THE ECONOMICS OF BIOMASS LOGISTICS AND CONVERSION FACILITY MOBILITY: AN OREGON CASE STUDY

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ABSTRACT. *This article presents an analysis of transportable biomass conversion facilities to evaluate the conceptual and economic viability of a highly mobile and modular biomass conversion supply chain in the Pacific Northwest of the United States. The goal of this work is to support a broader effort to more effectively and sustainably use residual biomass from commercial harvesting operations that are currently piled and burned as part of site preparation. A structural representation is first developed to include sources of biomass feedstock, distributed preprocessing hubs (centralized landings), and centralized processing facilities (biomass to product conversion sites) to produce desired products and byproducts. A facility costing model was developed to evaluate potential economics of scale, which then informed the optimization study. A mixed integer linear programming model was developed to characterize, evaluate, and optimize biomass collection, extraction, logistics, and facility placement over a regional landscape from a strategic level to evaluate the mobility concept. The objective was to minimize supply chain operational costs in order to quantify financial advantages and identify challenges of the proposed system modularity and mobility. A Lakeview, Oregon case study was evaluated with an assumed modular biochar facility servicing the region. In particular, we review economies of scale, mobility, energy costs, and biomass availability tradeoffs. This analysis points towards a modular system design of movement frequency between 1 to 2 years being most viable in the conditions evaluated. It was found that the impact of plant movement, scale, and biomass availability can increase supply chain costs by \$11/BDMT (\$10/BDT), \$33/BDMT (\$30/BDT), and \$22/BDMT (\$20/BDT) above the base case cost of \$182/BDMT (\$165/BDT) for a large-scale facility [45,000 BDMT yr^{-1}(50,000 BDT yr^{-1})]in the conditions evaluated. Additionally, potential energy cost savings of a non-mobile modular stationary site as compared to one which utilizes off-grid electrical powers about \$11/BDMT (\$10/BDT) for a biochar facility. From the cases evaluated, a large-scale plant with limited mobility would be preferred under low availability of biomass conditions, whereas a stationary grid-connected plant would be more cost effective under higher availability conditions. Results depend greatly on the region, assumed harvest schedule, biomass composition, and governing biomass plant assumptions.*

Keywords. *Biomass products, Biomass supply, Facility location, Mixed integer programming, Strategic planning, Transportable plants.*

Millions of tons of biomass produced as a byproduct of commercial timber harvesting operations are burned every year (USDOE, 2011). In this study, biomass is a generic term applied to forest harvest residues, a heterogeneous group of woody material left after commercial harvest. Depending upon markets, this biomass can include small diameter trees not meeting mill specifications, noncommercial species, small diameter logs (pulpwood), tree tops, branches, breakage, log defect, and short log sections (long butts) cut off to meet customer specifications. The objective of this research is to help make extraction of this biomass cost effective by bringing a conversion facility for different potential products closer to the biomass source, reducing logistics and transportation costs, and potentially lowering the system costs associated with product production. To accomplish near-woods product production, smaller scale modular units would be used to permit scale flexibility and efficient movement from site to site to leverage the transportable aspect of the system design. The ultimate goal is to convert biomass into marketable products at a low cost, enabling a viable and profitable supply chain for these goods. The production of higher value products (e.g., Biochar, briquettes, and torrefied wood) have been proposed as the markets and technology lend themselves to these operations (W2W, 2016).In this study, we focus on a case study in Lakeview, Oregon, where a hypothetical biochar plant is proposed.

The basic concept of modular, transportable, and mobile bio production facilities and associated supply chains has been studied over the last decade (Polagye et al. 2007; Badger et al., 2010; Brown, 2013; Mirkouei et al., 2015; Mirkouei et al., 2017). This class of facility design can be

