



Techno-economic analysis of two bio-oil upgrading pathways

Yanan Zhang^a, Tristan R. Brown^b, Guiping Hu^c, Robert C. Brown^{a,b,*}

^a Department of Mechanical Engineering, Iowa State University, Ames, IA 50011, United States

^b Bioeconomy Institute, Iowa State University, Ames, IA 50011, United States

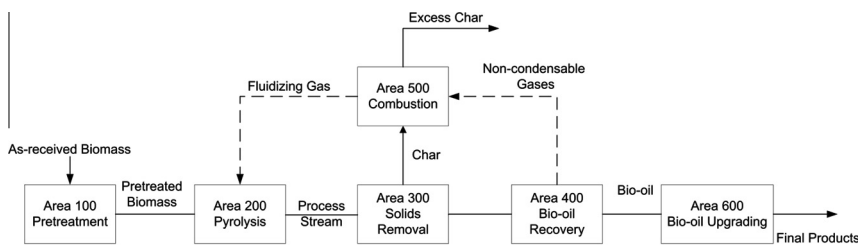
^c Industrial and Manufacturing Systems Engineering, Iowa State University, Ames, IA 50011, United States

HIGHLIGHTS

- ▶ Two bio-oil upgrading pathways are investigated.
- ▶ Product yield, fixed capital cost, and biomass cost strongly affect facility IRR.
- ▶ Investment for commodity chemicals production is of low risk.

GRAPHICAL ABSTRACT

Generalized process diagram for bio-oil production and upgrading.



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ABSTRACT

We evaluate the economic feasibility for two bio-oil upgrading pathways: two-stage hydrotreating followed by fluid catalytic cracking (FCC) or single-stage hydrotreating followed by hydrocracking. In the hydrotreating/FCC pathway, two options are available as the hydrogen source for hydrotreating: merchant hydrogen or hydrogen from natural gas reforming. The primary products of the hydrotreating/FCC pathway are commodity chemicals whereas the primary products for the hydrotreating/hydrocracking pathway are transportation fuels and hydrogen. The two pathways are modeled using Aspen Plus[®] for a 2000 metric tons/day facility. Equipment sizing and cost calculations are based on Aspen Economic Evaluation[®] software.

The bio-oil yield via fast pyrolysis is assumed to be 65% of biomass. We calculate the internal rate of return (IRR) for each pathway as a function of feedstock cost, fixed capital investment (FCI), hydrogen and catalyst costs, and facility revenues. The results show that a facility employing the hydrotreating/FCC pathway with hydrogen production via natural gas reforming option generates the highest IRR of 13.3%. Sensitivity analysis demonstrates that product yield, FCI, and biomass cost have the greatest impacts on facility IRR. Monte-Carlo analysis shows that two-stage hydrotreating and FCC of the aqueous phase bio-oil with hydrogen produced via natural gas reforming has a relatively low risk for project investment.

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1. Introduction

Thermochemical conversion has attracted recent attention as a biorenewable pathway for its ability to produce hydrocarbons [1].

Pyrolysis, liquefaction, gasification, and combustion are frequently investigated as thermochemical pathways, and each generates a different range of products [2]. This paper investigates fast pyrolysis as a route for the production of hydrocarbon-based fuels and hydrocarbon-based commodity chemicals. A primary benefit of fast pyrolysis over other thermochemical pathways (i.e., liquefaction, gasification, combustion) is its conversion of solid biomass feedstocks to bio-oil, which is a more convenient and thus more readily marketable liquid product [3]. Bio-oil is attracting attention

* Corresponding author at: Department of Mechanical Engineering, Iowa State University, Ames, IA 50011, United States. Tel.: +1 515 294 7934; fax: +1 515 294 3091.

E-mail address: rcbrown3@iastate.edu (R.C. Brown).

due to its lower sulfur and nitrogen content compared with fossil fuels [4]. Fast pyrolysis rapidly heats biomass feedstock in a high-temperature and oxygen-free environment, yielding a mix of a liquid (bio-oil, combustible gases, and solid char) [3].

Bio-oil has been considered as an alternative fuel in turbines and diesel engines or a co-firing feedstock with fossil fuels in heat and power generation plants [5], but bio-oil may also be upgraded to produce a variety of energy products, including hydrogen [6] and transportation fuels [7]. Bio-oil is a viscous and oxygenated mixture of compounds with a wide range of molecular weights. Polymeric and oligomeric bio-oil compounds must be depolymerized to yield hydrocarbons in the gasoline and diesel fuel ranges. Biofuels and hydrocarbon products via fast pyrolysis can utilize one of two upgrading pathways for this purpose: fluid catalytic cracking with a zeolite catalyst [8] or hydrocracking [7]. Both upgrading methods employ one or more hydrotreating steps to stabilize and deoxygenate the bio-oil prior to cracking.

Elliott et al. [7] found that hydrotreating to deoxygenate bio-oil greatly improves yields of hydrocarbons from hydrocracking. Hydrocracking of hydrotreated bio-oil produces alkenes (i.e., naphthene) and aromatics, which are valuable molecules for transportation applications [7,9,10]. Vispute et al. [11] found that increasing bio-oil's hydrogen content via hydrotreating also greatly improves yields of hydrocarbons from fluid catalytic cracking (FCC). FCC of hydrotreated bio-oil produces olefins and aromatics (i.e., BTX) [12–19]. In Vispute's study, five scenarios are investigated: FCC of whole bio-oil; one-stage hydrotreating and FCC of whole bio-oil; FCC of the aqueous phase of bio-oil; one-stage hydrotreating and FCC of the aqueous phase; and two-stage hydrotreating followed by FCC of the aqueous phase. The results found that initial hydrotreating with a Ru/C catalyst at 398 K and 52 bar pressure, followed by a second, higher-temperature stage of hydrotreating with a Pt/C catalyst at 523 K and 100 bar pressure, followed finally by FCC resulted in the highest carbon selectivity for the final products. The final products of FCC of hydrotreated bio-oil include olefins and aromatics (i.e., BTX), which have high market values [20].

