Techno-economic analysis of producing solid biofuels and biochar from forest residues using portable systems

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HIGHLIGHTS

- Economic feasibility of portable systems to utilize forest residues was investigated.
- Forest residues were processed into raw and torrefied briquettes and biochar.
- Minimum selling price (MSP) of biochar was estimated to $1044/ODMT.
- MSP of raw and torrefied-briquettes were $162 and $274/ODMT respectively.
- MSPs could be reduced by at least 50% with improved portable systems.

ARTICLE INFO

ABSTRACT

Wildfires are getting extreme and more frequent because of increased fuel loads in the forest and extended dry conditions. Prevention of wildfire by fuel treatment methods will generate forest residues in large volumes, which in addition to available logging residues, can be used to produce biofuels and bioproducts. In this study, the techno-economic assessment of three portable systems to produce woodchips briquettes (WCB), torrefied-woodchips briquettes (TWCB) and biochar from forest residues were evaluated using pilot-scale experimental data. A discounted cash flow rate of return method was used to estimate minimum selling prices (MSPs) for each product, to conduct sensitivity analyses, and to identify potential cost-reduction strategies. Using a before-finance-and-tax 16.5% nominal required return on investment, and a mean transport distance of 200 km, the estimated delivered MSPs per oven-dry metric ton (ODMT) of WCB, TWCB, and biochar were $162, $274, and $1044 respectively. The capital investment (16–30%), labor cost (23–28%), and feedstock cost (10–13%) without stumpage cost were the major factors influencing the MSP of solid biofuels and biochar. However, the MSPs of WCB, TWCB, and biochar could be reduced to $65, $145, and $470/ODMT respectively with technologically improved portable systems. In addition, the MSPs of solid biofuels and biochar could be further reduced by renewable energy and carbon credits, if the greenhouse gas (GHG) reduction potentials are quantified and remunerated. In conclusion, portable systems could be economically feasible to use forest residues and make useful products at current market prices while simultaneously reducing potential wildfires and GHG emissions.

1. Introduction

Our society is now faced by overwhelmingly interlinked global threats–climate change [1], natural resources degradation and food insecurity [2,3], and catastrophic wildfires [4,5]. Wildfires cost lives and huge economic impacts – direct (i.e., billions of dollar annual cost for fire suppression and property damage [5,6]) and indirect (i.e., adverse health impacts cost annually $76-$130 billion from 2008 to 2012 only [7]). Forest residues from logging operations not only pose major

fire risks [8] but also causes air pollution and other adverse human health impacts [9].

In the United States, the Healthy Forests Restoration Act of 2003 (P.l. 108–148), promotes the idea of broad-scale forest thinning and fuel treatments to remove hazardous fuels while reducing fire risks as well as maintaining forest health and growth [10,11]. In addition to logging residues, forest fuel treatments could generate a large volume of biomass, e.g., about 97–103 million ODMT/year [12]. Forest residues can be used to meet the goals of existing policies such as EISA (Energy

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Independence and Security Act, 2007) mandate and RPS (Renewable Portfolio Standards) [13] to significantly increase the share of renewable liquid fuels and electricity/power, respectively.

The major economic hurdle to produce renewable energy from forest residues is the high logistics cost [14–16]. Forest residues are dispersed across large areas, and thus incur high harvesting costs during aggregation [17,18]. Furthermore, biomass transport and handling costs are high due to low bulk density, low energy density, and high moisture content [19–21].

Biomass densification such as pelleting or briquetting can reduce the handling and transport cost [22]. Compared with pelleting technology, briquetting technology requires lower energy and infrastructure requirements [22], while handling large variability of biomass quality such as particle size and moisture content [23]. If biomass is thermally pretreated by torrefaction – a mild pyrolysis of biomass carried out at low temperature (200–300 °C) – prior to densification, it can produce a high energy density solid fuel similar to coal [24]. Alternatively, forest residues can be used to produce biochar – slow pyrolysis at temperatures ranging from 450 to 500 °C [25] often used as a soil amendment and a carbon sequestration agent [2].

Economic analysis of liquid biofuels or bioenergy products in large-scale facilities has been conducted considering supply chain networks that may be categorized as either a centralized (type-I), i.e., a large-scale biomass conversion facility with a large biomass draw radius [19,26–29]; decentralized (type-II), which consists of many smaller-size conversion facilities with smaller biomass draw radii [28,30]; or a hybrid (type-III) that consists of a centralized large-scale biomass conversion facility and many preprocessing facilities (i.e., depots) to densify biomass and transport high-energy dense biomass to the centralized facility. In both type-I [31–33] and type-II [28] supply chain network designs, the total cost of biofuel or bioenergy or bioproducts will be higher due to large biomass logistics and high investment costs, respectively. Previous studies have estimated that the final product cost from type-III supply chain networks was lower compared with that of type-I and II [18,34–37]. Depots (in type-III) can substantially reduce the transport and handling costs but still require large total investments due to lack of scale economies at the preprocessing facilities. Therefore, a higher bioenergy or bioproduct production cost is always expected with any of these three types of supply chain networks either due to high logistics costs or due to high infrastructure cost.

The economic performance of a bioenergy/biofuel plant is affected by facility location, and biomass supply uncertainties have been shown to have a significant impact on a facility's location [14]. The flexibility offered by the option of changing a preprocessing facility's location (i.e., portable systems) can reduce biomass supply risk. For type-III supply chain networks, if depots are portable (that is, pre-processing systems that can be transported from one location to another based on biomass availability) and send densified biomass to a centralized energy conversion facility, then the total cost of investment for the entire supply chain can be reduced along with the logistics cost [15,31,38]. Issues such as high logistics cost, higher uncertainties in biomass availability, higher investment risk for large biomass conversion plant, etc. can be addressed through portable manufacturing units [26,35,39].

In order to economically utilize forest residues generated from fuel reduction treatments with minimal investment, the feedstock location and conversion platforms should be vertically integrated using portable conversion systems to produce solid fuels and bioproducts. Portable systems can be classified based on ease of mobility and relative capacities, i.e., (i) mobile, (ii) transportable, and (iii) relocatable [37,40]. In order to evaluate the tradeoff between centralized large-scale and relatively small mobile, or transportable, or relocatable conversion units, Polagye et al. [37] assumed cost inputs for pilot scale facilities and compared the production of wood pellets, bio-oil, and methanol using four different classes of production facilities ranging from large-scale stationary (1653 MT/day) to small-scale mobile systems (10 MT/day). Among the different scales of production facilities, the pellet production

cost using the portable system was the highest mainly due to the use of diesel generators and labor. However, it was suggested that the production cost can be reduced by operating multiple parallel units at a location [41] due to more efficient labor use and the use of waste heat from the production process to dry input feedstocks, especially in pyrolysis or torrefaction [42].

There are a handful of research studies on portable systems and most are related to producing bio-oil from biomass [31,33,37,43] and bio-oil needs upgradation to produce transportable biofuels. Mirkouei et al. [31] presented an optimal design of bio-oil supply chain considering portable systems and found that capital intensity of these systems is the most influential factor affecting the economic performance of portable biorefineries. Hence, it's important to carry an in-depth economic analysis of portable systems. Previous research on the portable system was on cost estimation and short supply chain perspectives [44–46]. Production of biochar and torrefied woodchips through mobile pyrolysis system was studied by Kim et al. [45,46] and Brown et al.[47], respectively but focused on estimating the cost rather than the financial performances of the system. Furthermore, portable systems are considered to produce value-added chemicals [48]. Alternatively, portable systems focussed on the production of densified wood (such as woodchips briquettes) and biochar could have a better market in the U.S. [49]. Therefore, the economic feasibility of portable systems to produce solid biofuels and biochar has to be further investigated to develop new market opportunities for forest residues. In addition, an in-depth financial analysis of portable systems is necessary to help stakeholders (e.g. forest owners, investors, and policymakers) and to make key financial decisions on the efficient use of forest residues in the U.S.

In this paper, a comprehensive discounted cash flow rate of return (DCFROR) model was developed to estimate the financial performances and the economic feasibility of producing woodchips briquettes (WCB), torrefied-woodchips briquettes (TWCB), and biochar from forest residues using portable manufacturing systems in the near-forest settings. A detailed sensitivity analysis was conducted on the critical input parameters affecting the financial feasibility of portable systems to propose potential cost-reduction strategies. The hypothesis of this study was that portable systems at near-forest setups are economical to produce solid biofuels and bioproducts using forest residues.

