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A Techno-Economic Analysis Comparing a Hammermill and a Rotary Shear System to Process Woody Biomass for Biofuel Production

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Abstract: Woody biomass feedstock processing, including sorting, drying, and size reduction of biomass to provide standardized reactor-ready biomass to the biorefinery, is crucial to biofuel conversion. This study compares two comminution technology systems applied to woody biomass processing at a depot before being utilized for biofuel production at a biorefinery. The conventional comminution technology, known as the hammermill system, is compared with a rotary shear system developed by Forest Concepts™. Potential economic savings of using the new technology are evaluated by applying a deterministic and a stochastic partial capital budgeting model based on results from an experiment that processed chipped hybrid poplar chips and forest residues with both systems. The stochastic partial capital model estimates that savings will vary between approximately USD 28 and USD 42 per ton of reactor-ready processed biomass, with mean and median values around USD 34 per ton. It is 90% likely that savings will be between USD 30 and USD 39 per ton of reactor-ready processed biomass. The estimated savings are mainly due to differences in input (feedstock) to output (reactor-ready biomass) yields between technologies, affecting feedstock and drying costs.

Keywords: techno-economic analysis; partial capital budgeting; stochastic model; hammermill and rotary shear; agricultural finance; biofuel

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1. Introduction

The US Department of Energy (DOE) promotes the production of advanced transportation fuels from lignocellulosic renewable biomass transformed into commercially viable biofuels [1]. Still, technical and economic barriers in lignocellulosic biomass feedstock logistic systems exist. Current efforts to overcome feedstock supply and logistic challenges focus on (1) reducing the delivered cost of sustainably produced biomass, (2) preserving and improving the quality of harvested or collected biomass feedstock to meet the requirements of biorefineries, and (3) expanding the quantity of feedstock [1,2]. Therefore, identifying, demonstrating, or verifying economical practices from the establishment through the processing of raw feedstock into reactor-ready biomass is relevant for developing the bioenergy industry [1].

This study focuses on the processing of raw feedstock into reactor-ready biomass occurring in a conceptualized network of depots to supply the demand of one biorefinery, using chipped hybrid poplar feedstock as a case study. Critical activities at a depot to convert woody feedstock into reactor-ready biomass include drying high-moisture content feedstock and comminuting it (i.e., size-reducing and screening) into a target particle size, meeting the conversion needs of a biorefinery. Drying and comminution at a depot, together referred to in this study as depot processing activities, are also called preprocessing activities in the literature because they can alternatively be performed at the biorefinery before the conversion into biofuel process. Drying at a depot can reduce transportation costs if the depot system is efficiently located close to raw biomass supply areas [3]. Comminution increases the biomass bulk density through a smaller particle size, reducing the cost of handling, storage, and transportation [4,5]. Regardless of where the comminution is carried out—at a depot or a biorefinery—this activity contributes directly to the efficiency of the biomass-to-biofuel conversion process. Uniformly comminuted biomass in size, shape, and length-to-thickness ratio improves biomass flowability and yields in bioconversion reactors [6,7].

The conventional system to process feedstock into reactor-ready biomass uses a hammermill technology [4,8]. This conventional technology is widely used due to its versatility to handle different types of feedstocks and its ease of operation and maintenance [4]. An alternative processing system, commercially known as the Crumbler® rotary shear system (rotary shear technology hereafter), has been recently introduced to improve processing efficiency relative to the hammermill technology. Specifically, compared to the hammermill technology, this new technology is claimed to consume less energy, waste lower amounts of feedstock during processing, and produce more uniform reactor-ready biomass that improves conversion output yield or operational efficiency [4,5]. However, this new equipment is more expensive. Appendix A describes the technicalities of these two technologies.

The objective of this study is to compare these processing technologies in terms of processing efficiencies and ultimately operating cost differences (including investment needed). To achieve the research goal, an experiment was conducted by processing samples of woody feedstocks at the facilities of Forest Concepts™, a US manufacturer of woody and herbaceous feedstocks. This experiment provided processing yields and energy consumption parameters per technology for analysis. Data from this experiment and other parameters from biofuel studies were applied to model a network of depots meeting the needs of one biorefinery. Using deterministic and stochastic partial capital budgeting [9], this techno-economic analysis (TEA) estimates potential savings of replacing the hammermill with the rotary shear technology in the network of depots processing woody biomass over 20 years. Previous studies, in which Forest Concepts™ teamed with Idaho National Laboratory and others, have compared these two technologies and found that the new technology is more efficient and economical than the conventional technology [8,10]. This TEA enhances those studies in two dimensions: (1) it provides additional insights because it is not limited to operating and investment cost comparisons for the first year of operations as the previous studies are (i.e., we forecast the complete enterprise business horizon) and (2) it incorporates uncertainties into the analysis by building and analyzing a stochastic model.

2. Materials and Methods

2.1. Processing Technologies

The hammermill (HM) technology includes the following activities:

(1_{HM}) Drying: The chips, received with full field moisture content (MC), typically from 40–50% wt% moisture [4], are dried to a range of 5 to 10% wt% moisture. This system uses a rotary high-temperature (300 °C) drum drier, which is consistent with the designs in the US Department of Energy and other studies [11,12].

(2_{HM}) Size reduction: Using a hammermill, the dried chips are reduced to a target geometric mean particle size, specified at 4 mm in this study.

(3_{HM}) Sorting: The feedstock is screened to remove particles smaller than 2.44 mm or 0.096 inches and separate oversized particles larger than 10.0 mm. Chips smaller than 2.44 mm are called fines and are considered waste materials in this study. Oversized chips are conveyed back to the infeed of the hammermill for further size reduction.

The alternative technology, the rotary shear (RS), includes the following activities:

(1_{RS}) Size reduction: Using a two-module Crumbler® P24 rotary shear system, the green (i.e., high-moisture content) chips are reduced to the specified 4 mm target geometric mean particle size. This is the same size target specified for the HM.

(2_{RS}) Sorting: The same process as with the hammermill technology.

(3_{RS}) Drying: The chips are dried from the full field MC to a range of 5 to 10% wt% moisture. Unlike the HM system, the RS system uses a medium-temperature (120 °C) downdraft belt drier.

Following the convention in research on biorefineries, which calls the biorefinery feedstock preparation section 'area 100′ [13,14], we refer to the entire depot configuration as area 100 and further provide subdivision areas within the depot. These subdivisions are given on the left side of Figures 1 and 2, which provide flow diagrams for the hammermill and the rotary shear technology, respectively. These diagrams show that the HM technology, which starts with the drying activity (1_{HM}), dries all the chips received, including those that will be considered fines later in the process. In contrast, the RS technology dries (3_{RS}) only the 'accepted' fraction of the chips, the feedstock that meets the 2.44–10.00 mm particle size range in the sorting activity (2_{RS}). This sequence in the processing flow under the rotary shear system saves energy, which represents the most critical processing cost component.

