



Review

A techno-economic review of thermochemical cellulosic biofuel pathways



Tristan R. Brown*

Department of Forest and Natural Resources Management, SUNY-ESF, Syracuse, NY 13210, United States

HIGHLIGHTS

- Techno-economic analyses of thermochemical cellulosic biofuel pathways are reviewed.
- The results of the techno-economic analyses are compared.
- Differences in assumptions result in a wide range of financial result values.
- The importance of justifying assumptions and analyzing uncertainty is discussed.

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ABSTRACT

Recent advances in the thermochemical processing of biomass have resulted in efforts to commercialize several cellulosic biofuel pathways. Until commercial-scale production is achieved, however, techno-economic analysis is a useful methodology for quantifying the economic competitiveness of these pathways with petroleum, providing one indication of their long-term feasibility under the U.S. revised Renewable Fuel Standard. This review paper covers techno-economic analyses of thermochemical cellulosic biofuel pathways in the open literature, discusses and compares their results, and recommends the adoption of additional analytical methodologies that will increase the value of future pathway analyses.

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1. Introduction

In 2007 the U.S. Congress created the revised Renewable Fuel Standard (RFS2) in an effort to replace domestic consumption of petroleum with liquid biofuels. The RFS2 mandates the annual blending of increasing volumes of biofuel with gasoline and diesel fuel for retail. While 1st-generation biofuels such as cane ethanol, grain ethanol, and soya biodiesel have been the largest contributors to the RFS2 to date, the program requires the blended volume of cellulosic biofuels to become the largest biofuel blending category by 2022 at 16 billion gallons (60.6 million liters) on an ethanol-equivalent basis (see Fig. 1) (Schnepf and Yacobucci, 2013). Unlike 1st-generation biofuel feedstocks, which are easily converted to transportation fuels via both biological and catalytic processes, lignocellulose is highly recalcitrant, plants having evolved sophisticated defenses against microorganisms that are able to

metabolize polysaccharides. While various lignocellulose pretreatments have been developed to overcome this recalcitrance (Kazi et al., 2010), their technical complexity and expense have slowed efforts to commercialize biological pathways for cellulosic biofuel production, causing it to fall well short of the RFS2's mandated volumes to date (Schnepf and Yacobucci, 2013).

A growing body of research is focused on using heat and/or catalysts to convert lignocellulose to biofuels. Lignocellulosic biomass has long been used as a feedstock for heat and power generation and the technology for the conversion of carbonaceous feedstocks to gaseous products has been employed commercially since the 19th century. Subsequent processes have been developed for the catalytic conversion of biomass-derived synthesis gas ("syngas") to liquid fuels and even for the conversion of biomass directly to liquid fuel intermediates (Huber et al., 2006). In 2012 the thermochemical platform achieved the distinction of becoming the first platform to commence operations at a commercial-scale biorefinery in the U.S. when a catalytic fast pyrolysis and hydroprocessing (CPH) facility yielding 10 million gallons per year (MGY) (37.9 million liters) of biobased gasoline and diesel fuel blendstocks from

* Address: Department of Forest and Natural Resources Management, 320 Bray Hall, 1 Forestry Dr., SUNY-ESF, Syracuse, NY 13210, United States.

E-mail address: trbro100@esf.edu

yellow pine feedstock became operational (Lane, 2012). A recent review of U.S. cellulosic biofuel commercialization lists multiple commercial-scale thermochemical biorefineries that are expected to become operational by 2015 (Brown and Brown, 2013).

Overall cellulosic biofuel production has continued to fall well short of the volumes required to achieve the blending mandates established by the RFS2 (see Table 1). Concerns about the lack of cellulosic biofuel competitiveness with petroleum have hampered the large capital investments (company estimates frequently exceed \$10/gal or \$2.64/l of installed annual capacity) (Brown and Brown, 2013) necessary for widespread capacity construction (Downing and Gismatullin, 2013). This underinvestment has resulted in a chicken-and-egg dilemma: investors are unwilling to finance widespread capacity construction due to production cost uncertainty but the lack of actual cellulosic biofuel production prevents additional knowledge of production costs from being gained. Several universities and the national laboratories of the U.S. Department of Energy have employed a research methodology known as techno-economic analysis (TEA) to quickly and inexpensively calculate this missing information. TEA uses process models to quantify the technical and economic performance of a biorefinery employing one or more specific process pathways and generates a financial return on capital investment. While the uncertainty of an individual TEA's result is high due to the methodology's necessary simplification of complex processes, it enables economic comparisons of pathways to be made that would otherwise not be possible given the current state of commercialization.

This paper reviews the recent TEAs published in the open literature for cellulosic biofuel pathways within the thermochemical platform and compares their results on an adjusted basis. The pathways covered all fall into one of three broad categories based on the primary process step: gasification, pyrolysis, and solvent liquefaction. TEAs of integrated processes that combine two or more pathways from the above categories in a single biorefinery are also covered. This review focuses on pathways that employ thermochemical processes to yield liquid biofuels capable for use in unmodified internal combustion engines as their primary output, although these can take the form of both alcohols (e.g., ethanol, methanol) and hydrocarbons (e.g., diesel fuel, gasoline). A number of co-products taking gaseous, liquid, and solid forms are also considered. This review excludes pathways yielding non-liquid biofuels such as electricity, hydrogen, and synthetic natural gas as their primary outputs; while these products can be broadly categorized as cellulosic biofuels if used in automobiles, the automobile and/or infrastructure upgrades and subsequent costs that must be incurred prior to their use prevent the pathways'

Table 1

Originally-mandated, revised, and actual cellulosic biofuel production under RFS2. All figures in million liters ethanol-equivalent.

Year	Original	Revised	Actual
2010	379	25	0
2011	946	23	0
2012	1893	40	0
2013	3785	53	4
2014	6624	64	0 (to June)

straightforward comparison with liquid transportation fuel pathways on a financial basis. (While it can be argued that alcohol fuels also require automobile and infrastructure upgrades prior to use, they are included in this review due to ethanol's widespread blending with gasoline in unmodified vehicles at volumes of up to 15% in the U.S.) Similarly, this review also excludes the acid and enzymatic hydrolysis and fermentation pathways despite their use of combustion to convert lignin co-product into electricity. They are excluded despite their employment of a thermochemical process since they employ a biochemical process to yield a liquid fuel as the primary product. TEAs of these biochemical pathways have been reviewed previously in this journal (Gnansounou and Dauriat, 2010). Finally, all monetary figures are adjusted to 2011 dollars based on inflation and, when the source material employs other currencies, the prevailing dollar exchange rate for the year the analysis was conducted.

2. Pathway overviews

2.1. Gasification

Gasification has been employed on a commercial-scale as a means of converting carbonaceous feedstocks to liquid transportation fuels since the 1940s, when Nazi Germany attempted to make up a wartime shortfall in petroleum by converting coal to diesel and jet fuels via the gasification and Fischer–Tropsch synthesis (FTS) pathway. In the decades since several additional gasification pathways have been developed to convert biomass feedstock to both ethanol- and hydrocarbon-based fuels by reacting the syngas over various metal catalysts or even biocatalysts. These include gasification and acetic acid synthesis (AAS), gasification and methanol-to-ethanol (MTE), gasification and methanol-to-gasoline synthesis (MTG), gasification and mixed alcohols synthesis (MAS), gasification and syngas-to-distillates (S2D), and gasification and syngas fermentation (SF).

