Modeling and Analysis

Biofpr Biofuels Bioproducts & Biorefining

Impact of co-product selection on techno-economic analyses of alternative jet fuel produced with forest harvest residuals

Kristin L. Brandt, Composite Materials and Engineering Center, Washington State University, Pullman, WA, USA
Robert J. Wooley, Biomass ad infinitum, LLC, Cedar Key, FL, USA
Scott C. Geleynse, Washington State University Tri-Cities, Richland, WA, USA
Johnway Gao, International Paper, Seattle, WA, USA
Junyong Zhu, USDA Forest Service, Forest Products Lab, Madison, WI, USA
Ralph P. Cavalieri, Biological Systems Engineering Department, Washington State University, Pullman, WA, USA
Michael P. Wolcott, Civil and Environmental Engineering Department, Pullman, WA, USA

Received July 11 2019; Revised April 21 2020; Accepted April 23 2020;
View online May 18, 2020 at Wiley Online Library (wileyonlinelibrary.com);
DOI: 10.1002/bbb.2111; *Biofuels, Bioprod. Bioref*. 14:764–775 (2020)

Abstract: This article details techno-economic analyses for producing alternative jet fuel (AJF) at a greenfield integrated biorefinery (IBR) using softwood forest residues. The scenarios and their corresponding economic outcomes differ based on the co-product selections. The selected technology to produce AJF uses a mild bisulfite pretreatment process to prepare the feedstock for enzymatic hydrolysis and fermentation to isobutanol, which is then upgraded to hydrocarbon 'drop-in' fuels using an alcohol-to-jet process. The hydrocarbons are a combination of jet fuel and aviation gasoline (AvGas). The residuals are used to produce co-products. Four co-product scenarios are compared to quantify the impact of co-product selection on the primary products, jet fuel, and AvGas minimum selling prices (MSPs). For the baseline (BL) scenario, residuals are burned to create steam for conversion to electricity. The excess power generated is sold at a wholesale price to the grid. The total capital investment for an IBR with a forest residue feed rate of 721 k dry metric ton year^{-1} is 1027 MM US$, and the AJF MSP is 2.07 US$ L^{-1}. The BL scenario is compared with three co-product selections: 1) liquid calcium lignosulfonate and electricity; 2) activated carbon; and 3) a combination of liquid calcium lignosulfonate and activated carbon. As anticipated, the conversion of residuals into higher value co-products provides additional revenue to offset the production cost of hydrocarbons. The alternative co-product scenarios reduced the predicted MSPs; however, the most cost-competitive model, the scenario where both activated carbon

Correspondence to: Kristin L. Brandt, Composite Materials and Engineering Center, 2001 E Grimes Way, Washington State University, Pullman, Washington, 99164. E-mail: kristin.brandt@wsu.edu

© 2020 Society of Chemical Industry and John Wiley & Sons, Ltd

and calcium lignosulfonates are produced, reduced the jet fuel MSP to 1.49 US$ L^{-1}, a 28% reduction.
© 2020 Society of Chemical Industry and John Wiley & Sons, Ltd

Supporting information may be found in the online version of this article.

Keywords: techno-economic analysis; co-products; alternative jet fuel; alcohol-to-jet; ratio factors; SPORL

Introduction

Aviation petroleum transportation fuels are limited and demand is growing. The US Department of Transportation reported the 2018 airline fuel consumption for US and international carriers as 17.9 billion gallons, a 3.3% increase from 2017.[1] This growth is predicted to continue with the demand for jet fuel increasing 40% from 2016 through 2040.[2] A need for a more sustainable fuel sources as well as a source that is not dependent on foreign oil has encouraged research into biofuels through the Energy Independence and Security Act of 2007.[3] The use of woody biomass as a feedstock has been shown to reduce localized air pollution in addition to surpassing the 60% global warming potential threshold set by the US Environmental Protection Agency for biofuels.[4] Much of the completed biofuel research has focused on ethanol. However, biodiesel and alternative jet fuel (AJF) are gaining attention as second-generation biofuels.[5-7] These drop-in fuels add a level of complexity to processing. However, they have the potential to reduce a large source of greenhouse gas emissions and replace a significant volume of petroleum fuel.[8]

Researchers have investigated the use of lignocellulosic feedstocks in the production of transportation fuel. This material is a low-cost, plentiful feedstock. However, researchers cite that high lignin materials have low yields and require complex pretreatment processes.[9-12] Co-products are necessary to balance the increased cost associated with lower yield and complicated process requirements, including, but not limited to, pretreatment. The financial success of a facility depends on the efficient manufacture of hydrocarbons and co-product(s) as well as having strong volume and price markets for the entire production slate. In addition to creating income, co-products can reduce risk through product diversification.[12-16] Co-product selection will affect the final fuel minimum selling price (MSP).[17]

Pretreatment of lignocellulosic biomass is often complex and expensive. This process must disrupt the natural crystalline structure to facilitate enzyme access to cellulose and hemicellulose for saccharification.[12,15,18-23] The most frequently studied lignocellulosic materials for use in fuels are corn stover, grasses, and hardwoods.[23] However, the Northwest Advanced Renewables Alliance (NARA) project chose to study softwood forest residues (FR), a material that is plentiful in the northwest USA. Breaking the recalcitrant structure of this feedstock is challenging compared with other lignocellulosic feedstocks.[20,24-27]

The integrated biorefineries (IBRs) described in this paper convert Douglas-fir forest residuals into two drop-in hydrocarbon fuel products produced through the biochemical alcohol-to-jet conversion pathway, along with co-products generated from utilization of the lignin-rich byproducts. While a wide range of thermochemical processes may be used to process streams of this kind, such as pyrolysis or hydrothermal liquefaction to produce bio-oil, this paper compares three specific co-product strategies effective with recalcitrant woody feedstocks: combustion for electricity generation, a catalyzed pyrolysis process to produce activated carbon, and the evaporation of liquid calcium lignosulfonate. The process uses a mild sulfite pretreatment to overcome the recalcitrance of lignocellulose (SPORL) before enzymatic hydrolysis, which is followed by fermentation to isobutanol and the alcohol-to-jet process to upgrade the isobutanol to hydrocarbons. The SPORL pretreatment was chosen for its performance in reducing the recalcitrance of softwood feedstock compared with other pretreatment processes, such as steam explosion.[28]

The cost to build and time to ramp up production at an IBR is often underestimated and has led to financial challenges for the initial adopters of these technologies. These conditions, combined with uncertain subsidy policies and market prices, make new processes of the type and scale envisioned in this paper a high financial risk.[29,30] The high capital cost can be an obstacle to new technologies such as production of fuel from lignocellulosic feedstock.[12] The intermingled barriers to AJF production of high fuel price and high capital requirements can be partially addressed by the selection of valuable co-products. The purpose of this paper is to address the quantitative impact of co-product selection on the financial viability of AJF.

