Financial Performance of a Mobile Pyrolysis System Used to Produce Biochar from Sawmill Residues

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Abstract

Primary wood products manufacturers generate significant amounts of woody biomass residues that can be used as feedstocks for distributed-scale thermochemical conversion systems that produce valuable bioenergy and bioproducts. However, private investment in these technologies is driven primarily by financial performance, which is often unknown for new technologies with limited industrial deployment. In this paper, we use shift-level production data collected during a 25-day field study to characterize the conversion rate and system productivity and costs for a commercially available pyrolysis system co-located at a sawmill, and then evaluate the net present value (NPV) of the operation in light of a cost structure that is realistic for the industry. Baseline costs on a feedstock throughput basis were estimated as $16.41 t^{-1} for feedstock preparation, $308.14 t^{-1} for conversion, and $65.99 t^{-1} for biochar bagging. The NPV estimated for the worst-case scenario of observed productivity and conversion rate was −$536,031 for a 10-year project period, while the best case scenario generated an NPV of $467,353. In general, NPV is highly sensitive to labor costs and biochar price, and less sensitive to fuel cost and interest rate. Results also show clear opportunities for technical and operational improvements that are expected to increase the financial viability of this system.

Sawmills and other wood products manufacturers produce large quantities of woody biomass in the form of wood chips, sawdust, shavings, and bark. These by-products, also called mill residues, are commonly sold as raw material for the manufacture of paper and engineered wood panels (e.g., clean chips for pulp and sawdust for particle board), for landscaping applications (e.g., bark mulch), and as fuel for combustion boilers (e.g., hog fuel). Over the last decade, permanent closures of paper and panel mills in the interior western United States have decreased the regional demand for mill residues. As a result, sawmills in this region often haul residues long distances to market, sometimes hundreds of miles. In general, higher transportation costs resulting from low local and regional demand for residues negatively impact the financial viability of solid wood products manufacturing by reducing revenues and potentially turning previously marketable by-products into waste materials with disposal costs.

The use of biochemical or thermochemical biomass conversion technologies to produce liquid fuels, chemicals, and other high-value bioproducts has been proposed as a solution to this problem (Badger and Fransham 2006, Briens et al. 2008). Depending on the feedstock used and the substitutability of end products, these outputs have potential to offset fossil fuel use and associated emissions with renewable forest resources. Furthermore, they can improve energy security by displacing imported fuels and petrochemicals with domestic biomass energy products. These benefits potentially apply to a broad range of market products made from woody biomass, including torrefied wood (Uslu et al. 2008), charcoal and biochar (Antal and Gronli 2003, Anderson et al. 2013), ethanol (Duff and Murray 1996), methanol (Hamelinck and Faaij 2006), bio-oil (Bridgewater 2004, Mohan et al. 2006), and producer gas used for heat and power or as chemical feedstock (i.e.,

synthesis gas; Bridgewater 2003). In some cases, the primary products of conversion can serve as intermediates in the production of drop-in liquid fuels, chemicals, and other industrial products, including activated carbon (Azargohar and Dalai 2006), Fischer–Tropsch liquids (Tijmensen et al. 2002), and organic distillates (Briens et al. 2008). Some of these products have well-established markets (e.g., ethanol and activated carbon), while others are characterized by nascent and emerging markets (e.g., biochar and bio-oil).

A large body of research is devoted to laboratory and pilot-scale study of thermochemical conversion of woody biomass (Mohan et al. 2006, Kumar et al. 2009, van der Stelt et al. 2011), and an increasing number of companies are developing and marketing commercial technologies for biomass conversion. At least several companies manufacture distributed-scale conversion systems, and some have marketed these systems for forest biomass processing (e.g., Biochar Solutions Inc. [BSI] 2011, PHG Energy 2011). Furthermore, a small but growing body of research is being developed to guide the optimization of supply chain logistics for distributed-scale forest biomass processing and production, especially through techno-economic analysis (e.g., Brown et al. 2013).

As this industry evolves across multiple agricultural, forestry, and waste management sectors, there are at least three operational characteristics of thermochemical conversion systems that are spurring interest by the forest industry, in addition to the potential environmental and economic benefits of products derived from woody biomass. First, these systems can be configured to produce heat and power for mill operations, in addition to liquid and solid products that can be shipped to distant markets. Second, these technologies are scalable. Distributed-scale systems and their mobility have the potential to allow individual firms to match their residue streams with appropriate conversion capacity. Finally, in contrast to a biorefinery model using a biochemical conversion pathway such as fermentation or anaerobic digestion, thermochemical systems are more similar to the traditional biomass combustion systems that are already widely deployed in the industry, making them appear less risky from an operational standpoint.