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described as transportable where the facility can be transported using multiple trailer loads [90 tonne d^{-1} (100 ton d^{-1}) of feedstock throughput] as compared with purely mobile systems [a single semi-trailer at 9 tonne d^{-1}(10 ton d^{-1})], or a relocatable system [450 tonne d^{-1} (500 ton d^{-1})], requiring a standard industrial site and months of setup (Polagye et al., 2007). As a general rule, facility cost per unit of energy produced (or subsequent product) decreases with the increasing size of the conversion facility (Jenkins, 1997; Dornburg and Faaij, 2001). It has also been shown that the cost of logistics (transportation and material transfer) becomes a higher proportion of the total cost structure as a plant scale increases (Dornburg and Faaij, 2001). The larger the facility, the greater the supply radius, increasing average transportation distance and thus extraction logistic costs. Studies within the bio-energy field have suggested optimal system design ranging anywhere from 30 MW to over 400 MW (235,000 Bone Dry Metric Tonnes (BDMT) per year - 3,200,000 BDMT yr^{-1} [260,000 Bone Dry Tons (BDT) per year - 3,500,000 BDT yr^{-1}] depending on the feedstock availability, plant type, and associated efficiencies (Larson and Marrison, 1997; Kumar et al., 2003; Wolfsmayr and Rauch, 2014; Mirkouei et al., 2015). Cameron (2007) modeled optimal facility size solely a function of facility cost and distance variable cost to facility. Kaznian et al. (2009) and Asikainen et al. (1998) refer to the increase in supply cost with plant scale as the 'scale of operation effect. Caputo et al. (2005) suggested supply costs can be a driving factor and dominate the cost structure even within a plant scale less than 50MW [400,000 BDMT yr^{-1}(440,000 BDT yr^{-1})] due to the total cost structure. In summary, results depend on the underlying landscape and operational conditions with the main benefits of stationary plant being lower overall production costs while transportable solutions are more adaptive under fluctuating and or limited feedstock conditions.

The benefit of a mobile conversion facility is the potential reduced transportation and logistics cost due to higher density biomass product. This reduces transportation and downstream handling costs (Mirkouei et al., 2015; Mirkouei et al., 2016). The Wolfsmayr and Rauch (2014) review of the primary forest fuel supply chain also highlights the importance of material density, material handling and transportation, and their crucial role for economic viability. Common processing options preparing material for transport include drying, chipping, baling and grinding (Gold and Seuring, 2011; Zamora-Cristales et al., 2014). Biomass extraction operations involve the comminution of material in the woods (at the landing), at a central in woods-facility or its shipment directly to a conversion facility. Biomass processing, conversion and transportation technologies, methods and limitations are generally well known with a number of studies analyzing these different supply chain options (Anderson et al., 2012; Zamora-Cristales et al., 2013; Johnson et al. 2012; Wolfsmayr and Rauch, 2014). Other studies and proposed methods for forest biomass operations include the use of hook-lift trucks, dump trucks, as well as baling and bundling (Rawlings et al., 2004; Harrill and Han, 2010; Kash and Dodson 2010; Bisson et al., 2015; Zamora-Cristales et al., 2015). In general, from these studies, there is a trend towards central processing being more economical given the advantages in economies of scale, reduced mobilization, and lower processing costs, though it is site dependent and highly contingent on associated transportation costs.

There have been many supply chain studies within forestry and the broader biofuel fields to optimize processing, transportation, product set, facility location and other key variables (Van Dyken et al., 2010; Cambero et al., 2014b; Troncoso et al. 2015. The most common operations research technique used to solve these problems is generally mixed-integer linear programming (MILP) for exact solutions (Sharma et al., 2012; Wolfsmayr and Rauch, 2014; Cambero et al., 2014a). When evaluating strategic decisions most authors consider aggregated data using a single time period (Holo et al., 2015). The concept of facility location is a mature science that has incorporated objective functions ranging from minimizing overall setup cost, minimizing time/distance traveled, minimizing number of located facilities to maximizing service or responsiveness (Farahani et al., 2010). In particular, there have been significant contributions in biorefinery placement and supply chain product production incorporating many of these same elements as well as economies of scale (Bowling et al., 2011). However, the pairing of optimized and detailed system logistics coupled with transportable scale design evaluating mobility and scale economic tradeoffs has not yet been studied.

The goal was to examine the economic tradeoffs and concepts related to Biomass Conversion Facility (BCT) mobility including: implications of mobilization (e.g., costs, downtime), cost savings related to transportation cost (raw vs. converted), effects of increased energy costs (i.e. off-grid vs. on-grid) and the impacts of smaller scale operations (economies of scale). The impact of biomass residual availability (tons/acre) and site location are also analyzed as they directly feed into the logical framework and cost structure of mobility. These items are first discussed and analyzed in concept and then applied to a specific instance in Lakeview, Oregon. A mixed integer program was developed to quantitatively analyze these impacts using Lakeview, Oregon and a proposed biochar plant as a case study. The model framework incorporating a realistic harvest schedule (biomass availability assumptions), detailed facility costing model (capital, operational and mobilization costs), breadth of supply chain options (transportation, processing and conversion logistics) along with accompanying level of analysis (scale, movement frequency, energy costs and biomass availability) provides a novel look into the technical and economic tradeoffs of transportable facility design.