Methods

The technology to manufacture hydrocarbons and co-products from softwood forest residue described in this article was separated into manufacturing process areas (Fig. 1). The baseline (BL) scenario, which is the basis for all comparisons, is the production of AJF, AvGas, and electricity. This scenario was selected as a baseline to match a common literature choice and because generating steam and electricity from process residues is a low-risk process for utilizing residual material.[14,31–34] Brief process area descriptions are included in this paper for processes classified as inside battery limits (ISBL). Outside battery limit (OSBL) process areas are not detailed, and capital costs are represented through the use of ratio factors. The technical details and process descriptions of the ISBL conversion processes are presented in Chen *et al.*,[35] Humbird *et al.*,[31] Aden *et al.*,[36] Zhu *et al.*,[37] Gu *et al.*,[38] and Geleynse *et al.*[39]

Hydrocarbon production process model

The process model begins with feedstock preparation: screening and hammermilling the Douglas-fir FR, which are then sent to pretreatment. Forest residue is waste material created in the logging process. The material is chipped in the forest before transport to the IBR. The SPORL pretreatment process is described in depth in Zhu *et al.*[37] and Gu *et al.*[38] There are two streams leaving pretreatment: an aqueous mix of carbohydrates and lignin, similar to wood pulp, and spent sulfite liquor (SSL), a combination of soluble sugars and lignosulfonates. The pretreated pulp proceeds to enzymatic hydrolysis and the SSL is sent directly to fermentation.

The enzyme production and enzymatic hydrolysis process areas are adaptations of the same process areas presented in Humbird *et al.*[31] The enzyme production process area manufactures cellulase for use in enzymatic hydrolysis and the enzymatic hydrolysis process area cools the pretreated pulp, adds water and adjusts the pH using lime before it enters a batch saccharification reactor to convert the pulp into sugar monomers.

Fermentation to isobutanol of the saccharified pulp and SSL is completed along two parallel pathways using a process adapted from Humbird *et al.*[31] following the method used in Geleynse *et al.*[39] After fermentation, the two streams are combined into a single unit for upgrading and separation. An alcohol-to-jet process is used to upgrade the isobutanol into hydrocarbons in four stages: dehydration, oligomerization, hydrogenation, and fractionation.[39] The hydrocarbon products generated by this process proceed through the fractionation process with the hydrocarbon stream being separated into two hydrocarbons: 70% AJF blendstock and 30% AvGas blendstock.[39]

In the BL case, the SSL proceeds to the evaporator. The resulting SSL syrup is sent to the boiler / turbogenerator for conversion into electricity. The fermentation residual solids (FRS) are sent to a centrifuge prior to the evaporator with the resulting solids and FRS syrup routed to the boiler / turbogenerator. Ten percent of the evaporated condensate is sent to wastewater treatment (WWT) and the remainder is recycled to the process. The centrifuge, evaporator, WWT, and boiler / turbogenerator capital and operating costs are adapted from Aden *et al.*[36]

Economic analysis

The analysis chosen to evaluate the relative financial performance of the SPORL pre-treated AJF among the co-product scenarios is a financial analysis following the

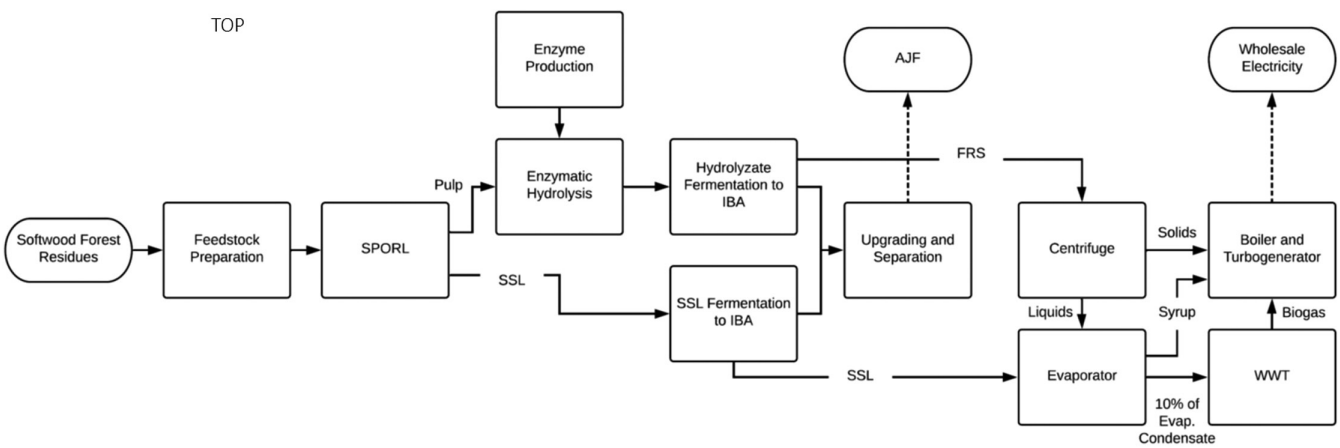

Figure 1. Process area-level flow diagram for baseline AJF process.

© 2020 Society of Chemical Industry and John Wiley & Sons, Ltd

methods used by Petter and Tyner[40] and Brandt *et al.*[41] One of the key differences in this analysis compared to an engineering analysis, is that a financial analysis includes the impact of inflation. This work was completed with a nominal financial discount rate of 12.2%, calculated from the assumed real discount rate of 10% and an inflation rate of 2%. The MSP values for the two hydrocarbons were determined using the nominal financial discount rate and a net present value (NPV) of zero. The value of the AvGas was determined using a linear relationship with kerosene jet fuel that was calculated for the months between January 1993 and August 2019.[42,43]

Table 1 lists assumed economic parameters. In addition to the tabulated assumptions, the IBR is assumed to be an *n*th plant, a facility that uses mature technology that has been deployed successfully previously. The boundaries of this analysis begin when the forest residues are delivered to the wood yard and end with the storage of hydrocarbons and co-products. All prices of products are mill-gate prices that do not include the cost of transportation after manufacturing. The average corporate tax rate in the USA from for 2017, 17.3%, was assumed.[44] The cost year selected is 2017 and is applied throughout this work, with equipment costs updated using the Chemical Engineering Plant Cost Index.[45]

The capital costs for the baseline facility were determined using a detailed list of ISBL costs in combination with modified ratio factors, which allow for approximation of the fixed capital investment (FCI) using the delivered equipment costs.[47] The costs used are Aspen estimates, quotations, and adaptations of literature sources (Table 3, supporting information). The capital costs for the baseline techno-economic analysis (TEA) were estimated using ratio factors applied to total delivered equipment cost (TDEC) for ISBL process areas. Using ratio factors to estimate facility cost is suitable for preliminary and study estimates with a predicted accuracy of ±20–30%.[47] This level of accuracy corresponds to a strategic study and is appropriate for the initial verification of the economic viability of a process and can simplify case studies that rely on capital cost alterations. Ratio factors have been applied successfully to compare processes and for siting decisions.[11,21,32,41,48-50]

The economic parameters (Table 1) and the process variables (Table 2) are applied for the TEAs. The energy costs are national, industrial electricity and natural gas rates averaged from 2013–2017.[51-53] A five-year average was selected to alleviate some of the inherent fluctuations in energy prices. It is assumed that all excess electricity is sold at the 2013–2017 average wholesale electricity rate for the USA.[52] Energy costs are geographically specific and will vary from national averages for any given location. The intent of this paper is not to calculate a precise MSP values but to quantify MSPs within the error bounds of the input variables and determine the scale of MSP changes based on co-product selection.

