Methodology for quantifying the impact of repurposing existing manufacturing facilities: case study using pulp and paper facilities for sustainable aviation fuel production

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Abstract: Sustainable aviation fuel (SAF) is vital for the reduction of the environmental impact of the aviation industry while decreasing the dependence of the USA on foreign petroleum fuels. To date, SAF, especially from cellulosic feedstocks, have struggled to overcome two barriers: (1) meeting price parity with their petroleum counterparts and (2) the large capital investment required for industrial-scale biorefineries. Repurposing of industrial facilities has been suggested as a means of addressing both challenges. In this study we look at the financial impact of manufacturing SAF using three repurposing value levels. To demonstrate the application of this methodology, we examine case studies based on a wood-based alcohol-to-jet process. Each level evaluated assumes a different portion of the existing facility is useable. The impact on capital costs and minimum fuel selling price is estimated for generalized case studies as well as for specific case studies spread across multiple regions of the USA. The best economic outcomes are achieved when large-scale facilities have both inside and outside battery limit assets that can be repurposed. The geospatially explicit variables that have the largest economic impact are feedstock price, feedstock composition, and industrial natural gas price. However, the scale and value of repurposing both outweigh the geospatial variables within reasonable limits. Of the locations studied, the lowest minimum selling price (MSP) of $1.16/L was calculated at the Washington facility, a nearly 19% reduction from a matching scaled greenfield facility, a result of existing equipment and infrastructure reducing total capital investment by one-third and plentiful feedstock. © 2022 Society of Chemical Industry and John Wiley & Sons, Ltd

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Introduction

While sustainable aviation fuel (SAF) is seen as a critical part of the solution for meeting carbon emission targets for the commercial aviation industry, it is still limited in commercial deployment. In addition to impacting environmental remediation, SAF provides a solution to the aviation industry that relies on liquid carbon fuel and is not currently amenable to electrification to reduce carbon footprint.[1] Large-scale manufacture of sustainable aviation fuel (SAF) is hindered by a high minimum selling price (MSP). In part, the high MSP is a result of the large capital investment required to build an industrial-scale facility. The capital requirement is difficult to secure with the additional factor of the new and changing technology landscape, which discourages investors needed to initiate construction.[2] However, producing SAF and biofuel in general does not allow for cost parity with petroleum fuels, especially for cellulosic biofuels.

The comparatively high MSP of SAF is a result of multiple cost drivers, one of which is the large, required capital investment. Second-generation biofuel production facilities require much more capital than similarly scaled first-generation ethanol or biodiesel plants, up to ten times the total capital investment (TCI).[3] Gonzalez *et al.*[4] stated that cellulosic biofuels need to overcome two major cost obstacles: (1) the relatively high feedstock cost and (2) the expensive pretreatment required to overcome recalcitrance. This is corroborated by Reeb *et al.*[5], adding low yield, value of biomass residues for other products and siting choices to produce cellulosic sugar. This outcome was verified by Phillips *et al.*[6] and Eisentraut,[3] who both found that the production of cellulosic biofuels suffers from initial capital intensity combined with unproven technology. Biomass to liquid (BTL) diesel and lignocellulosic ethanol production costs are dominated by capital costs at approximately 50% and 38%, respectively. Even with the projected future capital cost reductions, production costs resulting from high capital requirements will be a third or more of the total costs.[3]

In addition to being financially hindered by capital costs, second-generation biofuels often struggle economically, in part from low yield.[7] This low yield makes it important to use low-cost feedstocks such as forest residues to create significant revenue.[8] It is critical that all material be utilized for the highest value products possible to support the financial success of a cellulosic biorefinery.[4] Although the selection of high-value co-products helps to decrease the required price of SAF, additional cost-reducing measures are needed.[9]

One solution is to reduce capital costs by repurposing existing facilities.[4–6,9,10–13] Among the multiple ASTM approved pathways to produce SAF is alcohol to jet (ATJ). Pulp and paper mills have infrastructure that aligns well with wood-based, cellulosic ATJ SAF production. In addition, the pulp and paper industry is in transition as markets are moving from paper copies towards electronic media and communication.[14] This transition is forcing mills to close, locations that can be repurposed industrial sites. Repurposing a brownfield location can reduce the risk of establishing a biorefinery through reduced capital requirements.[13]

Reeb *et al.*[5] found that co-location or repurposing decreased the required capital expenditure, one of the most influential cost components, by approximately one-third or one-half, respectively, when manufacturing cellulosic sugar. Gonzalez *et al.*[4] compared the financial viability of manufacturing cellulosic ethanol at a greenfield location and at a repurposed kraft pulp mill. The total capital costs decreased by nearly two-thirds from US $311 MM to US $106 MM, primarily from the removal of the pretreatment costs, buildings and the outside battery limits (OSBL) facilities, for example boilers and wastewater treatment. No cost for purchasing the facility, equipment or land to repurpose was included. Phillips *et al.*[6] modeled a reduction in the capital cost for cellulosic ethanol by more than a factor of four through repurposing a kraft pulp and paper mill, which reduced the resulting ethanol price to as low as $0.52/L. Phillips *et al.*[6] assumed a zero value for the asset at transfer in a repurpose scenario. The asset was assumed to be shuttered and that the scrap value would be offset by not having to pay to close and remediate the site. Gunukula *et al.*[13] evaluated the economic impact of repurposing pulp and paper facilities for use as biorefineries and calculated a 23–27% capital cost reduction. This reduction is a combination of reusing infrastructure and select process equipment. As in the previous study, no costs were associated with acquiring the site to repurpose.