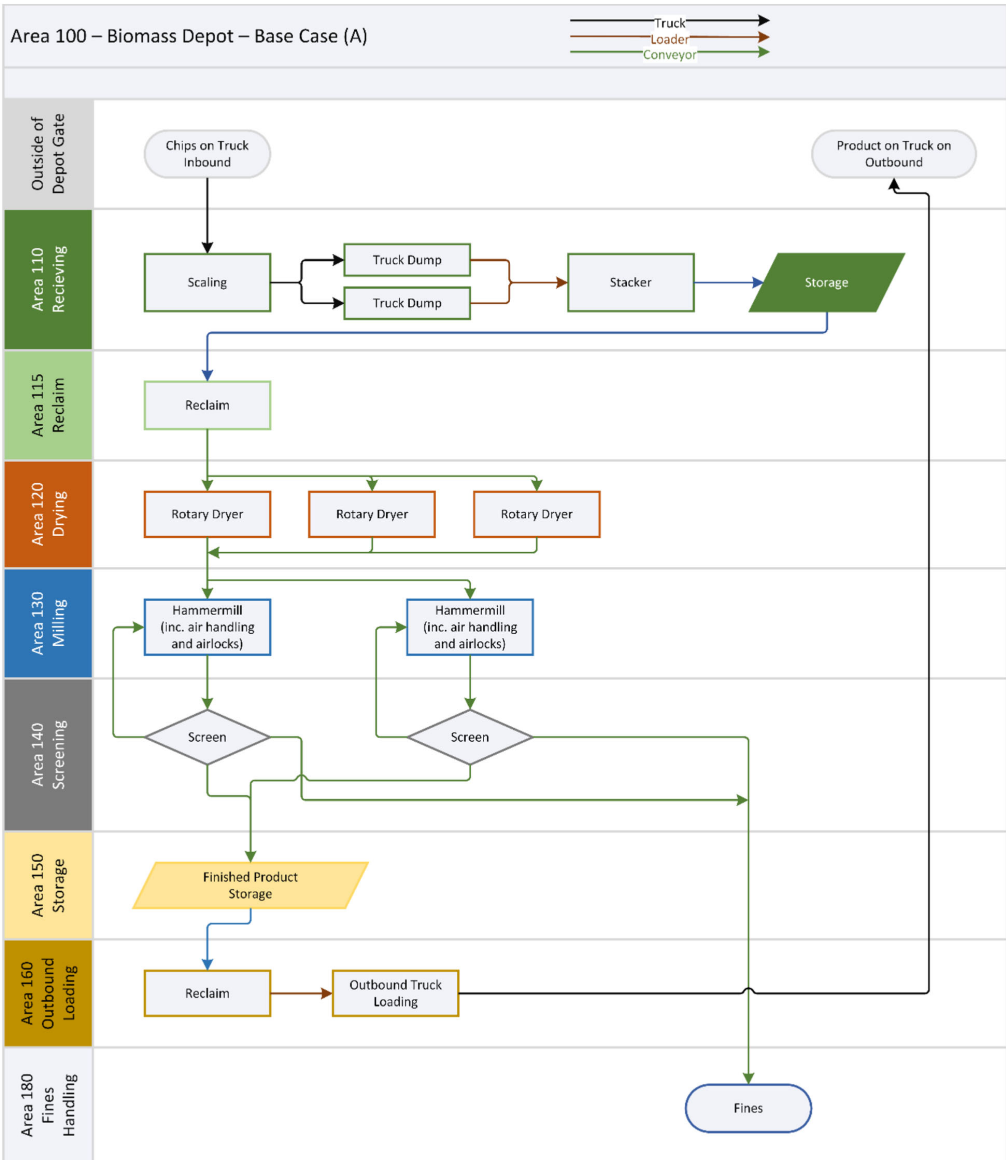


Figure 1. Hammermill technology flow diagram.

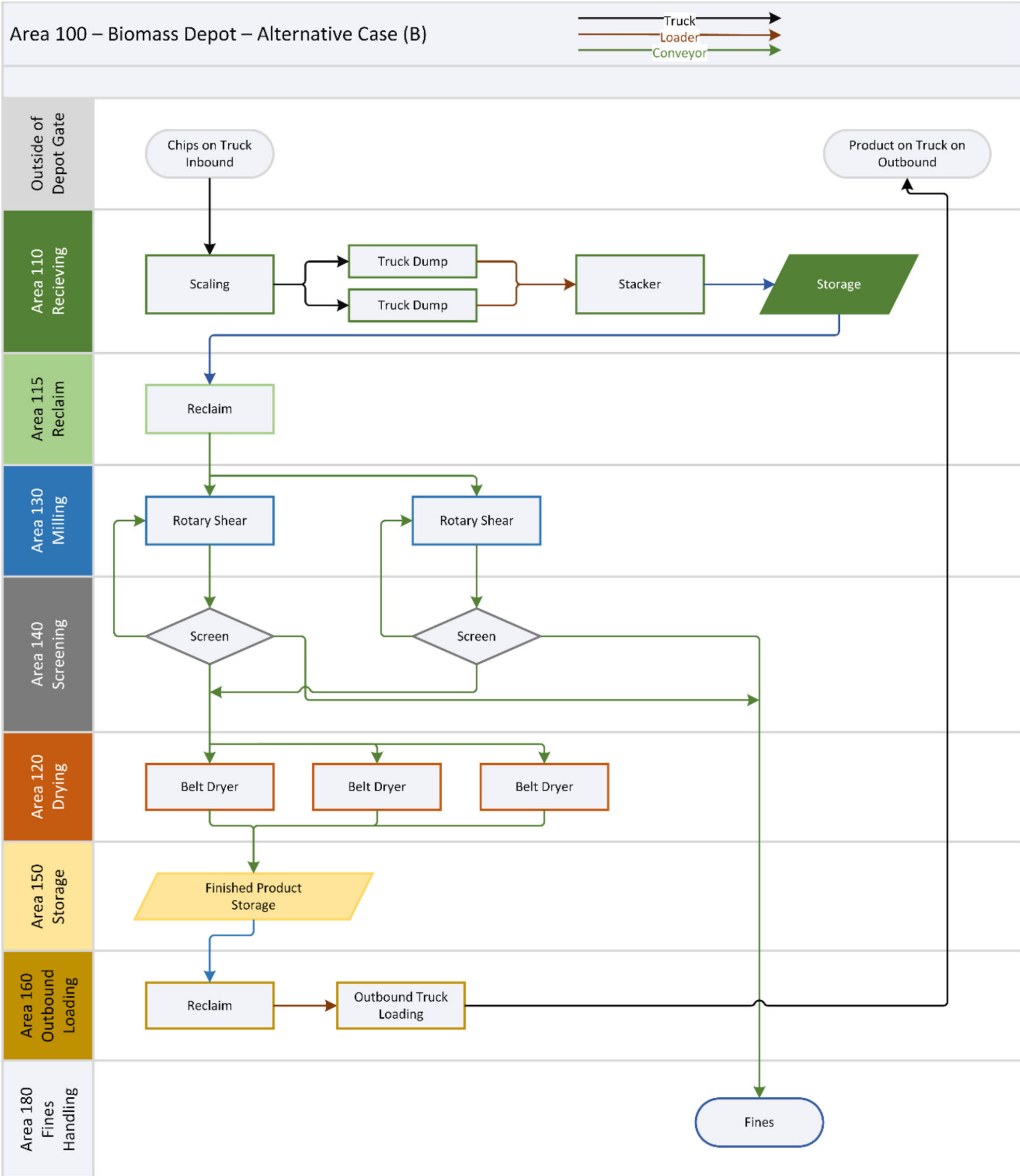


Figure 2. Rotary shear technology flow diagram.

