer plant PV estimates are \$6.55 and \$3.41 per gallon (\$1.73 and \$0.90 per liter) for the hydro-

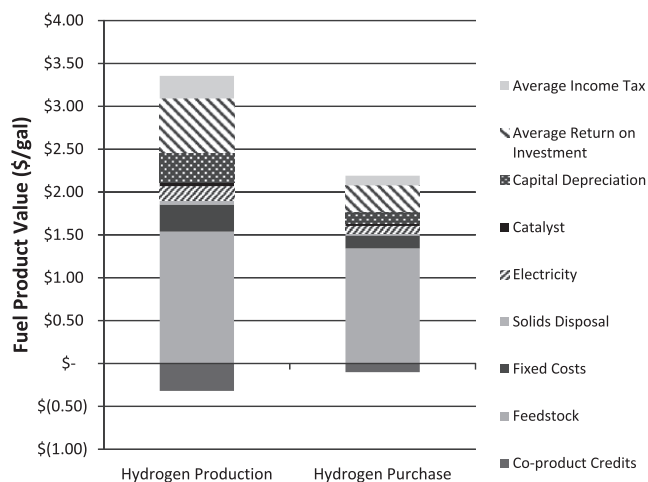


Fig. 4. Corn stover fast pyrolysis and bio-oil upgrading operating costs for 2000 tpd.

gen production and purchase scenarios respectively. These high pioneer plant PVs reflect a potential high risk of commercializing fast pyrolysis and bio-oil upgrading based on the regression data from RAND Corporation [15].

Electricity costs are estimated to contribute 16.4 cents per gallon (4.33 cents per liter) to the cost of fuel. Investment in power generation could yield additional income from sale of excess electricity, but this scenario is not explored in this project. Efforts have been made to ensure that these scenarios avoid consumption of fossil fuel resources. For example, process heat is provided from the combustion of biomass-derived products instead of using natural gas or other forms of fossil fuels. Nevertheless, purchased electricity could come from fossil fuels, and most available hydrogen derives from fossil fuels. The hydrogen production scenario produces more fuel gas due to the bio-oil reforming process.

Sensitivity results suggest greater negative sensitivity to key process variables. This implies that poor process performance could have a stronger impact on the PV than improvements in the technology. Sensitivity analysis results shown in Fig. 5 indicate a strong impact from fuel yield. This implies that slight improvements in the bio-oil upgrading process could reduce the cost of fuel significantly whereas lower yields result in a rapid increase in fuel cost. Biomass cost sensitivity is also important not only because of its impact, but also because the cost to acquire feedstock can vary

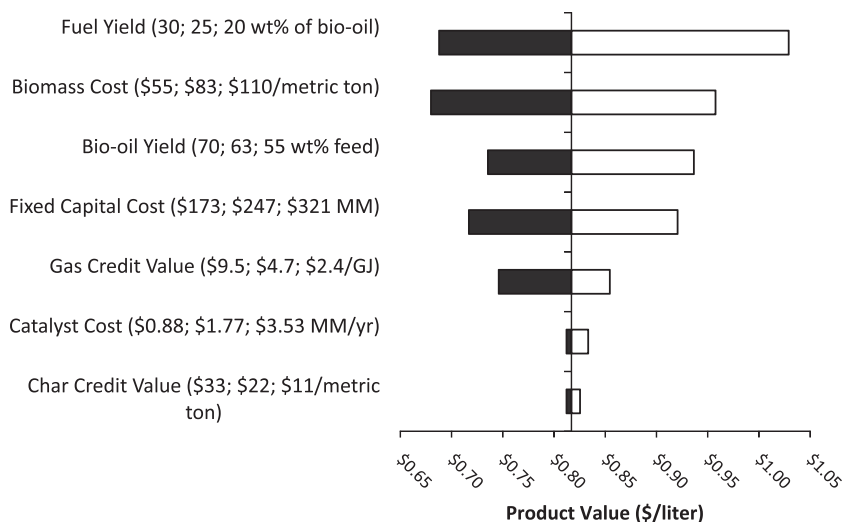


Fig. 5. Sensitivity analysis for 2000 tpd fast pyrolysis and bio-oil upgrading with hydrogen production. Legend indicates assumed values from favorable to unfavorable.