High carbon utilization during the conversion of bio-oil to hydrocarbons is desirable as it results in greater hydrocarbon yields. However, high utilization is generally only achieved via the consumption of large quantities of hydrogen during upgrading. Hydrogen can be produced from a number of sources: steam reforming of natural gas; coal gasification; and partial oxidation of hydrocarbons, to name a few. Steam reforming of natural gas (mainly methane) is a well-developed and important technology for large-scale hydrogen production. It typically includes natural gas desulfurization, steam methane reforming, and water gas shift processes [21]. However, the utilization of fossil fuels by a biofuel pathway increases its lifecycle greenhouse gas (GHG) emissions. In the US, which defines biofuel pathways under the revised Renewable Fuel Standard (RFS2) according to their lifecycle GHG emission reductions relative to gasoline [22], such an increase in emissions can prevent a pathway from qualifying for high-value Renewable Identification Numbers (RINs) under the RFS2. To reduce CO₂ emissions associated with hydroprocessing, production of hydrogen from biorenewable sources is of interest. Bio-oil derived from biomass fast pyrolysis consists of an aqueous phase and a water-insoluble phase. Following phase-separation, the aqueous phase can be reformed to produce the hydrogen while heavy molecules in the water-insoluble phase can be hydrocracked to lighter hydrocarbons. The aqueous phase, mostly derived from the carbohydrate in biomass, often contains highly-decomposed light compounds that are not only highly oxygenated, but often contain too few carbon atoms to permit efficient conversion to gasoline-range fuels. Thus, the aqueous phase is attractive as a source of hydrogen for upgrading through steam reforming [23]. The water-insoluble

phase, mostly derived from the lignin in biomass, is attractive for upgrading because of its low oxygen-to-carbohydrate ratio [24].

Previous techno-economic analyses (TEA) have attempted to quantify the economic feasibility of each upgrading pathway [20,25–26]. Brown et al. [20] calculated the 20-year internal rate of return (IRR) for a facility employing two-stage hydrotreating and FCC to be as high as 14% (assuming a high bio-oil yield of 70 wt% of dry biomass). Wright et al. [25] analyzed transportation fuels production from hydrocracking of hydrotreated bio-oil derived from biomass fast pyrolysis and estimated the minimum selling price of the transportation fuels based on that analysis. These TEAs found that both two-stage hydrotreating followed by FCC and hydrotreating followed by hydrocracking generate positive returns on investment. However, there are no TEAs in the open literature on the production of multiple products (i.e., hydrogen and transportation fuels) via upgrading of both bio-oil phases (the aqueous phase and the water-insoluble phase). Moreover, previous TEAs on fast pyrolysis and upgrading have quantified economic feasibility by calculating a minimum fuel selling price [25–27], which is less suitable than calculation of IRR for multi-year analyses due to the volatile nature of energy prices.

The objective of this paper is to provide a detailed evaluation of the economic feasibility of two bio-oil upgrading pathways: hydrotreating/FCC and hydrotreating/hydrocracking. For the hydrotreating/FCC pathway, the aqueous phase undergoes two-stage hydrotreating followed by FCC process. There is a large demand for hydrogen during the two-stage hydrotreating process for this pathway. To investigate the impact of hydrogen, two options are explored for meeting this demand: purchasing hydrogen from the market; and producing onsite hydrogen via natural gas reforming. For the hydrotreating/hydrocracking pathway, the water-insoluble phase of bio-oil undergoes one-stage hydrotreating followed by one-stage hydrocracking and the aqueous phase bio-oil is reformed to hydrogen. Both of the upgrading pathways are modeled for facilities with a capacity of 2000 metric tons per day (MTPD) of biomass feedstock. The projected prices of commodity chemicals, gasoline, and diesel fuel over a 20 year period (2011–2030) are calculated using a discounted cash flow rate of return (DCFROR) model for both pathways. Facility capital costs and operating costs are estimated and used to calculate a 20-year IRR as a measure of pathway economic feasibility.

2. Process model description

The two bio-oil upgrading pathways are divided into six technical areas (see Fig. 1) including: biomass pretreatment (A100) where the biomass is chopped, dried, and finely ground to particles 3 mm in diameter with 7% moisture; biomass pyrolysis (A200) where biomass is converted into bio-oil using a fluidized bed reactor operating in an oxygen-free environment at around 500 °C and ambient pressure; solids removal (A300) where ash and char are removed from the pyrolysis gas stream before it is condensed to liquid; bio-oil recovery (A400) where bio-oil is condensed and stored to preserve the oil compounds and obtain high yield of good quality bio-oil; combustion (A500) where non-condensable pyrolysis gases and part of the char generated from pyrolysis are combusted to provide heat for pyrolysis; and bio-oil upgrading (A600) where bio-oil is upgraded into various final products including hydrogen, gasoline, diesel fuel, and commodity chemicals (i.e., aromatics and olefins).

The analysis of the bio-oil production through biomass fast pyrolysis (Areas 100–500) is similar to previous TEAs conducted at Iowa State University [20,25,28]. Two bio-oil upgrading pathways are analyzed in Area 600 in this study. For the first pathway, two-stage hydrotreating and FCC processing is employed to up-

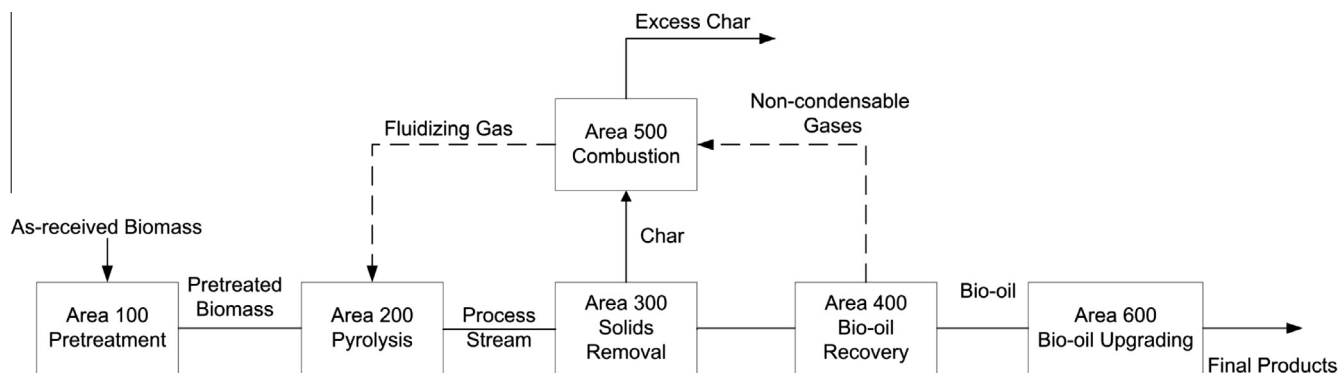


Fig. 1. Generalized process diagram for the two pathways.