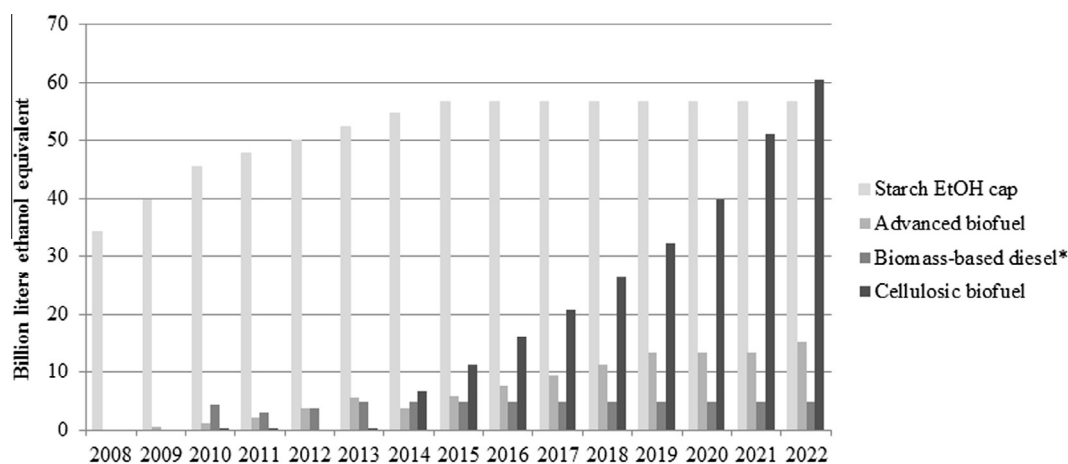


Fig. 1. The RFS2 volumetric mandate by biofuel category. *To be set annually but not to fall below pictured volume.

Gasification thermally decomposes biomass at temperatures of up to 1500 °C to a gaseous mixture of carbon monoxide (CO), hydrogen (H₂), methane (CH₄), carbon dioxide (CO₂), and small amounts of light hydrocarbons. This versatile intermediate product is known as syngas and can be converted to heat and power via combustion or upgraded over catalysts to liquid transportation fuels such as ethanol (Zhu and Jones, 2009), methanol (Andersson et al., 2014; Phillips et al., 2011), gasoline (Phillips et al., 2011), diesel and jet fuels (Swanson et al., 2010; Zhu et al., 2012). More recently a novel *Clostridium* bacterium has been identified as being capable of fermenting switchgrass-derived syngas to ethanol (Datar et al., 2004; Piccolo and Bezzo, 2009), combining the thermochemical and biochemical platforms to yield cellulosic biofuel.

The AAS, FTS, MTE, MTG, MAS, and S2D syngas upgrading routes all employ catalysts that are readily poisoned by contaminants in raw syngas, including hydrogen sulfide (H₂S), carbonyl sulfide (COS), ammonia (NH₃), hydrogen cyanide (HCN), hydrogen chloride (HCl), alkali metals, particulate matter, and tar. These require a series of expensive gas cleaning steps prior to upgrading (Woolcock and Brown, 2013). A number of chemical synthesis routes are possible with syngas, which are described in the following paragraphs. For more detailed information, the reader should consult Dayton et al. (2011) or Brown and Brown (2014a).

The AAS route reacts the syngas over a ZnO/CuO catalyst to yield methanol.

The raw methanol is distilled and reacted with iodide- and iridium-based catalysts to yield acetic acid (Zhu and Jones, 2009). Finally, the acetic acid is hydrogenated to produce a mixture of ethanol and water that is distilled to produce fuel-grade ethanol. The MTE, MTG, and S2D pathways resemble the AAS pathway in that they also convert the syngas to methanol as an initial step. Both pathways then react the methanol over a dehydration catalyst to yield dimethyl ether (DME). From here the pathways diverge, with the MTE pathway converting the DME to methyl acetate via heterogeneous catalytic carbonylation. Finally, the methyl acetate is hydrogenated to yield methanol, which is recycled, and ethanol. The MTG pathway instead reacts the DME over a zeolite catalyst to yield alkenes and ultimately a blend of aromatics and alkanes belonging primarily in the gasoline boiling range (Phillips et al., 2011). The S2D pathway combines the methanol dehydration and hydrocarbon synthesis steps by reacting the syngas-derived methanol with the catalysts responsible for both in a single reactor.

The MAS pathway compresses the syngas prior to combining it with methanol and reacting mixture over a metal-sulfide catalyst to yield a mixed alcohol stream. The mixed stream is dehydrated and separated into individual methanol, ethanol, and high molecular-weight alcohol streams. The methanol stream is recycled while the ethanol stream undergoes further distillation to yield fuel-grade ethanol.

The FTS pathway reacts clean syngas over a cobalt, iron, or ruthenium catalyst to yield long-chain alkanes and hydrocarbon waxes. The waxes and other high molecular weight hydrocarbons are hydrocracked to fuel range molecules suitable as refinery blendstock. While effective, the inclusion of this final step results in a pathway that includes a depolymerization step (biomass gasification), a repolymerization step (Fischer–Tropsch, or FT, synthesis), and a final depolymerization step (hydrocracking), increasing its expense while decreasing its energy efficiency.

The SF pathway ferments syngas that has been cleaned of contaminants (although not to the same extent as required by the catalytic synthesis pathways) with *Clostridium* bacterium (Abubackar et al., 2011). The biocatalyst synthesizes the CO and H₂ in the syngas to ethanol. This biochemical syngas upgrading process has a number of advantages over the catalytic synthesis processes described above, including high selectivity for desired products,

consolidation of process steps (it effectively combines the acetic acid synthesis and hydrogenation steps employed by the AAS pathway), operation at much lower pressures, and reduced sensitivity of the biocatalyst to sulfur and nitrogen contaminants in the syngas relative to metal catalysts. Disadvantages include low rates of mass transfer between the gaseous feedstock and the microorganisms, the need for sterile reaction environments, and the relative lack of information on operation of syngas fermenters (Choi et al., 2011).

2.2. Pyrolysis

Pyrolysis is the thermal decomposition of biomass in the temperature range of 350–700 °C to produce gases, liquids, and solids. There are four pathways to transportation fuels via pyrolysis: slow pyrolysis and upgrading of syngas; fast pyrolysis and hydroprocessing (FPH); catalytic pyrolysis and hydroprocessing (CPH); and hydropyrolysis and hydroprocessing (HPH). A general review of these variations is provided by Brown and Brown (2014b).

Slow pyrolysis (SP) thermally decomposes biomass over many minutes or even days at a temperature of around 400 °C to produce mostly biochar and syngas. Relatively little liquid is produced, which is mostly an aqueous solution of acetic acid. It has historically been used to produce charcoal for cooking, but it has recently been proposed as a pathway for production of methanol from the syngas and a soil amendment/carbon sequestration agent from the biochar product (Shabangu et al., 2014).

Fast pyrolysis is the rapid heating of biomass to temperatures around 500 °C in a few seconds to produce mostly liquid (known as bio-oil) with smaller amounts of syngas and biochar. While the syngas and biochar are relatively low-value products suited for combustion to process heat and power, the bio-oil is a viscous mixture of oxygenated compounds of varying weights that can be deoxygenated to alkanes and aromatics in the gasoline and diesel fuel boiling ranges. Hydroprocessing is the name given to the integrated processes of hydrotreating and hydrocracking. Hydrotreating is the reaction of organic compounds in the presence of high pressure hydrogen to remove oxygen (deoxygenation) along with other heteroatoms (nitrogen, sulfur, and chlorine). Hydrotreating is relatively carbon efficient, since oxygen is mostly removed as water, but it consumes a large amount of hydrogen (Brown and Brown, 2014b). The product is substantially deoxygenated but still contains many molecules too large to be used as transportation fuels. These are further reacted with hydrogen under more severe reaction conditions to break large molecules into fuel range molecules, a process known as hydrocracking (Brown and Brown, 2014b).