Martinkus and Wolcott[12] created a framework to determine the possible capital cost savings of repurposing existing facilities into biorefineries. Case studies estimated

the percentage reduction in total capital investment for repurposing multiple types of pulp and paper facilities into a cellulosic ATJ facility with co-products to be 27–40%.[12] These reductions are largely from OSBL manufacturing areas and infrastructure. However, the authors did not include a cost to purchase the pulp and paper facilities.

Fornell *et al.*[8] presented a techno-economic analysis (TEA) that repurposed a kraft mill into a facility that produces ethanol from the pulp stream and dimethyl ether from the residue liquor. The authors assumed that the kraft mill, which processed 2065 dry t/day of softwood, was purchased for $236 MM (updated to 2017$). Wu *et al.*[10] studied the manufacture of ethanol in a repurposed kraft mill, comparing softwood lignin contents and calculated an MSP for ethanol that was below the selling price of ethanol at publication.

A comparison of the financial readiness of multiple SAF facilities was completed by de Jong *et al.*,[11] as well as an analysis that assessed co-production strategies, which resulted in lower final fuel costs. Although de Jong *et al.*[11] discussed costs for repurposing existing facilities, no costs were included in the analyses. When choosing a location to repurpose, geospatially determined operating costs, including labor and feedstock, impact the cost to produce SAF and could influence chosen production locations. However, non-economic priorities will also be considered when a facility is built.[11]

The purpose of this paper is to quantify the impact of repurposing on two barriers to SAF production: capital costs and MSP. To accomplish this goal, a methodology to quantify the financial impact of repurposing is presented. This methodology is then applied to both generalized and site-specific repurposing case studies to highlight the most influential variables for reducing both capital requirements and MSP, which allows for informed site selection.

Methods

The methodology presented builds upon the framework outlined by Martinkus and Wolcott[12] for quantifying capital cost and MSP reductions for generalized repurposing scenarios. The backbone of this framework is a TEA built using ratio factors that estimate OSBL costs from inside battery limit (ISBL) equipment costs. The framework with factors allows researchers to choose which costs should be eliminated for specific repurposing scenarios (Fig. 1). Once a greenfield TEA is built, this method can be applied widely to locations and processes, as shown by the three specific case studies.

Economic method

The TEAs used were built following the method presented in detail for greenfield facilities in Brandt *et al.*[9] All financial analyses were completed with 2% inflation, a real discount rate of 10%, and a net present value of zero, to determine the minimum selling price of SAF.[9,15] Key assumptions for economic parameters are listed in Table 1.
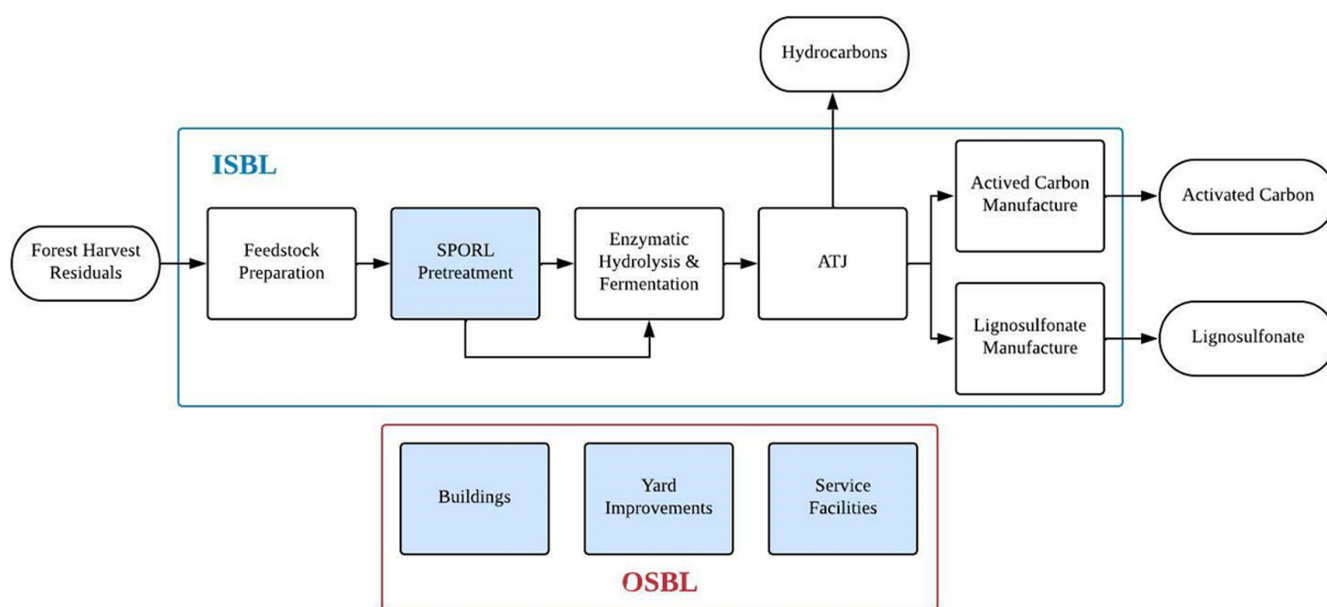

Figure 1. Flowchart of greenfield forest harvest residuals to SAF process. Shaded boxes are areas of possible cost reductions from repurposing a pulp and paper facility.