Literature sources estimate delivered feedstock costs for forest residue using a variety of methods and locations. Richardson *et al.* focused on the Yakima region in Washington state and found that the volume of forest thinnings available for purchase plateaued at approximately 40 US$/dry t delivered cost, with a volume jump to a secondary plateau at 70 US$/dry t delivered cost.[53] The second plateau correlates with the addition of state and federal land.[54] Skog *et al.*[55] reported similar results, finding that the volume of forest thinnings available at 40 US$/dry t is nearly the same as the volume at 70 US$/dry t. Skog *et al.*[55] also reports the volume of wood available at a

Table 1. Economic parameter assumptions.

Economic parameter	Assumed value
Cost year	2017
Plant financing	30% equity, 70% loan
Loan rate	8%
Loan term	10 years
Plant life	20 years +3 years to build
Income tax rate	17.3%
Working capital	20% yearly operating cost
Nominal financial discount rate	12.2%
Inflation	2%
Depreciation schedule (general plant)	7 years,[a] double declining balance to straight line
Depreciation schedule (boiler/ turbogenerator)	20 years,[a] double declining balance to straight line
Construction schedule	3 years (8% first year, 60% second year, 32% third year)[b]
Operational days/year	329[c]

[a]IRS 2017.[46]
[b]Percentage of fixed capital investment (FCI) spent during each year of construction.
[c]90% uptime.[7]

Table 2. Base case variables for hydrocarbon minimum selling price calculations.

Variable	Base case value	Unit
Feedstock, after losses	656	t/year
Electricity rate (purchase)	0.07	US$/kWh
Natural gas rate	4.5	US$/MMBtu
Wholesale electricity rate (sale)	0.04	US$/kWh
Feedstock cost, delivered	65.0	US$/dry t
Hydrocarbon yield	215	L/t

© 2020 Society of Chemical Industry and John Wiley & Sons, Ltd

procurement price of either 30 US$/dry t and 50 US$/dry t. When combined with the truck transportation costs listed, the estimated average delivered cost is approximately 50–70 US$/dry t.[55] Perlack and Stokes[8] suggest a biomass price of 93 US$/dry t. However, this is a combined feedstock price for multiple biomass sources. Logging residues are identified as a low-cost feedstock for the composite price of 93 US$/dry t; thus, it is reasonable to assume that forest residue could be purchased for less than the quoted 93 US$/dry t.[8] Gonzalez *et al.*[12] studied the use of logs as a feedstock for biofuels with a delivered feedstock cost near $70/dry t. For this paper, we assumed a feedstock cost of 65 US$/dry t, which fits the literature data trends and is an adaptation of the Martinkus *et al.* data.[56] We acknowledge that the feedstock cost will vary based on the chosen facility location and the impact of this variation is investigated in this paper.

Results

Capital costs – Baseline scenario

Ratio factors for a solid–liquid processing plant were applied to the total ISBL equipment costs to estimate total direct costs (TDC) and FCI (Table 3). The standard ratio factors were increased to account for a greenfield location. Specifically, the buildings factor was increased from 0.29 for an on-site addition to 0.47 for greenfield construction.[32,47,50] The portion of the ratio factor that covers the cost of boilers was removed as the boiler / turbogenerator process area cost exceeded the typical amount covered by the ratio factor. The cost of this process area was treated as ISBL following the method outlined in Martinkus and Wolcott.[50] A similar decision was made for the WWT process area. The cost is much lower than the cost estimated using ratio factors, excluding the centrifuge and evaporation processes. These three items are considered one process area and are treated as ISBL. The supporting information includes the BL scenario TEA spreadsheet and provides detailed equipment costs and scales for each process area. The price of land was estimated at 1.5% of FCI.[47] Working capital is intended to cover the cost of operating when cash is scarce. It was assumed that 20% of the annual operating costs is a sufficient value for working capital.[41]

Table 3. Total delivered equipment cost (TDEC) for inside battery limit departments.

Department	TDEC (MM US$)	Source
Feedstock handling	22.5	Adapted from[57]
Pretreatment	69.0	Adapted from[57]
Enzyme production	14.2	Adapted from[31]
Enzymatic hydrolysis	9.9	Adapted from[31]
Conversion to hydrocarbons	19.4	Adapted from[39] and[31]
Boiler / turbogenerator	63.8	Adapted from[36]
Wastewater treatment	29.6	Adapted from[36]
Total direct costs	700	47
Fixed capital investment (FCI)	991	47
Total capital investment	1027	FCI + working capital

Operating costs – Baseline scenario

The operating costs were adapted from material and energy flows in Humbird *et al.*,[31] Pierobon *et al.*,[4] Marrs *et al.*,[57] Aden *et al.*,[36] and Geleynse *et al.*[39] with standardized energy and chemical costs. For the BL scenario, the turbogenerator produces more electricity than is needed for the process, which means that no electricity is purchased. As a result of the excess power generation, the costs in Table 4 do not include the cost of purchasing electricity, but the electricity demand is included in the supporting information. The FRS and SSL provide enough energy to the boiler so that no additional fuel is required to meet the steam demand.

The economic analysis of the BL scenario, applying the assumed economic parameters, capital costs, and operating costs, was utilized to calculate an estimated jet fuel MSP of 2.07 US$ L^{-1} and an AvGas MSP of 2.46 US$ L^{-1}. These MSP values include the annual income from selling excess electricity of 6.9 MM US$. The values reported in the literature vary widely, even after updating to a cost year of 2017,[58] including values as low as 1.1 US$ L^{-16} and as high

Table 4. Annual operating costs separated into departmental costs for the BL scenario.

Item or department	Operating costs, MM US$ $year^{-1}$
Feedstock	46.8
Labor	13.3
Maintenance	59.4
Taxes and insurance	24.8
Feedstock handling	0.1
Pretreatment	4.5
Enzyme production	21.5
Enzymatic hydrolysis	1.1
Fermentation, separation, and alcohol to jet	7.6
Boiler / turbogenerator	0.1
Wastewater treatment	0.02
Utilities	2.1
Total	181

© 2020 Society of Chemical Industry and John Wiley & Sons, Ltd

as 2.6 US$ L^{-1}[32] with others falling within this range.[23,49,59,60] It is important to note that these values are based on varying financial and process assumptions and thus direct comparisons should be made with caution. The peak annual petroleum jet fuel price recorded by the EIA for the past decade is 0.8 US$ L^{-1}, the average price from 2012.[43] These results reinforce that substantial cost reduction is required to eliminate the difference in market price for jet fuel and our estimated production cost. One method to achieve a financially viable IBR is to choose high-value co-products.