For forest industry firms, the decision to invest in a thermochemical conversion system for processing residues hinges on the cost structure and financial performance of such an operation. Unfortunately, there is a high degree of uncertainty related to the performance of these systems and little market data to support selling their outputs, especially for biochar and bio-oil. This is primarily due to the fact that distributed pyrolysis systems are not yet widely deployed in industrial settings, resulting in a lack of economic data and market transactions for products. Existing studies tend to rely on theoretical production estimates based on engineering specifications and short laboratory and field trials rather than empirical data collected during manufacturing operations (e.g., Sorenson 2010, Badger et al. 2011, Brown et al. 2011). To our knowledge, prior to this work, no study examined the use of distributed-scale thermochemical conversion using operations research methods (i.e., work study) to quantify costs, productivity, and financial performance.

The objective of this study was to evaluate a commercially available system in the context of co-locating with forest industry operations. Objectives included: (1) observation of a mobile pyrolysis reactor operating at a sawmill in Colorado, (2) collection of shift-level production data to characterize conversion rate and system productivity and costs, and (3) evaluation of the net present value (NPV) of the operation in light of a cost structure that is realistic for the industry. This new knowledge is needed by technology firms, investors, and managers to evaluate the potential costs and benefits of integrating distributed-scale thermochemical processing systems into existing operations.

Methods

Biomass conversion using mobile pyrolysis

Thermochemical conversion can occur across broad ranges of temperature, pressure, heating rate, oxidation conditions, and residence time. The Biochar Solutions Inc. pyrolysis system (BSI, Carbondale, Colorado) used in this study was engineered to produce biochar from biomass including agricultural residues and wood waste (Fig. 1). This small-scale mobile pyrolysis system produces biochars with high fixed carbon content and high sorption using an exothermic reaction at temperatures between 350°C and 750°C (Anderson et al. 2013). Gas and heat are generally considered co-products of biochar production. Though a fraction of the gas stream could technically be condensed into bio-oil, the system does not produce a liquid output.

The BSI system uses a two-stage reactor. In the primary reactor, the feedstock is carbonized in a controlled aerobic environment with limited oxygen at a temperature between 700°C and 750°C for less than 1 minute. Then the material passes into a second reactor, where material is held in a sweep gas environment for approximately 10 to 15 minutes at a temperature between 400°C and 550°C before it is removed from the machine by a liquid cooled auger with an air lock. The dust fraction of biochar present in the gas stream is collected by a cyclone trap before the gas is evacuated from the system by a blower. Dust does not receive the same sweep gas treatment as the coarse biochar output, which receives full residence time in the second reactor. The gas produced during the first stage of pyrolysis is used as sweep gas for the second stage and is pulled through the system by a blower. This gas is composed primarily of carbon monoxide, nitrogen, methane, and hydrogen, with some oxygen. Some limited oxidation occurs in the first stage, but oxidation is very low in the second stage.

Figure 1.—The Biochar Solutions Inc. mobile pyrolysis system field-deployed and evaluated in this study.

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Data collection and productivity study

A system productivity study was designed to evaluate the production and financial performance of a BSI mobile pyrolysis system deployed at a sawmill in Pueblo, Colorado. Data collection was carried out at the site for 25 working days in October and November, 2011. Two different types of mill residues were used as feedstock in thermochemical biomass conversion: green mixed conifer mill residues and beetle-killed mill residues. Mixed conifer mill residues were composed of ponderosa pine (*Pinus ponderosa* Douglas ex C. Lawson, 90% by mass) and other conifer tree species (10%), such as Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco). Beetle-killed mill residues were produced from beetle-killed lodgepole pine (*Pinus contorta* Douglas). Debarked logs with a minimum small-end diameter of 15 cm were harvested in October 2011, from the White River National Forest in northwest Colorado (39°34′3″N, 106°51′41″W), delivered to the mill, and sawn into lumber. The resultant edge slabs and other mill residues were chipped at the mill site, and then preprocessed by grinding and screening to a particle size of less than 7.62 cm in the longest dimension. The average moisture content of the resultant feedstocks measured in the laboratory was 9.89 percent for mixed conifer feedstocks and 15.78 percent for beetle-killed feedstocks at the time of conversion. This moisture content includes the effects of pre-conversion drying on the conveyor, which passes through hot gasses in the exhaust stack (Fig. 1).