Table 1. Economic parameter assumptions.[9]	
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	16.9%
Working capital	20% annual operating cost
Nominal financial discount rate	12.2%
Inflation	2%
Operational days/year	329

Table 2. Definitions of assets available for each repurposing value.		
Repurposing value	Existing facility assets	Example of repurposing value
High	>10% ISBL TDEC, buildings, yard improvements, and a portion of the service facilities	Operational pulp mill with pulping process that aligns with selected pretreatment
Medium	>0% and <10% ISBL TDEC, buildings, yard improvements, and a portion of the service facilities	Operational pulp mill with a small portion of the pulping equipment available to the selected SAF process
Low	Buildings, yard improvements, and a portion of the service facilities	Long-term shuttered pulp mill

Greenfield TEA

The fixed capital investment (FCI) for the greenfield scenario applies modified ratio factors to the total delivered equipment cost (TDEC) of the ISBL manufacturing areas. Ratio factors estimate the cost of OSBL manufacturing areas and infrastructure from TDEC (Eqn 1). Multiplying a ratio factor with TDEC results in FCI. Ratio factors are divided into two categories: direct costs (DC) and indirect costs (IC). Direct costs are physical assets such as installation of equipment, electrical systems, yard improvements, and service facilities. Indirect costs cover services including engineering, legal fees, and contractor fees.[16] The use of ratio factors has an estimated accuracy of ±20–30%.[16] TCI for a greenfield facility is sum of the FCI and working capital, which is assumed to be 20% of the annual operating costs.[9] Both FCI and TCI are reported rounded to the nearest $10 million.

$$FCI = \left(DC_{rf} + IC_{rf}\right) \cdot \left(TDEC_G\right) \qquad (1)$$

where *rf* is ratio factor and *G* is greenfield.

Repurposed facility TEA

The impact of repurposing requires comparative TEAs to assess capital cost and MSP changes. For this purpose, we define three investment levels of repurposing value: high, medium, and low, based on the value of both OSBL and ISBL assets at a repurposed pulp or paper mill. Each level assumes specific asset viability at the repurposed facility, which will in turn impact the expected capital cost and MSP reductions (Table 2).

The usable portion of each facility classification is considered in determining the FCI. Ratio factors applied to ISBL costs for greenfield facilities were modified for repurposing and vary among the repurposing values (Table 2). Equation (1) was modified into Eqns (2–4), which reflect the existing assets, required new assets, and the cost to purchase an existing facility.

For total direct costs (TDC), the repurposed ratio factor was applied to the greenfield TDEC value for both the newly purchased equipment and the equipment available for repurposing at the acquired facility.[11] However, the portion of the ratio factor that covers equipment installation was removed for the existing equipment (Eqn 2). The greenfield TDEC was selected for direct costs because physical assets not available at a location need to be purchased at a scale that supports the entire facility, not just the new portion. The total indirect costs (TIC) ratio factor was applied to only the new TDEC. Existing equipment costs were not included as indirect costs are designed to cover services that will not be necessary for existing assets.

$$TDC_{RP} = DC_{rf,RP} \cdot TDEC_G - Install_{rf} \cdot \left(TDEC_G - TDEC_{RP}\right) \quad (2)$$

$$TIC_{RP} = IC_{rf,RP} \cdot TDEC_{RP} \qquad (3)$$

$$FCI_{RP} = TDC_{RP} + TIC_{RP} + Existing\ Facility - Land \qquad (4)$$

where *RP* is repurposed, and *Install* is the portion of the ratio factor that covers equipment installation.

For scenarios where SAF capacity exceeds that of the original facility, the FCI increases to cover OSBL requirements that exceed the existing site capacity (Eqns 5 and 6).

$$DC_{rf,RP,new} = DC_{rf,buildings} + DC_{rf,G} - DC_{rf,og} \qquad (5)$$

$$FCI_{RP,new} = FCI_{RP} + DC_{rf,RP,new} \cdot \left(TDEC_{G,new} - TDEC_{RP,new} \right) \qquad (6)$$

where *new* is the value at the larger capacity, *buildings* is the ratio factor for buildings at an existing site, and *og* is the value at the existing facility's original scale.

Ratio factors for repurposing the existing facilities are modified from the values presented in Peters *et al.*[16] for processes that handle both solids and liquids following a modified version of the framework detailed in Martinkus and Wolcott[12] (Table 3). Three components of the direct cost ratio factor are possible cost reduction sources with repurposing: buildings, yard improvements, and service facilities (Fig. 1). For all repurposing values, we assume that the cost of buildings is reduced to 7% of TDEC and costs for yard improvements were removed, as recommended by de Jong *et al.*[11] and Martinkus and Wolcott.[12] The typical value for each of the service facilities provided by Peters *et al.*[16] was chosen and converted from a percentage of FCI to a percentage of TDEC (Table 4). For the medium and high repurposing values we assumed that repurposing sites would be chosen so that product storage is the only service facility that would need to be procured. The medium and high repurposing scenarios have the same ratio factors; the difference is a result of ISBL equipment availability. For the low-value repurposing scenario, only sanitary waste disposal and raw material storage costs were avoided. The sum of the individual service facility components is the service facilities

Table 3. Components of ratio factors for greenfield facilities and facilities with low, medium, and high repurposing values. Ratio factors are adapted from liquid–solid Peters *et al.*[16] values.