METHODS

BIOMASS AVAILABILITY

Biomass availability following commercial timber harvest was provided by the University of Washington

Spatial Informatics Group and Rural Technology Initiative (RTI, 2017). This data identified the amount and composition of forest harvest residues from forestlands that are likely to be harvested in the next five years in the Lakeview, Oregon area. The underlying vegetation database is the Gradient Nearest Neighbor (GNN) vegetation layer developed by the USDA Forest Service (Ohmann and Gregory, 2002) using federal inventory data from various sources. The biomass estimation draws heavily from biomass estimates made by Jenkins et al. (2003) and harvest data from University of Montana Bureau of Business and Economic Research (BBER, 2017). It is available to the public as a web-enabled biomass calculator from the Washington State Department of Natural Resources (WDNR, 2017). The spatial data is represented on a per-parcel basis, where the parcel is identified by likely harvest system (informing residual quantity and placement), probable management approach (clear cut, heavy thin, light thin), and assumptions for biomass recovery to roadside. Recovery rates include assumptions about the local pulp market and local evidence for defects and breakage. Pulp wood is calculated as stem wood biomass from 15 to 10 cm (6 to 4 in.) diameter while tops are assumed to be stem biomass less than a 10 cm (4 in.) diameter. Studies typically show overall recovery of biomass in the range of 35% to 70% (of the total biomass left on site after harvesting operations) depending on the residual type, landscape and system implemented (Perlack et al., 2005; Thiffault et al., 2015; Kizha and Han, 2015). In this study, as a base case, we assume there is not an active pulp market and material traditionally meeting pulpwood specifications are not being sold at the market price for pulpwood. In this model, pulpwood type material is available for extraction and generally corresponds to a lower cost of delivery compared to branches. In this study we assume the top material has already been sorted, processed into pulp-like material and is in log-like form that can be transported. All biomass is assumed to be a waste product available at no cost.

Estimated forest residues at roadside are key inputs into the analysis. Pulpwood and top material are the easiest material to handle with the lowest corresponding cost of delivery as they can be transported in log form using conventional short log trailers (Keefe et al., 2014). Due to its lower collection cost, this material would be the first utilized from the forest residue supply. Utilization of branches requires more handling and processing and transportation costs (Keefe et al., 2014). A landscape dominated by pulpwood and tops would likely use a self-loading log truck (i.e., no mobilization and efficient transportation) whereas a landscape dominated with branches would likely involve in-woods grinding at the landing (LX) or central landing (CL) depending on the characteristics of the individual parcel.

BIOMASS CONVERSION TECHNOLOGIES

Feedstock needs to be matched to the biomass conversion technology used (table 1). Acceptable feedstock inputs for the torrefier, briquette press, and biochar machine vary by composition, size, shape, and required moisture content (table 1). In this study we focus on the biochar technology which produces a char-like soil amendment or filtration media thought to have potential market viability (Sasantani and Eastin, 2018). For this biochar analysis, feedstock is assumed to be acceptable without drying. The production units are modular and with no economies of scale with respect to core capital technology costs. For brevity, the term BCT is sometimes used synonymously to refer to the specific biomass conversion technology and to the biomass conversion facility.

FACILITY MOBILIZATION

Facility mobilization costs for a transportable facility are particularly important as they drive the economics of when and how far a facility should be moved in order to balance savings in transportation with mobilization costs. These costs include labor costs for dismantling the systems/units, costs for moving equipment, site preparation required for a new location, and installation and setup costs associated with the move. Labor, time, and supporting equipment requirements for mobilization were estimated using assumptions for the individual biomass conversion technology used and facility type with direction provided by Humboldt State University's Schatz Energy Research Center (SERC, 2017). Supporting equipment, site preparation and moving transportation costs were estimated based on the associated scale and the approximate number of truckloads required. Mobilization costs varied from $60,000 to $350,000 depending on the operating scale (number of modular units and auxiliary equipment required), facility configuration, duration of move and other factors. Previous studies typically reduce the working

Table 1. Capital costs and production rates per module for several biomass conversion technologies provided by Schatz Energy Center (SERC2017).