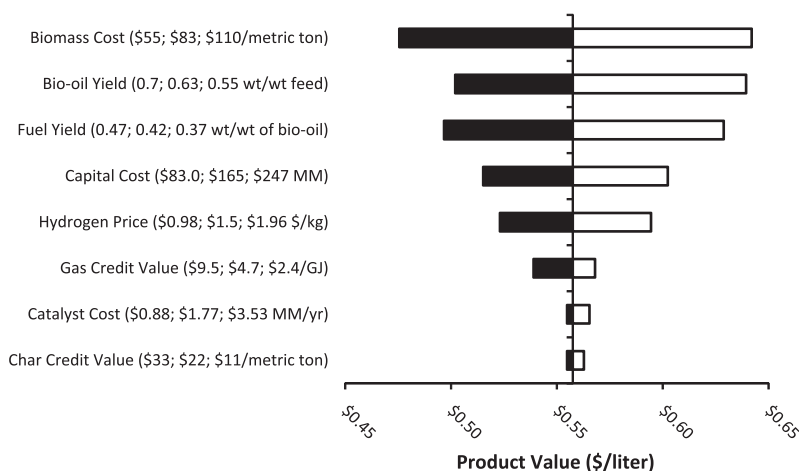


Fig. 6. Sensitivity analysis for 2000 tpd fast pyrolysis and bio-oil upgrading with hydrogen purchase. Legend indicates assumed values from favorable to unfavorable.

widely between locations and throughout the year. Sensitivity analysis results for the hydrogen purchase scenario are shown in Fig. 6. Biomass cost has a significant impact on the cost of fuel, and at \$100 per short ton (\$91 per tonne) fuel costs are \$2.43 per gallon (\$0.64 per liter) for the hydrogen purchase scenario.

4. Conclusions

This techno-economic study explored the cost of producing naphtha and diesel range fuels from corn stover via fast pyrolysis and bio-oil upgrading. Two scenarios are developed: one based on hydrogen production from bio-oil, and the other based on purchasing merchant hydrogen. The hydrogen production scenario diverts a portion of its bio-oil to generate requisite hydrogen required for upgrading. The second scenario employs hydrogen from a remote source.

Based on the current analysis, naphtha and diesel range products can potentially be produced from biomass at a competitive PV of \$3.09–2.11 per gallon (\$0.82–0.56 per liter) based on hydrogen production or purchase scenarios respectively. The hydrogen production scenario produces a lesser amount of fuel compared to the hydrogen purchase scenario (134–220 million liters per year) while incurring higher capital costs (\$287–200 million capital cost). Purchasing merchant hydrogen incurs higher annual costs (\$123 million), but results in increased fuel output and lower per gallon cost of fuel. The pioneer plant analysis employed in this paper fits the *n*th plant analysis to linear regressions of commercial data. This approach attempts to estimate costs for a first-of-a-kind biomass fast pyrolysis and upgrading plant based on the experience of commercial plant. Pioneer plant calculations estimate the cost of fuel for a pioneer plant to be as high as \$6.55 per gallon (\$1.73 per liter). This estimate underlines the potential impact of key challenges for biomass fast pyrolysis. Feed handling at a plant capacity of 2000 dtpd could pose a challenge that is not addressed in this study, and that has been identified by the RAND survey as a significant factor on the performance of a commercial plant. It is uncertain if biomass-washing pretreatments would be necessary to limit performance penalties associated with fast pyrolysis of biomass in the presence of alkali material. Condenser technology at this scale may affect the yield of liquid bio-oil collected and suffer from material buildup problems. Bio-oil upgrading could face several major challenges including: catalyst performance and lifetime, uncertainty over bio-oil separation technology performance, and the need for multiple process steps for hydrotreating.

Sensitivity analysis of key process variables found fuel conversion yields to have significant impact on the final cost of transportation fuel. The hydrogen production scenario's high fuel cost is primarily due to the low fuel yield, and 5% variations on the bio-oil upgrading yield result in fuel costs of \$2.60–3.89 per gallon (\$0.69–1.03 per liter). Both scenarios are highly sensitive to the cost of biomass. Other sensitivity parameters were found to have a small impact on the final cost of fuel even over wide ranges (i.e. capital costs varied $\pm 30\%$). Some sensitivity variables reflect the potential impact from various challenges. Fuel conversion yield could be lowered due to reduced performance in the pyrolysis reactor, reduced liquid bio-oil collection, losses that occur during storage, and poor bio-oil upgrading yield among others.

Biomass fast pyrolysis and bio-oil upgrading is in a very early stage of development. Whereas other thermochemical technologies have been employed for at least a century, fast pyrolysis only dates to the 1970s. Before this technology can achieve the level of commercialization of transportation fuel industries, various challenges need to be addressed. The impact of some of these challenges is explored in the sensitivity analysis. There are other scenarios that were not within the scope of this study. Future techno-economic

studies could shed light on advantages and disadvantages of different system designs and assumptions. Biochemical and gasification platforms can also provide promising pathways for biofuel production, and this paper provides results that can be compared to companion studies exploring these other technologies.

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