Ratio factor elements	Greenfield	Low repurposing value	Medium and high repurposing values
Other direct	1.67	1.67	1.67
Installation	0.39	0.39	0.39
Buildings	0.47	0.07	0.07
Yard improvements	0.12	0	0
Service facilities	0.55	0.52	0.05
Total direct plant costs (DC)	3.20	2.65	2.18
Total indirect plant costs (IC)	1.26	1.26	1.26

line item in Table 3. We acknowledge that these scenarios will not match specific repurposing sites; however, the values represent a generalized, realistic set of expected cost savings.

Generalized case studies

In addition to reductions in OSBL costs, some ISBL equipment can be repurposed, depending on the facility purchased and the SAF conversion process. For the case studies in this paper SAF is manufactured using sulfite pretreatment to overcome the recalcitrance of lignocellulose (SPORL) to prepare forest residuals for enzymatic hydrolysis. After hydrolysis, fermentation and ATJ creates SAF and aviation gasoline along with two coproducts: activated carbon and lignosulfonates (Fig. 1). Aviation gasoline is fuel for aircraft with piston engines.[17] The details of the techno-economic analyses are provided in Brandt *et al.*.[9] Additional ISBL technical and process details are available in.[18–23]

For the process selected in this paper, the high repurpose value is based on converting an acid bisulfite pulp mill into an ATJ biorefinery using the SPORL pretreatment process. The pulping process is similar to the SPORL pretreatment process and for an acid bisulfite mill, the digesters have metallurgy and scale that are compatible, eliminating the capital costs associated with the pretreatment manufacturing area. However, the SPORL process requires less time than traditional acid bisulfite pulping. Llanoa *et al.*[24] used an acid bisulfite pulping process for delignification prior to sugar production from hardwood and found that the pulping process was 9–10 h. Gu *et al.*[22] stated that not only are acid bisulfite pulp mills able to utilize the SPORL process chemistry for pulping, but the time to pulp drops to 25% of the original time of 4+ h to 1 h. Anderson and Gao[25] evaluated SPORL pretreatment for multiple time and temperature combinations with times from 1.25 to 4 h. A 1.25 h pretreatment cycle was used for the mass balance and yield for biorefinery scaling purposes. Based on pulp cook times of 4–10 h from the literature and the known impact of temperature on this process, we conservatively assume the pulping equipment can process twice as much material using SPORL. The ISBL and OSBL capital costs required for this expansion to meet increased throughput are included; however, it is assumed that land is available, which will need to be verified at each location. The assumption that throughput will double is included in the sensitivity analysis, looking at both more and less conservative assumptions. For simplicity, it was further assumed that the amount of sulfur needed is the same for all feedstocks, using the higher value required for softwood residuals. The loading for hardwoods was reported at half that of softwoods; however, the impact of this reduction translates to an MSP drop of less than 1%.[26,27]

Table 4. Detailed ratio factor components for service facilities for greenfield production as well as for low, medium, and high repurposing values.			
Service facilities	Greenfield	Low repurposing value	Medium and high repurposing values
Steam generation	0.094	0.094	0
Steam distribution	0.031	0.031	0
Water supply/cooling/pumping	0.057	0.057	0
Water treatment	0.041	0.041	0
Water distribution	0.025	0.025	0
Electric substation	0.041	0.041	0
Electric distribution	0.031	0.031	0
Gas supply/distribution	0.009	0.009	0
Air compression/distribution	0.031	0.031	0
Refrigeration with distribution	0.031	0.031	0
Process waste disposal	0.047	0.047	0
Sanitary waste disposal	0.013	0	0
Communications	0.006	0.006	0
Raw material storage	0.016	0	0
Finished-product storage	0.047	0.047	0.047
Fire protection system	0.016	0.016	0
Safety installations	0.013	0.013	0
Total	0.55	0.52	0.05

The high repurposing value scenario was analyzed twice using two different scale facilities. First, the amount of feedstock processed was kept constant, which results in an equivalent amount of fuel to the low and medium repurposing value scenarios, but the facility purchased is half the scale of the biorefinery so that the pretreatment manufacturing areas are fully utilized. Although a facility of this scale is less expensive to purchase, it does not benefit from the economies of scale for the manufacturing areas downstream from pretreatment. The second analysis assumes that the facility purchased is the same as the other locations, which allows twice the feedstock to be pretreated and thus double the fuel to be manufactured.

The medium repurposing value assumes that an operational pulp and paper facility is being converted, such as a kraft pulp mill. Kraft mills are common and the OSBL infrastructure will help reduce the capital costs needed compared to a greenfield facility. However, the only ISBL equipment that can be reused is the blow gas system, which is required in the pretreatment manufacturing area.[12] If the capacity of a kraft mill matches the pretreatment digester, it will align with the assumed SPORL pretreatment time of 75 min.[28] Fornell and Berntsson[29,30] found an equivalent feedstock throughput for kraft pulping and ethanol production. It was assumed that the scale of the kraft pulp mill is the same as the ATJ biorefinery, measured by feedstock throughput.

The final scenario, low repurposing value, represents the cost reductions that might be available at a shuttered facility. Lack of use can quickly lead to degradation of equipment and infrastructure, so it was assumed that buildings and only a small portion of the service facilities could be assumed to reduce capital costs. The high, medium, and low repurposing values are general terms that are meant to demonstrate differences in a range of representative, generalized site selections. Precise evaluation of each potential location is required to refine this analysis based on the existing facility's equipment and condition.