Catalytic pyrolysis and hydroprocessing (CPH) achieves deoxygenation both during pyrolysis and hydroprocessing. A zeolite catalyst is mixed with the biomass or located downstream of the pyrolysis reactor to decarbonylate (remove CO) and decarboxylate (remove CO₂) pyrolysis vapors in the absence of added hydrogen. These upgraded vapors are subsequently condensed and hydroprocessed in a manner similar to for the bio-oil from FPH. The advantage of CPH is that the catalytic pyrolysis step produces a partially deoxygenated and stabilized bio-oil, which eases hydroprocessing. Although CPH is more hydrogen efficient than FPH, it is typically less carbon efficient as much of the carbon appears as CO, CO₂, and even coke.

HPH involves pyrolysis in the presence of pressurized hydrogen and a hydroprocessing catalyst. The resulting liquid is subsequently hydroprocessed to fuel molecules. Because oxygen is removed as water during hydropyrolysis and hydroprocessing, the process is more carbon efficient than CPH and usually does not require a separate hydrocracking step to yield fuel range molecules. However, it consumes more hydrogen than CPH.

2.3. Solvent liquefaction

Solvent liquefaction is the processing of biomass in a pressurized solvent at elevated temperatures to directly produce liquid products (Elliott, 2011). Under relatively mild conditions the products are sugars and partially deconstructed lignin. At more severe conditions the products resemble the bio-oil produced from fast pyrolysis although the product is reported to be more deoxygenated than pyrolysis-derived bio-oil. A number of solvents are possible although water is frequently used because of its low cost and the ability to directly process wet feedstocks. When water is used as a solvent, the process is known as hydrothermal liquefaction (HTL). The products of solvent liquefaction require further upgrading to finished fuels.

2.4. Integrated pathways

A major hurdle to cost competitiveness of cellulosic biofuels is the relatively low energy density of lignocellulose biomass. Unlike most forms of petroleum, which are liquid and can be transported through pipelines over large distances, unprocessed lignocellulosic biomass takes the form of a low density solid that must be transported by truck from the field to the biorefinery. Furthermore, it is often assumed that up to 67% of corn stover, a major source of U.S. lignocellulose, will remain on the field to prevent wind and soil erosion (Thompson and Tyner, 2014), resulting in a large harvest radius to meet the feedstock needs of a commercial-scale biorefinery. These two factors limit the amount of agricultural residue feedstock that can be inexpensively harvested and collected, limiting the size of cellulosic biorefineries to capacities that are only a fraction of petroleum refineries and preventing them from taking full advantage of economies of scale (Wright and Brown, 2007a). It has been proposed that a combination of the fast pyrolysis and gasification pathways into a single, integrated pathway provides a means of increasing the optimal size of biorefineries employing it (Manganaro and Lawal, 2012; Ng and Sadhukhan, 2011; Wright et al., 2008). The lignocellulosic feedstock is first converted to bio-oil via fast pyrolysis, a step that can be performed at small, distributed facilities. The energy-dense bio-oil is then transported to either a centralized gasifier or an autothermal reformer (Manganaro and Lawal, 2012) where it is converted to syngas that is upgraded to biofuel via FT synthesis (although other upgrading routes are also feasible).

3. Pathway techno-economics

3.1. Gasification

3.1.1. Acetic acid synthesis

In 2009 researchers at the Pacific Northwest National Laboratory (PNNL) published a techno-economic comparison of cellulosic ethanol produced via the AAS pathway under two gasification scenarios: one in which an indirectly-heated gasifier is employed and the other in which a directly-heated oxygen-blown gasifier is employed (Zhu and Jones, 2009). Both scenarios consider biorefineries with hybrid poplar wood chip feedstock capacities of 2000 metric tons per day (MTPD) and assume that the CO and hydrogen employed for acetic acid synthesis and acetic acid hydrogenation, respectively, are purchased from external sources rather than produced on-site. The TEA identifies high total project investments (TPI) for both scenarios at \$655 million and \$752 million for the indirectly-heated and directly-heated scenarios, respectively, with the latter driven by the need to purchase an air separation unit and a higher gasifier cost. Assuming a feedstock cost of \$69/metric ton (MT), a 20-year biorefinery lifespan, and an internal rate of return

(IRR) of 10%, the TEA calculates minimum selling fuel prices (MFSP) of \$4.37/gallon of gasoline equivalent (gge) (\$1.15 L of gasoline equivalent, or lge) and \$4.41/gge (\$1.16/lge) for the indirectly-heated and directly-heated scenarios, respectively.

A 2014 analysis by researchers at Iowa State University updates PNNL's AAS analysis by incorporating 20-year projected energy commodity prices from the U.S. Energy Information Administration into the TEA assumptions and employing a feedstock cost of \$83/MT (Brown and Wright, 2014). Price uncertainty is accounted for by stochastically simulating future price movements rather than assuming static prices for the period. Furthermore, since the Iowa State University analysis employs energy commodity prices as model inputs rather than outputs, its results are presented in the form of a 20-year net present value (NPV) rather than MFSP. The analysis calculates 20-year average NPVs of −\$254 million and −\$360 million for the indirectly-heated and directly-heated scenarios, respectively, with large standard deviations for both results, indicating a projected lack of profitability for this pathway.

3.1.2. Fischer-Tropsch synthesis

The FTS pathway has been the subject of frequent TEAs by because of its historical success in producing liquid fuels for economies cut-off from petroleum supplies. A 2002 paper by researchers at Utrecht University and Shell Global Solutions International BV models eleven pathway configurations based on five different gasifiers with Aspen Plus (Tijmensen et al., 2002). It calculates TPIs ranging from a low of \$408 million to a high of \$587 million for a 1371 MTPD biorefinery, with the pretreatment, oxygen-blown gasification, and gas cleaning equipment accounting for almost 75% of the total equipment costs. The MFSP for the resulting FT liquids is calculated to be about \$2.70/gge (\$0.71/lge) assuming a poplar wood feedstock cost of \$30.17/MT and an IRR of 10%, although the authors state that future increases to biorefinery capacity, CO conversion, and C₅₊ hydrocarbon selectivity could reduce this to \$1.52/gge (\$0.40/lge).

In 2007 researchers at Iowa State University incorporated the Tijmensen et al. analysis into a comparative techno-economic study of the FTS pathway with grain ethanol, cellulosic ethanol produced via the biochemical platform, methanol produced via biomass gasification, and hydrogen produced via biomass gasification (Wright and Brown, 2007b). The comparison considers biorefineries yielding 150 MGY of gasoline-equivalent biofuels employing lignocellulosic biomass costing \$57.59/MT. This analysis finds that a biorefinery employing the FTS pathway and utilizing 5876 MTPD of feedstock incurs the largest capital and operating costs at \$984 million and \$1.80/gge (\$0.48/lge), respectively. Feedstock cost is identified as a major operating cost component.

A 2010 analysis by researchers at Iowa State University uses Aspen Plus to model the FTS pathway at a 2000 MTPD biorefinery and a spreadsheet to calculate the capital costs, operating costs, and MFSP of the resulting FT liquids (Swanson et al., 2010). The authors consider two gasifier scenarios: a low-temperature scenario in which the gasifier operates at 870 °C and a high-temperature scenario in which it operates at 1300 °C. The analysis finds that the high-temperature gasification scenario incurs the highest TPI at \$657 million versus \$540 million for the low-temperature scenario due to its higher cold gas efficiency, which results in a higher yield at 61.0 gge/MT (230 lge/MT) and 47.2 gge/MT (178.7 lge/MT) for the high-temperature and low-temperature scenarios, respectively, and larger capacity. Assuming a stover feedstock cost of \$89.69/MT and a 10% IRR, however, the authors find that this higher yield more than offsets the higher capital cost, resulting in lower MFSPs at \$4.63/gge (\$1.22/lge) and \$5.24/gge (\$1.38/lge) for the high-temperature and low-temperature scenarios,

respectively. Finally, the authors report that the MFSP result is most sensitive to TPI and feedstock cost.