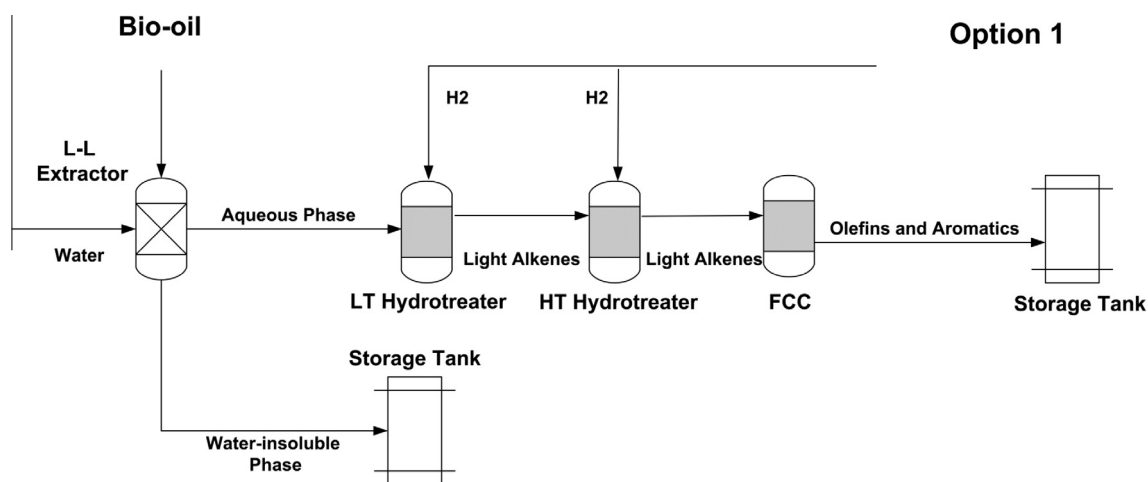


Fig. 2. Bio-oil upgrading process for hydrotreating/FCC pathway under Option 1.

grade the aqueous phase bio-oil to commodity chemicals (olefins and aromatics). In the second pathway, single-stage hydrotreating and hydrocracking is employed to upgrade water-insoluble bio-oil to biobased transportation fuels (synthetic gasoline and diesel fuel).

In the hydrotreating/FCC pathway, two-stage hydrotreating followed by FCC of the aqueous phase scenario presented in Vispute et al. [11] is adopted. The aqueous phase is separated from the bio-oil through a liquid–liquid (L–L) extractor before being hydrotreated and catalytically cracked. The first stage of hydrotreating is carried out at 125 °C and 100 bar hydrogen pressure over a Ru/C catalyst in a low-temperature hydrotreater while the second stage occurs at 250 °C and 100 bar hydrogen pressure over a Pt/C catalyst [11]. Following the two-stage hydrotreating process, the hydrotreated aqueous phase undergoes fluidized catalytic cracking in an FCC reactor over HZSM-5 catalyst at 600 °C. This converts the hydrotreated aqueous phase to aromatics and olefins. The separated water-insoluble fraction, which has high phenolic oligomer content, is sold as boiler fuel.

The difference between Options 1 and 2 is the source of hydrogen (see Figs. 2 and 3). In Option 1, hydrogen is purchased from the market while Option 2 employs natural gas as the hydrogen feedstock via a two-stage steam-reforming process. The natural gas is first scrubbed of sulfur in a desulfurizer, and then sent onto the two-stage steam reforming process. The first stage is a steam methane reformer (SMR) operated at 700–1100 °C, where steam reacts with the natural gas to yield syngas. In the second stage, further hydrogen is generated through a lower-temperature water gas

shift (WGS) reaction occurring at about 130 °C. A pressure swing adsorption (PSA) unit is employed to separate hydrogen from the syngas, and the remaining syngas is treated as a fuels gas with commercial value of \$5/MMBTU.

Fig. 4 describes the bio-oil upgrading process for the hydrocracking pathway. The previous TEA study shows that purchasing hydrogen for hydrotreating process is not as profitable as producing hydrogen via reforming part of bio-oil [25]. In this pathway, the bio-oil is first phase-separated into water-insoluble and aqueous phases through the liquid–liquid (L–L) extractor. The aqueous phase undergoes two-stage catalytic reforming. First, the aqueous phase is sent to the pre-reformer, where water–gas-shift and steam–methane-reforming reactions take place. Then the stream is sent to the reformer to produce hydrogen through catalytic steam reforming. The reformer is modeled by REquil module operating at 700 °C. All of these reactions are assumed to be simultaneous and reach at equilibrium. The steam-reforming reaction mechanism used in the reformer is based on Markevich et al. (see Table 1) [29]. It is assumed that all the hydrogen is separated by the PSA and then compressed in a two-stage process (compressors 1 and 2) for further use. A portion of the hydrogen is employed in the hydrotreating/hydrocracking process and the rest is sold to the market. The water-insoluble phase with its lower oxygen content is hydrotreated and hydrocracked to produce liquid fuels such as synthetic gasoline and diesel fuel.

The Pacific Northwest National Laboratory (PNNL) has conducted several experiments on hydrotreating and hydrocracking of bio-oil derived from various biomass feedstocks. The pyrolysis

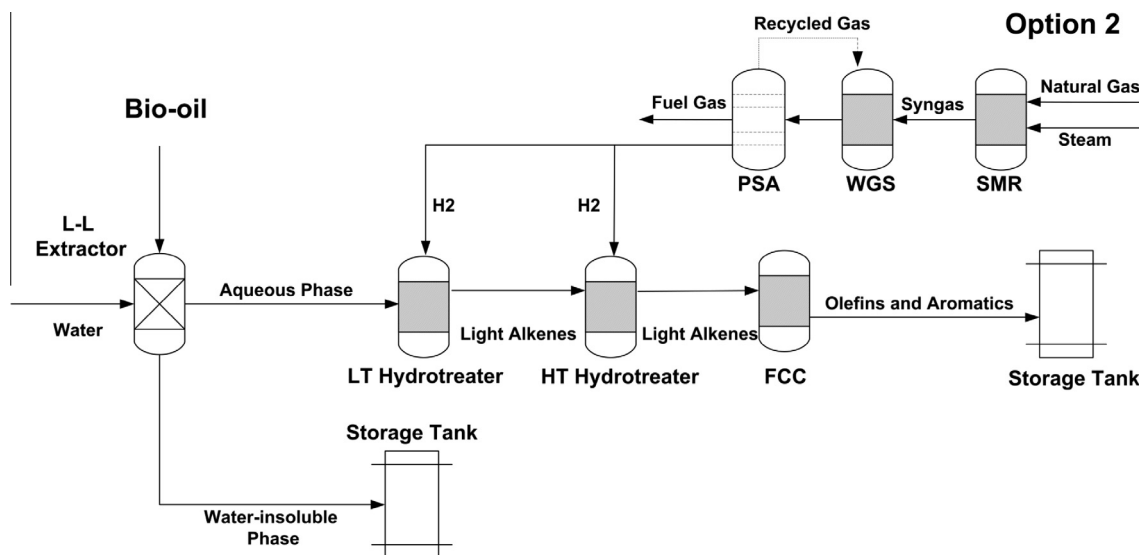


Fig. 3. Bio-oil upgrading process for hydrotreating/FCC pathway under Option 2.