The BSI pyrolysis system was operated by either one or two operators in one 8-hour shift per day during the 25-day study period. The system was started in the morning by turning on the blower and initiating combustion in the first stage reactor with a propane torch. After startup, system operation typically included four steps: feedstock loading, feedstock conveying and drying, thermochemical conversion, and biochar collection (Fig. 2). First, a front-end wheeled loader is used to load preprocessed feedstock into a hopper. Feedstock is then slowly moved into the reactor through a conveyor system, while being dried by heat generated from the thermal oxidizer exhaust stack. The two-stage reactor converts feedstock into biochar, and finally biochar is collected into barrels in two different forms: coarse biochar from a liquid cooled auger and dust removed from the gas stream by a cyclone. Feedstock loading occurred only when the hopper was almost empty, while the other operations took place simultaneously during productive operation.

To estimate the system productivity, shift-level time study data were collected during operation and included start time, end time, weather conditions, and delays. Start time was measured when the system blower was turned on at the beginning of each shift, and end time was measured when the entire system was shut down and the operators left the site. All delays during operation were recorded and described, and delay time was removed from scheduled machine hours to calculate delay-free productive machine time. Delays were defined as any break times longer than 10 minutes in blower operation, with an assumption that the system does not produce biochar when the blower is off. This assumption is based on the design of the two-stage reactor, which uses blower pressure to evacuate biochar from the reactor body. Delays recorded include operational delays (e.g., empty feedstock hopper), mechanical delays (e.g., maintenance and repair), and operator delays (e.g., meal time). To estimate system productivity and conversion rate on a per unit weight basis, the total weight of feedstock was measured using an in-ground certified platform truck scale at the site to weigh feedstock at the beginning of each shift, and the weights of biochar chips and dust output in barrels were measured using an electronic floor scale. In addition, the pressure and temperature of reactors and gas-paths of the BSI system were monitored and recorded with a computer during the operation.

Estimating productivity and conversion rate

Productivity and biochar conversion rate are important measures of pyrolysis system performance. In this study, shift-level productivity is defined as a ratio of the amount of feedstock consumed during the shift in green tonnes (t) to productive machine hours (h). Gross level productivity of the system (t h^{-1}) then can be estimated by compiling shift-level data for the entire field study period. Productivity is calculated on a productive machine time basis, which does not include delay, not on a scheduled machine time basis, which does include delay. The ratio of productive time to scheduled time is known as the utilization rate, and is typically quantified using long-term production data. The BSI pyrolysis system used in this study is an early design, and stable utilization rates have not been established for the system. Because productivity on a productive machine time basis provides delay-free productivity, it is often considered an appropriate productivity measure for machines in an early stage of development, and can be used with generalized equipment utilization rates to estimate productivity on a scheduled machine time basis (Miyata 1980, Olsen et al. 1998). For example, in the baseline case scenario described below, the assumed utilization rate for equipment is 80 percent.

In addition, in this study the productivity measure is based on the amount of feedstock consumption rather than biochar production because several cost factors considered in the financial analysis depend on feedstock characteristics, such as feedstock loading and preprocessing costs, and because feedstock throughput is an important metric when
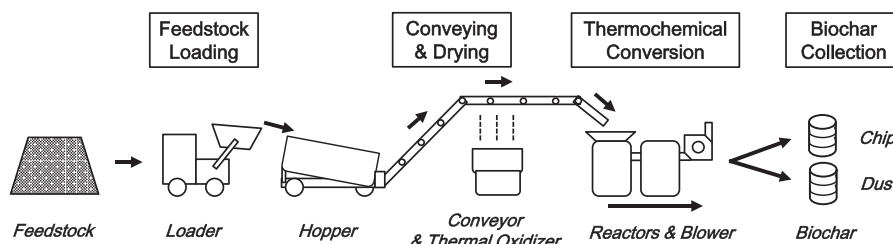

Figure 2.—Operational steps to convert mill residues into biochar using the Biochar Solutions Inc. pyrolysis system.

considering pyrolysis systems for management of biomass by-products, including mill residues. Conversion rate was defined as a mass ratio of the total biochar produced to the total feedstock consumed during production. The total amount of biochar produced includes biochar chips and dust, which are both marketable products of the operation.