In 2013 researchers at Iowa State University analyzed a variation of the FTS pathway in which a geothermal energy component responsible for providing the biorefinery with process steam for the gasification and steam methane reforming steps and excess electricity is included (Banerjee et al., 2013). The analysis calculates a TPI of \$550 million for a 2000 MTPD FTS biorefinery utilizing stover feedstock. Assuming a stover cost of \$80.83 and a 10% IRR generates a MFSP of \$5.04/gge (\$1.33/lge). Utilizing geothermal steam generated on-site for the gasification and reforming steps increases this MFSP to \$5.31/gge (\$1.40/lge), while producing sufficient geothermal steam for both the process steps and excess electricity generation yields an MFSP of \$5.13/gge (\$1.36/lge), assuming that the electricity is sold for \$0.06/kWh.

Researchers at the Karlsruhe Institute of Technology and University of Saskatchewan also published an analysis in 2013 of the FTS upgrading process in which two scenarios are considered based on syngas pressures of 4 MPa and 8 MPa (Trippe et al., 2013). This analysis is simplified by assuming a clean syngas supply is available at \$0.34/m³ rather than evaluating the cost of the gasification and gas cleaning processes in detail. (The authors state that this cost is comparable to a biomass feedstock cost of \$112/MT.) TPIs of \$359 million and \$371 million for the FT synthesis reactor are calculated for the 4 MPa and 8 MPa scenarios, respectively, both of which consume syngas at a rate of 2472 MTPD. Assuming a 20-year biorefinery lifespan and an IRR of 10% generates MFSPs for the produced FT liquids of \$7.13/gge (\$1.88/lge) and \$6.93/gge (\$1.83/lge) for the 4 MPa and 8 MPa scenarios, respectively. A sensitivity analysis identifies the MFSP as being most sensitive to feedstock cost and TPI.

An analysis from researchers at Northwestern University employs a multi-objective, mixed-integer nonlinear programming model to balance an economic objective in the form of 20-year NPV at a FTS biorefinery with an environmental concern in the form of global warming potential (Wang et al., 2013). The model also selects between high-temperature and low-temperature gasification technologies, direct and indirect quench cooling, hydrogen generation from syngas and merchant natural gas, and cobalt, iron, and nickel catalysts for FT synthesis. The authors find that selection of high-temperature gasification, direct quench cooling, hydrogen from syngas, and cobalt catalyst maximize NPV while minimizing global warming potential. Furthermore, a NPV of \$810 million is calculated for a biorefinery yielding 84.5 MGY of FT liquids, assuming a 12% IRR, a feedstock cost of \$83/MT, and a product value of \$3.17/gge (\$0.84/lge).

Two 2014 analyses compare the techno-economics of the FTS pathway to other cellulosic biofuel pathways belonging to the biochemical and thermochemical platforms. The first, from researchers at Lund University, calculates a TPI of \$760 million for a biorefinery utilizing woody biomass feedstock. Assuming an IRR of 10%, a biorefinery lifespan of 20 years, and a poplar feedstock cost of \$140/MT (including a transportation cost of \$17/MT) yields a pathway MFSP of \$5.95/gge (\$1.57/lge). The second study, published by researchers at Iowa State University, updates the Swanson et al. (2010) analysis to reflect projected energy commodity prices and price uncertainty (Brown and Wright, 2014). The authors calculate mean 20-year NPVs of -\$455 million and -\$493 million for the high-temperature and low-temperature gasification scenarios, respectively, due to the FTS pathway's production costs exceeding the products' projected future market values.

Finally, Laser et al. (2009) compares two scenarios in which the FTS pathway is employed to convert a waste lignin stream generated by the biochemical platform to biofuels with several additional integrated scenarios. The authors find that the scenarios employing FTS generate the highest IRRs of the scenarios

considered despite their high TPIs due in large part to their high process efficiencies and biofuel market value.

3.1.3. Mixed alcohols synthesis

The MAS pathway has been the subject of several TEAs published by researchers at the U.S. national laboratories, including the National Renewable Energy Laboratory (NREL) and PNNL. Phillips (2007) uses Aspen Plus to calculate a TPI of \$220 million for a 2000 MTPD biorefinery utilizing woody biomass feedstock. A MFSP of \$1.74/gge (\$0.46/lge) is calculated based on a 10% IRR, a 20-year biorefinery lifespan, and a feedstock cost of \$44.43/MT. This model is adjusted slightly in a 2009 analysis to compare the MAS pathway with a biochemical pathway and calculates a MFSP of \$1.98/gge (\$0.52/lge) (Foust et al., 2009). Dutta et al. (2012) updates the 2007 analysis to reflect new data and developments on feedstock costs, gasifier syngas yields, mixed alcohols synthesis, and capital and operating cost estimates. The updated model calculates a significantly higher TPI of \$560 million and a MFSP of \$3.33/gge (\$0.88/lge) with an assumed feedstock cost of \$73.48/MT. The increased MFSP is especially notable since the 2012 analysis assumes that the biorefinery remains operational for 30 years instead of the 20 year period assumed in the 2007 (Phillips, 2007) and 2009 (Dutta and Phillips, 2009) analyses. Finally, Dutta et al. (2014) presents the most recent update of the model which is based on the results of a combination of bench- and pilot-scale experiment performed by NREL, Dow Chemical, and Rentech. This analysis concludes that it is possible based on current technology to achieve the \$3.33/gge (\$0.88/lge) MFSP calculated by Dutta et al. (2012), although it again assumes a 30-year biorefinery lifespan.

Gonzalez et al. (2012) uses a modified version of NREL's MAS pathway model to quantify the pathway's techno-economics under five lignocellulosic feedstock scenarios: loblolly pine, natural hardwood, eucalyptus, stover, and switchgrass. A TPI of \$284 million is calculated for a 1295 MTPD biorefinery. The analysis calculates both NPV and IRR for each feedstock scenario under the assumption that the biorefinery receives \$4.64/gge (\$1.23/lge) of ethanol and operates for 15 years. The stover and switchgrass scenarios yield the lowest returns (\$38 million/14.2% and \$84 million/16.5%, respectively) while the pine scenario yields the highest returns (\$192 million/21.4%). The authors attribute the different results to the composition, moisture content, and alcohol yield associated with each feedstock.

Okoli and Adams (2014) employ Aspen Plus to expand upon NREL's MAS pathway model by simulating the production of butanol rather than ethanol. A TPI of \$351 million is calculated for a biorefinery converting 2000 MTPD of pine feedstock to butanol and higher alcohols. A MFSP of \$3.37/gge (\$0.89/lge) is calculated based on the assumptions of a 10% IRR, 30-year biorefinery lifespan, and \$73.49/MT feedstock cost.

NREL researchers have also analyzed a MAS pathway scenario in which a high-temperature gasification process is considered (Dutta et al., 2010). The analysis uses Aspen Plus to calculate a TPI of \$403 million for a biorefinery utilizing 2000 MTPD of woody biomass feedstock. The assumptions of a 10% IRR, 20-year biorefinery lifespan, and \$55/MT feedstock cost generate a MFSP of \$3.90/gge (\$1.03/lge). The authors attribute the high MFSP to the feed handling cost, high oxygen demand, and high gasifier equipment cost.