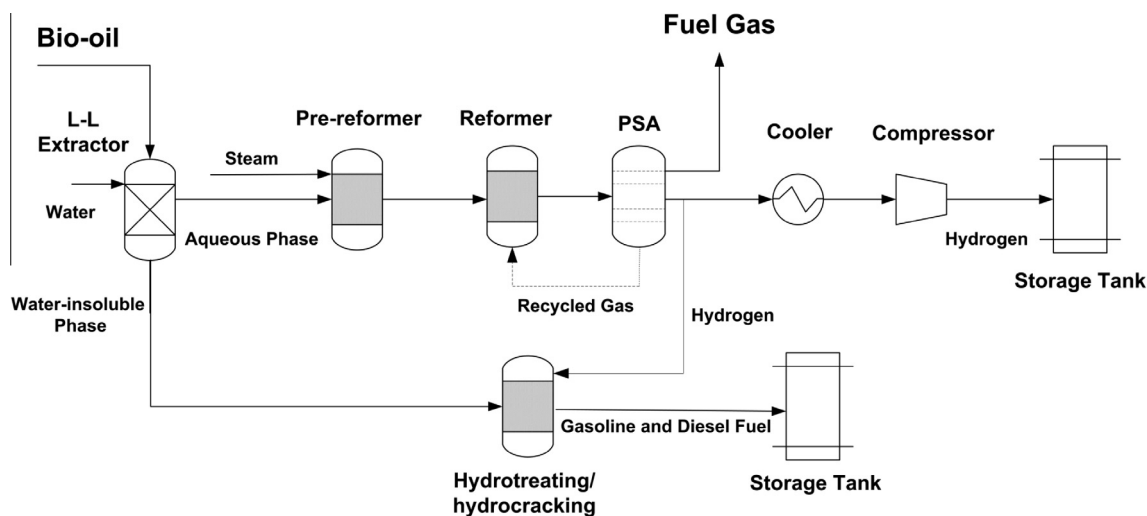


Fig. 4. Bio-oil upgrading process for the hydrotreating/hydrocracking pathway.

products are categorized as solids, gases, and liquid fractions. PNNL researchers found that hydrotreating and hydrocracking bio-oil from the pyrolysis of corn stover produces a higher yield of stable oil layer products than other biomass feedstocks (mixed wood, poplar, etc.) [7]. As a result, corn stover is employed in this paper as the biomass feedstock for synthetic gasoline and diesel fuel production through the hydrotreating/hydrocracking pathway.

Mixed wood usually has a lower ash content, which results in bio-oil with a lower level of metals compared to corn stover bio-oil [7]. Fast pyrolysis produces 60–75 wt% of liquid bio-oil depending on the feedstock used [4]. For woody biomass, 75 wt% of liquid bio-oil can be generated through fast pyrolysis [19], which is higher than for bio-oils derived from other kinds of biomass. To achieve the highest yields of aromatic hydrocarbons, mixed wood is employed as the biomass feedstock for commodity chemicals production through the hydrotreating/FCC pathway. Table 2 details the properties of mixed wood [30] and corn stover [25].

Equipment sizing and cost estimation are calculated with Aspen Economic Evaluation software. The methodology developed by Peters and Timmerhaus [31] for installation costs and rate of return analysis is employed for the capital cost analysis (see Table 3). A

Table 1

Main reactions for water soluble phase reforming.

Number	Equilibrium reactions
1	$C_2H_4O_2 \rightarrow 2H_2 + 2CO$
2	$CH_2O_2 \rightarrow H_2O + CO$
3	$C_5H_4O_2 + 8H_2O \rightarrow 10H_2 + 5CO_2$
4	$C_3H_6O_2 + 4H_2O \rightarrow 7H_2 + 3CO_2$
5	$C_6H_6O + 11H_2O \rightarrow 14H_2 + 6CO_2$
6	$C_7H_8O_2 + 12H_2O \rightarrow 16H_2 + 7CO_2$
7	$C_8H_{10}O + 15H_2O \rightarrow 20H_2 + 8CO_2$
8	$C_7H_8 + 14H_2O \rightarrow 18H_2 + 7CO_2$
9	$C_{10}H_{12}O_2 + 18H_2O \rightarrow 24H_2 + 10CO_2$
10	$CH_2O_2 \rightarrow H_2 + CO_2$
11	$CO + H_2O \rightarrow CO_2 + H_2$
12	$CO + 3H_2 \rightarrow CH_4 + H_2O$
13	$CH_4 + H_2O \rightarrow CO + 3H_2$

Lang factor of 5.46, which has been employed in previous analyses of pyrolysis-based biofuels production, is employed to calculate the total investment cost based on the total purchased equipment cost [20,25,28]. A modified discounted cash flow rate of return

Table 2

Properties of mixed wood and corn stover

Element	Mixed wood (wt%)	Corn Stover (wt%)
<i>Ultimate analysis (dry basis)</i>		
Carbon	47.51	47.28
Hydrogen	5.24	5.06
Nitrogen	0.28	0.8
Chlorine	0.01	0
Sulfur	0.21	0.22
Oxygen	43.07	40.63
<i>Proximate analysis (wet basis)</i>		
Moisture	5.23	25
Fixed Content	12.91	17.7
Volatile Matter	81.39	52.8
Ash	0.48	4.5

Table 3Methodology for capital cost estimation for an n^{th} plant.

Parameter	Assumption
Total purchased equipment cost (TPEC)	100%
Purchased equipment installation	39%
Instrumentation and controls	26%
Piping	10%
Electrical systems	31%
Buildings (including services)	29%
Yard improvements	12%
Service facilities	55%
Total installed cost (TIC)	$3.02 \times \text{TPEC}$
Indirect cost (IC)	$0.89 \times \text{TPEC}$
Engineering	32%
Construction	34%
Legal and contractors fees	23%
Total direct and indirect costs (TDIC)	$\text{TIC} + \text{IC}$
Contingency	20% of TDIC
Fixed capital investment (FCI)	$\text{TDIC} + \text{Contingency}$
Working capital (WC)	15% of FCI
Land use	6% of TPEC
Total capital investment (with land)	$\text{FCI} + \text{WC} + \text{Land}$

Table 4

Assumptions for DCFROR analysis.