Calculating machine rates and operation costs

Pyrolysis system costs are estimated on a dollar per green tonne of feedstock basis using costs broken into three categories: feedstock preparation, pyrolysis conversion, and biochar bagging (Fig. 3). Feedstock preparation includes feedstock grinding, screening, and loading operations. Each operation requires the use of machinery, such as a tub grinder, rotary screener, loader, pyrolysis system, and biochar bagging equipment. The cost of each operation can then be estimated using a standardized machine hourly cost (i.e., machine rate) required for the operation, and machine productivity (Eq. 1).

$$\text{Cost} (\$\,t^{-1}) = \text{Machine rate} (\$\,h^{-1})/\text{Productivity} (t\,h^{-1}) \tag{1}$$

Widely accepted standard methods for machine rate calculations were used to calculate machine rates for individual machines used in the pyrolysis operation (Brinker et al. 2002). Machine rate parameters for a tub grinder and a wheel loader were obtained from the default values suggested in the Forest Residue Trucking Simulator v 5.0 (FoRTS v 5.0; US Department of Agriculture [USDA] 2005), while the price of the screener was obtained from the machine owner (Table 1). For the BSI pyrolysis system, most machine rate parameters in Table 1 were obtained from the manufacturer's suggestions except for the productive machine hours per year of the machine. The machine is assumed to operate productively for 8 h/d and 260 d/y. The purchase price of the BSI mobile U5 beta unit of $350,000 (Table 1) includes a $9,880 initial setup cost, which includes $5,000 transportation of the unit to the site, $2,400 in setup labor, $1,480 in administration and overhead, and $1,000 in electrical work, with all cost estimates provided by the manufacturer.

For machine productivity, the default values from FoRTS v.5 were used for a tub grinder and a wheel loader, which are 13.608 t h^{-1} and 54.432 t h^{-1}, respectively. For the screening equipment, a productivity of 13.608 t h^{-1} was used as the operator's estimate, based on the fact that the screener has a higher productivity than the tub grinder and is therefore constrained by grinder productivity. The productivity of the BSI pyrolysis system observed during the field study was used in the cost calculation.

Unlike the aforementioned cost calculations using machine rates and productivity, biochar bagging costs were estimated based on the pyrolysis system owner's suggestion, which was $52.31 m^{-3} for bagging operation costs and $10 for each 0.76 m^{-3} bulk bag. To be consistent with other cost measures, these bagging operations costs were converted into dollars per green tonne of feedstock using the conversion rate and biochar density observed during the field study.

Analyzing financial performance

To evaluate the financial performance of the pyrolysis operation, yearly cash flows for an assumed 10-year project period were developed and NPV was calculated based on a 7 percent real interest rate (i.e., discount rate). Using a riskless real rate of 3.0 percent that includes a nominal rate of 2.5 percent and a long-term average rate of inflation of 0.5 percent, this rate includes an implied risk premium of 4 percent. Our interest rate of 7 percent falls between the 3.75 percent rate that Federal agencies use for natural resources projects (US Federal Register 2013) and the 10 percent rate commonly used in techno-economic studies of larger scale projects (Anex et al. 2010, Wright et al. 2010, Davis et al. 2011). We chose a 4 percent risk premium in this case to quantify risks in both production and product marketing, with biochar being produced for nascent, negotiated spot markets by an emerging technology, rather than a lower rate that might be used for a project supplying commodity markets using a proven commercial technology.

All monetary values are presented as 2011 US dollars ($). It was assumed that sale of biochar was the only revenue source and that both biochar chips and dust were sold at the same price. Though it is possible to use producer gas combustion as a heat source for lumber drying and heat treating products to kill insects before export, the value of the producer gas is assumed to be zero in this analysis because the system was not configured for this use at the time of field data collection.

A market price for biochar of $2.2 kg^{-1} for mine reclamation soil amendment markets near the study site was used in the analysis after being converted into dollars per green tonne of feedstock value ($ t^{-1}). This price does not include any monetary value related to carbon sequestration in the soil, which has been identified as a potential source of revenue for biochar projects (Galinato et al. 2011), because this value was not monetized at the time of the study. The value of feedstock prior to feedstock processing was considered to be zero because the mill residues used in pyrolysis conversion were considered to be a by-product with neither disposal costs nor alternative markets (e.g., pulp) that would generate net revenue.

Sensitivity analyses were conducted to evaluate the sensitivity of financial performance (i.e., NPV) of the pyrolysis operation to cost and revenue variables, such as wages, fuel cost, interest rate, and biochar market price. The range of each variable from −30 to +30 percent of the baseline value was used in the sensitivity analyses while the other variables remained constant. Analyses were also conducted to identify the value of each variable that resulted in an NPV of zero, holding all other variables constant at the baseline value. For the interest rate, the value that makes the NPV equal to zero is known as the internal rate of return

Figure 3.—Cost elements of the entire pyrolysis operation from feedstock preparation to packaging the final product.

Table 1.—Machine rate parameters used in calculating hourly cost of machine with operator.