The flow diagrams also show that activities related to woody chip receiving, scaling, storage, and reclaiming are identical for both technologies. Reclaimed chips are conveyed to rotary driers (HM pathway) or rotary shear (RS pathway) comminution islands. At the end of processing, dry reactor-ready feedstock is assumed to be piled in covered sheds for storage before shipping it to a biorefinery or a larger supply terminal [15].

2.2. Depot System Configuration within the Supply Chain

The conceptualized depot is a facility that processes one or several biomass types to supply uniform feedstock 'commodities' for biofuel conversion. The feedstock processed in this case is dry reactor-ready biomass assumed to be delivered to a biorefinery. In other cases, processed biomass at depots can be transported to a network of much larger supply terminals, where the material aggregated from several depots may be blended and further processed to meet the specification required by each biorefinery conversion process [15].

This study assumes that a series of eight depots will supply the demand of a biorefinery, which typically needs 800,000 short tons year^{-1} [1,3,8]. The nameplate capacity of one depot is 100,000 bone dry tons year^{-1} of reactor-ready biomass output operating at 16 h per day and 328 days a year, implying a 95% on-stream factor. The depot output rate is 20 dry tons per hour, a typical depot output rate for analyzing processes for the USDA and DOE. Input rates or raw woody feedstocks are scaled up from the reactor-ready biomass stream to account for fines losses during processing (details in Results, Section 3.1). This depot network configuration assumes that depots are modular and scaled stepwise without economies of scale, given limitations by commercially available equipment capacities [3].

2.3. The Processing at the Depot Experiment

Forest Concepts™ is a US-based firm manufacturing woody and herbaceous feedstocks to support research, pilot, and demonstration-scale production of biofuels and bioproducts by universities, governmental labs, and the industry. Forest Concepts™ received and processed two types of feedstocks for this research, hybrid poplar (PO) and forest residues (FR). Specifically, Forest Concepts™ processed 20 supersacks (samples) of PO and FR. The target was to process and analyze the processing parameters of the 20 samples. However, three samples were compromised with regard to energy consumption during the experiment, with results considered incomparable across samples and technologies, and removed from the economic analysis.

As discussed in Section 2.1, primary processing activities at the Forest Concepts™ facility included drying and size reduction and sorting (these two activities are referred to as comminution hereafter) of raw, high-moisture-content feedstock. These are typical activities of a standard depot [3], which improves feedstock stability, storability, flowability, and bulk density. Forest Concepts™ generated processing yields and energy consumption parameters per technology and biomass type for analysis.

2.4. Economic Framework: Partial Capital Budgeting

Economic savings due to the technology: This TEA applies partial capital budgeting analysis, an economic framework designed to compare potential savings when using a new technology (referred to in economics as a challenger), the RS, instead of a conventional technology (i.e., a defender), the HM [9,16,17]. Partial capital budgeting is more convenient than complete capital budgeting because it requires budgeting only the items that would differ between technologies. In other words, the partial analysis requires identifying and budgeting only cash flow items (i.e., uniquely identified investment, revenue, or cost item amounts) that differ between the HM and RS technology. Cash flow items that remain the same regardless of the technology are irrelevant to the analysis.

For instance, in this TEA, total revenues will not change across technologies because both technologies are assumed to produce and sell the same amount (100,000 tons year^{-1} per depot) of reactor-ready biomass. Similarly, some costs (e.g., administrative costs) will not depend on the used technology. However, the energy cost of comminution and drying the woody feedstock will likely vary by technology due to differences in equipment and processing sequence (Figures 1 and 2).

Therefore, this partial economic-based TEA identified and forecasted cash flow items that differ between the HM and RS technologies. For a complete budget, free cash flow (FCF) is defined as [16]

$$FCF = EBIT \times (1 - tax) + depreciation - FCI - WCI + TV \quad (1)$$

where EBIT stands for earnings before interest and taxes (i.e., operating income), tax represents the firm's effective tax rate, FCI is fixed capital investment, WCI is working capital investment, and TV is a terminal or salvage value at the end of the project's life (estimated in this TEA as the book value of depreciable assets). For this application, FCF for a complete budget would be

$$\begin{aligned} FCF = {} & [(revenue - costs\ other\ than\ depreciation - depreciation) \times (1 - tax)] \\ & + depreciation - FCI - WCI + TV \end{aligned} \quad (2)$$

As discussed, given that revenues and certain costs and investments will not differ across technologies, partial free cash flow (PFCF) per technology i (i = 1, 2; HM, RS) is projected for 22 years, with t = 0, 1, . . ., T, for T = 22, according to:

$$PFCF_{i,t} = \left[\left(feedstock_{i,t} - comminution_{i,t} - drying_{i,t} - depreciation_{i,t}\right) \times (1 - tax)\right] \\ + depreciation_{i,t} - FCI_{i,t} - WCI_{i,t} + TV_T \quad (3)$$

where feedstock represents differential (across HM and RS technologies) feedstock costs, and comminution, drying, and depreciation are differential processing costs. The business horizon is 20 productive years plus 2 years to build the depot facilities, hence T = 22. Equation (3) represents negative values because the partial budget mainly has cost and investments (i.e., cash outflows). Equation (3) is multiplied by negative 1 to facilitate the interpretation of results.

Economic savings due to technology ($NPV_{RS\text{-}HM}$) are defined as the net present value (NPV) of differential PFCFs. Differential PFCFs are the partial free cash flows of the challenger minus the partial free cash flows of the defender technology over time, $PFCF_{RS\text{-}HM}$,

$$NPV_{RS-HM} = \sum_{0}^{22} \frac{PFCF_{RS-HM}}{(1 + WACC)^t} \quad (4)$$

with WACC representing the weighted average cost of capital or opportunity cost of the multiperiod depot investment. A positive $NPV_{RS\text{-}HM}$ would represent expected savings using the RS instead of the HM and vice versa. This total economic saving value is also expressed in terms of anticipated annual savings per depot by calculating the $NPV_{RS\text{-}HM}$'s equivalent value of an ordinary annuity [16,18], which represents equal savings over the 20 *productive* years, using:

$$Annual\ Savings_{RS-HM} = NPV_{RS-HM} \times \left(\frac{1 - \frac{1}{(1+WACC)^{20}}}{WACC}\right)^{-1} \quad (5)$$

Because this TEA conceptualizes a network of eight depots meeting the demand of one biorefinery, we express annual savings for the network by multiplying Equation (5) by eight. We also express annual savings per reactor-ready processed ton by dividing Equation (5) by the 100,000-ton depot production capacity.

The WACC parameter in this TEA is 8% [19]. A 17% tax rate (Equation (3)) is assumed according to the Aviation Sustainability Center's guidelines for investment evaluation [20]. The following sections discuss assumptions regarding operating parameters.