2. Methods

In this study, the techno-economic assessment of three portable systems each based on biomass conversion technologies (BCTs) at a near-forest setup was investigated. BCTs refer to: (i) densification of woodchips to produce briquettes (WCB); (ii) torrefaction of woodchips and subsequent densification to produce torrefied-briquettes (TWCB); (iii) slow pyrolysis of woodchips to produce biochar.

Most of the operational inputs used in this study were obtained from experimental studies performed by the WTW project partners (Fig. 1) [42,50–53]. However, the throughput of these production systems varied widely, which would have created inconsistent results and analysis, especially if the results were compared among different products. The feasibilities of putting more than one parallel system had been proposed based on the previous studies [41]. So to more-closely match the capacities of these three production systems, and to make more efficient use of labor, it was assumed that the WCB system would operate with two woodchips briqutters, the TWCB system would have one torrefier and one briquetter, and the biochar system would operate with two biochar machines.

2.1. Feedstock source and system boundary

This study used the forest residues generated from timberland during commercial logging operations to harvest sawtimber in northern California. The logging residues include non-merchantable trees (i.e., hardwood, small-diameter trees, dead trees, etc.) and the remaining
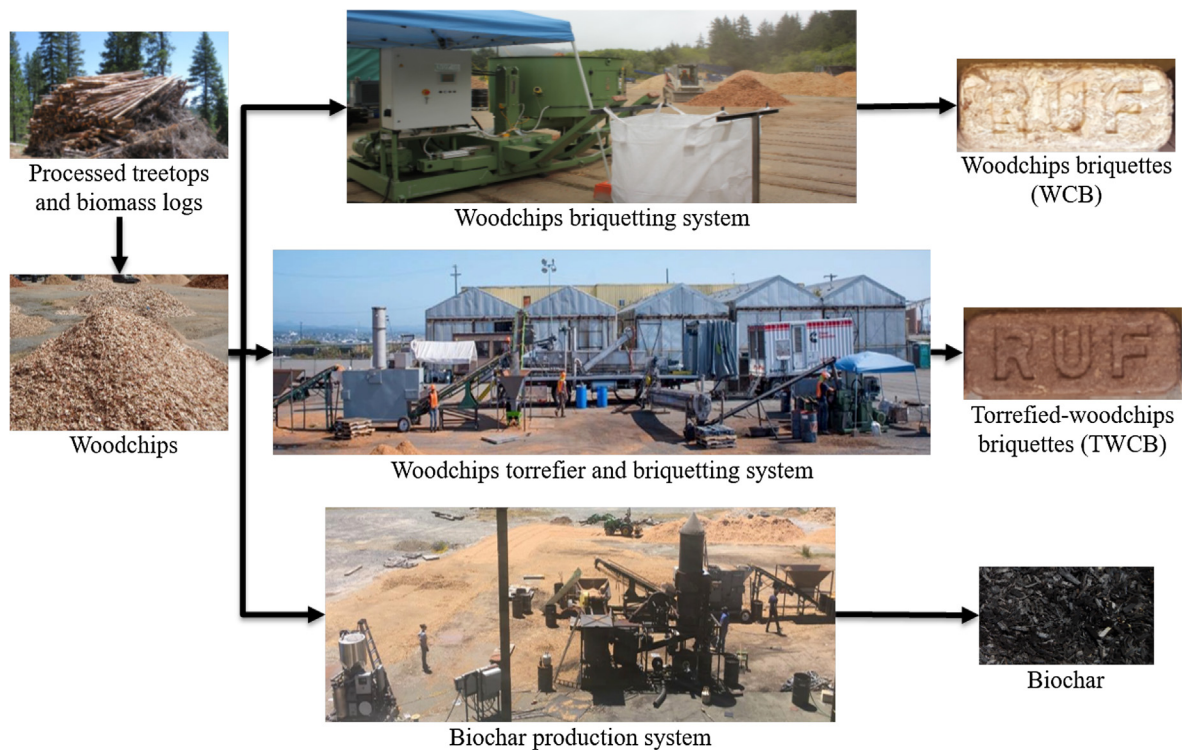
Fig. 1. Biomass conversion technologies (BCTs) used in WTW project.

portions of trees (i.e., treetops, branches, etc.) after removing saw-timber [54,55]. Biomass sorting and treetop processing have been proposed as the best management practice for timberland to handle forest residues [54]; and this generates high-quality feedstocks necessary for efficient production of bioenergy and bioproducts [56]. To conduct a fair comparison among three portable systems, the moisture content of all incoming feedstock was used as 36% (wet basis).

Based on previous studies [54], it was assumed that forest residues would be available at no cost or free at the forest logging site. Cull trees are often required to be felled and removed; tops are hauled to the landing along with the sawlogs. The least-cost logistics option for delivering feedstocks to a BCT site is to process treetops and biomass trees at the forest landing, transport them in log trucks, and chip or microchip the treetops and logs at the BCT site [57,58].

Fig. 2 illustrates the schematic diagram of the products supply chain produced through a portable BCT system using forest residues. There will be few possibilities of electricity grid connectivity near a forest BCT site, thus requiring generators to operate portable systems. In this study, the portable gasifier-based generators were considered to fulfill the electricity demand of each production system. Woodchips (36% MC_{wb}) were dried with a belt-drier to a required moisture content (e.g., WCB and TWCB systems require biomass about 10% MC_{wb} [52,53], and biochar system requires about 22% MC_{wb} [42,50]) using waste heat from the BCT and gasifier-based generator and/or external propane (if required). Dried woodchips were processed to either WCB, or TWCB, or biochar, and then packaged and, stored temporarily before transporting (i.e., 200 km, one-way) to end consumers.

The annual woodchips consumption capacity of a BCT site assuming production of either WCB (with two briquetters), TWCB (with one torrefier and one briquetter) or biochar (with two biochar machines) was about 2800, 2600, and 2300 ODMT of woodchips (36% MC_{wb}) respectively. Table 1 provides specifications for three products manufactured with portable systems.

2.2. System descriptions and technologies

2.2.1. Woodchips briquettes (WCB) system

The W2W project used commercial-scale hydraulic operated presses, (i.e., RUF 440, designed capacity of 0.44 MT/h) to produce WCB from woodchips. Severy et al. [52] provided detailed descriptions of the experiment. Annually, two RUF briquetter would produce about 2800 ODMT of WCB @ 10% MC_{wb}. Fig. 3 shows the mass balance, and heat and electricity requirements for a BCT site producing WCB.

Three gasifier-based generators (20 kW each) were able to generate sufficient electricity for the BCT facility's operations. In addition to electricity, each gasifier-based generator can provide about 20 kW of heat through a heat exchanger (assuming 80% efficiency) [59] which was considered as a source of heat for drying woodchips. High MC woodchips (36% MCwb) were dried to a recommended moisture level (i.e., 10% MC_{wb}) using a conveyor belt dryer [52] with additional propane (if required). The woodchips were then densified into WCB, packed and transported to end users in trucks.
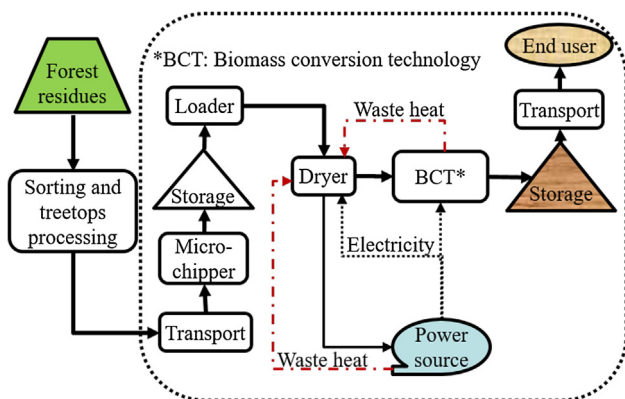

Fig. 2. Process flow diagram and system boundary of a portable biomass conversion technology's (BCT's) supply chain (* woodchips briquette, or torrefied-woodchips briquette, or biochar).

Table 1
Specification of densified solid fuels produced from portable systems.