Parameter	Grinding (tub grinder)	Screening (rotary screener)	Loading (wheel loader)	Pyrolysis (BSI mobile U5 beta)
Purchase price ($)	350,000	50,000	205,000	350,000
Productive machine hours (h y^{-1})	1,664	1,664	1,664	2,080
Scheduled machine hours (h y^{-1})	2,080	2,080	2,080	NA[a]
Utilization rate (%)	80	80	80	NA
Machine life (y)	7	7	7	10
Salvage (% of price)	20	20	20	10
Interest (%)	7	7	7	7
Fuel cost ($ L^{-1})	0.85	0.85	0.85	NA
Electricity cost ($ MJ^{-1})	NA	NA	NA	0.02
Hourly labor wage ($)	17.89	17.89	17.89	17.89
Labor benefits (%)	35	35	35	35

[a] NA = not applicable.

(IRR), which is a measure of how fast the investment grows. In financial analysis, an NPV of zero generally indicates the threshold of an economically desirable project because it includes an established rate of return (7% in our baseline case, for example). In addition, sensitivity analyses of financial performance to the pyrolysis system's productivity and conversion rate were performed to assess the potential benefits from machine improvements that would result in a stable biochar production rate. The empirical ranges of productivity and conversion rate observed during the field study were used in these sensitivity analyses.

Results

BSI pyrolysis system productivity

During a total of 25 days of field study, the pyrolysis system was productive for 22 days and undergoing maintenance for 3 days due to unexpected mechanical problems. As with other delays, this unexpected maintenance period is not included in the productivity analysis because we used delay-free productive machine time. Total hours worked during 22 working days were 167.0 hours ranging from 3.8 to 10.2 hours per working day or an average of 7.6 hours per shift (Table 2). Hours worked in each shift varied depending on operators' working schedules, pyrolysis system performance, and weather conditions. The system operated in the open, and was not operated during heavy rain or snow. There were a total of 31.4 hours of delays recorded during 22 working days with an average of 1.4 hours of delay per shift. The highest proportion of delay time was attributed to mechanical delay caused by problems such as reactor clogging and auger malfunction, but operational and personal delays are also included in this total. For comparison to the 80 percent utilization rate applied to feedstock preparation equipment, the observed utilization rates for the pyrolysis system including and excluding the 3-day maintenance period were 75.1 and 84.2 percent, respectively. However, as discussed previously, the design and duration of this study make it inappropriate for measuring utilization rate.

A total of 21.2 t of feedstock were consumed during the field study, while a total of 3.0 t of biochar were produced, for an observed conversion rate of 14.1 percent by mass. The biochar production amount in Table 2 includes both biochar chips and dust. During the field study, weight of biochar chips produced was measured at the end of each shift, but biochar dust was measured only when the dust-collecting barrel was removed from the system and replaced, normally once every two to three shifts. To estimate the shift-level biochar dust production, the ratio of dust to chips was calculated using the gross amount of production of each product, and then shift-level biochar chip production was multiplied by the resultant ratio (0.315).

Based on the observed gross feedstock consumption and productive work hours over the 22 working days, the productivity of the BSI pyrolysis system is estimated as 0.156 t h^{-1} (Table 2). The shift-level productivity ranged from 0.114 to 0.219 t h^{-1}.

Machine rates and costs of pyrolysis operation

Machine rates estimated for a tub grinder, a rotary screener, and a wheel loader used for feedstock preparation were $163.81, $39.78, and $78.86 h^{-1}, respectively (Table 3). The machine rate of the BSI pyrolysis system was $48.07 h^{-1}. Total feedstock preparation costs were estimated as $16.41 t^{-1} of feedstock. Among the three individual operations of feedstock preparation, grinding was the most expensive component, accounting for 73 percent of the total feedstock preparation costs. The cost of pyrolysis conversion using the BSI system was estimated as $308.14 t^{-1}

Table 2.—Summary statistics of the shift-level production data.

Statistic	Shift time (h)	Delay time (h)	Productive work time (h)	Feedstock consumed (t)	Biochar production (t)
Total	167.03	31.35	135.68	21.183	2.993
Shift-level					
Mean	7.59	1.43	6.17	0.963	0.136
Min.	3.75	0	2.23	0.219	0.041
Max.	10.23	5.3	9.2	1.433	0.285

Table 3.—Pyrolysis operation costs estimated on a green tonne (t) of feedstock basis.