2.5. Parameters for the Estimations

2.5.1. Operating Cash Flows

The price of feedstock to process typically represents the highest operating cost, and in this application the feedstock cost, calculated as feedstock price times quantity, varies across technologies because the input (raw feedstock) to output (reactor-ready biomass) yields differ between the HM and RS. Processing energy costs, including comminution—size reduction and sorting—and drying activities, represent the second highest operating cost and vary between technologies, given the technologies' capabilities and flow processing sequence (shown in Figures 1 and 2). Feedstock and energy costs (comminution and drying) were estimated for the first productive year based on output-to-input ratios (yields), consumption parameters obtained from the experiment conducted by Forest Concepts™, and energy and feedstock market prices.

Feedstock operating cost: While the Forest Concepts™ experiment was conducted with hybrid poplar and forest residue feedstocks, the results showed no difference between the two feedstocks in terms of processing cost and quality. Therefore, this TEA assumes the use of one feedstock type only, hybrid poplar. The feedstock price is exogenous to the analysis and estimated at USD 68.75 per dry equivalent ton at the depot gate [21]. This price included the cost of establishing, maintaining, harvesting, and transporting to a depot 100,000 dry tons year^{-1} (the annual processing capacity of one depot in this TEA) of chipped hybrid poplar.

According to the Forest Concepts™ experiment for this study, approximately 33.3 dry tons of chipped feedstock was required to process 20.0 dry tons^{-1} of reactor-ready biomass output (as discussed in Section 2.2, this is the depot's output capacity per hour) using the HM. In contrast, with the RS, 25.2 dry tons of raw chipped feedstock was required to process the same output amount. This implies an output-to-input ratio (feedstock yield hereafter) of 0.792 for the RS and a 0.601 feedstock yield for the HM technology. Equivalently, to obtain 100,000 tons year^{-1} of reactor-ready wood biomass, one depot needs approximately 166,500 dry tons year^{-1} of feedstock if it uses the HM technology. In contrast, the same depot would need 126,200 dry tons year^{-1} if the RS is employed. (Details of output-to-input yields are discussed in the Results section.) Therefore, the feedstock cost for the first productive year is calculated by multiplying the USD 68.75 dry ton^{-1} feedstock price by the corresponding feedstock quantity per technology.

Energy cost: Forest Concepts™ measured the natural gas and electricity consumption to process the chipped feedstock samples. Table 1 provides the energy consumption of drying and comminution (i.e., design comminution energy, DCE) activities per technology from this experiment. As shown in Table 1, on average, electrical power consumption on a per oven dry ton equivalent of accepted material (material leaving the depot on a dry matter basis) was 20% greater for the HM pathway than the RS pathway, 22.1 and 18.7 kwh odt^{-1}, respectively. Similarly, drying energy per unit accepted was 57% higher on average for the HM pathway than the RS pathway, 8.7 and 5.6 MMbtu odt^{-1}, respectively. In addition to the economic benefit of reduced natural gas consumption, implementors of this technology will be contributing to the national goals of decarbonizing industrial processes.

Table 1. Electricity, natural gas consumption per technology (HM and RS), and energy prices for processing one dry ton of reactor-ready woody biomass.

	Hammermill		Rotary Shear		Gas	Electricity
	Drying Energy	DCE	Drying Energy	DCE	Price	Price
	MMbtu odt^{-1}	kwh odt^{-1}	MMbtu odt^{-1}	kwh odt^{-1}	USD Mmbtu^{-1}	USD kwh^{-1}
Median	9.1334	22.8002	5.2099	18.0639	4.7799	0.0801
Average	8.7514	22.1377	5.6041	18.6571	5.8004	0.0806
Std. dev.	2.2225	3.5233	1.6219	3.7691	3.2127	0.0059
Minimum	4.6712	16.1449	4.0814	13.7297	1.7628	0.0681
Maximum	12.1575	27.8926	9.3362	24.3323	18.7827	0.0979

Notes: Drying energy expresses total natural gas consumption, in millions of British thermal units (MMbtu), to dry raw feedstock with 50 wt% moisture to 4 mm reactor-ready wood biomass with 10 wt%. DCE represents design comminution energy, the total kilowatt-hours (kwh) of electricity needed to reduce raw feedstock from 14 mm into reactor-ready feedstock with a target geometric mean particle size of 4 mm. The statistics in Table 1 are from 17 sample replicates of woody chips. Table 1 shows cpi-adjusted natural gas and electricity price statistics from monthly prices spanning January 2001 to December 2021, available on the US Energy Information Administration's website [22].

For the baseline model—defined as the deterministic model—this TEA used the median values multiplied by the median energy prices (the last two columns in Table 1) to obtain processing energy costs for the first productive year. Natural gas and electricity price statistics were calculated from a series of monthly prices from January 2001 to December 2021, available on the US Energy Information Administration's website [22]. The natural gas and electricity prices were adjusted for inflation with the consumer price index [23].

Depreciation: Depreciation expenses vary between technologies because the equipment cost differs between the HM and RS technologies. Depreciation expenses are estimated using the straight-line depreciation method, assuming 20 years of useful life [24].

Other operating costs: Other operating costs—maintenance, labor, administrative expenses, etc.—are assumed not to vary across technologies. Therefore, these are irrelevant costs for the economic comparison of the HM and RS technologies. In other words, the differential cash flow across technologies when comparing the HM with the RS is zero.

Operations in productive years 1 through 20: Operating costs other than depreciation, for productive years 1 to 20, were assumed to grow according to the expected inflation rates projected by the USDA [25]. Depreciation expenses are not updated by inflation due to accounting rules that keep equipment values at historical book values.

2.5.2. Capital Investment

Total capital investment includes fixed capital and working capital investment (FCI and WCI in Equations (1) through (3)), with FCI including direct and indirect investments. (FCI is also referred to as capital expenditures or CAPEX in the finance jargon.) Direct FCI typically includes purchased equipment cost, instrumentation and controls, piping, insulation, electrical systems, and land. Indirect FCI generally includes engineering and supervision, legal, construction, and contractor fee expenditures. WCI represents an investment in inventories, money tied to accounts receivable to finance customers with trade credit, and, in general, short-term assets needed to operate the enterprise.

Fixed capital investment: Following Peters et al. [26], FCI is calculated in two stages: (1) preparing a budget for purchased equipment and (2) using the equipment budget as a basis to calculate the rest of the direct and indirect FCI components.

For the first stage, based on the partial capital budgeting method, equipment differing between the RS and HM systems was identified and budgeted according to previous studies and vendors. Panel A of Table 2 shows equipment that is uniquely tied to the use of a particular technology. It is estimated that purchased equipment for an RS system costs approximately USD 1.741 million more than for an HM depot ($5.244 - 3.503 = 1.741$). The rotary shear machine is more expensive than the hammermill, whereas the belt dryer needed for an RS depot is slightly less costly than the rotary drum dryer for an HM depot. The rest of the necessary equipment for a depot to operate (e.g., equipment in areas 110 and 115, conveyors in 120, electromagnets and dust collectors in 130, and equipment in areas 150 and 160) are the same for both technologies and, therefore, irrelevant to this comparative analysis.