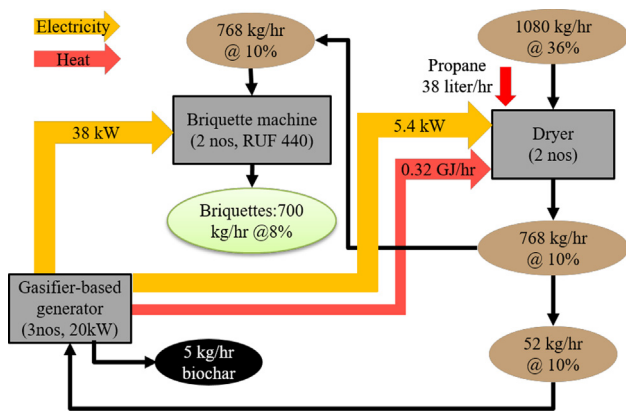| Description	Units	Woodchips briquettes (WCB) [52]	Torrefied-woodchips briquettes (TWCB) [53]	Biochar [50,51]
Product dimensions (length × width × thickness)	mm	152.4 × 63.5 × 109	152.4 × 63.5 × 109	
Mass throughput (output)	kg/h	325	552	75
Packing density	kg/m^3	800	977	105
Energy density	MJ/kg	16	21.2	32.3
Moisture content	(% wb)	8	0.6	2.2

Fig. 3. Mass balance, heat, and electricity requirements for woodchips briquettes (WCB) production at a BCT site using portable systems.

2.2.2. Torrefied woodchips briquettes (TWCB) system

The torrefaction process requires woodchips with lower moisture content and little size variations to produce better-quality products. Severy et al. [53] described the experimental setup and performance of the portable torrefied briquettes production system. The optimal operating conditions for the torrefaction and briquetting were lower moisture content of input feedstock (< 11%), a short residence time (10 mins) with the reactor setpoint temperature between 400 °C and 425 °C [53].

Fig. 4 describes the mass balance, heat and electricity requirements of an integrated torrefaction and briquetting portable system with an annual woodchips processing capacity of 2848 ODMT/year (36% MC$_{wb}$). High MC woodchips can be dried to 10% MC$_{wb}$ (Norris Thermal Technologies, 123B Beltomatic) [50] using torgas from the torrefaction
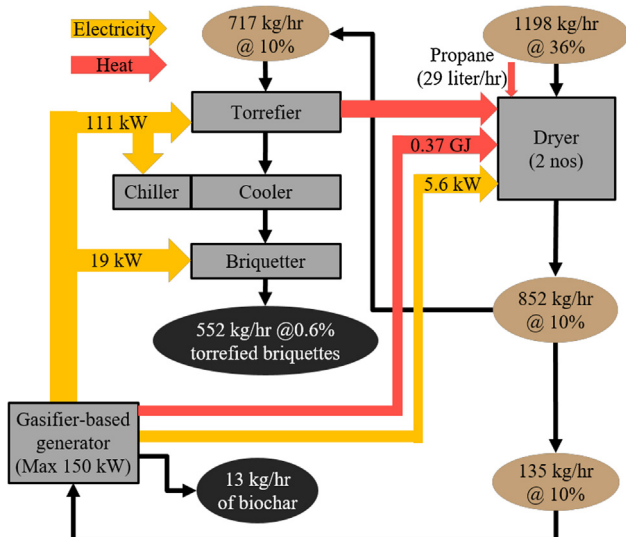
processes (Norris Thermal Technologies, CM600) [53], waste heat from the gasifier-based generator (All Power Lab's Powertainer PT150, 150 kW) [59] and propane (if required). The torgas from the torrefaction process had low energy content that required propane supplement during flaring to initiate and maintain the correct combustion temperature [53].

The mass and energy balance estimation illustrated that the gasifier-based generator and torrefier consumed about 16% (135 kg/h @ 10% MC$_{wb}$) and 84% (852 kg/h @ 10% MC$_{wb}$) of total dried woodchips (input to the production system) respectively. The torrefaction process was able to retain about 85% of the total mass of woodchips [53]. The moisture content of torrefied woodchips was about 0.6%. Following torrefaction, torrefied-woodchips were then cooled with a chiller and densified into briquettes (i.e., TWCB). TWCBs were then packed properly before sending by trucks to the end customers.

2.2.3. Biochar system

Eggink et al. [50] presented an experimental setup to produce biochar from woodchips using an integrated portable system. A biochar machine (Biochar Solutions, Inc.) is able to process about 500 kg/h of woodchips at 36% MC$_{wb}$ to produce about 75 kg/h of biochar at 2% MC$_{wb}$ (Fig. 5). Each integrated system consisted of a biochar machine, a dryer (Beltomatic 123B belt dryer), a cross-flow air-to-air heat exchanger to capture waste heat from biochar machine and a power producing unit [two 20 kW gasifier-based generators from All Power Labs, Inc. [59]].

Two biochar machines and attached dryers consume on average 13.2 (2 × 6.6) and 5.6 (2 × 2.8) kWh respectively to process 1015 kg/h of woodchips (36% MC$_{wb}$) and produce 152 kg/h of biochar (including biochar from the gasifier-based generators) [50]. The power requirements of a biochar system vary widely based on a number of input parameters [42]. Based on the maximum power requirements of the biochar units and their dryers, two 20 kW gasifier genset were considered in this study. The gasifier-based generators used about 3% of total dry woodchips input to the integrated system.
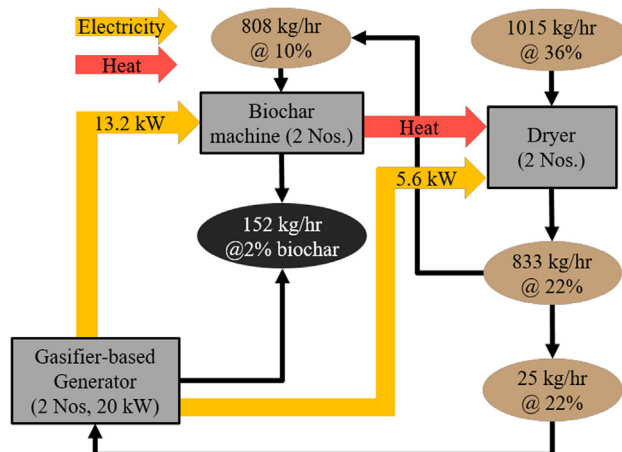

Fig. 4. Mass balance, heat, and electricity requirements of an integrated woodchip torrefaction and briquette production system.

Fig. 5. Mass balance, heat, and electricity requirements of an integrated biochar production system.

2.3. Financial model

2.3.1. Minimum selling price (MSP)

The MSP is the price at which a system's net present value (NPV) is zero, i.e., if a product is sold for the MSP and all the costs and revenues are as projected, the discounted revenue generated will be just equal to total discounted costs over the project's life. Of course, all the assumptions that go into the DCFROR model will have an impact on the MSP. The major general financial assumptions for the DCFROR model were a 16.5% discount rate (nominal, before finance and tax), 6.51% loan interest rate (nominal), 40% income tax rate, and 2% inflation per year (for both costs and revenues) [58,60]. We assume that the initial capital cost is partly financed through debt (40% of initial capital cost with a 5-year loan term) and equity (60%) composing the remainder of the financing and a 10-year project planning period. A declining balance (DB) depreciation of 200% on the assets' values using Internal Revenue Service guidelines was considered here. All capital and operating cost estimates were adjusted to U.S. 2017 dollars using the Chemical Engineering Price of Construction Indices (CEPCI) and the Consumer Price Index (CPI).

The portable system requires a significant amount of time for startup and shut-down each day. For example, the biochar system requires one hour for startup and a half hour for cooldown [50]. To help reduce the portion of non-productive hours, it was assumed that all equipment would be operating 16 h/day (2 shifts × 8 h/shift) and 300 days/year. Furthermore, to allow for start-up, it was anticipated that the BCT operates at 50% of its nameplate capacity in the first year and at 80% from the second year onward. The input cost in the financial models is categorized into the capital cost and operating cost. The capital and operating cost for the three portable systems are presented in Tables 2 and 3 respectively.

2.3.2. Capital cost

Table 2 presents the purchase price, useful economic life, and salvage value associated with each piece of equipment used for producing woodchips briquettes (WCB), torrefied-woodchips briquettes (TWCB), or biochar in a portable production system near the forest. Each site requires a front-end loader to handle the raw materials and products.