	Feedstock preparation				Biochar bagging
	Grinding	Screening	Loading	Pyrolysis	
Machine rate ($ h^{-1})	163.81	39.78	78.86	48.07	NA[a]
Productivity (t h^{-1})	13.608	13.608	54.432	0.156	NA
Cost ($ t^{-1})	12.04	2.92	1.45	308.14	65.99

[a] NA = not applicable

based on the system machine rate and observed system productivity (Table 3). Biochar bagging cost was estimated as $65.99 t^{-1}. In the bagging cost calculation, a biochar density of 0.141 Mg m^{-3} (Anderson et al. 2013) and a conversion rate of 14.1 percent were used. In summary, the total cost of the entire pyrolysis operation for biomass-to-biochar conversion was estimated as $390.54 t^{-1} of feedstock, and the conversion process was the most expensive component of the operation, accounting for 79 percent of the total cost.

Financial performance

Using the operational cost estimation and the cost structure and assumptions used in the baseline case, including a 7 percent interest rate, an annual total cost was estimated as $126,567 including $5,295 for feedstock preparation, $99,976 for pyrolysis conversion, and $21,296 for biochar bagging. Annual revenue from biochar was $101,013 for the baseline case, resulting in an NPV of −$168,955 for a 10-year project period.

Figure 4 shows the sensitivity of NPV to changes in hourly wages, fuel cost, interest rate, and biochar market price. The results indicate that biochar price is the most influential variable for the financial performance of the pyrolysis operation. With a 30 percent increase in biochar price from $2.2 to $2.86 kg^{-1}, the NPV increases to $43,887. The second largest influencing factor among those tested was labor cost. Increases in both interest rate and fuel cost negatively affect the NPV of the operation, but the marginal influence is lower than that of biochar price and labor cost. The values for biochar price and hourly labor wage at NPV = 0 were calculated to be $2.73 and $9.59 h^{-1}, respectively. For the baseline case, NPV was negative for both a fuel cost of $0 and an interest rate of 0 percent, with the latter indicating a negative IRR (Fig. 4).

The results of the sensitivity analyses for different levels of pyrolysis productivity and conversion rate are presented in Table 4. The ranges of shift-level machine productivity and conversion rate observed in the field were used for the range of variation, and each range was divided by four to provide input values for the sensitivity analysis. The NPV estimated for the worst-case scenario was −$536,031, where the pyrolysis system is assumed to work at the lowest observed productivity level and produce the least observed

Table 4.—Changes in net present value (NPV) in response to different levels of pyrolysis productivity and conversion rate.

Conversion rate (%)	NPV (in USD 1,000) at productivity level (t h^{-1}):				
	0.114	0.141	0.167	0.192	0.219
6.3	−536.0	−500.2	−464.4	−429.8	−394.0
10.2	−422.7	−360.8	−298.9	−239.2	−177.3
14.1	−309.4	−221.4	−133.5	−48.5	39.5
17.9	−199.0	−85.6	27.8	137.2	250.6
21.8	−85.7	53.8	193.2	327.9	467.4

amount of biochar per unit weight of feedstock over the duration of the 10-year project period. In contrast, the best case scenario, with the highest observed productivity and conversion, generated an NPV of $467,353. Pairs of productivity and conversion rate values for each shift are plotted along with an NPV = 0 line in Figure 5. A total of three points are located above the NPV = 0 line, indicating there were three shifts when the system worked efficiently enough to generate a positive NPV. The majority of the shifts are, however, located below the NPV = 0 line in the negative NPV zone. The wide ranges of variation in machine productivity and conversion rate also indicate that the system did not run consistently during the field study. In fact, several mechanical problems, such as reactor clogging, were experienced that slowed down the operation and thus lowered the system productivity. The most productive single shift in terms of NPV had an average productivity of 0.204 t h^{-1} with an average conversion rate of 21.8 percent, representing an NPV of $390,406.