Table 2. Partial fixed capital investment related to the HM and RS technologies.

Equipment (Quantity)	HM	RS
Panel A: Equipment		
Area 120: drying area:		
Rotary drum dryer (2)	1,913,362	
Belt dryer (3)		1,800,000
Areas 130 and 140: milling and screening area:		
10 tph comminution island hammermill (2)	1,590,000	
10 tph comminution island Crumbler (2)		3,444,000
Equipment cost	3,503,362	5,244,000
Panel B: Other direct FCI and indirect FCI		
Direct FCI other than equipment and land	4,335,410	6,489,450
Indirect FCI	2,627,522	3,933,000
Other FCI cost	6,962,932	10,422,450
Total FCI cost	10,466,294	15,666,450

Notes: Values in 2020 USD. Area numbers refer to the activity areas depicted in Figures 1 and 2. Budgets from vendors. Tph refers to tons per hour.

Panel B of Table 2 shows direct FCI other than equipment and land (i.e., land is omitted because the land value is the same across technologies) and indirect FCI. In this second stage of the FCI estimation, the purchased equipment cost was multiplied by a factor of 1.238 to obtain other direct FCIs and a factor of 0.750 to obtain indirect FCIs. These factors are weighted averages of factors for specific direct and indirect FCIs suggested by Peters et al. [26] for a typical chemical facility. Table 2 shows that total FCI represents around three times the equipment cost.

FCI over time: Table 2 provides the initial investment (i.e., in non-productive years) in fixed capital. Given that this TEA assumes two years of building the facilities, the fixed capital investment values in Table 2 are supposed to be equally spent in the two non-productive years (years 0 and 1). Given the useful life of equipment, this TEA assumes equipment is replaced after eight years of operation.

Working capital investment: WCI is forecasted to be 10% of total FCI, according to the literature. Jones at el. [27] and Davis et al. [15] assume WCI is 5% of FCI, and Peters et al. [26] suggest most chemical plants start with WCI between 10% and 20% of FCI.

2.6. Simulations and Scenarios

Making the deterministic model stochastic: The capital budgeting model (Equations (3)–(5)) was made stochastic by simulating (1) the consumption of electricity per technology, (2) the consumption of gas per technology, (3) the electricity price, and (4) the gas price, according to a PERT distribution using the series of data that is summarized in Table 1. Energy consumption data were obtained from the experiment, and energy prices are historical monthly prices over 20 years. Relative to deterministic models, stochastic models have the potential to capture and model uncertainties better. This is because instead of using only point estimates for relevant variables, stochastic models simulate potential values drawn from a series of historical data according to a statistical distribution and iterate the model thousands of times to provide descriptive statistics of the evaluated outputs. Therefore, stochastic analysis becomes particularly important for highly uncertain projects in the biofuel sector [19]. Previous biofuel TEAs have used the PERT distribution [19,28–30].

The simulations were performed with the software @RISK® [31]. @RISK® is an add-in software package for Microsoft Excel® that performs risk analysis when uncertainty is expected by simulating distributions of selected outputs given assumed distribution functions for selected inputs. Furthermore, this software has advanced features for stochastic what-if or scenario analysis.

Stochastic scenarios: The analysis provides results for alternative scenarios, considering deviations from the baseline parameters for (1) hybrid poplar feedstock purchase prices and (2) the feedstock processing yields per technology. These variables were selected because the feedstock procurement price for biofuel is widely recognized as one of the critical components in the preprocessing cost structure and because there are recognized variations of feedstock yields between the HM and RS technologies, according to Forest Concepts™ experience in this industry. The Advanced Sensitivity Analysis module of @RISK® was implemented for the scenario analysis.

3. Results

3.1. Feedstock Yields

One of the critical results of this experiment is the output (reactor-ready biomass) to input (feedstock) ratio, referred to as feedstock yield. These yields, driven mainly by the percentage of fines (i.e., waste or losses), were measured in this experiment for each technology. Table 3 gives the mass flow per hour by depot area of activity. (For calculations and assumptions, refer to the footnotes in the table). Results show that the HM technology takes approximately 33.3 dry tons of equivalent feedstock (receiving area 110 and column 'In' in the first panel of Table 3) to process the 20.0-dry-ton processing target of outbound reactor-ready biomass in area 160. In contrast, the RS technology needs 25.2 dry tons of equivalent feedstock to process 20.0 tons of reactor-ready biomass. This is equivalent to a feedstock yield of 0.792 for the RS and 0.601 for the HM. Therefore, it is concluded from this experiment that the RS is operationally more efficient than the HM, and this efficiency translates into cost savings, as discussed next.

Table 3. System mass flow per hour by depot area of activity (dry tons per hour equivalent unless otherwise specified).

Area #	Activity	Overs %	Fines %	In	Out	Rec. Overs	Fines
	HM technology:						
110	Receiving		1%	33.3	33.0	0.0	0.3
115	Reclaim		1%	33.0	32.6	0.0	0.3
120	Drying		1%	32.6	32.3	0.0	0.3
130	Milling		0%	34.0	34.0	0.0	0.0
140	Screening	5%	35%	34.0	20.4	1.7	11.9
150	Storage		1%	20.4	20.2	0.0	0.2
160	Outbound loading		1%	20.2	20.0	0.0	0.2
180	Fines handling					0.0	13.3
	RS technology:						
110	Receiving		1%	25.2	25.0	0.0	0.3
115	Reclaim		1%	25.0	24.7	0.0	0.2
130	Milling		0%	41.2	41.2	0.0	0.0
140	Screening	40%	10%	41.2	20.6	16.5	4.1
120	Drying		1%	20.6	20.4	0.0	0.2
150	Storage		1%	20.4	20.2	0.0	0.2
160	Outbound loading		1%	20.2	20.0	0.0	0.2
180	Fines handling					0.0	5.2

Notes: Area numbers and activities relate to Figures 1 and 2. Column 'Overs %' represents the percentage of milled woody chips larger than 10 mm after screening. 'Fines %' gives an assumed 1% loss due to material degradation, material handling, and other factors in each area except for areas 130 and 140, where the fines separation in area 140 includes losses of 130, according to the experiment. Column 'In' represents feedstock input, estimated by dividing the output column (Out) by 1-(Fines% + Overs%). In other words, input mass flows are back-calculated from the 20-dry-ton processing target of outbound reactor-ready biomass in area 160. Column 'Out' starts with the 20-dry-ton reactor-ready processing target in area 160. The output in activity areas other than 160 equals the input in the subsequent area, except for activities before milling/screening (e.g., drying for the HM and reclaiming for the RS technology), that excludes recirculated overs. Recirculated overs, 'Rec. Overs,' provides tons of overs, milled woody chips larger than 10 mm after the screening, recirculated into the system, that is, In × Overs%. Fines are losses calculated by multiplying column 'Fines %' by 'In.'