Due to the portability of the production system, the costs of site preparation and installation were considered as an annual fixed operating cost. Land purchase or rental cost was not accounted as (i) a portable system will require only a small land area, and (ii) the rent paid for the land near the forest will be very low or negligible. If a price for equipment of a required capacity was not available, we have used a scaling factor (i.e., 0.6) to estimate capital cost for that equipment with respect to the available cost figures for existing equipment.

2.3.3. Operating cost

Operating cost includes all fixed and variable costs associated with the production systems. The fixed operating cost includes annual insurance (1.5% of average annual investment), property taxes (0.2% of the present value of the equipment), repair and maintenance expenses (estimated at 15% of straight-line depreciation), and total cost of relocations (two relocations in a year [41]). Table 3 presents the operating costs considered in this study.

2.3.3.1. Feedstocks procurement.
The feedstock for the portable systems was received from nonmerchantable logs and processed treetop that were transported to the BCT location and microchipped [54,64]. The capacities of the microchippers were much larger than the capacities of the portable BCT systems. Therefore, we assumed that chipping was performed by a third party who would chip a large volume of logs (i.e., 1–2 weeks demands of the portable systems) and store the chips at the site. The estimated cost of chipped forest residues was about $14/ODMT. The input cost of woodchips includes transport cost of small logs ($5/ODMT) and microchipping ($9/ODMT) [57].

Table 2
Capital costs in woodchips briquettes, torrefied briquettes, and biochar production systems.

	No of units	Equipment	Description	Purchase price($)	Economic life (year)	Salvage value (%)	Reference
Woodchips briquettes (WCB)	1	Tractor + loader	Tractor 1023E (22.4 PTO hp) + loader	15,000	10	20	Manufacturer price
	2	Dryer	Beltomatic 123B (3.6 m × 0.69 m)	45,000	25	20	Manufacturer price
	2	Briquetter	RUF 440	105,000	21	20	Manufacturer price
	3	Genset	20 kW, PP20GT gasifier	25,000	18	10	Manufacturer price
		WCB production facility total		*$390,000*			
Torrefied-woodchipsbriquettes (TWCB)	1	Dryer	Beltomatic 123B (3.6 m × 0.69 m)	45,000	25	20	Manufacturer price
	1	Torrefier	Norris Thermal Technologies Biogreen CM600	600,000	10	20	Manufacturer price
	1	Briquetter	RUF 400	105,000	15	20	Manufacturer price
	1	Genset	150 kW, Powertainer-PT150 gasifier genset	150,000	15	10	Manufacturer price
		TWCB production facility total		*$960,000*			
Biochar	2	Dryer	Beltomatic 123B (3.6 m × 0.69 m)	45,000	25	20	Manufacturer price
	2	Biochar machine	Biochar Solutions, Inc., 0.5 MT/h	340,000	10	20	Manufacturer price
	2	Genset	20 kW, PP20GT gasifier	25,000	18	10	Manufacturer price
		Biochar production facility total		*$955,000*			

Table 3
Annual operating costs incurred in different production systems.

Sl no	Descriptions	Units	Woodchips -briquettes (WCB)	Torrefied-woodchips briquettes (TWCB)	Biochar	Comments
1	Feedstocks[a]	$/ODMT	14.0	14.0	14.0	Micro-chipping and transportation
2	Relocations[b]	$/year	20,868	24,460	22,636	Assuming two relocations in a year
3	Repair and maintenance[c]	$/year	8,072	32,912	19,246	15% of SLD
4	Consumables[d]	$/year	74,334	53,132	1,785	Annual usage of diesel and propane
5	Packaging[e]	$/ODMT	5.5	6.1	124.1	[46,61]
6	Finished good transportation[f]	$/ODMT	21.0	20.0	52.0	Estimated, [57]
7	Labor[g]	$/Year	114,904	181,841	181,841	
8	Insurance and miscellaneous[h]	$/2000 hr	5,200	17,100	11,100	

[a] The cost of transportation and micro-chipping were estimated to be $7.0/MT and $3.5/MT assuming 36% MC_{wb} of logs and processed treetops [57].

[b] Relocation cost includes site preparation (leveling and putting gravel), disassembling and assembling of equipment at the site. We assumed a 50×25 m land area was leveled and filled with gravel (@$13/m^2) [62]. For each relocation, the BCT site for both biochar and WCB production facilities require 8 h of assembly and disassembly ($28/h); 4 h of loading and unloading equipment ($100/h) and 50 km of transportation ($2.6/km) and two trucks. However, relocations of TWCB production facility require 12 h of labors for assembly and disassembly, 12 h of loading and unloading.

[c] We have used 15% of SLD (straight-line depreciation) as repair and maintenance cost.

[d] Consumables includes propane (in the exhaust) and diesel (in front-end loader).

[e] Woodchips Briquette packaging cost was $5.5/tonne [61]. Biochar bulk density was 106 kg/m^3. Biochar was packaged in bulk bag (0.76 m^3/bag) and each bag cost $10 [46].

[f] Estimated as mentioned in Sahoo et al. [57].

[g] Labor cost includes basic salary and 35% of fringe benefits [63].

[h] Miscellaneous include unpredictable cost, administrative cost, 10% of annual salaries @80,000.

2.3.3.2. Relocation and site preparation. The cost incurred for relocating the portable system depends on the size of the manufacturing unit, travel distance, and machine and labor hours required for disassembly and assembly of the production system. Polagye et al. [37] noted that the time required for relocating a plant varied from 4 h for a plant with a capacity of 10 MT/day to 2 months with a 500 MT/day capacity. Relocating a portable plant includes the cost of preparation, disassembly of equipment, loading equipment onto trucks, transportation, unloading equipment at the site, and reassembling the equipment.

A land area (40 m × 20 m) can be sufficient for operating a portable system and space needs to be leveled and filled with gravel (@$13/m^2) for proper equipment installation. For each relocation, a biochar and briquetting system requires 8 h of assembly and disassembly (@ $28/h); 4 h of loading and unloading equipment (@ $100/h) and 50 km of transportation (@ $2.6/km); and two trucks. However relocations of torrefied woodchips briquettes portable system requires 12 labor hours for assembly and disassembly, and 12 h for loading and unloading. The annual relocation cost for each portable production system is shown in Table 3.

2.3.3.3. Repair and maintenance. Equipment repair and maintenance consists of fixed expenses, as well as variable expenses that are based on annual usage. While in general, repair and maintenance may be expected to increase as equipment is used and ages, it is also an expense that depends on how individual pieces of equipment are used and on operator skill. Long-term repair and maintenance record datasets are not available for most equipment, and not for the new mobile systems used in the Waste to Wisdom project. As a result, repair and maintenance expenses were assumed as a fixed percentage of a straight-line depreciation calculation over each piece of equipment over its economic life. The percentage was based on repair and maintenance costs observed by Severy et al. [51–53], and Eggink et al. [50]. For example, the estimated labor hours required for maintenance for a biochar, dryer, and torrefaction equipment were about 20, 21, and 90 h per 2000 h of use which can be about 10–20% of annual depreciation cost. Therefore, we assumed a 15% of straight-line depreciation as the annual repair and maintenance cost.

2.3.3.4. Consumables. Diesel was used to operate a front-end loader to load feedstocks into the production systems and to handle final products. It was estimated that the front-end loader uses about 3.7 liters of diesel per working hour [65,66]. While it was estimated that there was sufficient waste heat generated from gasifier-based generators and biochar or torrefaction production processes to dry high moisture content woodchips coming to the system, the WCB production system would require additional external drying heat that can be supplied with propane. In the WCB production system, about 0.32 GJ/h of waste heat from three gasifier generators would be available to dry woodchips. However, each dryer would require about 1.01 GJ of heat to dry 1080 kg of woodchips from 36% MC_{wb} to 10% MC_{wb} (assuming 3.5 MJ of heat required per kg of water removed from woodchips [67]). Therefore, for a wood briquettes system, in addition to waste heat from gasifiers, we estimated that about 38.15 liters/h of propane would be consumed to provide supplemental heat for drying woodchips assuming 80% burner efficiency and a lower heating value of propane of and 26 MJ/l [68]. The RUF briquetters were able to form durable briquettes from both woodchips and torrefied chips without any additional binders. Therefore, the budgeted consumables did not include binders.

Propane was used to maintain the flame during flaring of gases (torgas in the torrefaction process and syngas in the biochar production process) and during daily startup of equipment in torrefaction and biochar production. The torgas produced from the torrefaction process did not burn itself and required external fuel for flaring (i.e., 29 liters/h of propane). Although the syngas produced during biochar production can burn itself, it still requires a small amount of propane (i.e., 1 liters/h) to maintain the flame.