Parameter	Assumption
Working capital (% of FCI)	15%
Salvage value	0
Type of depreciation	DDB
General plant	200
Steam plant	150
<i>Depreciation period (years)</i>	
General plant	7
Steam/electricity system	20
Construction period (years)	2.5
% Spent in year –3	8%
% Spent in year –2	60%
% Spent in year –1	32%
Start-up time (years)	0.5
Revenues (% of normal)	50%
Variable costs (% of normal)	75%
Fixed cost (% of normal)	100%
Income tax rate	39%
Facility type	n^{th} facility

(DCFROR) analysis spreadsheet is employed to calculate IRRs for the facilities analyzed in this study.

Table 4 details the major assumptions employed in the DCFROR analysis. The process design is based on the current state of technology and is assumed to be an n^{th} plant of its kind with a 20 year facility life. All costs are provided in 2010 dollars.

3. Analysis and results

For Options 1 and 2 of the hydrotreating/FCC pathway, the total olefins and aromatics yields are 223 metric tons per day and 88.9 metric tons per day, respectively. In addition to the commodity chemicals, char and pyrolytic lignin are also produced regardless of the source of hydrogen. The yields of char and pyrolytic lignin are 174 MTPD and 166 MTPD, respectively. Detailed commodity chemicals yields are shown in Table 5. The chemical yields data is calculated based on carbon selectivity and final products yields presented in Vispute et al. [11]. For the hydrotreating/hydrocracking pathway, hydrogen yield is 63.2 MTPD, total synthetic gasoline and diesel fuel yields are 165 MTPD, and the yield of the by-product char is 206 MTPD.

Installed equipment costs for the two pathways are summarized in Fig. 5. The total installed equipment costs for the two hydrogen source options under the hydrotreating/FCC pathway are \$130 million and \$155 million, respectively, and is \$190 million for the hydrotreating/hydrocracking pathway. Differences in installed equipment costs result primarily from differences in the costs of the bio-oil upgrading process: upgrading costs are \$35 million for a facility employing the hydrotreating/FCC pathway under Option 1; \$58 million for a facility employing the hydrotreating/FCC pathway under Option 2; and \$69 million for a facility employing the hydrotreating/hydrocracking pathway. For the hydrotreating/FCC pathway, Options 1 and 2 share some installed equipment costs, including those attributed to pretreatment, pyrolysis and oil recovery, combustion, and storage. Differences in bio-oil upgrading installed equipment costs for Options 1 and 2 are the result of the \$23 million equipment incurred by the natural gas reforming process.

Table 6 details the operating parameters employed in the analysis. The biomass feedstock purchase price is assumed to be \$83/metric ton. The prices for electricity, natural gas, hydrogen, and char are based on the averages from the U.S. Energy Information Administration's (EIA) Annual Energy Outlook's 20-year price forecasts [32]. The price of merchant hydrogen is calculated as a function of natural gas prices under the assumption that it is produced via steam reforming [33]. It is assumed that the char is sold as a low-value coal substitute with a price of \$18.21 per metric ton, which is equal to one-half the predicted 20-year average price of US coal. Catalyst costs are based on a previous TEA study that calculated the 20-year internal rate of return for an Integrated Catalytic Pyrolysis (i.e., hydrotreating/FCC) facility [20].

Total annual facility operating costs are calculated based on assumed input costs (see Fig. 6). Feedstock costs represent the majority of the operating costs at \$54.4 million annually. For Option 1, hydrogen consumption is the second largest operating cost at \$30.2 million on the basis of a \$3.33/kg market price. This additional operating cost results in a much higher total operating cost for Option 1 compared to Option 2 under the hydrotreating/hydro-

Table 5

Commodity chemical yield distributions for Option 1 and Option 2 of hydrotreating/FCC pathway.

Chemicals	Yield (MTPD)
Ethylene	71.4
Propylene	120
Butylene	31.7
Benzene	23.8
Toluene	43.9
Xylenes	17.0
Ethylbenzene	2.1
Styrene	1.2
Indene	0.4
Naphthalene	0.4

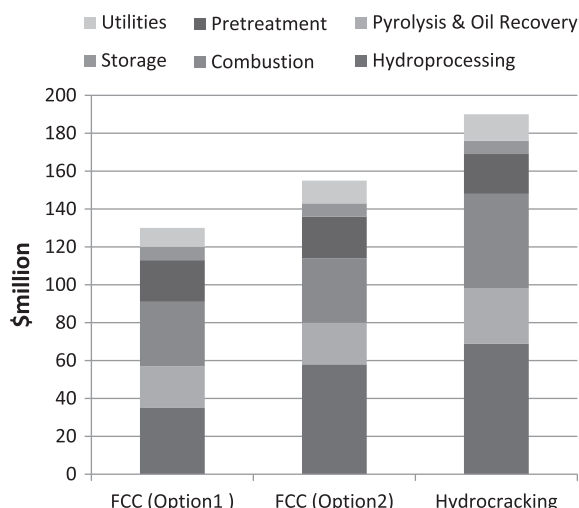


Fig. 5. Installed equipment costs for the two pathways.

Table 6
Material and operating parameters employed in the evaluation.

Commodity	Price
Feedstock	\$0.83/kg
Hydrogen	\$3.33/kg
Pt	\$56.29/kg
Ru	\$5.60/kg
Zeolite	\$1.60/kg
Natural gas	\$5/MMBTU
Electricity	\$0.061/kW h
Process water	\$0.032/MT
Solids disposal cost	\$19.84/MT
Char	\$18.21/MT

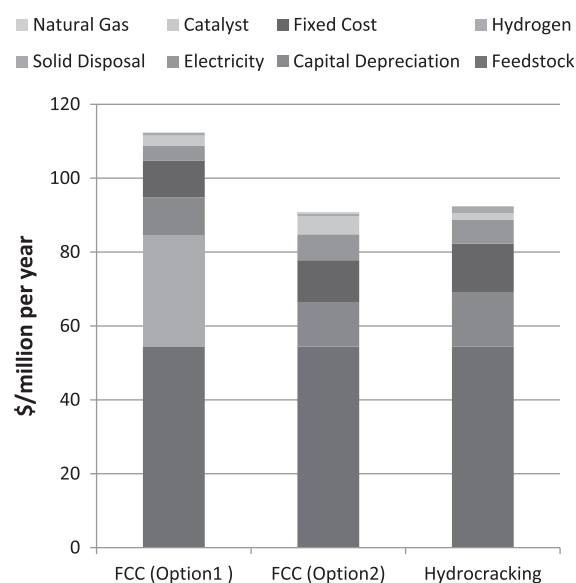


Fig. 6. Annual operating costs for the two pathways.

cracking pathway. Option 2 has the highest catalyst cost (\$4.9 million), which includes the costs of Pt, Ru, and zeolite catalysts for two-stage hydrotreating and hydrocracking and WGS catalyst. Compared with Option 1 under the hydrotreating/hydrocracking