Researchers at PNNL published a comparative TEA of ethanol production from municipal solid waste (MSW) and lignocellulosic biomass via the MAS pathway in 2009 (Jones et al., 2009b). The analysis calculates that the use of MSW increases the TPI for a 2000 MTPD biorefinery by \$111 million over that incurred by a biorefinery utilizing hybrid poplar chips due to its need to convert the MSW, which is comprised of numerous materials including minerals and hazardous waste, into refuse-derived fuel (RDF).

Similarly, the MSW biorefinery yields less ethanol than the lignocellulose biorefinery. Despite these disadvantages, however, the analysis determines that the MFSP for ethanol produced at the MSW biorefinery is significantly lower at \$2.90/gge (\$0.77/lge) with an assumed IRR of 10% than the lignocellulose biorefinery MFSP of \$4.79/gge (\$1.27/lge). The authors attribute this difference to two factors: the sale of scrap minerals collected during the conversion of the MSW to RDF and the lack of a cost for the MSW feedstock (compared to a poplar feedstock cost of \$68.95/MT).

Villanueva Perales et al. (2011) and Reyes Valle et al. (2013) compare the MAS pathway under two reactor type scenarios: an indirectly-heated circulating fluidized bed gasifier and an entrained-flow gasifier. The biorefineries in both scenarios consume 2140 MTPD of poplar chip feedstock. The entrained-flow gasifier TPI is calculated to be \$511 million. The indirectly-heated circulating fluidized bed gasifier is determined to incur a lower TPI than the entrained-flow gasifier when it employs either steam-methane reforming (\$478 million) or partial oxidation (\$482 million) processes, although its TPI is higher when autothermal reforming (\$538 million) or tar reforming (\$515 million) processes are used. Under the assumptions of a \$66/MT feedstock cost, 10% IRR, and 20-year biorefinery lifespan the entrained-flow gasifier yields the highest MFSP at \$5.73/gge (\$1.51/lge) while the indirectly-heated circulating fluidized bed gasifier scenarios range from a high of \$5.62/gge (\$1.48/lge) for autothermal reforming to a low of \$4.37/gge (\$1.15/lge) for partial oxidation.

3.1.4. Methanol-to-gasoline

NREL's research on the MAS pathway also served as the starting point for its work on the MTG pathway. Phillips et al. (2011) uses an Aspen Plus model to calculate a TPI of \$217 million for a MTG biorefinery with a hybrid poplar feedstock capacity of 2000 MTPD. A feedstock cost of \$60.63/MT and 10% IRR yields a MFSP of \$2.12/gge (\$0.56/lge). A sensitivity analysis reveals that the MFSP is most sensitive to assumptions regarding the feedstock, capacity, and economic factors (IRR and TPI).

Trippe et al. (2013) arrives at a much higher estimate than Phillips et al. (2011) despite considering syngas rather than biomass feedstock, calculating TPIs of \$287 million and \$301 million and MFSPs of \$6.26/gge (\$1.65/lge) and \$6.10/gge (\$1.61/lge) for its 4 MPa and 8 MPa syngas MTG scenarios, respectively. While both analyses assume a 10% IRR, Trippe et al. (2013) employs a syngas cost that translates to a feedstock cost that is roughly twice that employed by Phillips et al. (2011). Haro et al. (2013b) expands upon Trippe et al. (2013) by comparing the MTG pathway with variations in which either only alkenes or both alkenes and gasoline are produced. Capital costs are higher when alkene production occurs, with gasoline and alkene production incurring TPIs of \$378 million and \$391 million for the two pressure scenarios, respectively. The market value of the alkenes offsets this TPI increase, however, yielding gasoline MFSPs of \$5.78/gge (\$1.53/lge) and \$5.67/gge (\$1.50/lge), respectively under a 10% IRR and \$112/MT lignocellulose feedstock cost.

Rather than consider the full MTG pathway, Andersson et al. (2014) analyzes three separate scenarios for the production of syngas-derived fuel methanol: a standalone gasifier, a gasifier integrated with a pulp and paper mill, and an integrated gasifier combined with a parallel black liquor gasifier. The results find that integration has relatively little impact on capital costs, reducing the TPI from \$517 million for the standalone scenario to \$478 million. Adding a second gasifier for black liquor feedstock increases the TPI to \$1224 million. The increased capacity and efficiencies achieved by the integrated and parallel systems outweigh the increases to TPI, however, as the authors calculate 20-year IRRs of 24.3%, 26.7%, and 27.8% for the standalone, integrated, and par-

allel scenarios, respectively, based on contemporary energy commodity prices.

3.1.5. Methanol-to-ethanol

The techno-economics of the MTE pathway are quantified by Haro et al. (2013a) alongside pathways for the production of methyl acetate, hydrogen, and DME. The pathways are also divided according to steam-methane reforming, autothermal reforming, and tar reforming processes. The analysis calculates TPIs ranging from a low of \$367 million to a high of \$506 million for the ethanol scenarios. The 20-year IRRs range from a low of 5.4% for the tar reforming scenarios to a high of 12.1% for the steam-methane reforming scenarios. The authors find that the production of both ethanol and DME yields higher IRRs than the production of ethanol alone does when an ethanol price of \$3.58/gge (\$0.95/lge) is assumed.

3.1.6. Syngas-to-distillates

Zhu et al. (2012) compares the MTG pathway with the S2D pathway to determine whether the combination of the methanol dehydration and hydrocarbon synthesis reactions into a single process step is cost-effective. The analysis calculates TPIs of \$408 million and \$519 million for 2000 MTPD biorefineries employing the MTG and S2D pathways, respectively, with the latter being driven primarily by the expense of the hydrocarbon synthesis and product separation equipment. The MFSPs for the two scenarios under a 10% IRR, 20-year biorefinery lifespan, and \$75.94/MT woody feedstock cost is calculated to be \$7.32/gge (\$1.93/lge) and \$3.57/gge (\$0.94/lge), respectively. The authors attribute the high MFSP for the S2D pathway to the high capital costs and low process yields relative to the MTG pathway. However, the analysis also includes a S2D "goal" scenario in which the pathway achieves the same performance as the MTG pathway but with the S2D technology, allowing it to benefit from reduced capital costs and higher yields. The TPI and MFSP for this scenario are calculated to be \$375 million and \$3.02/gge (\$0.80/lge), respectively.

3.1.7. Syngas fermentation

The final gasification pathway considered is SF, which has attracted interest in recent years despite its novelty due to commercialization plans by companies such as Coskata, INEOS, and Lanzatech. Piccolo and Bezzo (2009) conduct a TEA comparing the SF pathway with enzymatic hydrolysis and fermentation for the production of cellulosic ethanol. The analysis calculates a TPI of \$562 million for a 2030 MTPD biorefinery utilizing lignocellulosic feedstock and a MFSP of \$7.29/gge (\$1.93/lge) assuming a feedstock cost of \$85.77/MT, a 15-year biorefinery lifespan, and an IRR of 7.7%. The authors identify the feedstock cost as a driver of the high MFSP, although the relatively short biorefinery lifespan assumption is another contributor.

3.2. Pyrolysis

3.2.1. Fast pyrolysis and hydroprocessing

One of the earliest TEAs of the fast pyrolysis pathway is provided by Bridgwater (1996), which calculates that the MFSP of diesel fuel produced via FPH is 158% higher than the contemporary diesel fuel market price. The analysis presents MFSPs for several scenarios involving different process and upgrading configurations, including catalytic upgrading, but provides relatively few details on capital costs. Furthermore, its conclusion that the FPH pathway cannot compete with petroleum is largely driven by its use of a \$20/bbl petroleum price that, while appropriate at the time, is much too low for current comparisons.