Discussion
Limitations of the study design

These results should be interpreted in light of several constraints related to study design. There were several occasions during which the pyrolysis system was running without generating biochar, especially when the reactor was clogged and the operators were working to resolve the problem. Because the study was designed with a clear threshold for delay focused on breaks in blower operation of 10 minutes or more, these unproductive times were not recorded as a delay in the field study. Typically, the blower
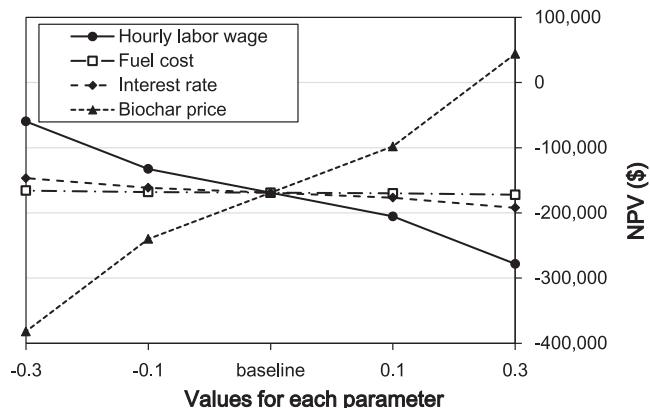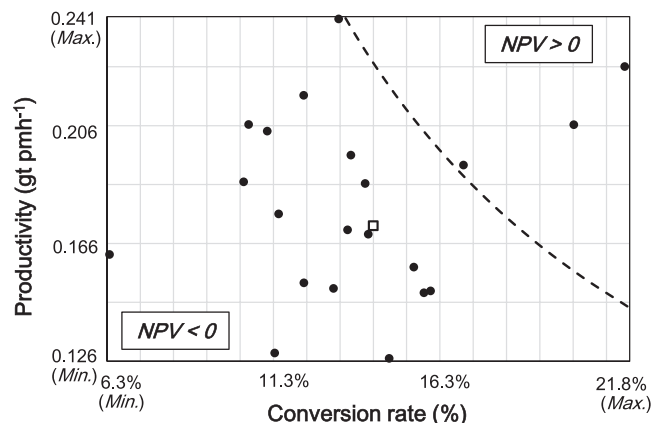

Figure 4.—Sensitivity of financial performance of the pyrolysis operation to changes in hourly labor wage, fuel cost, interest rate, and biochar market price.

Figure 5.—Scatterplot of the observed shift-level productivity and conversion rate of the Biochar Solutions Inc. pyrolysis system.

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remained on during work to unclog the reactor. A classification of these unproductive times as delay would have lowered the system's utilization rate, but increased its productivity. As a result, the measurement of productivity using productive machine hours may underestimate the potential productivity of the system using a later-model reactor design that experiences less clogging.

Another limitation in this study is that biochar production was measured only at the shift level. A constant monitoring of biochar output, assessment of temperature and pressure conditions, and measurements of productivity over shorter time periods, such as hourly, might have provided an opportunity to observe the system conditions with more resolution and thus account for cause and effect relationships leading to productivity losses. Even so, shift-level analysis is useful in quantifying productivity and financial viability. Subsequent versions of the BSI system have incorporated design elements to overcome some of the problems observed in the field—the effects of which might have been predictable with higher resolution data.

Improving operational and financial performance

The pyrolysis system used in this study produced biochar without major mechanical or technical breakdowns while operating outside under variable weather conditions for 22 working days. However, wide variation in shift-level productivity and conversion rates shows that the system did not run consistently during the observation period. In general, the results of the financial analysis indicate that the pyrolysis operation observed in this study, though technically viable, is not financially viable as a stand-alone enterprise. However, it is worth noting that the NPV for the baseline case was calculated using the gross average productivity and conversion rate obtained from this early model prototype system with high lifetime machine hours, and the system has ample opportunity for improvement in both operation and design. Furthermore, because biomass conversion is the most costly component of the operation as a whole, accounting for 79 percent of the total cost, relatively small gains in the technical and economic efficiency of the conversion process have the potential to result in large improvements in the financial viability of the enterprise.

There are two primary ways the financial viability of the pyrolysis system could be improved. First, technical and operational changes could result in higher efficiency by increasing productivity and conversion rate. Three of 22 shifts had efficiency high enough to generate a positive NPV (Fig. 5). The highest productivity and conversion rate observed at a shift level were 0.219 t h^{-1} and 21.8 percent, with an NPV of $390,406. However, these values do not represent the maximum theoretical limit of the conversion technology. The observed maximum conversion rate is still below the technical limit in this temperature range (Meyer et al. 2011), and higher productivity could be achieved through improvements in machine design and operation. Reactor clogging appeared to be one of the major mechanical issues that lowered both system productivity and conversion rate. Manually timed feeding that occurred in pulses of green feedstock entering the reactor and high moisture content in the feedstock from precipitation falling on an uncovered hopper and conveyor system also lowered the system efficiency. These problems have relatively simple technical

solutions, and improvements in these areas are likely to lead to efficiency gains. The manufacturer has already sought to improve system performance through operational and design changes, such as fabricating the reactors of stronger steel that resists warping, installing paddles on the primary reactor shaft to break up the feedstock bridging that causes clogs, using a larger blower, and improving feedstock drying using waste heat and a multi-tiered dryer/conveyor rather than the single pass system used in this study. Furthermore, the feasibility of multiple units running in parallel, which has been proposed as an option to spread fixed costs over higher biochar output, was not evaluated in this study. For example, from observations it does appear that the efficiency of labor and support equipment could be improved with a multiple unit configuration.