3.2. Partial Cost Structure

Table 4 summarizes the partial cost of producing one ton of reactor-ready wood biomass by technology for the first productive year. Processing with the RH technology is about USD 44 ton^{-1} less expensive than processing with the HM. This saving represents about one-fourth of the cost of processing with the challenger instead of the defender technology. The highest savings from using the RS technology are related to feedstock quantity. As discussed, the RS technology needed less input (1.262 tons, for an equivalent 0.792 feedstock yield) to process 1 ton of reactor-ready output than the HM technology (1.665 tons, 0.601 yield). The cost of drying the feedstock biomass represented the second leading source of savings. The reason is that the RS technology/mass flow process can comminute feedstock as received—with relatively high, about 50 wt%, moisture—while the HM technology needs to dry the feedstock before comminution. Drying before comminution implies drying feedstock that will be converted into reactor-ready biomass and feedstock that will be wasted. In contrast, depreciation expense is higher for the RS because fixed capital investment is higher for this technology. Finally, the cost of comminution is slightly lower through the RS, but the difference between technologies is negligible.

Table 4. Partial cost structure to process feedstock into reactor-ready biomass for the first year of production per technology (USD ton^{-1}).

Operating Cost Item	HM	RS	HM-RS
Hybrid poplar feedstock	114.46	86.75	27.71
Comminution	1.83	1.45	0.38
Drying	43.66	24.90	18.75
Depreciation	5.00	7.60	−2.60
Partial operating costs	164.95	120.70	44.25

3.3. Deterministic Partial Capital Budgeting Savings

Partial free cash flows were forecasted over the 22-year business horizon per technology. This was carried out by adding partial investments to the partial cost structure discussed in the previous section and projecting PFCFs according to Equation (3), discussed in the Materials and Methods section. Next, economic savings due to technology ($NPV_{RS\text{-}HM}$) were calculated by applying Equation (4). Table 5 summarizes the outcomes of the economic comparison across technologies for the determinist baseline model.

Table 5. Economic comparison between the HM and RS technologies. Deterministic savings model.

$NPV_{RS\text{-}HM}$ (USD million per depot) [1]	35.19
Annual $Savings_{RS\text{-}HM}$ (USD million per depot) [2]	3.58
Annual $Savings_{RS\text{-}HM}$ for 8 depots (USD million) [3]	28.67
$NPV_{RS\text{-}HM}$ (USD per ton) [4]	35.84

Notes: [1] Calculated with Equation (4), [2] with Equation (5), [3] by multiplying Equation (5) by eight, and [4] by dividing Equation (5) by 100,000 tons.

The first line of Table 5 shows that the RS, the challenger technology, can provide anticipated savings of USD 35.19 million per depot—relative to the HM technology—over the anticipated 22-year life of a depot. In annual terms, using the RS technology is expected to generate savings equal to USD 3.58 million per depot, the equivalent annuity estimation shown in the second line of Table 5. Extrapolated to eight depots—the network of depots to supply one biorefinery—the RS technology could save USD 28.67 million annually, according to these estimations. Table 5 also shows that savings per unit of processed reactor-ready woody biomass equal USD 35.84 per ton. This is economically relevant since it represents about 22% of the USD 164.95 ton^{-1} partial cost to process with an HM (previous section).

3.4. Stochastic Simulation

Table 6 gives statistics of the stochastic partial capital budgeting model that simulated energy consumption quantities and prices with a PERT distribution. The simulations show that the RS technology is expected to save between USD 2.66 to USD 4.35 million annually per depot, with mean and median values of USD 3.45 million. Table 6 also shows that savings per ton of reactor-ready woody biomass vary between USD 26.56 and USD 42.53, with mean and median values of USD 34.49 and USD 34.45 odt^{-1}. Annual savings for the network of eight depots are expected to vary between USD 21.25 and USD 34.82 million accruing due to the use of the RS technology. Figure 3 shows that employing the RS technology (instead of the HM) is 90% likely to save between USD 30.34 and USD 39.15 per reactor-ready processed ton.

Table 6. Economic comparison between the HM and RS technologies. Stochastic savings model.

	Mean	Median	Min	Max
$NPV_{RS\text{-}HM}$ (USD million per depot) [1]	33.86	33.82	26.08	42.74
Annual $Savings_{RS\text{-}HM}$ (USD million per depot) [2]	3.45	3.45	2.66	4.35
Annual $Savings_{RS\text{-}HM}$ for 8 depots (USD million) [3]	27.59	27.56	21.25	34.82
$NPV_{RS\text{-}HM}$ (USD per ton) [4]	34.49	34.45	26.56	42.53

Notes: [1] Calculated by making Equation (4) stochastic, [2] with stochastic Equation (5), [3] by multiplying Equation (5) by eight, and [4] by dividing Equation (5) by 100,000 tons. Stochastic variables include gas and electricity consumption, according to the experiment, and 20 years of historical energy prices, according to a PERT distribution. Statistics simulated with 1000 iterations.

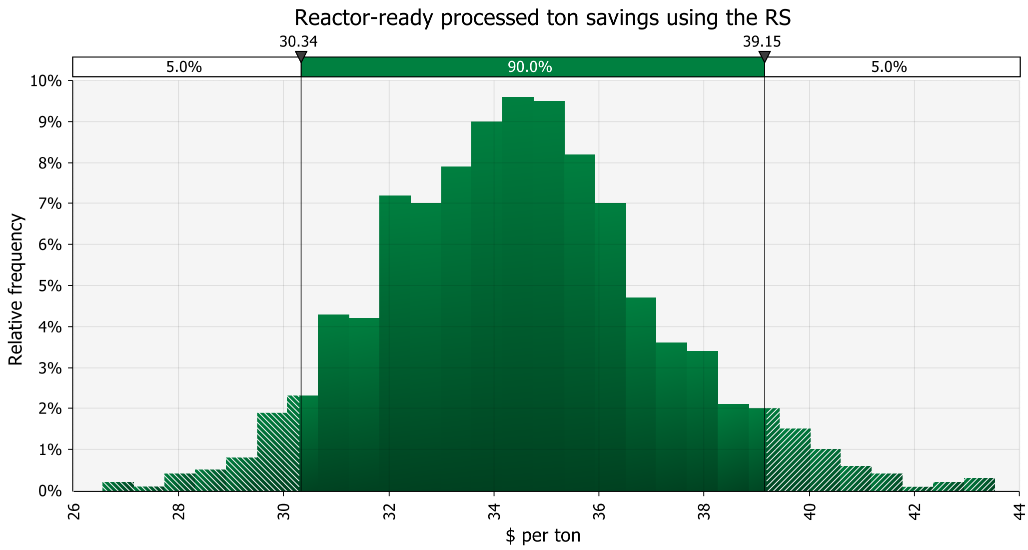


Figure 3. Expected annual savings per depot using an RS instead of an HM technology.

3.5. Stochastic Scenarios

The results for alternative scenarios, with variables deviating from the baseline parameters, are discussed in this section. The first panel of Table 7 has simulation statistics of potential savings (due to an RS) under alternative feedstock yields. The first scenario, called high overs and low fines, implies a 0.839 feedstock yield for the HM and 0.932 for the RS. A second scenario, with typical overs and typical fines, relates to a 0.701 feedstock yield for the HM and 0.878 for the RS. Finally, the low overs and high fines scenario has a 0.571 feedstock yield for the HM and 0.832 for the RS.

Table 7. Stochastic savings of using an RS instead of an HM under different scenarios.