Co-product scenarios

Producing AJF at or near price parity with petroleum jet fuel continues to be a challenging goal. Although local and federal government incentives are currently available, it is unlikely that capital intense facilities will be built based on meeting the requirements of government policy-dependent incentives. Process improvements will likely aid in cost reductions of this technology over time; however, additional solutions are required. The two simplest methods of dropping the MSP are to increase revenue and /or decrease costs. This paper focuses on increasing revenue through co-product selection, which, as a result, impacts both capital and operating costs. The scenarios evaluated, including acronyms used in the text, are listed in Table 5.

Activated carbon (AC) and lignosulfonates (LS) are used in industrial markets and were selected as the higher value co-products for evaluation (Fig. 2). The manufacture of these two co-products utilize residual streams recovered from the bottoms streams of beer stills in the baseline hydrocarbon production process. Activated carbon is produced by pyrolyzing FRS after removing water in a two-step process. Initial water removal is completed with belt presses, which is followed by a rotary drum dryer to ensure a maximum moisture content of 15%. The dry FRS are carbonized and then activated at 650–700 °C and 700–800 °C, respectively.[61] The yield of activated carbon from FRS is 20% (w/w).[35] Lignosulfonate is produced by removing water from SSL stillage until a solids content of 50% is reached, and the pH is adjusted to 6.5.[35] These co-products are generated from separate residuals streams. The financial impact of producing them is thus assessed both individually and in combination. Marrs *et al.*[57] mill-gate sales prices of $1653/t for activated carbon and $220/t for lignosulfonate were selected for the analysis. The capital and operating costs listed in Table 5 include the impact of process changes to steam requirements, cooling water, and wastewater treatment. Details surrounding costs, including the amount of hog fuel purchased to generate process steam, are available in the supporting information, and, for ease of comparison, the supporting information also provides a summary of operational parameters including steam, cooling water and energy used in each scenario.

A summary of the impact on capital and operating costs of each scenario as well as AvGas MSP and annual co-product

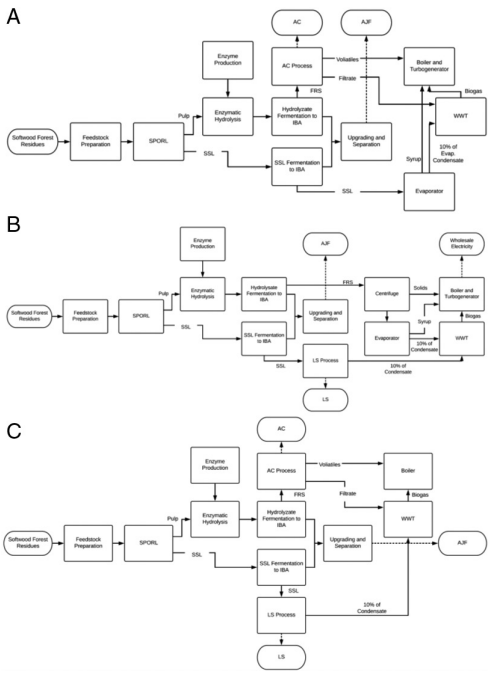

Figure 2. Process flow for AC (a), LS (b), and AC + LS (c) co-product scenarios.

Table 5. Co-product scenario definitions, fixed capital investment (FCI), AvGas MSP, co-product revenue and yearly operating expenses for comparative analyses.

Scenario	Acronym	FCI	AvGas MSP (US$ L^{-1})	Annual co-product revenue	Annual OPEX
Baseline	BL	991	2.46	6.9	181
Baseline with AC	AC	1301	2.42	105.3	238
Baseline with LS	LS	1048	2.33	34.3	188
No electricity, AC and LS	AC + LS	915	1.80	134.3	235

All values are MM US$ unless labeled otherwise. AC is activated carbon and LS is lignosulfonates.

© 2020 Society of Chemical Industry and John Wiley & Sons, Ltd

revenue are listed in Table 5, with the full details provided in the TEA spreadsheets (supporting information). The two scenarios that add either AC or LS to the BL include a turbogenerator. The turbogenerator is used to process the hydrocarbon residue not utilized for a higher-value co-product. For the LS scenario, the turbogenerator creates excess electricity that is sold and included as a second co-product. However, for the AC scenario, the turbogenerator does not meet the facility requirements, and thus, electricity is purchased to meet the demand. The capital cost is lowest in the scenario that produces LS and AC (Table 6). This is a result of the removal of the costly turbogenerator and a reduced WWT load. The authors chose to include WWT as an ISBL process area for all the scenarios to unify the procedure for comparison. The AC + LS scenario has a small WWT process area that could have been covered by the ratio factor.

The decision to proceed with all WWT process areas handled with the same method increased the cost of the AC + LS hydrocarbons by 0.09 US$ L^{-1}, or 6% for a real discount rate of 10%, a value that is well below the ±30% accuracy of the ratio factor methodology. This method may overestimate the capital costs but the simplicity of comparisons justifies the possible error.

Table 6. Delivered equipment cost for co-product production, boiler / turbogenerator and evaporation / wastewater treatment (WWT) for each scenario in MM US$. BL is baseline, AC is activated carbon and LS is lignosulfonates.

Scenario	Co-products	Boiler/ turbogenerator	Evaporation/ WWT
BL	—	63.8	29.6
AC	43.4	40.3	81.0
LS	10.9	64.9	30.9
AC + LS	54.3	27.4[a]	16.5

[a]Value estimated using typical value for ratio factor of 3% FCI.[47]

Table 7. MSP in US$ L^{-1} for three real discount rates for all co-product TEA scenarios. BL is baseline, AC is activated carbon and LS is lignosulfonates.

	Real discount rate			
TEA methodology	5%	10%	15%	20%
BL	1.85	2.07	2.31	2.56
AC	1.75	2.03	2.32	2.62
LS	1.72	1.95	2.18	2.43
AC + LS	1.29	1.49	1.70	1.92

Results and discussion

A sensitivity analysis was completed for each scenario to identify the controlling variables. The most influential parameters identified are assumed discount rate, total capital investment (TCI), and fuel yield. The TCI was evaluated over the range of predicted accuracy, ±30% and the MSP impact was 21–27% with the larger impact occurring for the higher capital scenarios. The assumed yield from sugar to isobutanol was assumed to be 90%. The MSP dropped by 10% when the yield was set to the theoretical maximum. However, a drop to 80% yield increased the MSP by 12%. Labor, electricity price, natural gas price, working capital and hog fuel price do not significantly increase or decrease MSP within a reasonable range.