Many of the authors who have investigated repurposing facilities have assumed zero cost for the acquisition of a site/facility.[4,6,11,12,31] Although assuming the value of the facility is offset by the cost to shutter a facility and complete any required environmental remediation is traditional in the literature, we are not confident that assumption is realistic, especially for functioning facilities. Fornell *et al.*[8] and Jansson *et al.*[32] both used a cost for purchasing an existing facility and found that the price of this facility was a controlling variable in production of cost competitive ethanol. The value used in both Jansson *et al.*[32] and Fornell *et al.*[8] is for a European facility with a cost year of 2007, making this a difficult value to apply to either the general or specific sites analyzed in this paper, both assumed to be in the USA.

Although any value chosen is at best an educated guess, a non-zero value will likely be more accurate and is the fiscally conservative choice. To determine the market value of a repurposed mill, a list of sold pulp and paper facilities in the USA, with public sales prices was compiled. These prices were plotted versus the annual pulp production and a line was fit to the data. The assumed cost for an operational mill is the result of the linear trend at a given scale, less the land value which was fixed at 1.5% of the greenfield TCI (Appendix S1). The value of the shuttered facility was assumed to be half that of an operational location. We acknowledge that this estimation method is rough and that the values determined using this linear fit are not perfect. However, public data on the cost of operational or shuttered mills are not readily available. This variable is included in the sensitivity analysis to ensure the impact of the assumed values is understood. For operational facilities being compared to the greenfield mill costs, the repurposed mill is assumed to be US $53 million, less the land value and the shuttered facility is $27 million minus land cost for facilities that process 721 k t/year of feedstock. For analyses at alternate mill sizes, the facility purchase price is recalculated.

Location specific case studies

Three existing pulp and paper locations in the USA were identified with high repurposing values, located in Florida (FL), Washington state (WA), and Wisconsin (WI). For each location, TEAs were created using the existing facility size, local energy costs, delivered feedstock costs, regional labor costs, and softwood/hardwood proportions. Although many details of each facility are proprietary, public information was utilized to set realistic parameters at each location (Table 5).

The existing pulping equipment was assumed to replace the pretreatment manufacturing area in the biorefinery. The baseline assumption is that twice as much material can be pretreated as pulped, which is referred to as a pretreatment factor of two. This does require that a biorefinery purchase OSBL facilities beyond what exists at the purchased facility. The assumption that the throughput would be doubled is believed to be cautiously realistic; However, three additional levels were evaluated as part of the sensitivity analyses: pretreatment throughput that is one, three and four times the original pulping capacity.

The information about existing boilers and steam/hydro turbines for power generation was determined using information included in Georgia Tech Center for Paper Business and Industry Studies.[33] The total electricity demand was reduced by generated hydroelectric power, where applicable. However, for simplicity the steam generators are not utilized. Use of turbo generators may further alleviate

Table 5. Location specific case study variables.			
Variable	FL	WA	WI
Estimated facility Price (US $MM)	55.4	55.2	42.6
Pulp scale (t/yr)	155	154	119
Repurposed feedstock scale (k t/yr)	751	747	577
Electricity cost ($/kWh)	0.0659	0.0607	0.0608
Natural gas cost ($/MMBtu)	10.6	8.0	5.8
Feedstock cost – mixed species ($/t)	63.0	65.9	59.0
Feedstock cost – all SW ($/t)	69.0	68.4	104.0
Percent softwood	47%	80%	14%
Yield factor for mixed species	0.93	0.97	0.89
Wage factor	0.99	1.01	0.97
Hydro power savings (US $MM/yr)	0	0	2.1

costs depending on the local price of industrial electricity and the price of hog fuel required to create the additional steam.

The feedstock in the base case is assumed to be all softwood. However, it is possible that the repurposing locations will have feedstock that is mixture of hardwood and softwood. Zhou *et al.*[27] found 63.6% sugars in poplar chips when processed for ethanol production using SPORL pretreatment. Zhou *et al.*[26] studied the use of beetle-killed pine chips in a SPORL fuel conversion process and started with sugars at 63.7%. Finally, Chen *et al.*[21] looked at the use of Douglas-fir residue for conversion to AJF using SPORL pretreatment and started at 62% sugar in the residue. We conservatively assumed that the sugar yield from both hardwood and softwood feedstocks is equal, with an initial feedstock sugar level of 62%. It was further assumed that the C5 sugar xylan was not fermented and was thus not considered in the final fuel yield. This is critical when comparing feedstocks consisting of various amounts of hardwood, which typically has more xylan than softwoods. Zhou *et al.*[26] provides a xylan value for pine of 5.5% whereas Zhou *et al.*[27] provides a value of 12.7% for poplar. These values were assumed to be close approximations for the generalized hardwood and softwood species categories discussed in this paper. The increased xylan for hardwoods results in a 7% sugar loss entering fermentation for a feedstock that is 75% hardwood, which results in an increase in MSP of 3% for all repurposing scenarios. The xylan could be recovered, processed and sold as an additional co-product. Although completing this analysis is outside of the scope of this work, it should be noted

that xylan can be converted to xylitol, which is a high-value product bringing approximately US$3000/t.[34,35]

Results and discussion

The generalized case studies used compare the process area costs as well as FCI for the three repurposing values using fractions of the greenfield costs for a 721 kt/year feedstock, before screening facility (Table 6). The high repurposing value is presented two ways. First, the feedstock throughput and thus fuel output are held constant, which reduces the scale of the repurposed facility and is denoted as a high-equal fuel. For the second high repurposing scenario we maximized the throughput of the 721 kt/year pre-treatment area, doubling the input feedstock and output fuel. This scenario is termed high-max fuel.