Scenario	Mean	Median
$NPV_{RS\text{-}HM}$ at alternative processing yields (USD per ton)		
High overs and low fines	16.85	16.64
Typical overs and typical fines	27.28	27.07
Low overs and high fines	43.49	36.48
$NPV_{RS\text{-}HM}$ at alternative feedstock prices (USD per ton)		
Feedstock purchase price is base +10%	36.69	36.48
Feedstock purchase price is base +3%	35.04	34.83
Feedstock purchase price is base −3%	33.40	33.18
Feedstock purchase price is base −10%	31.75	31.54

Notes: Processing yield scenarios: (1) high overs and low fines: 0.839 feedstock yield for the HM and 0.932 for the RS, (2) typical overs and typical fines: 0.701 feedstock yield for the HM and 0.878 for the RS, and (3) low overs and high fines: 0.571 feedstock yield for the HM and 0.832 for the RS. Feedstock price scenarios: percentage of deviation, as defined in the table, from the baseline hybrid poplar feedstock price of USD 68.75 per ton. Statistics in the table represent anticipated savings calculated by dividing *stochastic* Equation (5) by 100,000 tons. Simulations (1000 iterations per scenario × 7 scenarios = 7000 iterations) conducted with the Advanced Sensitivity Analysis module of @RISK®.

These scenarios were defined according to a Forest Concepts™ database of hundreds of processing runs and are alternative scenarios to the baseline, which used the yield results of the experiment, 0.601 for the HM and 0.792 for the RS (discussed). As expected, the results in Table 7 show that the larger the yield gap (i.e., efficiency) between the two technologies, the higher the savings are. This is because, in all scenarios, the rotary shear is more efficient (i.e., needs less input per processed output). According to the mean and median simulation values in Table 7, savings of processed reactor-ready biomass vary between approximately USD 17 and USD 43 per ton, with a typical overs/typical fines scenario generating savings of about USD 27 per ton. The estimated saving of the 'typical' scenario is more conservative, below the approximately USD 34 per ton mean/median value of the model's baseline or UT experiment result (Table 6) and close to the 90% likelihood range shown in Figure 3.

The second panel of Table 7 gives statistics of potential savings if the assumed feedstock price (USD 68.75 per ton) deviates between 3% and 10% above and below this baseline price. These potential deviations include the simulated feedstock price variations in Li [21]. As expected, results in Table 7 show that the higher the feedstock purchased price, the higher the anticipated savings are because less input is needed for the RS than for the HM technology. For instance, if the feedstock price increases by about USD 7 per ton (10%), savings increase from the average of USD 34 in Table 6 to around USD 37 per ton.

3.6. Physical Characteristics of the Processed Biomass

The previous analyses consistently show that economic savings are expected by processing feedstock biomass with the RS instead of the HM technology. However, it is important to ensure that savings are not achieved at the expense of losing the desirable physical characteristics of the processed reactor-ready biomass. Two characteristics that affect the efficiency of the conversion process at the biorefinery are reactor-ready biomass aspect ratio and particle size variability [32].

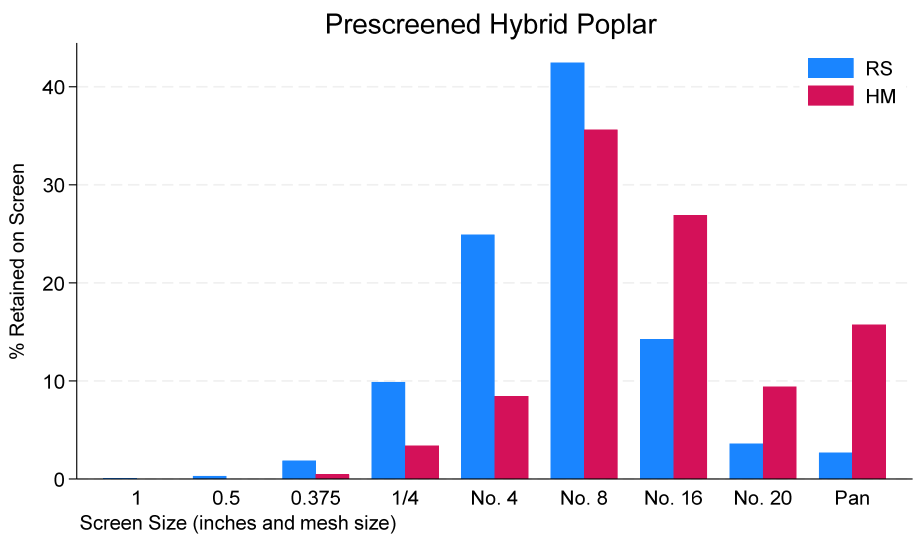
Aspect ratio, defined as the processed particle's length divided by width [33], matters because reactor-ready biomass with high aspect ratio tends to experience low flowability in material-handling systems and poor pumpability. The results of this experiment, in Table 8, show that processing feedstock with the HM does not negatively affect aspect ratios, which is consistent with the previous studies [8,10]. On the contrary, the lower mean, median, and standard deviations of processing with the RS suggest fewer downstream material-handling problems. (The sample size of this experiment is not large enough to provide conclusive results, however).

Table 8. Aspect ratio statistics per technology.

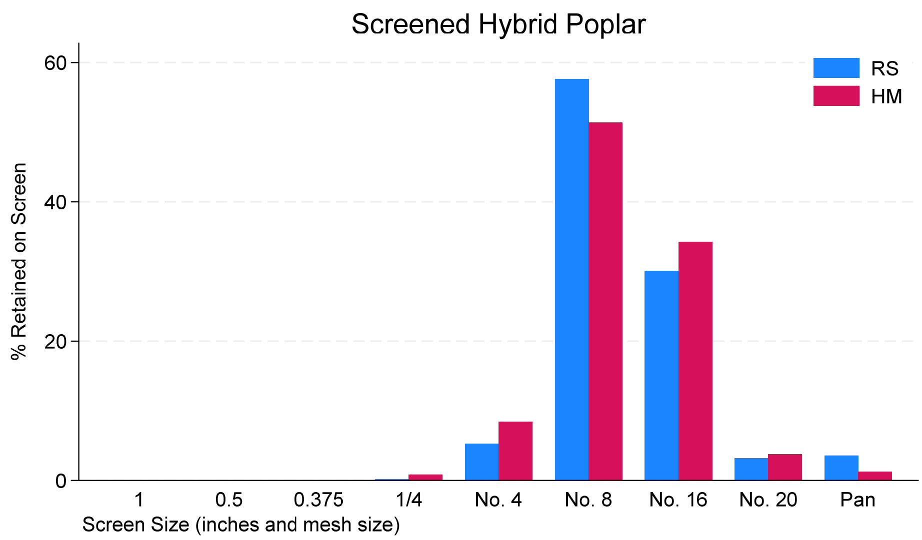
	HM	RS
Mean	5.202	3.615
Median	5.210	3.430
Standard deviation	0.923	0.782

Notes: Statistics of PO and FR feedstock processed in this experiment.