The MSP for AJF was determined for each of the co-product scenarios for three nominal financial discount rate values: 5%, 10%, 15% and 20% (Table 7). The evaluation of discount rates was completed to illustrate the impact of the real discount rate on MSP. A real discount rate above the assumed 10% might be required to motivate investors for a facility of this financial scale.[15,21,40] The real discount rate of 5% is included to demonstrate that reducing returns alone will not align MSP values with current petroleum jet fuel prices. The average wholesale kerosene-type jet fuel cost in the US for 2013–2017 was 0.54 US$ L^{-1}.[43] The price of this fuel is volatile but trends up over time. However, the peak price, attained in July 2008, is 1.05 US$ L^{-1}, which is approximately two-thirds of the price needed to attain a 10% real discount rate with the best co-product selection. If the BL or AC scenarios are selected, the MSP is closer to double the peak price. The data provided in Table 7 illustrate that co-product selection can lead to practical MSP differences. However, more work is needed to further reduce the cost of AJF.

The cost of feedstock is a key variable influencing MSP. The assumed feedstock cost is 65 US$/dry t; however, this value will vary based on facility location. In an effort to quantify not only the impact of feedstock cost but the relative impact among the co-product scenarios, two additional feedstock prices were assessed: 45 US$/dry t and 85 US$/dry t. As expected, lowering the feedstock price decreased the MSP, and increasing the feedstock price increased the MSP (Fig. 3). The change in delivered feedstock price was 20 US$/dry t, or 31%. Three of the scenarios' MSP values had a resultant change of 5%: BL, AC, and LS. The feedstock price influenced the AC + LS scenario more, with an MSP shift of 7%. Attaining lower cost feedstock will help reduce MSP but is not sufficient to bridge the gap from the current predicted MSP and petroleum jet fuel.

 © 2020 Society of Chemical Industry and John Wiley & Sons, Ltd

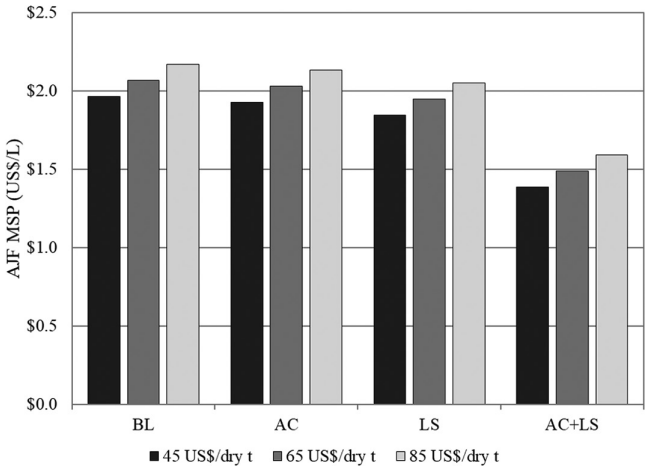

Figure 3. The AJF MSP for each co-product scenario for three delivered, dry feedstock prices.

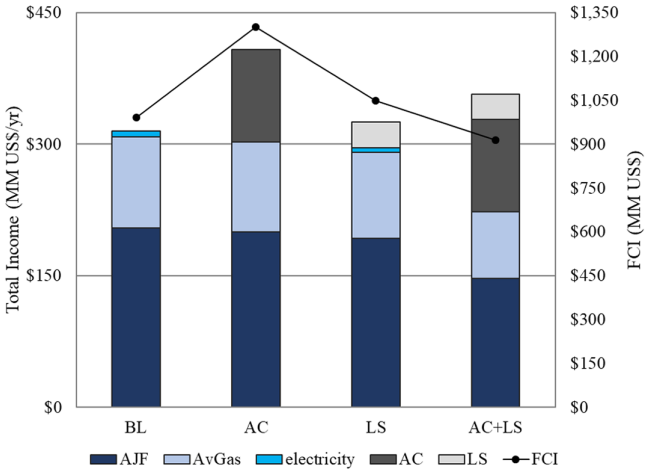

Figure 4. Total income by product and fixed capital income (FCI) for the four co-product scenarios.

Scenario comparison

Each of the co-product scenarios was analyzed to quantify the impact of co-product choice. In addition to the scenarios presented, we evaluated multiple WWT options to best match flow and COD levels as well as ensuring the lowest cost option was chosen for each process. The BL scenario reduces the WWT load through the use of a centrifuge and evaporator. These two processes account for 90% of the capital in the WWT process area. The co-product in this scenario is electricity generated using biogas from WWT and the solid portion of the waste material. The electricity generated exceeds the amount the plant requires. However, the income from electricity is low at only 6.9 MM US$/year (Fig. 4).

If the FRS are diverted and used to manufacture AC, the TCI increases by 31%. This increase is a combination of requiring a more expensive WWT process area as a result of higher COD water and the addition of the AC process area. These additions are partially offset by a reduction in the scale and cost of the turbogenerator. However, the electricity from the turbogenerator does not cover the entire facility demand, and excess electricity must be purchased from the grid. The products sold in this scenario are AJF, AvGas, and AC. Even with the large capital cost increase, the AJF MSP only drops 0.04 US$ L^{-1} to 2.03 US$ L^{-1} as a result of increased total income (Fig. 4). This 2% decrease is unlikely to convince investors to pay 322 MM US$ more than the baseline TCI to build a facility.

The SSL stream can also be diverted from the WWT and energy production stream to manufacture LS. This scenario increases the TCI by 6% from the addition of the LS process area equipment and causes a small increase in total income, which together drop the AJF MSP by 6% or 1.95 US$ L^{-1}. While any drop in MSP is positive, this small change falls short of closing the price gap.

The most promising co-product scenario is the AC + LS scenario. Both the TCI and the MSP drop. A reduction in TCI of 76 MM US$, or 6%, helps to drop the AJF MSP by 28% even with the 29% increase in annual operating costs. A large portion of the increased operating costs is from the purchase of electricity. Choosing a location with electricity costs below the national average will alleviate some of this spike. An electricity price of 0.04 US$/kWh will drop the AJF MSP 0.09 US$ L^{-1} to 1.40 US$ L^{-1}. The decrease in MSP is more substantial than for either AC or LS alone, but the price needs to be further reduced. It is important to note that the co-products selected diversify the types of products for sale, which will reduce a portion of the risk associated with manufacturing only commodity fuels with inherently volatile prices.[62]

Government incentives

At the time of writing, government programs exist to help with the financial viability of AJF; however, there is no certainty that they will continue past 2022. Until then, quotas for renewable fuel are mandated.[63] One mandate that must be met for biofuel to be qualified for Renewable Identification Numbers (RINs) is a reduction of greenhouse gases (GHG) of 60% or more compared to petroleum fuels.[3] Life cycle analyses for processes similar to those presented in this paper have been completed and GHG reductions greater than 60% were reported.[4,33] The feedstock chosen for the analysis did not include any biomass from federally owned forests. This means that the feedstock is a RIN-qualified cellulosic feedstock. Depending on the future of this government