Repurposing drops the FCI by 10%, 20%, and 40% for the low, medium, and high-equal fuel repurposing values, respectively. Translated into MSP, the drops are 6%, 14%, and 23%. The high-max fuel scenario has increased fuel output, which requires the FCI to surpass the greenfield cost by 20%; however, the SAF MSP drops 29% to just $1.0/L. This is clearly the most competitive MSP, but the capital cost required may sway investors to choose the high-equal fuel scenario. An MSP drop of about one-quarter for the high-equal fuel repurposing value to $1.08/L and high-max fuel $1.00/l provides a strong case for careful repurposing location investigation and the benefits of using both OSBL and ISBL equipment in a repurposed biorefinery.

Operating costs do not vary widely between the repurposing scenarios with the same fuel output; however, small differences exist based on operating costs that are tied to FCI such as taxes and insurance. Maintenance is also tied to FCI; however, maintenance costs were calculated using the greenfield FCI as it is not realistic to assume lower maintenance costs for an identical process at a partially repurposed facility. At most, operating costs vary by less than 5%.

Sensitivity analysis

A sensitivity analysis was completed to identify the most influential variables for the generalized scenario. Inclusion or exclusion from this list can help identify which location candidates should be further reviewed. The initial list of variables analyzed, which vary with location, are: cost to purchase the facility to repurpose, facility scale, electricity cost, natural gas cost, propane cost for locations without natural gas, feedstock cost, softwood/hardwood proportion, regional wages, existing hydroelectric power, existing hammermill and screen, and land value.

The value of each item was varied based on a survey of existing acid bisulfite pulp facilities, which provided realistic lower and upper bound values. The locations of the three acid bisulfite facilities, discussed in greater depth in the specific case studies section, are FL, WA, and WI. Although MSP is influenced by all the surveyed variables, this paper does not discuss variables that changed the MSP by less than 1% within realistic variable ranges. The low impact variables are regional wages, existing hammermill and screen, and land value. The base case, minimum, and maximum values of the variables included in the sensitivity analysis are listed in Table 7, all of which impact MSP by at least 1%.

Table 6. Greenfield capital costs and the corresponding fraction of greenfield capital costs for three repurposing value scenarios. All costs are MM US$ unless otherwise stated and facility purchase includes the cost of land.

Process area	Greenfield cost	Low	Medium	High – Equal fuel	High – Max fuel
Feedstock handling	$23.1	1	0.03	0.03	1.02
Pretreatment	$69.0	1	0.9	0	0
Enzyme production	$14.2	1	1	1	1.9
Enzymatic hydrolysis	$9.9	1	1	1	2.0
Fermentation & A2J	$19.4	1	1	1	2.0
LS	$10.9	1	1	1	1.5
AC	$43.4	1	1	1	1.5
Total equipment cost	$190	1	0.8	0.5	1.01
Catalyst costs	$3.0	1	1	1	2
Facility purchase	NA	$13.1	$39.6	$13.6	$39.6
FCI	$850	0.9	0.8	0.6	1.2
SAF (MM L/yr)	98.8	1	1	1	2
SAF MSP ($/L)	1.40	1.31	1.20	1.08	1.00

At a minimum, the value of each of the variables listed in Table 7 will need to be identified for any location being considered for repurposing. The two most influential variables are the cost to purchase the repurposed site and the facility scale. All other values move the MSP less than 10% within the range evaluated. A complete accounting of the variables and their changes are included in Appendix S2.

The cost to purchase a site is influential and difficult to predict (Fig. 2). Although assuming a zero cost to acquire a site is common, it is likely not realistic and the impact on financial viability is real. Conversely, assuming a very high price is also unlikely, as the most expensive mills are more likely to be newer, more technologically advanced, and better aligned with today's markets and thus less likely to consider sale or repurposing. For both the low and medium

repurposing value scenarios, there is a point at which greenfield construction becomes more economical. This is technically true for the high repurposing values too, but the purchase cost would be unrealistically expensive. The point at which greenfield is a less expensive choice can be calculated and used to make decisions about siting and in negotiations for potential locations to be purchased. Regardless of the price paid for a site, having some portion of the ISBL equipment and mostly functioning OSBL infrastructure results in lower MSPs compared to greenfield construction (Fig. 2).

The single most influential variable quantified is facility scale. As with greenfield builds, repurposing MSPs are influenced by the cost implications of economies of scale. Smaller scale facilities result in higher MSPs and, in general, large facilities have lower MSP values. However, at

Table 7. Minimum, base case and maximum values for each location-specific variable used in the sensitivity analysis.