In 2009 researchers at PNNL released a design case study of a 2000 MTPD biorefinery employing the FPH pathway as part of

the DOE's Biomass Program (Jones et al., 2009a). The analysis calculates a TPI of \$329 million for the biorefinery and, based on assumptions of a 10% IRR, 20-year lifespan, and \$60.50/MT hybrid poplar feedstock cost, a MFSP of \$2.21/gge (\$0.58/lge). A short time later researchers at Iowa State University published a TEA of the FPH pathway at a biorefinery converting stover to gasoline and diesel fuel blendstocks under two scenarios: one in which the requisite hydrogen is produced on-site via steam-methane reforming of bio-oil and the other in which it is purchased from an external source (Wright et al., 2010). The analysis calculates TPIs of \$311 million and \$217 million for the on-site and external hydrogen scenarios, respectively, with the on-site scenario requiring additional equipment for the hydrogen production steps. MFSPs of \$3.35/gge (\$0.88/lge) and \$2.29/gge (\$0.60/lge) are calculated for the on-site and external hydrogen scenarios, respectively, under a 10% IRR, 20-year biorefinery lifespan, and \$90/MT stover cost. The analysis also calculates MFSPs for a "first-of-its-kind" pioneer plant reflecting a lack of commercial-scale pathway experience. The pioneer plant analysis yields MFSPs of \$7.11/gge (\$1.88/lge) and \$3.70/gge (\$0.98/lge) for the two scenarios, respectively. The authors attribute the higher MFSPs reported for the on-site hydrogen production scenario to its lower fuel yield (since a fraction of the bio-oil is converted to hydrogen instead of liquid fuel) and higher capital cost. A relatively low assumed price for the external hydrogen scenario also contributes to the difference. Three years after the Wright et al. (2010) analysis, Brown et al. (2013b) published an updated analysis to reflect changing market conditions and pathway commercialization progress. The updated analysis calculates a much higher TPI of \$429 million (driven in part by the inclusion of splitting and blending stages) for a 2000 MTPD stover FPH facility utilizing an external hydrogen source, which translates into a MFSP of \$2.57/gge (\$0.68/lge).

Zhang et al. (2013) uses Aspen Plus to consider a 2000 MTPD FPH biorefinery employing a novel red oak feedstock pretreatment process that produces high yields of levoglucosan, an anhydrosugar derived from cellulose. The levoglucosan is hydrolyzed to glucose while pyrolytic lignin is hydroprocessed to gasoline and diesel using hydrogen produced on-site by steam reforming the aqueous phase of bio-oil. The analysis calculates a TPI of \$379 million for the biorefinery and identifies hydroprocessing and reforming equipment as the largest drivers of capital cost. A 20-year IRR of 11.4% is calculated based on a feedstock cost of \$86.52/MT, a 20-year biorefinery lifespan, and liquid fuel price of \$2.82/gge (\$0.74/lge).

Two recent publications have considered the co-processing of bio-oil in existing petroleum refineries. Co-processing can incur lower capital costs for the FPH pathway by eliminating the need for complete hydroprocessing equipment, although this is offset by reduced biorefinery revenues since it yields an intermediate rather than final product. Bals and Dale (2012) use a spreadsheet to model local biomass processing depots that convert lignocellulose to intermediates that are shipped to a refinery for upgrading. The analysis determines that a depot employing fast pyrolysis is slightly profitable under the assumed market prices. Arbogast et al. (2012) calculates large savings for the FPH pathway when more of the upgrading process is performed at an existing petroleum refinery rather than a FPH biorefinery due to the former's economies of scale. Specifically, fully-upgraded (but not refined) bio-oil incurs operating costs of \$21–31/bbl and \$6.1/bbl at the biorefinery and refinery, respectively, while partially-upgraded bio-oil incurs costs of \$16–23/bbl and \$6.5/bbl, respectively.

The logistics surrounding the FPH pathway have also been the subject of recent research due to the cost of transporting both lignocellulosic feedstock and raw bio-oil, both of which limit the pathway's ability to take advantage of economies of scale. Li et al. (2014) uses a mixed integer linear programming model to

compare a scenario in which Iowa stover is pyrolyzed and hydro-treated at distributed facilities and refined at an existing petroleum refinery in Louisiana with one in which the hydrotreated bio-oil is refined at a new, centralized biorefinery in Iowa. The authors calculate that the new biorefinery scenario yields a gasoline MFSP of \$1.93/gge (\$0.51/lge) compared to \$3.31/gge (\$0.87/lge) for the existing refinery scenario. While the existing refinery scenario generates lower capital costs, this is more than offset by the bio-oil shipping costs.

Brown et al. (2013a) uses TEA to examine the logistics of mobile distributed pyrolysis facilities in forested areas, where a lack of road access is a constraining factor, with centralized upgrading and refining. The analysis determines that the distributed pyrolysis facilities are limited by capacity and therefore less suited than other intermediate-producing pathways such as wood chipping and torrefaction. The authors suggest that gasification and syngas upgrading to fuels such as FT liquids is more economically competitive in forested areas than pyrolysis since the former can convert processed biomass products such as wood chips, torrefied wood, and bio-slurry in addition to bio-oil to liquid biofuels.

Wright et al. (2012) differs from other TEAs of the FPH pathway in that it exclusively analyzes the costs of the bio-oil hydroprocessing stage. The authors employ a response surface model to identify the economic and environmental trade-offs between utilizing hydrogen produced on-site via bio-oil reforming and hydrogen purchased from an external source for upgrading. While the on-site scenario generates the lowest greenhouse gas emissions due to its lower upgrading rate, the analysis concludes that it should only be selected when the market price of hydrogen is high relative to that of petroleum. The authors also suggest that the need to meet emission constraints imposed by policymakers could increase the MFSP of FPH-derived blendstocks by limiting upgrading rates.

Finally, TEAs of the fast pyrolysis pathway have been used to conduct policy analysis. The Wright et al. (2010) study is utilized in an analysis comparing the FPH pathway with slow pyrolysis under a cap-and-trade policy scenario in which co-product biochar has market value as a carbon sequestration mechanism (Brown et al., 2011). This analysis calculates annual returns on investment (ROI) of 15–26% for a 2000 MTPD stover FPH biorefinery based on escalating fossil fuel and carbon prices. The TEA model by Brown et al. (2013b) is adapted by Petter and Tyner (2014) to conduct an analysis of FPH uncertainty and private investment risk. The analysis with the adapted model finds that biofuel market value uncertainty results in a high risk to private investment, although the use of reverse auctions by governments could shift risk to the public sector and prove more effective at encouraging private investment than the capital subsidies that are currently employed in the U.S. Brown et al. (2013c) also employs the Brown et al. (2013b) model to identify those regional factors such as market conditions and tax rates that have the greatest impact on the economic competitiveness of the FPH pathway. The authors find that biorefinery location has a large impact on both IRR and NPV and conclude that these are most sensitive to feedstock type and regional market conditions.

3.2.2. Catalytic fast pyrolysis and hydroprocessing

Thilakarathne et al. (2014) conducts a TEA of a 2000 MTPD CPH biorefinery in which hybrid poplar is converted to gasoline and diesel fuel blendstock. The authors calculate a TPI of \$457 million and find that its main driver is the inclusion of a large co-generation unit to convert the pathway's relatively large yields of coke and biochar to heat and power. A MFSP of \$3.69/gge (\$0.97/lge) is calculated under the assumptions of a 10% IRR, 30-year biorefinery lifespan, and \$96.57/MT feedstock cost. The analysis also assumes that the hydrogen required for hydroprocessing is produced on-site from hydroprocessing off-gas.