© 2020 Society of Chemical Industry and John Wiley & Sons, Ltd

program, the biofuel MSP could be lowered by applying RIN values. The hydrocarbons produced in the SPORL process are considered advanced and are therefore eligible for D5 RINs. The forest residues are also eligible for cellulosic waiver credits (CWC), which are feedstock dependent. D5 RINs and CWCs can be combined for advanced, cellulose-based biofuels.[64] Very little cellulosic biofuel has been produced, which makes setting the value of CWCs difficult. The US EPA published CWC values for jet fuel, and the average for 2013–2017 is 0.26 US$ L^{-1}.[65] The D5 RIN values sold for an average price of 0.19 US$ L^{-1} for 2013–2017.[66] The combination of CWC and D5 RINs could drop the AJF MSP by 0.45 US$ L^{-1} to 1.62 US$ L^{-1} for the BL scenario. If, however, these credits are applied to the scenario that has AC and LS as co-products, the cost of hydrocarbons drops to 1.04 US$ L^{-1}. Average petroleum jet fuel prices from 2013 through 2017 were 0.54 US$ L^{-1}. The combination of higher value coproducts and government programs lower the hydrocarbon cost significantly compared to the baseline but additional measures are needed to achieve cost parity.

Conclusions

Manufacturing AJF fuel using forest residues and the SPORL process is not a financially profitable venture with current petroleum-based fuel. Conversion of this regionally abundant, yet highly recalcitrant feedstock for AJF fuel production through SPORL pretreatment and the alcohol-to-jet pathway in a greenfield facility remains uncompetitive against current petroleum-based fuel. The addition of value-added co-production capabilities to the biorefinery model offers a strong step toward cost reduction. However, additional work is required to drop the MSP, likely through a combination of reduced capital and operating costs with help by government programs as possible. For example, repurposing an existing facility may help the financial appeal. However, to reduce the risk of volatile fuel prices, energy prices, and government subsidies, this process, like much of the biofuel industry, needs a combination of technology, yield, and co-product improvements to continue moving toward financial viability. Future work should focus on a combination of cost-reduction efforts and additional high-value product-mix investigations.

Acknowledgements

The authors gratefully recognize the NARA contributors Tom Spink and Gevan Marrs for the building of the initial process techno-economic analysis. We sincerely thank Natalie Martinkus for modeling the delivered feedstock costs.

Funding

This work, as part of the Northwest Advanced Renewables Alliance (NARA), was supported by the Agriculture and Food Research Initiative Competitive Grant no. 2011-68005-30416 from the USDA National Institute of Food and Agriculture. This research was also funded by the US Federal Aviation Administration Office of Environment and Energy through ASCENT, the FAA Center of Excellence for Alternative Jet Fuels and the Environment, project 001 through FAA Award Number 13-C-AJFE-WaSU-013 under the supervision of Nathan Brown and James Hileman. Any opinions, findings, conclusions, or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the FAA.

References

1. BTS, Bureau of Transportation Statistics. F41 Schedule P12A. United States Department of Transportation. Airline Fuel Cost and Consumption (U.S. Carriers – Scheduled). Available: https://www.transtats.bts.gov/fuel.asp?pn=0&display=data4 [1 April 2019].
2. EIA, Annual Energy Outlook 2017 with projections to 2050. #AEO2017. Available: www.eia.gov/aeo [29 June 2017].
3. EISA, Energy Independence and Security Act of 2007, Pub. L. 110-140, 121 Stat. 1492. Available: http://www.gpo.gov/fdsys/pkg/BILLS-110hr6enr [14 March 2019].
4. Pierobon F, Eastin IL and Ganguly I, Life cycle assessment of residual lignocellulosic biomass-based jet fuel with activated carbon and lignosulfonate as co-products. *Biotechnol Biofuels* **11**:139 (2018). https://doi.org/10.1186/s13068-018-1141-9.
5. Naik SN, Goud VV, Rout PK and Dalai AK, Production of first and second generation biofuels: A comprehensive review. *Renew Sustain Energy Rev* **14**:578–597 (2010).
6. Diederichs G, Mandegari M, Farzad S and Görgens J, Techno-economic comparison of biojet fuel production from lignocellulose, vegetable oil and sugar cane juice. *Bioresour Technol* **216**:331–339 (2016).
7. Jones S, Meyer P, Snowden-Swan L, Padmaperuma A, Tan E, Dutta A, et al., Process design and economics for the conversion of lignocellulosic biomass to hydrocarbon fuels: Fast pyrolysis and hydrotreating bio-oil pathway. Report No.: PNNL-23053, NREL/TP-5100-61178 (2013).
8. Perlack RD and Stokes BJ, U.S. Billion-ton update: Biomass supply for a bioenergy and bioproducts industry. Report No.: ORNL/TM-2011/224 (2011).
9. He J and Zhang W, Techno-economic evaluation of thermo-chemical biomass-to-ethanol. *Appl Energy* **88**:1224–1232 (2011).
10. Piccolo C and Bezzo F, A techno-economic comparison between two technologies for bioethanol production from lignocellulose. *Biomass Bioenergy* **3**:478–491 (2009).
11. Dutta A, Sahir A, Tan E, Humbird D., Snowden-Swan LJ, Meyer P, et al., Process design and economics for the conversion of lignocellulosic biomass to hydrocarbon fuels thermochemical research pathways with in situ and ex situ upgrading of fast pyrolysis vapors. Report No.: NREL/TP-5100-62455, PNNL-23823 (2015).