2.3.3.5. Labor. The labor requirement may be different for different products. Biochar production required 0.92 labor hour per machine hour [50,69]. Therefore, we assumed two workers, that is one technician, and one helper/yard worker, would be needed to manage the biochar production facility. Similarly, two workers were considered necessary to operate the torrefied-briquetting unit. Briquetting technology is well established and relatively simple; far more so than either torrefaction or biochar production. Therefore, we assumed only one technician to manage the portable briquetting facility. The annual salaries of a technician and yard worker were assumed to be $52,700 and $30,700 respectively, which include benefits at 35% of basic salary [63,70]. Annual labor expenses for each BCT units are presented in Table 3.

2.3.3.6. Product handling and transportation. The bulk density of the

product dictates its transport and handling costs. Briquettes were assumed to be packed in smaller bags and loaded on pallets. The cost of packing was estimated to be about $5.5 and $6.1/ODMT for WCB and TWCB respectively [61]. Biochar bulk density is about 1/9th that of briquettes and it requires large bags for packing. The estimated cost of packing biochar in bags was $124/ODMT (0.76 m³/bag, $10/bag, biochar density = 0.106 ODMT/m³).

Biomass briquettes and torrefied briquettes also have lower unit transportation costs compared with biochar due to in large part due to differences in bulk density. The estimated transport cost of WCB, TWCB, and biochar were $21, $20, and $52 per ODMT of product respectively assuming a 200 km transport distance [57].

2.4. Sensitivity analysis

The portable systems using BCTs are relatively new and emerging concepts to utilize forest residues to make fuels and bioproducts. The performance of these systems will improve as the technologies grow and mature. Sensitivity analyses of input parameters for the base case portable BCT systems were conducted to determine key input parameter variations impacting each product's MSP. The DCFROR models for each product were simulated by changing the value of one input parameter by ± 20% of base value while keeping other parameters unchanged and measuring the changes in the MSP [66]. The variations of MSP were estimated with respect to positive and negative changes to each input parameter but presented the impact of only a few most sensitive ones as a bar chart and analyzed their scope.

In the field or practical applications, the changes to these input parameters can occur beyond ± 20% and these changes can occur simultaneously to a group of the most sensitive input parameters. Therefore, the maximum or minimum possible variations in the MSP were quantified with respect to the most sensitive input parameters for each product and to suggest possible strategies to achieve lower MSPs.

3. Results

The techno-economic performance of the portable systems used to convert residues into solid biofuels and biochar was evaluated. The financial performance indicators calculated were (i) before financing and tax, (ii) before tax, and (iii) after-tax.

3.1. Mass and energy balance

The mass and energy balances of the studied portable systems are presented in Table 4. Except for WCB, the excess heat is generated after fulfilling the heat requirement for drying woodchips. Higher the

Fig. 6. Contribution of different costs to the total cost of the plant (CAPEX and OPEX before finance and tax).

moisture content of woodchips, the larger is the heat requirement in the dryer system. But both TWCB and biochar systems can accommodate higher moisture content feedstock than in this study (i.e., 36%) without external heat supply. To use excess heat efficiently, a biochar system can be co-located with either a TWCB (utilizing feedstocks with very high moisture content) or a WCB unit, which can reduce the overall production cost for both.

The annual feedstock consumption by the briquetting, torrefaction and briquetting, and slow-pyrolysis (biochar production) systems would be about 2,625, 2,850, and 2,300 ODMT/year of woodchips to produce 2,450 ODMT of WCB, 2,040 ODMT of TWCB, and 535 ODMT of biochar respectively. Note that in the biochar production system, the mass conversion ratio of products to input is much lower (i.e., 23%) than others (i.e., 85% for TWCB and ~98% for WCB).

3.2. Capital and operating costs

The before finance and tax annual total costs [annual operating cost + annualized capital cost] incurred in WCB, TWCB, and biochar portable production systems were $580,000, $790,000, and $720,000 respectively. Fig. 6 shows the contribution of different types of costs incurred in each production system. The contribution of capital expenditure (CAPEX) was low (17–32%) compared with operational expenditure (OPEX) (68–83%). The feedstock cost was about 7–10% of the total cost of the final product.

A substantial portion of the OPEX in all three systems was the labor cost (31–44%) (Fig. 6). The productivity per unit labor of these portable systems was very low compared to that of a large-scale facility. For example, the torrefaction-briquetting portable system produces about 2850 ODMT/year of briquettes with two employees (= 1425 ODMT/employee/year) compared to nine employees for a large-scale torrefied pellet plant with an annual capacity 100,000 ODMT of pellets (= 11,111 ODMT/employee/year) [27].

In the WCB production system, a large portion of the total cost was consumables due to the use of propane to dry high moisture feedstocks (Fig. 6). TWCB and biochar systems use waste heat in drying high-moisture feedstocks and require propane only to burn torgas [53] or to maintain the flame in the flaring unit to oxidize pollutants such as volatiles in the exhaust gas [51].

Biochar packaging was about 12% of total cost (i.e., $124/ODMT) due to its low bulk density (0.1 ODMT/m³) [51] compared to the bulk density of WCB (0.8 ODMT/m³) [52] or TWCB (0.95 ODMT/m³) [53]. The unit transportation cost of biochar was about 2.5 times that of briquettes. But the total annual transportation cost was much lower for biochar compared with briquettes due to the low mass recovery of biochar.

In summary, Fig. 6 shows the different cost segments and their share

Table 4
Mass and energy balances of portable systems.

	WCB	TWCB	Biochar
Woodchips input @ MC 36% (kg/h)	1080.0	1198.0	1015.0
Solid biofuel (kg/h)	700.0	552.0	–
Biochar (kg/h)	4.7[a]	12.2[a]	152.0
Heat required for drying biomass (MJ/h)	1091.0	1211.0	637.0
Internal heat generated (biochar or torrefier) (MJ/h)	–	678.5	6,534.0
Internal heat (gasifier-generator) (MJ/h)	313.0	1658.6	186.0
External heat (propane) (MJ/h)	778.0	568.8	20.0
Heat surplus (MJ/h)	–	(1694.0[b])	(6,102.0[c])
Electricity required (kW/h)	43.6	135.5	20.5
Electricity supplied (kW/h)	43.6	135.5	20.5

[a] Biochar produced from gasifier-based generators.
[b] Includes heat from torrefier, gasifier-based generators, and propane (required to burn torgas).
[c] Includes heat from biochar machine, gasifier-based generators, and propane (required to maintain the flame in flaring unit to oxidize pollutants).
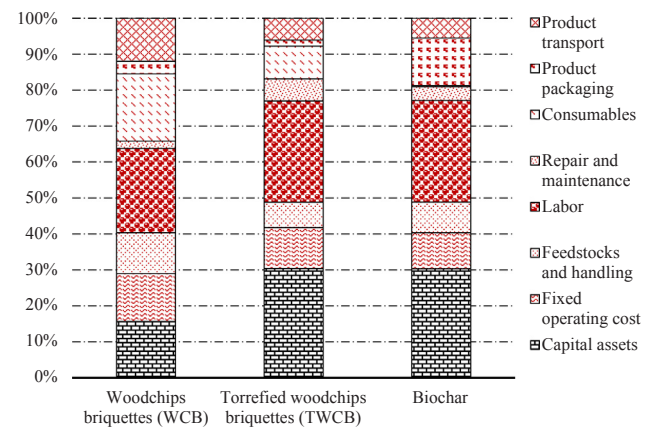
Table 5
Financial performance of portable BCT systems.