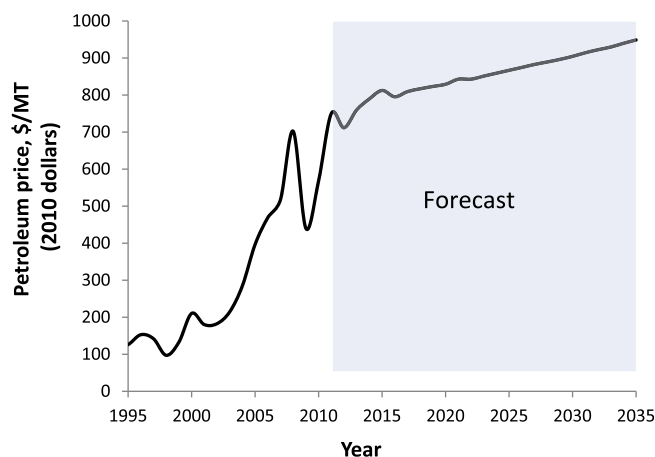


Fig. 7. Historical and forecasted petroleum prices (2010 dollars) [34,36].

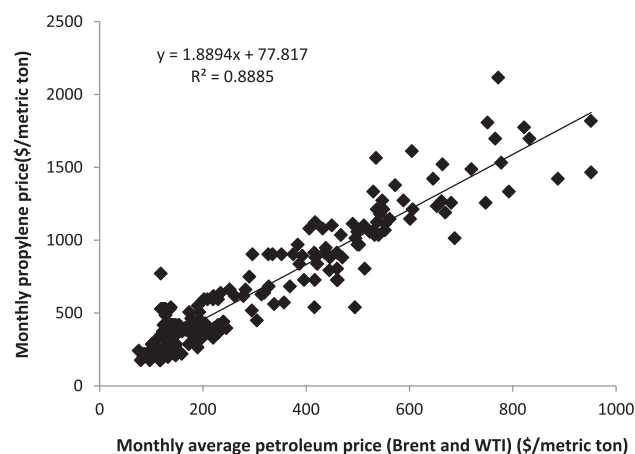


Fig. 8. Correlation between the monthly prices of petroleum and propylene [34,36].

Table 7
Correlations between the commodity chemicals and petroleum prices.

Chemicals	Correlations with petroleum	R ²
Benzene	$y = 4.5522x^{0.8501}$	0.8447
Toluene	$y = 4.6562x^{0.8194}$	0.9365
Xylenes	$y = 6.5132x^{0.774}$	0.9107
Ethylene	$y = 1.3326x + 284.18$	0.7063
Propylene	$y = 1.8894x + 77.817$	0.8885

pathway, Option 2 has a higher natural gas cost, although this contributes little to the total operating cost because of natural gas's low market price.

Previous TEAs have assumed a fixed product price. In reality the market prices of commodity products (particularly energy products) are volatile, fluctuating due to changing market conditions or government policies. To account for these fluctuations, the projected prices for commodity chemicals, gasoline, and diesel fuel over the next 20 years (2011–2030) are incorporated into the DCF-ROR model for both upgrading pathways. An annual petroleum price trend (1995–2035) is detailed based on historical petroleum prices and annual price projections provided by EIA [34,35] (see Fig. 7). The price trend shows that petroleum has a history of volatility and achieved a recent low in 2010. The EIA also forecasts a steady increase in the petroleum price after 2015 due to greatly increased petroleum demand in countries such as China and India.

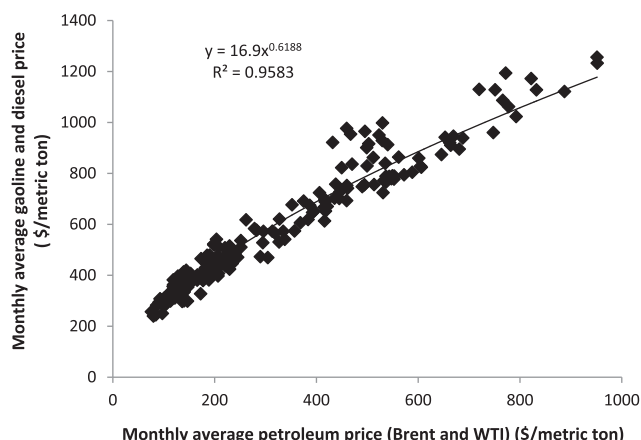


Fig. 9. Correlation between the monthly price of petroleum and average price of gasoline and diesel fuel [34,37].

In the hydrotreating/FCC pathway, commodity chemicals, especially olefins and aromatics, are the main products. Among all the commodity chemicals, propylene represents the largest yield (see Table 5). An analysis of historical monthly spot prices of petroleum (average of Brent and West Texas Intermediate [WTI] crude) [34] and propylene from April 1993 to July 2011 [36] shows a strong correlation ($R^2 = 0.89$) between the two (see Fig. 8). Similarly, the prices of other commodity chemicals (benzene, toluene, xylenes, ethylene, etc.) also have strong positive correlations with petroleum prices. The detailed correlations between the commodity chemicals and the petroleum prices are shown in Table 7. For the hydrotreating/hydrocracking pathway, the main products are gasoline and diesel fuel and the same analysis shows a strong exponential correlation ($R^2 = 0.96$) between the historical monthly spot prices of gasoline and diesel fuel from April 1993 to July 2011 [37] and the prices of petroleum over same period [34] (see Fig. 9).

The EIA projects petroleum to have a steadily increasing price over the next 20 years. As a result of these strong positive correlations, the prices of commodity chemicals and transportation fuels are expected to also increase over the same time period. The projected prices of commodity chemicals and transportations fuels for the next 20 years are calculated through these correlations and incorporated into the DCFROR analysis.

Based on the calculated capital costs, operating costs, and assumptions, facility IRRs of 7.6%, 13.3%, and 9.8% are obtained for Options 1 and 2 of the hydrotreating/FCC pathway and the hydrotreating/hydrocracking pathway, respectively, via a DCFROR analysis setting a goal of zero NPV at the end of the 20-year project.

4. Uncertainty analysis

The results of the sensitivity analysis for the two pathways demonstrate the sensitivity of facility IRR to parameter values (see Figs. 10–12). The parameters investigated are biomass cost, fixed capital cost, product yield, hydrogen price, catalyst cost, char credit value, gas credit value, income tax rate, and working capital amount. The uncertainty analysis finds that facility IRRs for the two pathways are most sensitive to hydrogen price, product yield, fixed capital cost, and biomass cost.