 © 2020 Society of Chemical Industry and John Wiley & Sons, Ltd

12. Gonzalez R, Treasure T, Phillips R, Jameel H and Saloni D, Economics of cellulosic ethanol production: green liquor pretreatment for softwood and hardwood, greenfield and repurpose scenarios. *BioResources* **6**:2551–2567 (2011).
13. Biddy MJ, Davis R, Humbird D, Tao L, Dowe N, Guarnieri MT *et al*., The techno-economic basis for coproduct manufacturing to enable hydrocarbon fuel production from lignocellulosic biomass. *ACS Sustain Chem Eng* **4**:3196–3211 (2016).
14. Davis R, Tao L, Tan ECD, Biddy MJ, Beckham GT, Scarlata C, et al., Process design and economics for the conversion of lignocellulosic biomass to hydrocarbons: dilute-acid and enzymatic deconstruction of biomass to sugars and biological conversion of sugars to hydrocarbons. Report No.: NREL/TP-5100-60223 (2013).
15. Crawford J, Techno-economic analysis of hydrocarbon biofuels from poplar biomass [thesis on the internet]. Seattle, WA: University of Washington (2013). Available: https://digital.lib.washington.edu/researchworks/handle/1773/25142 [10 January 2019].
16. Sims REH, Mabee W, Saddler JN and Taylor M, An overview of second generation biofuel technologies. *Bioresour Technol* **10**:1570–1580 (2010).
17. Kulas D, Winjobi O, Zhou W and Shonnard D, Effects of coproduct uses on environmental and economic sustainability of hydrocarbon biofuel from one- and two-step pyrolysis of poplar. *ACS Sustain Chem Eng* **6**:5969–5980 (2018).
18. McMillan JD, Pretreatment of lignocellulosic biomass, in *Enzymatic Conversion of Biomass for Fuels Production*, ed. by Himmel ME, Baker JO and Overend RP. American Chemical Society, Washington, DC, pp. 292–324 (1994).
19. Sun Y and Cheng J, Hydrolysis of lignocellulosic materials for ethanol production: A review. *Bioresour Technol* **83**:1–11 (2002).
20. Zhu JY and Pan X, Woody biomass pretreatment for cellulosic ethanol production: Technology and energy consumption evaluation. *Bioresour Technol* **101**:4992–5002 (2010).
21. Zhang Y, Brown TR, Hu G and Brown RC, Techno-economic analysis of monosaccharide production via fast pyrolysis of lignocellulose. *Bioresour Technol* **127**:358–365 (2013).
22. BETO, (2016). Multi-Year Program Plan: Bioenergy Technologies Office. US Department of Energy: Energy Efficiency and Renewable Energy (2016).
23. Yao G, Staples M, Malina R and Tyner W, Stochastic techno-economic analysis of alcohol-to-jet fuel production. *Biotechnol Biofuels* **10**:18 (2017). https://doi.org/10.1186/s13068-017-0702-7.
24. Morales M, Pielhop T, Saliba P, Hungerbühler K, von Rohr PR and Papadokonstantakis S, Sustainability assessment of glucose production technologies from highly recalcitrant softwood including scavengers. *Biofuels Bioprod Bioref* **11**:441–453 (2017).
25. Gao J, Anderson D and Levie B, Saccharification of recalcitrant biomass and integration options for lignocellulosic sugars from Catchlight Energy's sugar process (CLE sugar). *Biotechnol Biofuels* **6**:10 (2013). https://doi.org/10.1186/1754-6834-6-10.
26. Kumar L, Arantes V, Chandra R and Saddler J, The lignin present in steam pretreated softwood binds enzymes and limits cellulose accessibility. *Bioresour Technol* **103**:201–208 (2012).
27. Pan X, Xie D, Gilkes N, Gregg D and Saddler J, Strategies to enhance the enzymatic hydrolysis of pretreated softwood with high residual lignin content. *App Biochem Biotechnol* **124**:1069–1080 (2005).
28. Zhou H, Lou H, Yang D, Zhu JY and Qiu X, Lignosulfonate to enhance enzymatic saccharification of lignocelluloses: Role of molecular weight and substrate lignin. *Ind Eng Chem* **52**:8464–8470 (2013).
29. Morrison GM, Witcover J, Parker NC and Fulton L, Three routes forward for biofuels: Incremental, leapfrog, and transitional. *Energy Policy* **88**:64–73 (2016).
30. Zhao X, Brown TR and Tyner WE, Stochastic techno-economic evaluation of cellulosic biofuel pathways. *Bioresour Technol* **198**:755–763 (2015).
31. Humbird D, Davis R, Tao L, Kinchin C, Hsu D, Aden A, Process design and economics for biochemical conversion of lignocellulosic biomass to ethanol dilute-acid pretreatment and enzymatic hydrolysis of corn stover. Report No.: NREL/TP-5100-47764 (2011).
32. de Jong S, Faaij A, Slade R, Mawhood R and Junginger M, The feasibility of short-term production strategies for renewable jet fuels – a comprehensive techno-economic comparison. *Biofuels Bioprod Bioref* **9**:778–800 (2015).
33. Ganguly I, Pierobon F, Bowers TC, Huisenga M, Johnston G and Eastin IL, 'Woods-to-Wake' life cycle assessment of residual woody biomass based jetfuel using mild bisulfite pretreatment. *Biomass Bioenergy* **108**:207–216 (2018).
34. Davis R, Tao L, Scarlata C, Tan E, Ross J, Lukas J, Sexton D, Process design and economics for the conversion of lignocellulosic biomass to hydrocarbons: Dilute-acid and enzymatic deconstruction of biomass to sugars and catalytic conversion of sugars to hydrocarbons. Report No.: NREL/TP-5100-62498 (2015).
35. Chen S, Spink T, Gao A, Aspen modeling of the NARA conversion process. NARA Final Report (2016). Available: http://hdl.handle.net/2376/6470 [3 February 2017].
36. Aden A, Ruth M, Ibsen K, Jechura J, Neeves K, Sheehan J, et al., Lignocellulosic biomass to ethanol process design and economics utilizing co-current dilute acid prehydrolysis and enzymatic hydrolysis for corn stover. Report No. NREL/TP-510-32438 (2002).
37. Zhu JY, Chandra MS, Gu F, Gleisner R, Reiner R, Sessions J *et al*., Using sulfite chemistry for robust bioconversion of Douglas-fir forest residue to bioethanol at high titer and lignosulfonate: A pilot-scale evaluation. *Bioresour Technol* **179**:390–397 (2015).
38. Gu F, Gilles W, Gleisner R and Zhu JY, Fermentative high-titer ethanol production from Douglas-fir forest residue without detoxification using SPORL: High SO2 loading at low temperatrue. *Ind Biotechnol* **12**:168–175 (2016).
39. Geleynse S, Brandt K, Garcia-Perez M, Wolcott M and Zhang X, The Alcohol-to-Jet conversion pathway for drop-in biofuels: techno-economic evaluation. *ChemSusChem* **11**:3728–3741 (2018).
40. Petter R and Tyner WE, Technoeconomic and policy analysis for corn stover biofuels. *ISRN Econom* **2014**:1–13 (2014).
41. Brandt K, Gao J, Wang J, Wooley R and Wolcott M, Techno-economic analysis of forest residue conversion to sugar using three-stage milling as pretreatment. *Front Energy Res* **6**:1–11 (2018).
42. EIA. *U.S. Aviation Gasoline Wholesale/Resale Price by Refiner*. Available: https://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=pet&s=ema_eppv_pwg_nus_dpg&f=m [4 November 2019]
43. EIA, Energy Information Administration. *U.S. Kerosene-Type Jet Fuel Wholesale/Resale Price by Refiners*. Available: https://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=PET&s=EMA_EPJK_PWG_NUS_DPG&f=M [10 October 2019].