3.2.3. Hydrolysis and hydroprocessing

Singh et al. (2012) and Tan et al. (2014) analyze the techno-economics of the HPH pathway for 550 MTPD and 2000 MTPD facilities, respectively. The former analysis calculates that the pathway achieves a NPV of zero when petroleum prices exceed \$103/bbl under the assumptions of a \$94/MT feedstock cost, 10% IRR, and 20-year biorefinery lifespan. The latter analysis calculates a TPI of \$286 million and a MFSP of \$1.82/gge (\$0.48/lge) under the assumptions of a 30-year biorefinery lifespan, \$85.89/MT feedstock cost, and 10% IRR.

3.2.4. Slow pyrolysis

The final pyrolysis pathway covered is the conversion of lignocellulose to methanol via SP. Shabangu et al. (2014) calculates a MFSP of \$3.57/gge (\$0.94/lge) for a 2000 MTPD SP biorefinery under the assumptions of a 10% IRR, 25-year biorefinery lifespan, and \$48.99/MT feedstock cost. TPI is calculated to be \$671 million. The authors find that the methanol fuel's MFSP can be reduced substantially if the co-product biochar is sold as a soil amendment agent, however.

3.3. Solvent liquefaction

One of the earliest TEAs of the HTL pathway compares it with the FPH pathway (Elliott et al., 1990). A 1000 MTPD HTL biorefinery utilizing woody biomass feedstock is calculated to have a TPI of \$250 million (as compared to \$220 million for a 1000 MTPD FPH biorefinery). A MFSP of \$4.67/gge (\$1.23/lge) is calculated for the liquid fuel product, assuming a 20-year biorefinery lifespan, 10% IRR, and feedstock cost of \$118.81/MT. A TEA published by PNNL researchers 24 years later arrives at a very similar result, calculating a TPI of \$555 million and a MFSP of \$4.82/gge (\$1.27/lge) for a biorefinery utilizing 2000 MTPD of woody biomass feedstock under similar assumptions (20-year biorefinery lifespan, 10% IRR, and feedstock cost of \$75.94/MT) (Zhu et al., 2014). The authors find that the MFSP result is most sensitive to the fuel yield and upgrading equipment cost, leading them to calculate that a distributed processing and centralized upgrading system could reduce the intermediate product cost by 26%.

3.4. Integrated pathways

Three TEAs analyze the production of FT liquids via bio-oil. Wright et al. (2008) analyze a system in which distributed fast pyrolysis facilities convert stover to bio-oil that is then gasified and upgraded to FT liquids at a central facility. Three distributed facility sizes are considered: 500 MTPD, 50 MTPD, and 5 MTPD. The centralized upgrading system yields 550 MGY of biofuel. The authors find that the 5 MTPD distributed system achieves the lowest MFSP by incurring the lowest feedstock transportation costs, while the 500 MTPD system incurs a MFSP that is slightly higher than a standalone centralized FTS biorefinery. Manganaro and Lawal (2012) analyze a biorefinery that converts crop residue to bio-oil via fast pyrolysis, converts the bio-oil to syngas via auto-thermal reforming, and upgrades the syngas to FT liquids. A TPI of \$231 million is calculated for a 2000 MTPD biorefinery with a MFSP of \$3.74/gge (\$0.99/lge), assuming an 8% IRR, \$61.20/MT feedstock cost, and \$500/MT co-product biochar value. Ng and Sadhukhan (2011) find that while the integrated pyrolysis/FTS pathway is technically feasible, its high capital cost results in a MFSP that is more than 70% higher than for the standalone FTS pathway with either coal or biomass feedstock even under optimistic economic assumptions. However, the authors state that capital costs can be expected to fall by up to 69% should commercialization of the integrated pathway occur due to the learning curve effect.

4. Pathway modeling assumptions and uncertainty

The main results of the reviewed thermochemical pathway TEAs are summarized in Table 2. The TPIs for *n*th plant 2000 MTPD cellulosic biorefineries range from a low of \$217 million to a high of \$752 million. While some of this difference can be attributed to differences in the installation factors employed to calculate TPI (see Table 3), the TPIs calculated for a pathway can escalate over time as additional experimental data becomes available and researchers develop a better understanding of the pathway's equipment needs; see, for example, the increase to TPIs for the MAS and FPH pathways as researchers updated previous analyses. While large differences in assumptions limit the usefulness of comparisons across individual analyses, the results compiled in Table 2 indicate that the MTG, FPH, and HPH pathways incur the lowest TPIs for 2000 MTPD biorefineries while the FTS, MAS, and SP pathways incur the highest TPIs, although this categorization is not uniform. Of these estimates the FPH pathway TPIs are likely to be the most conservative in their analysis of costs due to the employment of the highest Lang factor (5.46) by the underlying analyses while the HPH pathway TPI is likely the most optimistic.

TPIs contribute to pathway MFSPs in the forms of depreciation and the assumption of partial debt-financing found in some of the analyses. The combination of highly variable capital costs and feedstock costs (see Table 3) results in a wide range of MFSPs. The lowest MFSP is reported by an early analysis of the MAS pathway while the highest is reported for the SF pathway. However, the usefulness of the MFSP results is limited by two factors. First, with the exception of the MFSPs that exceed \$5/gge (\$1.32/lge), it is difficult to determine how successful the pathways will be in the face of volatile petroleum prices. Of the results presented in Table 2 only one (Zhang et al., 2013) uses projected commodity prices to calculate a long-term IRR. Second, the MFSPs are highly sensitive to analytical assumptions. While assumptions frequently must be made due to a lack of necessary data when analyzing pathways for which commercial-scale data does not exist, the variety of assumptions found in the reviewed literature complicates efforts to compare TEA results.

The assumptions used in TEAs of cellulosic biofuels produced via the thermochemical platform vary widely (see Table 3). Capacity, Lang factors (i.e., the ratio of TPI to total purchased equipment cost), stream factor (the percentage of hours per year that the biorefinery is operational), feedstock cost, and biorefinery lifespan are rarely identical even across analyses for the same pathway. All of the analyses reviewed employ scaling factors of less than unity to represent economies of scale. Accordingly, large biorefineries will achieve lower TPIs on a volumetric basis than smaller biorefineries, other things being equal. The assumed base case capacities of the analyses reviewed range from a low of 550 MTPD to a high of 5876 MTPD, although the majority assumes 2000 MTPD. Even uniformity can be misleading, however, as optimal capacity is a function of feedstock density and therefore feedstock type. Several feedstocks are covered by the reviewed analyses ranging from very dense feedstocks such as MSW and woody biomass to low-density feedstocks such as stover. It is unclear in the reviewed analyses whether the assumed feedstocks are abundant enough to supply the assumed biorefinery capacities at the assumed feedstock costs, especially given previous research findings that there is an optimal plant size for minimum production costs (Wright and Brown, 2007a). Furthermore, despite analyses showing feedstock cost being one of the primary drivers of MFSP, IRR, and NPV, it is often based on unpublished data or little more than an unsubstantiated assumption of the authors of TEAs.

The assumed Lang factors, stream factors, and biorefinery lifespan also vary among authors with relatively little justification provided despite their substantial impacts on TEA results. Lang

Table 2
Results of selected thermochemical pathways for cellulosic biofuel production.