Commodity chemicals are the main products for both options of the hydrotreating/FCC pathway, so the yield of commodity chemicals has a significant impact on facility IRR. Increasing the commodity chemicals yield from 75% to 125% of the base case increases facility IRR from -7.4% to 16.2% for Option 1 and from 5% to 19.6% for Option 2. A variation of biomass cost from \$50/ton to \$100/ton results in a facility IRR range of $1.8\text{--}12.6\%$ for Option 1 and $9\text{--}16.9\%$ for Option 2. A $\pm 30\%$ range in fixed capital cost results in a facility IRR range of $5.4\text{--}10.9\%$ for Option 1 and $10.3\text{--}17.9\%$ for Option 2.

For the hydrotreating/hydrocracking pathway, hydrogen price, fixed capital cost, biomass cost, gasoline yield, and diesel fuel yield have the greatest impact on facility IRR. For Option 1 of the hydrotreating/FCC pathway and the hydrotreating/hydrocracking pathway, the facility IRRs are sensitive to hydrogen price. For the hydrotreating/hydrocracking pathway, however, the hydrogen price is the most important factor. Fig. 13 describes the facility IRR variation and the hydrogen market price for the two pathways. The figure shows that the hydrotreating/FCC pathway under Option 1 and the hydrotreating/hydrocracking pathway both have facility IRR of 8.5% when the hydrogen price reaches $\$3.02/\text{kg}$. The hydrotreating/hydrocracking pathway will have a higher facility IRR if the hydrogen price exceeds $\$3.02/\text{kg}$. When the hydrogen price is $\$4.20/\text{kg}$, the facility IRR for the hydrotreating/hydrocracking pathway reaches 13.3% , which is equal to the IRR of a facility employing Option 2 of the hydrotreating/FCC pathway. The IRR of a facility employing Option 1 is 13.3% at a hydrogen price of $\$1.04/\text{kg}$. The correlation between the IRRs of facilities employing Option 1 of the hydrotreating/FCC pathway and the hydrotreating/hydrocracking pathway and the hydrogen price are almost linear, suggesting that they will attain equal IRR values only when the hydrogen price is either very low ($\$1/\text{kg}$) or very high ($\$4.50/\text{kg}$).

Option 2 of the hydrotreating/FCC pathway is found to be the most favorable pathway in the initial sensitivity analysis, with a base case facility IRR of 13.3% , an upper bound facility IRR of 19.6% , and a comparatively low investment risk. However, the hydrogen for Option 2 is produced via natural gas steam reforming, and this reliance on a volatile fossil fuel source may pose a future challenge to the pathway's economic feasibility. Among all the fos-

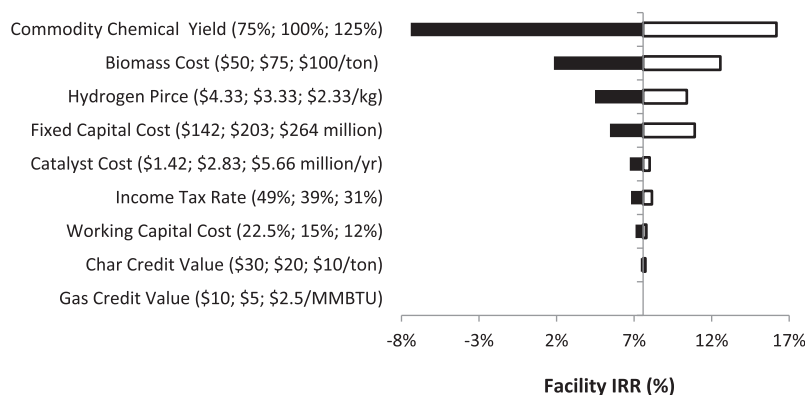


Fig. 10. Sensitivity analysis for Option 1 of the hydrotreating/FCC pathway.

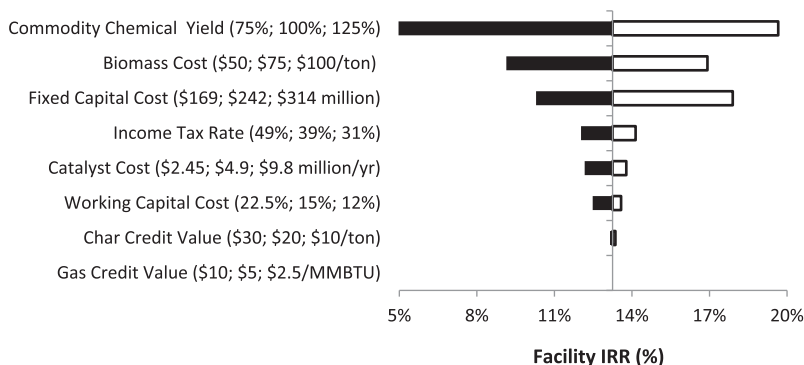


Fig. 11. Sensitivity analysis for Option 2 of the hydrotreating/FCC pathway.

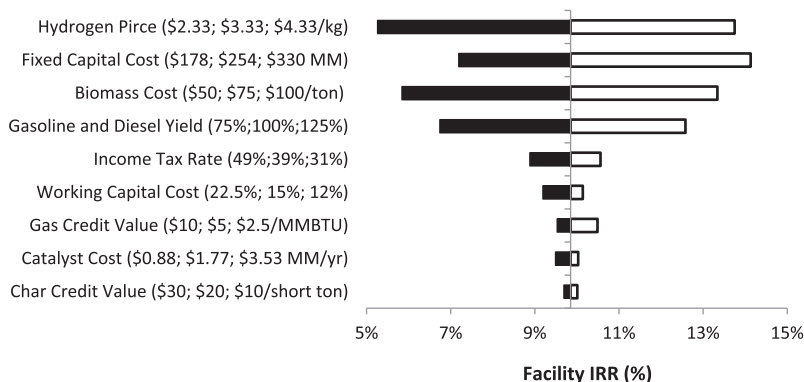


Fig. 12. Sensitivity analysis for the hydrotreating/hydrocracking pathway.

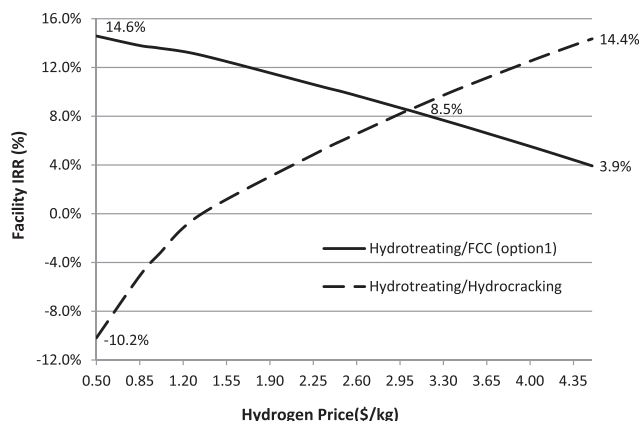


Fig. 13. Relationship between facility IRR and hydrogen price for Option 1 of the hydrotreating/FCC pathway and hydrotreating/hydrocracking pathway.

sil fuels, natural gas has the advantages of clean burning, lower greenhouse gas emissions, and very low cost. However, increased utilization resulting from its current low value in the North American market would spur demand and cause natural gas prices to rise, hindering the economic feasibility of the hydrotreating/FCC pathway under Option 2.