		Before finance and tax	Before tax	After Tax
Woodchips briquettes (WCB)	**Total cost ($, $\times 10^6$)**	**$2.2**		
	MSP ($/ODMT)	161.5	153.0	156.4
	Nominal IRR (%)	16.5%	19.8%	14.4%
	Break-even delivered feedstock cost ($/MT)	10.3	23.4	20.1
	Break-even product value [medium-term operating] ($/ODMT)	136.7		
	Break-even product value [short-term operating] ($/ ODMT)	113.2		
Torrefied woodchips briquettes (TWCB)	**Total cost ($, $\times 10^6$)**	**$3.1**		
	MSP ($/ODMT)	274.3	250.8	257.0
	Nominal IRR (%)	16.5%	19.8%	15.2%
	Break-even delivered feedstock cost ($/MT)	10.3	21.0	18.1
	Break-even product value [medium-term operating] ($/ODMT)	190.7		
	Break-even product value [short-term operating] ($/ODMT)	153.7		
Biochar	**Total cost ($, $\times 10^6$)**	**$2.9**		
	MSP ($/ODMT)	1044.2	941.3	962.8
	Nominal IRR (%)	16.5%	19.8%	14.4%
	Break-even delivered feedstock cost ($/MT)	10.3	23.4	20.1
	Break-even product value [medium-term operating] ($/ODMT)	710.1		
	Break-even product value [short-term operating] ($/ODMT)	588.7		

of the total annual production cost for all three portable systems. It helps to identify the most critical segments of these portable systems for improvements to reduce production cost. A detailed sensitivity analysis of input factors provides the specifics and opportunities to reduce cost, which are discussed in the later section of this paper.

3.3. Financial performance of portable BCT systems

The type of financing a project has and its taxes affect a production system's financial performance Table 5 provides the financial performance, including MSPs, of three portable BCT systems. Before finance and tax, the estimated minimum selling prices of WCB, TWCB, and biochar delivered to consumers were $161.5, $274.3, and $1044.2/ODMT respectively. These product MSPs would provide a nominal before finance and tax IRR [internal rate of return, which is a discount rate at which NPV = $0] of 16.5% including 2% inflation.

The MSPs estimated before-tax and after-tax were about 5–10% and 3–8% lower than the MSP for before-finance-and-tax. This illustrates the impact that favorable financing can have on reducing MSP. Alternatively, at a fixed product sales price, favorable financing would increase the owners' rate of return. However loans increase a firm's business risk by obligating cash flows to repay the loan; and the more a firm's cash flows become obligated, the riskier the loan repayment becomes, and the higher the interest rate will likely be, which is not incorporated into the financial model.

Table 5 also provides information about break-even procurement cost of feedstocks and break-even product price, in short, medium, and long-term. For example, if the TWCB selling price is $274.3/ODMT, the plant would be able to procure forest residues at the maximum cost of $18.1/MT and still achieve an IRR of 15.2% (after-tax basis). Similarly, portable production systems for WCB and biochar would be able to afford raw woodchips at the maximum cost of $20.1/MT (including transportation and chipping) to achieve an after-tax IRR of 14.4%. In the short-term, a plant must able to generate revenue by selling products to meet its variable operational expenses. In the medium-term, all operating expenses (fixed + variable), and loan repayment must be covered by selling the product. In the long-term, all of the short-term and medium-term costs must be met, and in addition, the investors must receive at least their required minimum rate of return in order to get capital reinvestment and maintain a vibrant industry. The short-term-MSP (or long-term-MSP) for WCB, TWCB, and biochar were estimated to be 70% (or 85%), 55% (or 69%), and 58% (or 69%) of MSP (before-finance-and-tax) respectively. The portable production systems may hold or stop operation, if the plants are unable to generate enough revenues by selling the products at these MSPs (short-term) to bear the

cost of plant operations.

3.4. Sensitivity analysis

3.4.1. Sensitivity analysis results

Uncertainties and variabilities in the input data and assumptions are inherent factors impacting the financial performances of any portable production system. All inputs to the financial model were changed by ± 20% of mean value and responses in terms of increase or decrease in the MSP were calculated. Fig. 7 presents the impact of the most sensitive input parameters in the model on MSP of WCB, TWCB, and biochar. The moisture content of woodchips is the most sensitive input parameter for WCB. But it was not a sensitive input parameter for the other two products. A large amount of heat energy (i.e., 4 MJ/kg of moisture removed from woodchips) is required to dry high moisture content woodchips. WCB requires external fuel such as propane for drying of woodchips (e.g., 0.0354 liters of propane/kg of woodchips @ 36% MC_{wb}). But the TWCB and biochar systems both generated enough waste heat in the production processes to dry wet woodchips. The MSP of WCB was decreased by 10% or increased by 12.5% by using woodchips at 29% or 43% moisture.

Improvements in burner efficiency (in the dryer) can reduce the MSP by reducing the use of propane during woodchips drying. An increase in the plant throughput by 20% could reduce the MSP by 12–20%. Plant throughput could be increased in a number of ways; e.g., through an improvement in machine throughput, or an increase in working days, or longer working hours in a day, or improved capacity utilization.

A substantial part of a day's working time was lost due to idle time in equipment startup and shutdown, especially for the biochar and torrefaction units. A 24 × 7 operation could reduce non-productive times such as startup and shutdown of equipment and enhance the daily throughput in each portable system. A 20% variation in the capital cost brought about 4–8% changes in the MSP. Feedstock cost was of the least sensitive among all input parameters to the model.

The sensitivity analysis shows wide variation in the relationship between changes in the model input variables and their impact on MSP. In practice, the quantum of variations is different for each input variable. Therefore, the total impact on the performance indicator by an input variable is a combination of its sensitivity and its actual variations from the mean value. For example, the scope of improvement in plant capacity utilization can be at maximum 20% assuming the mean capacity utilization of 80% but this can have a very large influence in changing a product's MSP. On the other hand, the feedstock cost can vary up to 300% or more but this had a very low impact on the
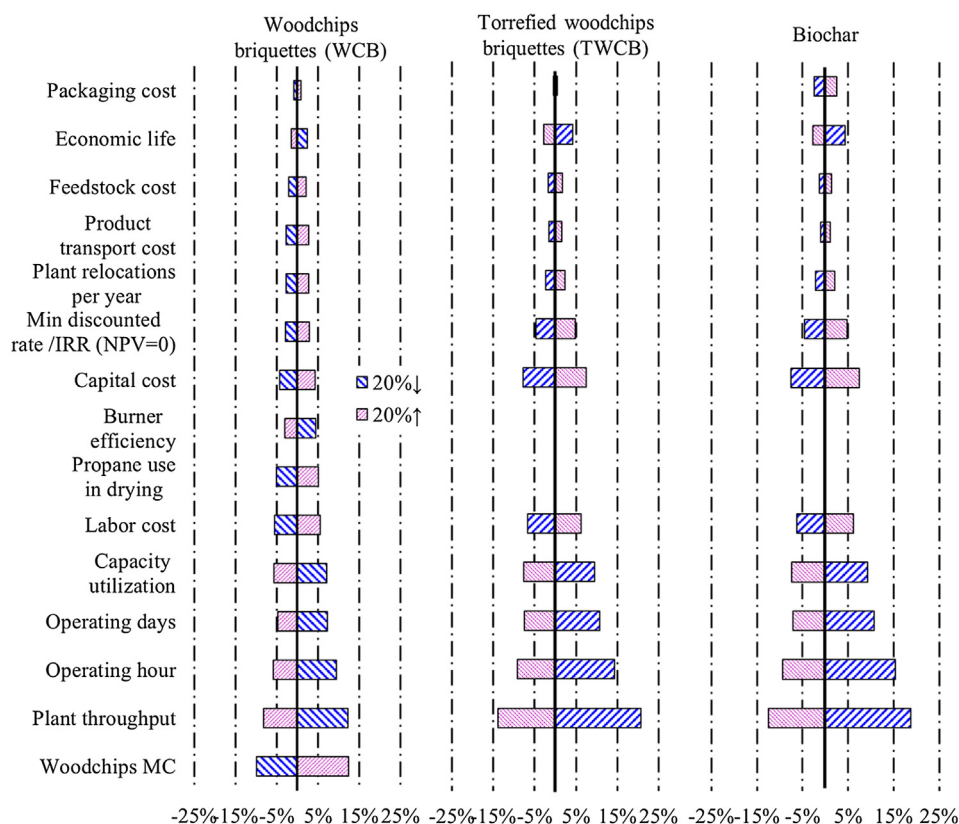
Fig. 7. Sensitivity analysis of input parameters on the minimum selling prices of products.

product's MSP. If feedstock cost increased by 300% (i.e., assuming additional $30/MT of forest residues compared to mean input $10/MT that we used) can push the MSP to a much higher level as estimated here. Therefore, a detailed analysis is required to quantify potential decrease or increase in the MSP considering the influence of input parameters and evidence-based variations of its values in real case studies.