| Variable	Min	Base	Max	References (min and max)
Medium and high repurposing value site cost (US $MM)	0	35	236	4, 6, 8, 11–13, 31
Low repurposing value site cost (US $MM)	0	17.5	118	
Facility scale (k BDt/yr feedstock)	300	721	1100	WI and NY locations
Proportion softwood	0.25	1		WI location
Electricity cost ($/kW h)	0.057	0.069	0.088	WA and NY single year min and max
Natural gas cost ($/MMBtu)	3.4	4.2	12.5	National average EIA 2016, 2017 FL value
Propane cost ($/MMBtu)			10.3	2013–2017 EIA national average
Feedstock cost ($/BDt)	60	65	75	Min, max for acid bisulfite locations
Hydro power savings (US $MM)		0	2.1	Max of 3 locations (WA)
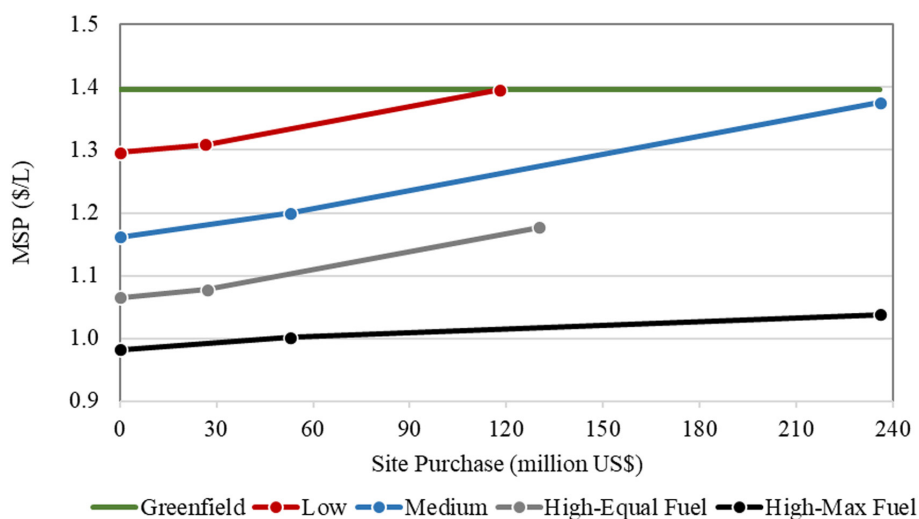
Figure 2. MSP for greenfield, low, medium, high-equal fuel and high-max fuel repurposing value scenarios for three potential site purchase costs. Greenfield is included for comparison only as no costs are included for purchasing an existing location.

some point larger facilities face increased costs, including feedstock that must be transported further.[36] The greenfield, low, medium, and high-equal fuel generalized scenarios were evaluated at three scales: small (300 kt/year), baseline (721 kt/year) and large (1100 kt/year). Of the scenarios analyzed, the lowest MSP scenario was for the high-equal fuel repurpose value at the baseline scale which results in an MSP of $1.08/L (Fig. 3). This scenario has a TCI of $560 MM, which is 37% below the capital needed for a greenfield facility of the same scale.

For the large-scale facilities, the medium and low repurpose values as well as the greenfield scenarios have TCI values that are more than a billion dollars, an increase of 12%, 27% and 40%, respectively when compared to the baseline scale greenfield TCI of $900 MM. The large-scale, high-equal fuel scenario and the baseline scale, greenfield scenario have virtually identical TCI values; however, the MSP is $0.29/L or 21% less for the large, high-equal fuel scenario. Regardless of repurposing value for the large-scale facilities, the TCI values are high and could limit facility construction regardless of MSP based on the difficulty of obtaining the requisite level of funding. The elevated TCI for the large-scale in this analysis reduces MSP for the greenfield, low, and medium repurposing scenarios. However, the elevated feedstock price resulting from increased transport distances generates a 3% increase for the high-equal fuel, large-scale repurposing scenario (Fig. 3). If feedstock can be procured without a cost increase for this scenario, a minor, 1% MSP drop could be realized. At large scales the cost of delivered feedstock increases assuming that the feedstock can be procured, something that will need verification. The capital cost required at large scales will have to be balanced with diminishing MSP reductions when specific locations, feedstocks, and scales are evaluated. Choosing the small facility scale has a
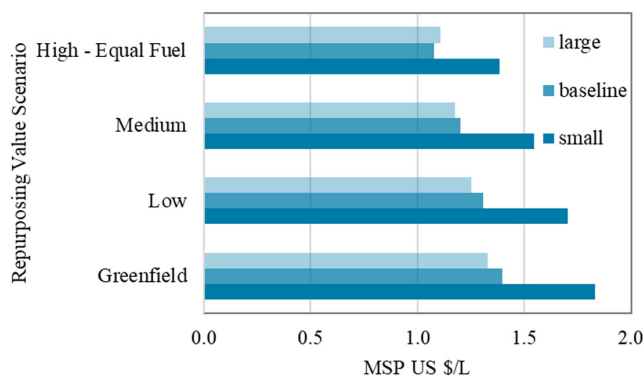
larger impact on MSP, increasing it nominally 30% for all repurposing values (Fig. 3).

Specific case studies

The generalized analysis illustrates that the inclusion of ISBL equipment in the selected repurposing sites decreases MSP more than locations that only contribute OSBL equipment and infrastructure. For the process used for case studies in this paper, the most ISBL equipment can be reused from acid bisulfite pulp and paper mills. These facilities were therefore chosen to further demonstrate the repurposing methodology and possible MSP reductions. Three potential acid bisulfite mills were identified across the continental USA located in FL, WA, and WI. The spread of these mills adds a national geospatial component to the repurposing decisions.

The location in WI was shuttered and reportedly sold for $2.2 million – much lower than estimated using the linear relationship applied throughout this paper.[37] The mill is likely in operational shape as it was reported that the town of Park Falls is loaning the current owners $1MM to reopen.[38] However, equipment from shuttered mills can degrade unless the mill is converted in a timely matter. As a result of the uncertainty surrounding the equipment at this location it was analyzed at both the high and low repurposing values.