For further risk analysis, Crystal Ball® is employed to conduct a Monte-Carlo simulation to generate a facility IRR distribution to quantify the uncertainty of the hydrotreating/hydrocracking pathway under Option 2. Commodity chemical yield, fixed capital cost, and biomass cost are treated as changing variables since these parameters were shown by the sensitivity analysis to have the

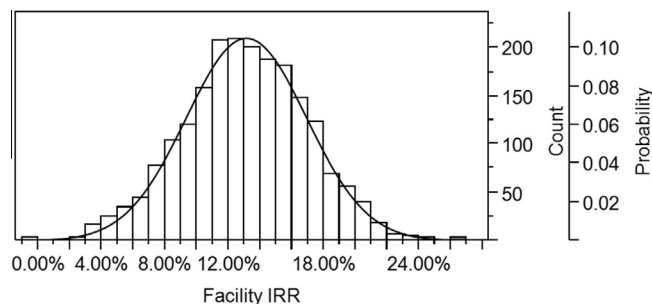


Fig. 14. Facility IRR distribution from Monte-Carlo simulation.

great impact on facility IRR. All of these variables are assumed to follow triangular distributions with the same variation ranges used in the sensitivity analysis (see Fig. 11). Two thousand random facility IRRs are generated during the Monte-Carlo simulation and JMP® software is employed to analyze the resulting data.

Fig. 14 details the facility IRR distribution from the Monte-Carlo simulation. The expected value of the mean facility IRR is 13.1% and the standard deviation is 3.8%. The minimum IRR is 0% and the maximum IRR is 26.2%. The median, 25% quartile, and 75% quartile facility IRRs are 13.1%, 10.6%, and 15.7%, respectively. For the cumulative probability distribution of the facility IRR, about 80% of facilities in the analysis have IRRs exceeding 10%, and 30% of facilities have IRRs exceeding 15% (see Fig. 15). This result shows that the hydrotreating/FCC pathway under Option 2 is likely to present a relatively low risk in the future, even if some economic parameters are pessimistic.

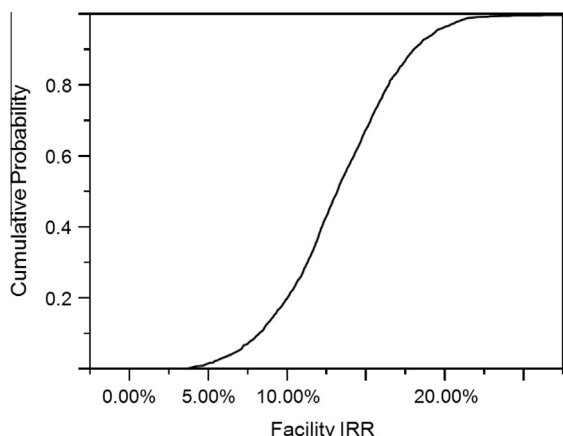


Fig. 15. Cumulative probability distribution of facility IRR from Monte-Carlo simulation.

5. Conclusions

This techno-economic analysis evaluates the economic feasibility of biomass fast pyrolysis and two bio-oil upgrading pathways. The two bio-oil upgrading pathways are: hydrotreating/FCC and hydrotreating/hydrocracking. Both upgrading methods require one or more hydrotreating steps to stabilize the bio-oil prior to cracking. For the hydrotreating/FCC pathway, the aqueous phase of the bio-oil is upgraded to commodity chemicals via a two-stage hydrotreating and FCC process. In this pathway, two options are developed regarding the hydrogen source (Options 1 and 2). Option 1 uses merchant hydrogen purchased from the market, and Option 2 uses hydrogen produced via on-site reforming of natural gas. For the hydrotreating/hydrocracking pathway, the water-insoluble phase is upgraded to transportation fuels (synthetic gasoline and diesel fuel) via a one-stage hydrotreating and hydrocracking process and the aqueous phase is reformed to hydrogen. Facility IRR is calculated as a function of annual revenues, fixed capital investment, and annual operating costs. The technology is assumed to be mature enough from the perspectives of reliability and performance to ensure that the facility operates as an nth plant rather than as a pioneer plant.

Based on a 2000 metric ton per day (MTPD) facility, the total olefins and aromatics yields are 223.3 MTPD and 88.9 MTPD for the hydrotreating/FCC pathway under Options 1 and 2, respectively. In addition to the commodity chemicals, char and pyrolytic lignin are also produced via this pathway. The yield of char and pyrolytic lignin is 174 MTPD and 166 MTPD, respectively. For the hydrotreating/hydrocracking pathway, the hydrogen yield is 63.2 MTPD, total synthetic gasoline and diesel fuel yield is 165 MTPD, and the yield of the by-product char is 206 MTPD. The estimated installed equipment costs for the hydrotreating/FCC pathway under Options 1 and 2, and the hydrotreating/hydrocracking pathway are \$130 million, \$155 million, and \$190 million, respectively. The fixed capital costs for the two options of the hydrotreating/FCC pathway and the hydrotreating/hydrocracking pathway are \$203 million, \$242 million, and \$296 million, respectively. The 20-year IRR is calculated to be 7.6%, 13.3%, and 9.8% for the two options of the hydrotreating/FCC pathway and the hydrotreating/hydrocracking pathway, respectively.

Sensitivity analysis is performed to determine the sensitivity of the facility's economic feasibility to the model parameter values for the two pathways. Sensitivity analysis results show that hydrogen price, fixed capital cost, feedstock cost, and product yield are key factors in the economic feasibility of the two bio-oil upgrading pathways. Facility IRR ranges from −7.4% to 16.2% and 5% to 19.7%

for Options 1 and 2 of the hydrotreating/FCC pathway, respectively. For the hydrotreating/hydrocracking pathway, facility IRR ranges from 5.3% to 14.1%.

A Monte-Carlo simulation analysis of Option 2 of the hydrotreating/FCC pathway predicts that more than 80% of facilities will have IRRs exceeding 10%, and 30% of facilities will have IRRs exceeding 15%, based on 2000 random runs of the simulation. This indicates that an investment in Option 2 of the hydrotreating/FCC pathway would present a relatively low risk.

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