3.4.2. Sensitivity analysis limita tions

While the sensitivity analysis highlights the potential impact of the most critical variables on the MSP and points to facets of the operation that offer the greatest potential for improvement (and conversely the variables that are most critical to achieving a target rate of return), there could be production relationships that exist that are not now included in the models. For example, the sensitivity analysis showed that increasing capacity utilization, perhaps by extending the working day, could reduce MSP. While this would result in better capital asset utilization, there may also be an increase in repairs and maintenance costs that are not reflected in the models that we developed. Extending the workday may result in having to hire and train additional workers, which may, in turn, require higher wages or may result in a loss of efficiency while new workers are learning the operation. Having existing workers work longer days may result in overtime wages and possibly lower productivity in the extended hours.

While we have tried to capture the critical variables and make models that are flexible to changed circumstances, there could be factors that we have not incorporated, so it is better to view our results as guidelines rather than as absolutes.

4. Discussion

Feedstock cost is one of the biggest hurdles for the wide-scale use of forest residues to produce solid fuels and biochar. To counter the high feedstock logistics costs, researchers proposed portable systems [71]

that can vertically integrate the feedstock location to end-use location. In this study, the MSPs of WCB, TWCB, and biochar produced through portable systems were estimated to be about $161.5, $274.3, and $1044.2/ODMT respectively. The MSP of WCB was less than domestic (i.e., $165-$180/ODMT) and export (i.e., $167-$216/ODMT) sales prices for densified biomass [49]. The production cost can decline with an increase in the plant capacity. For example, Chang et al. [72] estimated a $90-$115/ODMT production cost of briquettes including feedstocks cost for a plant capacity of 20,000 MT/year in China. Tumuluru et al. [23] estimated only production cost ($52-$60/ODMT) of briquettes from corn stover was (without considering feedstock cost) for a large capacity (8×10^5 MT/year) compared to $125/ODMT in this study. A previous study in Europe [61] estimated the cost of briquettes production of $161 (considering the exchange rate from Euro to US dollar 1.28 in 2012) similar to this study. Therefore, an increase in the annual production capacity of the portable plant can reduce the estimated MSP of briquettes provided that the equipment size does not hamper the plant portability or mobility.

At present commercial markets for torrefied-densified biomass are either niche [73] or nonexistent [74]. Several studies have shown that the production cost of torrefied-pellets was higher (up to 50%) than white pellets [27,75]. Pirraglia et al. [27] estimated a torrefied-pellets delivered cost of $282/ODMT (production cost was $190/ODMT) for a large-scale plant (100,000 MT/year) assuming input biomass cost of $45/ODMT. The production cost (i.e., $120-$190/MT) of torrefied-pellets varied widely depending on plant capacity and feedstocks cost [27,76]. Brown et al. [47] presented the cost of torrefied woodchips production as $223/ODMT through the portable system (capacity 50 ODMT/day). This production cost can be reduced if the torrefied woodchips can be densified into briquettes. The estimated cost of delivering TWCB in this study is higher compared with torrefied pellets or torrefied-woodchips due to a smaller plant capacity and higher cost of labor. Similarly, market selling price varied due to considerable uncertainties of market demand, feedstocks availability, and technology

maturity [74].

The current market for biochar is limited but diverse. The global market price ($80–13,480/ODMT) of biochar varies widely based on biochar quality and application [77]. The potential demand for biochar is large considering its use as a soil amendment in the agricultural and landscaping sectors. However, affordable prices for biochar use in agriculture will be much lower than other industries considering amounts necessary to show improvements in soil health and productivity, excluding other environmental benefits [39].

For the large-scale production of biochar (723 ODMT of biochar/day), the MSP was estimated to be $346/ODMT with 36% biochar yield [26]. The range of biochar yield (i.e., 36–58%) [78] for the large-scale facility was much higher than small-scale (~24%) or portable systems (~14.1%) [45]. Biochar yield and its quality (i.e., fixed carbon content) are inversely related [42], i.e., low yield may produce very high-quality biochar (fetch high market price [39]) and vice versa. Shabangu et al. [78] estimated biochar MSP of $220–280/ODMT assuming a plant capacity of 0.8 million MT/year and the biochar yield of 56%–26%. Biochar production cost in the small portable system was very high due to the inefficient use of labor, low biochar yield, and diseconomies of scale. For example, previous studies showed operational costs of biochar production using portable systems to be about $450 [45] and $406 [46] per MT of biochar.

A significantly large portion (> 50%) of the biochar production cost was labor [44]. The major reasons for the high MSP of biochar were due to the high labor cost, the low product yield from small-scale systems, and the low annual working hours [46]. The MSP of biochar as well as other products could be reduced by improved technology, yield, and productivity. Different improvements in the technology and productivity are discussed below with optimistic assumptions regarding potential reductions in biochar's MSP. A similar approach can be utilized to estimate the reduction in the MSP of both WCB and TWCB.

Figs. 8 and 9 show the effects of input parameters affecting the MSPs of final products. The largest reduction in the MSP could be achieved by

increasing the daily operating hours from 16 to 24 h. It had been proposed that more than one biochar unit could be used at the BCT site to increase the annual biochar production capacity without compromising on the labor cost [41]. A 20% reduction in the MSP alone can be achieved if five biochar units can be used in parallel at a BCT location. Similar dramatic reductions of MSP could be achieved by improving the biochar machine throughput. Opportunities exist to improve the unit throughput and energy use efficiency as demonstrated by Severy et al. [51]. For example, using a dual auger in place of a single auger to remove biochar from the system could increase the throughput by 45%, and biochar yield by 21%, while decreasing the energy use by 61%. Fig. 8(b) illustrates the possible reduction of the biochar MSP from $1044/ODMT to $467/ODMT if the seven proposed options could be adopted. If biochar is delivered in bulk shipment, an additional cost reduction of $124/ODMT is expected (not shown in Fig. 8(b)).

For TWCB, the most sensitive parameters that could reduce the MSP were similar to biochar except TWCB yield. In the torrefaction process, the mass yield varied from 70 to 90%, which is much larger than the biochar production process. Fig. 9(b) shows the potential reduction of the MSP of TWCB by up to 50% ($270/ODMT), if a series of system improvements can be adopted.

Furthermore, the production cost can be reduced by integrating two different portable systems. Both biochar machine [51,69] and torrefier produce waste heat [53] that can be used either internally or shared between two different portable systems. For example, WCB and biochar production systems could be used at the same location and the excess waste heat from the biochar machine could then be used to dry feedstocks for the portable briquetting system, which would decrease the use of propane and reduce the cost of WCB production. In the future with the advancement of technology and reduction in capital and operational expenses, biochar and TWCB production can be economical and competitive compared with alternatives from fossil-based resources without government subsidies and other revenue sources that may be achieved by monetizing the environmental benefits of biofuels and
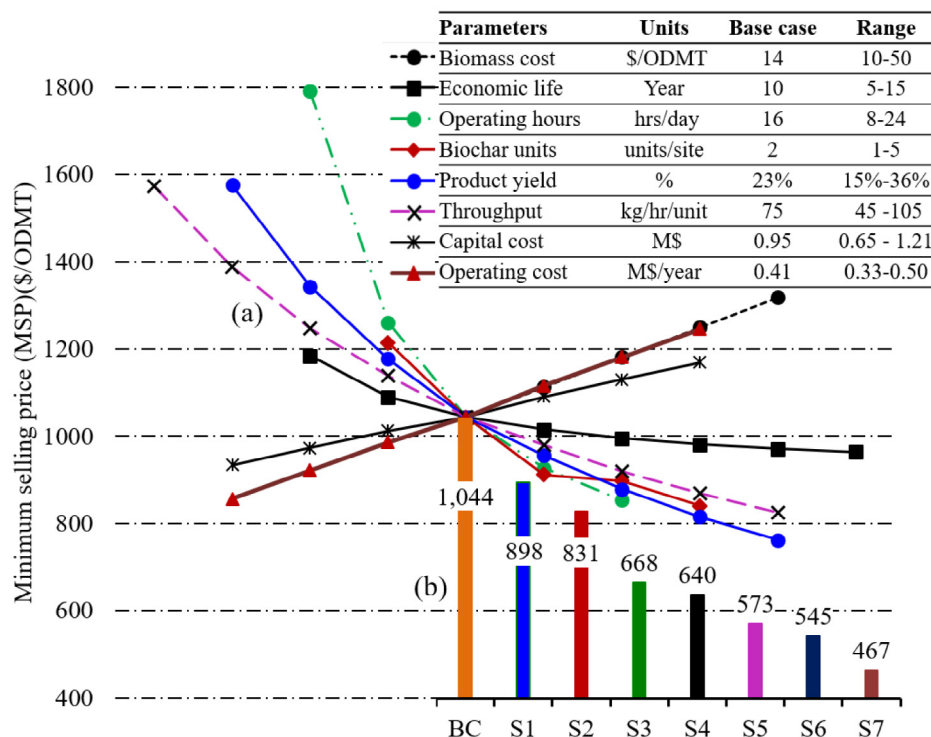

Fig. 8. (a) Impact of variations in the most sensitive parameters on biochar MSP and (b) an example of a reduction in biochar MSP w.r.t. probable improvements. BC: Base case, S1: Biochar yield (24% → 30%), S2: No. of Biochar units (2 → 4), S3: Operating hours (16 → 24 h/day), S4: Economic life (10 → 15 years), S5: Throughput (30% increase), S6: Capital cost (20% reduction), and S7: Operating cost (20% reduction).