© 2020 Society of Chemical Industry and John Wiley & Sons, Ltd

44. Organization for Economic Co-Operation and Development. *Composite Effective Marginal Tax Rate*. Available: https://stats.oecd.org/Index.aspx?DataSetCode=CTS_CIT [30 October 2019].
45. Chemical engineering magazine plant cost index. *Chemical Engineering Magazine* (2018). Available: https://www.chemengonline.com/ [23 April 2019].
46. IRS. How to depreciate property. 2017. Publication No.: #946. https://www.irs.gov/publications/p946/ar02.html [16 November 2018].
47. Peters MS, Timmerhaus K and West RE, Analysis of cost estimation, in *Plant Design and Economics for Chemical Engineers*, 5th edn. McGraw-Hill, New York, pp. 226–278 (2003).
48. Wright MM, Daugaard DE, Satrio JA and Brown RC, Techno-economic analysis of biomass fast pyrolysis to transportation fuels. *Fuel* **89**:S2–S10 (2010).
49. Astonios K, Kougioumtzis MA, Panopoulos KD and Kakaras E, Alternative thermochemical routes for aviation biofuels via alcohols synthesis: Process modeling, techno-economic assessment and comparison. *Appl Energy* **138**:346–366 (2015).
50. Martinkus N and Wolcott M, A framework for quantitatively assessing the repurpose potential of existing industrial facilities as a biorefinery. *Biofuel Bioprod Bioref* **11**:295–306 (2017).
51. EIA, U.S. Energy Information Administration. *Electricity: Detailed State Data. Average Price (Cents/kilowatthour) by State by Provider, 1990–2017* (2019). Available https://www.eia.gov/electricity/data/state/ [27 May 2019].
52. EIA, U.S. Energy Information Administration. *Wholesale Electricity and Natural Gas Market Data* (2019). Available https://www.eia.gov/electricity/wholesale/#history [27 May 2019].
53. EIA, U.S. Energy Information Administration. *Natural Gas Industrial Prices* (2019). Available: http://www.eia.gov/dnav/ng/ng_pri_sum_a_epg0_pin_dmcf_a.htm [27 May 2019].
54. Richardson JJ, Spies KA, Rigdon S, York S, Lieu V, Nackley L *et al*., Uncertainty in biomass supply estimates: Lessons from a Yakama Nation case study. *Biomass Bioenergy* **35**:3698–3707 (2011).
55. Skog KE, Patton-Mallory M, Rummer RB and Barbour RJ, *Western Governors' Association: Strategic Assessment of Bioenergy Development in the West Spatial Analysis and Supply Curve Development*. University of California, Davis, CA (2008) Available: https://www.fs.usda.gov/treesearch/pubs/34631 [15 May 2019].
56. Martinkus N, Latta G, Morgan T and Wolcott M, A comparison of methodologies for estimating delivered forest residue volume and cost to a wood-based biorefinery. *Biomass Bioenergy* **106**:83–94 (2017).
57. Marrs G, Spink T, Gao A, Process design and economics for biochemical conversion of softwood lignocellulosic biomass to isoparaffinic kerosene and lignin co-products. NARA Final Report (2016). Available: https://research.libraries.wsu.edu/xmlui/handle/2376/6422 [12 December 2018]
58. BLS, *United States Department of Labor, Department of Labor and Statistics: Consumer Price Index Inflation Calculator*. Available: https://www.bls.gov/data/inflation_calculator.htm [10 February 2019].
59. Tao L, Markham JN, Haq Z and Biddy MJ, Techno-economic analysis for upgrading the biomass-derived ethanol-to-jet blendstocks. *Green Chem* **19**:1082–1101 (2016).
60. Crawford JT, Shan CW, Budsberg E, Morgan H, Bura R and Gustafson R, Hydrocarbon bio-jet fuel from bioconversion of poplar biomass: techno-economic assessment. *Biotechnol Biofuels* **9**:141 (2016). https://doi.org/10.1186/s13068-016-0545-7.
61. Gao J, Techno-economics analysis on activated carbon production from lignin residuals, Version 5. International Paper Technical Report No. (2013).
62. Hu W, Dang Q, Rover M, Brown RC and Wright MM, Comparative techno-economic analysis of advanced biofuels, biochemicals, and hydrocarbon chemicals via the fast pyrolysis platform. *Biofuels* **7**:57–67 (2015).
63. McGarvey E and Tyner W, A stochastic techno-economic analysis of the catalytic hydrothermolysis aviation biofuel technology. *Biofuels Bioprod Bioref* **12**:474–484 (2017).
64. Christensen A, Searle S, Malins C, A conversational guide to renewable identification numbers (RINs) in the U.S. renewable fuel standard. ICCT Briefing (2014). https://theicct.org/sites/default/files/publications/ICCTbriefing_RINs_20140508.pdf [10 May 2019].
65. EPA, *Fuels Registration, Reporting, and Compliance Help: Cellulosic Purchase Credits Purchased Annually* (2019). https://www.epa.gov/fuels-registration-reporting-and-compliance-help/cellulosic-waiver-credits-purchased-annually [14 May 2019]
66. EPA, *Fuels Registration, Reporting, and Compliance Help: RIN Trades and Price Information* (2019). Available: https://www.epa.gov/fuels-registration-reporting-and-compliance-help/rin-trades-and-price-information [14 May 2019].

Kristin L. Brandt

Kristin L. Brandt is a staff engineer at Washington State University. Her research focuses on the techno-economic analysis of industrial processes.

Robert J. Wooley

Robert J. Wooley is president of Biomass Ad Infinitum, LLC, consulting on the evolving biomass conversion industry. Dr Wooley has worked in biomass research, development and industrial deployment at National Renewable Energy Laboratory, NatureWorks-Cargill, Abengoa Bioenergy and Gevo, Inc.

Scott C. Geleynse

Scott C. Geleynse is a postdoctoral research associate at in the the Bioproducts, Sciences, and Engineering Laboratory Washington State University Tricities. He provides technical engineering expertise to bridge the gap between chemical process design, economic analysis, and supply-chain assessment.

 © 2020 Society of Chemical Industry and John Wiley & Sons, Ltd

Johnway Gao

Johnway Gao contributed to the mild bisulfite pretreatment process for forest residual's conversion to sugar monomers. His research and development interests include biomass and biotechnology, sustainability, pulp and paper, cellulose fibers, techno-economics analysis, and new products.

Ralph P. Cavalieri

Ralph P. Cavalieri is Professor Emeritus of Biological Systems Engineering at Washington State University. He has served as the director of the Washington State University Office of Alternative Energy, as director of the USDA National Institute of Food and Agriculture project, Northwest Advanced Renewables Alliance, and as the director of the Federal Aviation Administration's Center of Excellence for Alternative Jet Fuels and Environment, ASCENT.

Junyong Zhu

Junyong Zhu is a co-inventor of the SPORL process. He has been recognized with the International Union of Forest Research Organizations Scientific Achievement Award and the United States Department of Agriculture Undersecretary-Natural Resource and Environment Honor Award. Dr Zhu is a Fellow of American Institute of Chemical Engineers, Technical Association for the Pulp, Paper and Converting Industry & the 2016 Fulbright-Aalto University Distinguished Chair, Finland.

Michael P. Wolcott

Michael P. Wolcott conducts research in biobased materials and fuels. He is the Director of ASCENT, the FAA Center of Excellence for Alternative Jet Fuel and the Environment and was formerly Project Co-Director for Northwest Advanced Renewables Alliance, a USDA Agriculture and Food Research Initiative Coordinated Agricultural Projects project, which most notably flew the first commercial cellulosic biofuels flight with partners Gevo and Alaska Airlines.

© 2020 Society of Chemical Industry and John Wiley & Sons, Ltd