Another way to improve financial viability is to lower the NPV = 0 line shown in Figure 5 to expand the positive NPV zone. This involves changes in the economic and financial environment in which the pyrolysis systems operate. A higher price of biochar through marketing and market development, including production of value-added products such as activated carbon, could increase net revenue of the pyrolysis operation and improve financial performance. On the feedstock supply side, in this analysis mill residues were considered to have a price of zero—being neither a waste output with disposal costs nor a by-product with market value, with costs incurred in processing residues into appropriate pyrolysis feedstock. If residues have disposal costs, this effectively improves the financial viability of these systems by offsetting these costs to the extent that waste production is balanced with pyrolysis capacity. Though mill residues, especially bark-free residues, have traditionally had value as raw material for pulp and wood panel manufacturing, mill closures can quickly make residues a liability in some markets.

There may be other factors that affect the position of the NPV line. Though the 4 percent risk premium incorporated into the 7 percent real interest rate used in the NPV calculations is realistic for evaluating the economic desirability of a project like this one, individual firms may have lower expectations for ventures intended to process by-products as a component of a larger manufacturing operation that produces many different value-added products. Furthermore, if distributed-scale conversion technologies become more widely deployed and proven in the forest sector, and biochar markets become more developed and less uncertain, this technology may be perceived as less risky from an investment and capital budgeting standpoint, lowering the risk premium and the corresponding real interest rate, perhaps as low as 4 percent.

In addition, value for the waste heat and energy gas from the system was not included in this analysis. Heat from the system could be used to heat buildings and kilns, offsetting fossil fuel use and associated costs. For example, the mill in this study uses propane to heat treat pallets and shipping products for export. Fossil fuel offsets may provide additional financial incentive for conversion, as well as the nonmarket benefits associated with renewable energy. Carbon sequestration represents another potential source of revenue for biochar production. Options for monetizing the value of carbon sequestration associated with biochar are evolving, but range from price premiums paid by willing retail consumers to formalized carbon offset programs and emissions trading schemes, especially those related to

forestry projects, bioenergy and biofuels (Gaunt and Cowie 2009, Weisberg et al. 2010, Galinato et al. 2011).

Potential for in-woods applications

High costs of transportation and handling of feedstock often make utilization of forest residues, such as logging slash, financially unviable. As a result, these materials are often considered waste and left on site to decompose or burned in piles to reduce wildfire risk and open space for regeneration. Pile burning results in added site preparation costs for contractors. As an alternative, in-wood processing of forest biomass with a small-scale, mobile biomass conversion unit that can be deployed near the source of feedstock would generate a marketable, higher density product that could be shipped off site (Badger and Fransham 2006, Brown et al. 2013). The BSI pyrolysis system used in this study is a small-scale conversion system designed for mobility, and can be easily trailer mounted (Anderson et al. 2013). This study evaluated the system for processing mill residues in a centralized location, but future studies should also investigate in-woods applications of the system using operations research methods. With enhanced consistency in operation and higher productivity, the system has the potential to improve the utilization of forest residues that would otherwise be burned for disposal.

In addition to potential economic benefits, there may also be broader nonmarket benefits associated with this application. For example, smoke from pile burning can have negative effects on recreation and human health. These broader benefits may be effective justification for financial incentives to use in-woods thermochemical conversion as an alternative to burning, especially on public lands (Loeffler and Anderson 2014). Direct subsidy, tax incentives or incentivized stewardship contracting for biomass utilization would obviously improve the financial viability of the pyrolysis operation to some extent, especially for early adopters of these technologies.

In-woods deployment of conversion technology is not without challenges. There could be additional feedstock handling and preparation costs. Unlike mill residues, logging residues are usually spread over multiple timber harvest areas and are frequently contaminated with soils. The heterogeneous particle size and composition of forest residues would also increase handling and screening costs if feedstock specifications for the system are narrow in terms of particle size, ash content, and moisture content. In addition, fixed mobilization costs of the pyrolysis system and associated support equipment, as well as difficult accessibility to electric power and maintenance support (e.g., engineering and fabrication personnel) would likely cause an increase in operational costs compared to sawmill deployment. However, the current pyrolysis system has significant room for mechanical and operational improvements that would potentially make the system financially viable for in-wood applications.

Conclusions

At the productivity and conversion rates observed, it is unlikely that the operation described here would be financially successful as a stand-alone enterprise. However, results show clear opportunities for technical and operational improvements that would increase the financial viability of this system. This research can be applied to other equipment and settings because it is based on generalized machine rates and standard project evaluation techniques. As distributed-scale thermal conversion becomes more widely deployed, financial and economic analysis grounded in operations research can be used to inform supply chain logistics, investment decisions and public policy.

Acknowledgments

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