It is also expected that processed biomass particle size—length—will have low variability to favor flowability in the conversion process and reduce the fines during the feedstock comminution and drying process. Figure 4 shows the particle size distribution before and after the screening activity per technology for hybrid poplar. The top of Figure 4 compares the prescreened distributions using the RS and the HM. The RS provided a tighter distribution (resembling a bell-shaped distribution) than the HM, suggesting fewer lost materials (fines) for a specified particle size processing target, confirming the waste differences between technologies in this TEA. The bottom of Figure 4 shows the after-screening and drying distributions per technology. The after-screening/drying distributions seem similar for the two technologies. Overall, the processed biomass processed with the RS seems *at least* similar in terms of aspect ratio and particle size variability compared to the biomass processed with the HM, which suggests that economic savings using the RS are not achieved at the expense of losing the desirable physical characteristics of the processed reactor-ready biomass.



(**a**)



(**b**)

Figure 4. Particle sieve size distribution before screen sort (**a**) and after screen sort and drying (**b**) per technology for hybrid poplar.

4. Discussion and Conclusions

Overall, the results of this experiment conducted to compare the processing cost of a challenger and a defender technology consistently show that the challenger saves processing costs. A deterministic partial capital budgeting model estimates that the rotary shear technology can save approximately USD 36 per ton of reactor-ready processed biomass at a depot instead of processing the biomass with a hammermill technology, using chipped hybrid poplar feedstock as an example. This potential saving is relevant because it represents about 22% of the estimated partial costs of using the HM technology. Moreover, results in this experiment suggest that economic savings using the RS are not achieved at the expense of losing the desirable physical characteristics (i.e., aspect ratio and particle size distribution) of the processed reactor-ready biomass.

Our first set of results, related to the cost structure of these technologies, is consistent with the results of two studies in which Forest Concepts™ collaborated with Idaho National Laboratory and others to compare the HM with the RS [8,10]. While these three studies are not directly comparable regarding technical and economic parameters, the three analyses report that the RS is more efficient and economical than the HM technology. For example, according to this TEA, partial processing costs with the HM and RS (including comminution, drying, and depreciation in Table 4) equal USD 50.5 and USD 34.0 per ton, respectively. Therefore, processing with the RS could save USD 16.5 per ton. This result is practically the same as in the most comparable of the two previous studies [8], which estimates that processing with the HM and RS costs USD 52.2 per ton and USD 35.1 per ton, thereby saving USD 17.1 per ton. However, this TEA estimates that savings related to feedstock equal USD 27.7 per ton, while Yancey et al. [8] estimate USD 45.5 per ton related to feedstock. Overall, our first set of results is similar to this previous study regarding operating costs other than feedstock and is more conservative regarding feedstock-related savings. The difference in feedstock-related savings is mainly explained by feedstock yields reported in both experiments (i.e., this experiment reports that the RS wasted 10% of raw feedstock—Table 3—and the previous experiment reports 1.1%, with the deviation due to different acceptable output particle size ranges between the studies). As discussed, our study conducted feedstock yield scenario analysis to address these types of potential deviation across experiments and commercial operations.

Our study provides other sets of results related to the deterministic and stochastic capital budgeting model. We are not aware of other studies comparing these technologies using these methods. When uncertainties are included in the analysis, a stochastic partial capital model estimates that savings will vary between approximately USD 27 and USD 43 per ton of reactor-ready processed biomass, with mean and median values around USD 34 per ton. According to the stochastic model, it is 90% likely that savings will be between USD 30 and USD 39 per ton of reactor-ready processed biomass. The estimated savings are mainly due to differences in input (feedstock) to output (reactor-ready biomass) ratios or feedstock yields between technologies, affecting feedstock and drying costs. Thus, feedstock purchase prices and feedstock processing yields are allowed to vary according to industry standards by introducing variations in the stochastic model. The stochastic scenario analysis showed that a 'typical' industry yield will save approximately USD 27 per ton of reactor-ready processed biomass.

Given that this TEA conceptualizes a series of eight depots supplying the demand of a biorefinery, the savings of eight depots within the biofuel supply chain can save about USD 27 million annually, ultimately reducing the biofuel minimum selling price. The results of this analysis do not suggest that a depot reduces costs for the complete supply chain but instead that the use of the new technology reduces costs. That is, preprocessing directly in the biorefinery might be more economical due to economies of scale and integration of facilities. However, this possibility was not evaluated in this study. One limitation of using partial rather than complete capital budgeting is that profits are not part of the analysis because the investment and cost structure budgets are incomplete. Thus, future research can complete the partial budget in this study for the winning technology and provide additional insights, such as depot minimum selling prices for the feedstock analyzed in this study and for other feedstocks.

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Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A. Technicalities of the Hammermill and Rotary Shear Technologies

The conventional system to process feedstock into reactor-ready biomass uses hammermills. Hammermills function by introducing biomass into a chamber with hammers rotating about a central shaft at high speed. The hammers impact the biomass, inducing fracturing. Fractures predominantly occur along the fiber structure of the material, characteristically producing high aspect ratio particles. Additional impacts further reduce the size of the material until the particle is small enough to be pulled through an exit grate by the negative pressure air handling system. Due to the reliance on impact fracturing of the biomass for size reduction, hammermills are known to be most efficient for processing materials below 15% moisture content and ineffective above 25–30% moisture content.

An alternative processing system, the Crumbler® rotary shear system—the rotary shear technology—has been recently introduced to improve processing efficiency relative to the hammermill technology. Specifically, compared to the hammermill technology, this new technology is claimed to consume less energy, waste lower amounts of feedstock during processing, and produce more uniform reactor-ready biomass that improves conversion output yield or operational efficiency. A rotary shear comprises two counter-rotating shafts of intermeshed cutting discs. Material is pulled into the cutting discs, sheared, and ejected from the machine. There are two classes of rotary shears. Low-speed, high-torque rotary shears, often referred to as shredders, are common on the market today and have been employed in many industries. Shredders are suitable for the production of particles down to approximately 12 mm. These mills often utilize an outfeed grate similar to a hammermill and can rely on a tearing mode of failure of the processed materials. The Forest Concepts™ Crumbler rotary shear falls into the second class of rotary shears, medium-speed shears suitable for producing particles between 2 and 12 mm. The Forest Concepts™ rotary shear does not have an outfeed grate and, when combined with a shearing mode of failure rather than a tearing (shredder) or impact (hammermill) mode of failure, allows the processing of high-moisture materials.

The Forest Concepts™ medium-speed rotary shear has successfully processed a wide range of biomass feedstocks at various moisture contents. Examples include woody materials such as softwoods, hardwoods, bamboo, and hemp stalks. Herbaceous materials processed include corn stover, rice straw, switchgrass, and bagasse. Utilizing a shearing failure mode without an outfeed grate allows for processing moisture contents up 'just-cut' levels. For example, forest residuals have been processed at 65% moisture content, wet weight basis (wb). More commonly, forest residuals are processed at 35–35% due to the natural air drying that occurs in storage between harvest and processing. Fresh harvested energy sorghum has been processed at 85% moisture content, wb. Similarly, fresh-cut corn stovers are processed at 60–70% moisture content. However, corn stover is commonly processed after baling and storage at approximately 12% moisture content.

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