BC: Base case, S1: Biochar yield (24% → 30%), S2: No. of Biochar units (2 → 4), S3: Operating hours (16 → 24 hours/day), S4: Economic life (10 → 15 years), S5: Throughput (30% increase), S6: Capital cost (20% reduction), and S7: Operating cost (20% reduction)
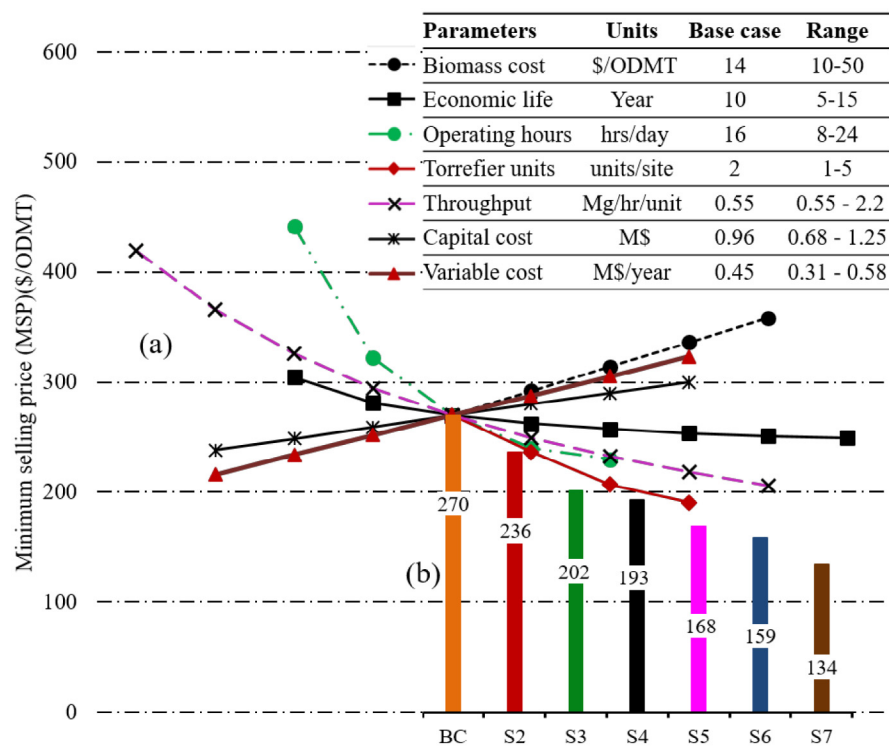
Fig. 9. (a) Impact of variations in the most sensitive parameters on MSP of TWCB and (b) an example of a reduction in MSP of TWCB w.r.t. probable improvements. BC: Base case, S2: No. of torrefier units (2 → 4), S3: Operating hours (16 → 24 h/day), S4: Economic life (10 → 15 years), S5: Throughput (30% increase), S6: Capital cost (20% reduction), and S7: Operating cost (20% reduction).

Parameters	Units	Base case	Range
Biomass cost	$/ODMT	14	10-50
Economic life	Year	10	5-15
Operating hours	hrs/day	16	8-24
Torrefier units	units/site	2	1-5
Throughput	Mg/hr/unit	0.55	0.55 - 2.2
Capital cost	M$	0.96	0.68 - 1.25
Variable cost	M$/year	0.45	0.31 - 0.58

BC: Base case, S2: No. of torrefier units (2 → 4), S3: Operating hours (16 → 24 hours/day),
S4: Economic life (10 → 15 years), S5: Throughput (30% increase), S6: Capital cost (20% reduction),
and S7: Operating cost (20% reduction)

bioproducts.

The MSPs estimated in this study were calculated from the direct revenues from selling products. There are other sources of revenues or credits that may be expected at present and in the future through measures such as the renewable energy certificate (REC) [13,79], low carbon fuel standard (LCFS) [80], etc. The social cost of carbon (in 2007 $/MT of CO_2) was estimated to be about $105 in 2015 and is projected to increase to $212 by 2050 [81,82]. The densified solid fuels (i.e., WCB and TWCB) considered in this study have potential to reduce GHG emissions and may be eligible to earn credits such as REC to support RPS in the United States [83]. The compliance market price of REC has varied widely and reached about $60/MWh in 2015 [79]. The LCFS in the state of California provide credits that varied between $20 and $120 per MT of CO_2 reduction in 2013 and 2016 respectively [80]. There has been strong growth projected for the use of densified biomass [84] in domestic and export markets (15% for the next 5 years from 2017 onwards [85]).

On the other hand, catastrophic forest fires in the U.S. have destroyed millions of hectares of lands and caused a loss of billions of dollars of property and life. There is a consistent increase in the cost of suppressing forest fires. If the government can provide credits to remove excess fuels from forests through thinning or removing forest residues after logging operations, the portable BCT technologies may be able to produce WCB or TWCB for industrial boilers or biochar for agricultural applications can be affordable. The fuel reduction credit, if proposed could also help drive the rural economies by creating new jobs and market for sustainable products, while reducing wildfire risks from forestlands.

5. Conclusions

In this study, the mass and energy balances of solid biofuel and biochar supply chain were estimated using input data from pilot scale experimental setups of portable systems. The discounted cash flow rate

of return (DCFROR) models were developed to assess the financial performances including the minimum selling prices (MSPs) of woodchip briquettes (WCB), torrefied woodchip briquettes (TWCB), and biochar produced from forest residues. The major contributors towards the total production cost of products include the capital investment (17%–32%) and labor (25%-30%). Woodchips drying contributed about 16% of total cost in WCB production due to the requirement of an external heat source, i.e., propane. A large portion of the total cost was due to product packaging and transport in the biochar production due to its low bulk density, i.e., 100 kg/m³. The estimated MSPs (providing a nominal before tax and finance IRR of 16.5%) for WCB, TWCB, and biochar delivered to customers 200 km from BCT sites were $161.5, $274.3, and $1044.2/ODMT respectively. Moreover, with improvements in the system performances, these MSPs can be reduced up to 60% of their estimated values.

The MSP of TWCB was higher than the market price of densified biomass [49] but TWCB has a higher energy content than WCB. If a premium price can be achieved for this premium energy product, then TWCB may be profitable. But the markets for TWCB are still in their infancy. While the biochar's estimated MSP was within the range of current market prices, those prices may come down as markets and technologies develop. Biochar production is economical perhaps for current niche markets but it may require certain additional credits (i.e., carbon credits) for better financial performance before it will be used for the widespread agricultural application. But there are many tipping points to be considered before making a decision about the most preferable options to use forest residues, which include (i) market dynamics, i.e., supply and demand affecting market prices for products [86], (ii) forest owners, who may ask for a premium for selling forest residues, which will increase production costs, (iii) government policies, etc. [60]. Other than economic benefits, the environmental and social benefits may also influence decisions regarding the best options to use forest residues.

In summary, the potential for production of WCB, TWCB, and

biochar using portable systems appears economical and promising. The current study has provided the critical information to all stakeholders and policymakers for a better understanding of the use of forest residues to produce solid biofuels and biochar. Opportunities exist to establish a sustainable forest bioenergy and bioproduct industry in the U.S., if forest thinning will be adopted to mitigate wildfire and offer incentives to produce solid biofuels and biochar from forest residues.

Acknowledgment

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