A set of inputs was analyzed for the case study locations, using the scale and geospatial costs at each location. The most influential is the pretreatment factor, or the ratio of the amount of forest residuals that can be pretreated to the amount of chips that can be pulped. To a lesser extent, ±50% for facility purchase price, land value, and feedstock species mix influence the MSP. The species mix used to calculate the MSP values in Fig. 4 were chosen as the low-cost option. For WA and FL, the addition of hardwood lowered the yield to the point that the reduced feedstock cost did not fully offset the impact on MSP. Thus, for WA and FL the MSP values are for 100% softwood. However, in WI the cost of pure softwood feedstock is $104/t, a value the yield drop could not compensate for and thus the WI feedstock is run of the woods mix of softwood and hardwood forest residues.

The baseline assumption for the pretreatment factor is 2. Dropping this value to 1 increases the MSP by over 20% for any of the case study scenarios, with the value approaching 30% for WI with a high repurposing value. The larger impact on the WI mill is a result of the smaller initial scale. The MSP does drop with higher pretreatment factors but the extent of the drop diminishes as a result of high TCI, increased feedstock transportation costs and diminishing value from repurposing as additional OSBL infrastructure has to be purchased to support the increasing mill scale (Fig. 4).

Figure 3. Impact of facility scale on MSP values for greenfield, low, medium, and high-equal fuel repurposing values.
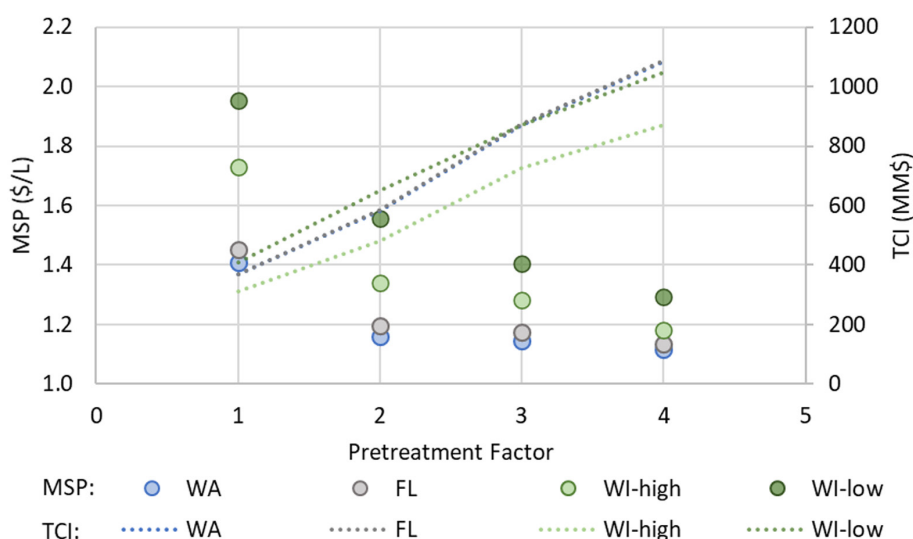
Figure 4. MSP and TCI versus pretreatment factor for FL, WA, WI-high and WI-low case studies.

The TCIs for the WA and FL locations are nearly identical as a result of their similar sizes, which translates to the TCI lines for these locations stacking in Fig. 4. The differences seen in the MSP values between these two locations are a result of geospatially controlled costs including feedstock, electricity, natural gas, and labor. The MSP of the WI location, regardless of repurposing value, is much higher than the other locations, principally because of the smaller scale.

The repurposing locations selected lower the MSP compared to greenfield builds of similar sizes, but the price of SAF is still above the 2013–2017 average of $0.54/L for wholesale kerosene-type jet fuel.[39] If the lowest MSP location, WA, is chosen, the SAF is estimated to cost $1.16/L. Although repurposing a facility and purposeful site selection helps to reduce the initial capital burden, it is not enough to make SAF financially viable. The addition of co-products not only diversifies a business, reducing risk; these products can also generate additional revenue, which, when combined with lower capital costs, reduces MSP.[9] Bioenergy production at an existing pulp and paper mill will likely need government assistance in the form of both environmental (quotas, credits) and economic (tax relief, loan guarantees) polices to create financially competitive energy.[40] The quotas that are set for bioenergy are market drivers on a local and an international scale.[41] Brandt *et al.*[42] looked at the impact of existing federal and state programs to estimate the combined impact of blender's tax credits that renewable fuel standard and California's low carbon fuel standard. They reported an MSP reduction of approximately $1/L for the existing policies, resulting in an effective price of $0.2/L a value that is better than cost parity.[42] This MSP may encourage this fuel pathway, even with the expected increase in costs for first of a kind, pioneer plants.

Limitations of the analysis in this work include the assumption that all ISBL equipment has a remaining life that matches the plant life of 20 years. No costs were included to cover the integration of existing equipment and infrastructure into new processes. These items should be addressed when an analysis increases accuracy from a scoping level.

Conclusions

Repurposing existing facilities is an effective method to reduce both capital costs and selling prices if the locations are selected thoughtfully. For SAF produced at repurposed pulp and paper facilities, the TCI drop by 10–37% resulting in an MSP reduction of 6–23% of for generalized scenarios. The magnitude of the reduction of these financial obstacles is related to the asset value available at the repurposed site for the chosen technology and process. The best results are attained when the site to repurpose includes both OSBL and ISBL assets. The reality of price parity of SAF with kerosene-type jet fuel will likely require the combination of repurposing, high-value co-products and national and local government incentives. However, specific financial outcomes are dependent on the chosen process and repurposing site.

Acknowledgements

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