Source	Pathway	Capacity (MTPD)	TPI (\$MM)	IRR (%)	MFSP (\$/gge)	MFSP (\$/lge)	Notes
Zhu and Jones (2009)	AAS	2000	655	10	4.37	1.15	Indirectly-heated
	AAS	2000	752	10	4.41	1.16	Directly-heated
Tijmensen et al. (2002)	FTS	1371	408	10	2.70	0.71	BCL scenario
Swanson et al. (2010)	FTS	2000	540	10	4.63	1.22	Low-temperature
	FTS	2000	657	10	5.24	1.38	High-temperature
Trippe et al. (2013)	FTS	2472	359	10	7.13	1.88	Syngas feed, 4 MPa
	FTS	2472	371	10	6.93	1.83	Syngas feed, 8 MPa
Phillips (2007)	MAS	2000	220	10	1.74	0.46	
Dutta et al. (2010)	MAS	2000	403	10	3.90	1.03	High-temperature
Dutta et al. (2012)	MAS	2000	560	10	3.33	0.88	
Phillips et al. (2011)	MTG	2000	217	10	2.12	0.56	
Trippe et al. (2013)	MTG	2472	301	10	6.10	1.61	Syngas feed, 8 MPa
Zhu et al. (2012)	MTG	2000	408	10	3.57	0.94	
	S2D	2000	519	10	7.32	1.93	State-of-technology
Piccolo and Bezzo (2009)	SF	2030	562	7.7 ^a	7.29	1.93	
Jones et al. (2009a)	FPH	2000	329	10	2.21	0.58	
Wright et al. (2010)	FPH	2000	217	10	2.29	0.60	External hydrogen, <i>n</i> th plant
Zhang et al. (2013)	FPH	2000	379	11.4 ^a	3.04	0.80	Monosaccharide co-product, higher IRR
Brown et al. (2013b)	FPH	2000	429	10	2.57	0.68	External hydrogen, <i>n</i> th plant
Thilakaratne et al. (2014)	CPH	2000	457	10	3.69	0.97	
Tan et al. (2014)	HPH	2000	286	10	1.82	0.48	
Shabangu et al. (2014)	SP	2000	671	10	3.57	0.94	No biochar revenue
Zhu et al. (2014)	HTL	2000	555	10	4.82	1.27	State-of-technology

^a Analysis output rather than input.

Table 3
Major assumptions used in selected thermochemical pathways for cellulosic biofuel production.

Source	Pathway	Lang factor ^a	Stream factor (%)	Feedstock cost (\$/MT)	Biorefinery life (years)	Notes
Zhu and Jones (2009)	AAS	3.73	90	69	20	Indirectly-heated
	AAS	3.73	90	69	20	Directly-heated
Tijmensen et al. (2002)	FTS	N/A	91	30.17	N/A	BCL scenario
Swanson et al. (2010)	FTS	4.16	85	89.69	20	Low-temperature
	FTS	4.16	85	89.69	20	High-temperature
Trippe et al. (2013)	FTS	3.43	80	112	20	Syngas feed, 4 MPa
	FTS	3.43	80	112	20	Syngas feed, 8 MPa
Phillips (2007)	MAS	3.43	96	44.43	20	
Dutta et al. (2010)	MAS	3.45	96	55	20	High-temperature
Dutta et al. (2012)	MAS	3.45	96	73.48	30	
Phillips et al. (2011)	MTG	3.40	96	60.63	20	
Trippe et al. (2013)	MTG	3.43	80	112	20	Syngas feed, 8 MPa
Zhu et al. (2012)	MTG	3.43	90	75.94	20	
	S2D	3.43	90	75.94	20	State-of-technology
Piccolo and Bezzo (2009)	SF	N/A	91	85.77	15	
Jones et al. (2009a)	FPH	3.73	90	60.50	20	
Wright et al. (2010)	FPH	5.46	90	90	20	External H ₂ , <i>n</i> th plant
Zhang et al. (2013)	FPH	5.46	90	86.52	20	Monosaccharide co-product, higher IRR
Brown et al. (2013b)	FPH	5.46	90	83	20	External H ₂ , <i>n</i> th plant
Thilakaratne et al. (2014)	CPH	5.10	90	96.57	30	
Tan et al. (2014)	HPH	3.19	96	85.89	30	
Shabangu et al. (2014)	SP	4.00	91	48.99	25	No biochar revenue
Zhu et al. (2014)	HTL	4.20	90	75.94	20	State-of-technology

^a Lang factor = total project investment/total purchased equipment cost.

factors range from a low of 3.19 to a high of 5.46 (see Table 3). For a biorefinery with a TPI of \$500 million this variation results in a TPI range of +/- \$132 million, or +/- 26%. Pathway differences do not fully explain this variation: for example, Lang factors for the FPH analyses alone cover the entire range of reported values. The variation in stream factors is not as large although it is still substantial, ranging from a low of 80% to a high of 96%. Few of the reviewed analyses include stream factor in their sensitivity analyses, although those that do find that the results are sensitive to the assumption (albeit not to the same extent as factors such as yields and market conditions) (Phillips et al., 2011; Swanson et al., 2010). Similarly, the number of years that the biorefinery remains operational directly affects the techno-economic result since lengthier biorefinery life spans lessen the contribution of TPI to MFSP, IRR,

or NPV. The absence of commercial-scale cellulosic biorefineries makes it impossible to identify an appropriate lifespan, making it important that this factor be included in future sensitivity analyses.

When considered together Tables 2 and 3 illustrate the lack of consistency across thermochemical cellulosic biofuel pathway TEAs in the literature. The large variances in pathway-neutral assumption values can have a substantial effect on pathway MFSP despite frequently being chosen either arbitrarily or in a manner that reflects optimistic rather than realistic assumptions. Some of these differences, such as the use of different base years and commodity prices over time or different capital and operating costs when considering region-specific scenarios, cannot be avoided and can even contribute to comparative analyses by illustrating

how time and location affect the pathways being analyzed. However, differences in assumption values that are the result of optimistic versus realistic scenarios, choice of financial and economic methodology, and operating conditions should be explicitly identified and justified if comparisons between analyses are to be informative.

Finally, the sensitivity analyses employed by the reviewed publications accomplish their task by adjusting a single factor value by a predetermined amount and quantifying the resulting impact on MFSP, IRR, or NPV. This methodology fails to account for the magnitude, frequency, and compound nature of factor variation that is likely to be encountered by a commercial-scale thermochemical cellulosic biorefinery. Some recent TEAs have included uncertainty analyses of the pathways considered in the form of Monte Carlo simulations or Latin Hypercube Sampling as a means of quantifying the impact of simultaneous factor changes on the TEA result (Thilakaratne et al., 2014; Zhang et al., 2013; Zhu et al., 2014). While superior to a sensitivity analysis, most of these uncertainty analyses employ factor probability distributions that are chosen arbitrarily. The development of distributions based on economic data and pathway experimental data increases the usefulness of the uncertainty analyses and the TEAs on which they are based by simulating biorefinery financial operations under more realistic conditions, although only two of the TEAs reviewed here include this step (Brown and Wright, 2014; Petter and Tyner, 2014). This uncertainty can have a large impact on NPV, with Brown and Wright (2014) calculating a standard deviation of \$62 million for the AAS pathway under its 2013 commodity price projection under uncertainty scenario and Petter and Tyner (2014) calculating a total NPV range of \$837 million for the FPH pathway under economic and technical uncertainty.

5. Conclusion

This paper reviews the published techno-economic analyses (TEA) of thermochemical cellulosic biofuel pathways. A wide range of results is reported for the thermochemical pathways covered. While this range is due in part to differences in processing conditions between the pathways, large differences in analytical assumptions also contribute to it. This paper makes two suggestions for future TEAs on cellulosic biofuel pathways. First, it recommends the inclusion of factors such as biorefinery lifespan and stream factors in sensitivity analyses due to their impact on TEA results. Second, it calls for the employment of uncertainty analyses based on economic and experimental data in future pathway TEAs and the explicit identification of important assumptions.

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