Machine	Cost Per Module	Input Feedstock	Feedstock Input (BDMT h^{-1})	Output Product	Product Conversion Rate (%)	Product Output (BDMT h^{-1})	Model
Microchipper	$500,000	Log-like material	38	Chips	100	38	Mobark (875 hp)
Grinder	$650,000	Branches/Slash	34	Grindings	100	34	Peterson (1050 hp)
Torrefier	$600,000	Dried microchips	0.61	Torrefied Wood	85	0.44	Norris Thermal Technologies CM-600
Briquette press	$105,000	Dried/Torrefied chips/Grindings	0.34	Briquettes	98	0.33	RUF 400
Biochar machine	$400,000	Chips/Grindings	0.45	Biochar	16	0.05	NA

days per year for a transportable plant (Polagye et al., 2007) but do not directly recognize the interactive dynamics of the landscape in determining the breakeven point between primary transport and facility mobilization costs.

ECONOMIES OF SCALE | PRODUCTIVE CAPACITY

Production facilities are scaled to the design quantity and throughput for a particular market demand to optimize the governing costs and anticipated revenues. When moving a plant, the facility effectively experiences a duration of closure and non-productive time. This unproductive time depends on the facility characteristics itself (e.g. type, scale, etc.) associated with the particular mobilization as well as the number of mobilizations per year. In order to maintain a desired level of annual output, scheduled mobilization downtime must be considered. For example, a 45,000 BDMT (50,000 BDT) input feedstock plant with anticipated five weeks of downtime for moves [5/ (50 wk yr^{-1}) = 10%], would likely need to be designed at a 50,000 BDMT (55,000 BDT) plant capacity in order to fulfill a 45,000 BDMT (50,000 BDT) annual production target (table 2).

FACILITY COSTING | ECONOMIES OF SCALE

Biomass conversion facilities can have significant economies of scale. Previous studies indicate a clear trend towards large stationary installations that benefit from these advantages (Larson and Marrison, 1997; Kumar et al., 2003; Wolfsmayr and Rauch, 2014; Mirkouei et al., 2015). In particular, for torrefied wood plants, the literature suggests plant sizes above 270,000 BDMT yr^{-1} (300,000 BDT yr^{-1}) are the most economical with significant economies of scale starting at 136,000 BDMT yr^{-1} (150,000 BDT yr^{-1}) (Svanberg et al., 2013). This case study concentrates on reducing transportation costs through mobile facilities with a capacity of 13,500 to 45,000 BDMT yr^{-1}(15,000 to 50,000 BDT yr^{-1}). A Facilities Support Costing Model was developed to evaluate economies of scale within our proposed mobile system design range. The costing model was adapted from the Biomass Enterprise Economic Model developed by the Oregon Wood Innovation Center and modified to represent mobile conversion facility designs for six BCT technology configurations: Biochar, Torrefied Wood, Briquettes, Biochar and Briquettes, Torrefied Wood and Briquettes, and Torrefied Briquettes. The analysis is limited to specific equipment studied by the Schatz Energy Laboratory and may not be representative for other specific machines or technologies producing similar products.

Because production is assumed linear to the number of modules, there are no assumed unit sizing economies of scale. However, the economics of site development, support equipment, operating labor, electrical load, and facility housing are scale dependent. We first address the scale dependent capital and operational costs and then add the modular BCT costs for the core biomass conversion technology as an operational ‘conversion’ cost. This separation between BCT supporting costs and BCT core technology allows development of a model that can be easily adapted to alternative BCT technologies, operating strategies, and internal electrical demands.

Rather than use a scale factor to describe the cost difference between different scales (Jenkins, 1997; Flynn et al., 2003; Svanberg, 2013), a more detailed approach based on project estimates and specific knowledge of conversion technologies was used (fig. 1). Operational expenditure (OPEX) costs follow a general power relationship over the time horizon signifying significant cost savings on a BDMT basis from small to large scale on the order of \$33-44/BDMT (\$30-40/BDT). Additionally, there is small variation between different product configurations as they required similar operating infrastructure in order to handle the overall throughput.

Similarly, we observe a decrease in capital cost per unit input as scale increases, though less dramatic (fig. 2). This scale effect was on the order \$5.5-11/BDMT (\$5-10/BDT) depending on system discussed. Figure 2 does not include capital or maintenance expenses related to the BCTs themselves. This is captured within product conversion cost estimates. The costs included overhead, auxiliary supporting equipment, and capital expenditures (assuming a 10 year payback horizon) on a per BDMT basis.

These curves can be approximated by a power regression over the anticipated range of influence. For biochar they are:

$$\text{OPEX (\$/BDMT)} = 1772 \times (\text{BDMT yr}^{-1})^{-0.28} \quad (1)$$

$$\text{CAPEX (\$/BDMT)} = 983 \times (\text{BDMT yr}^{-1})^{-0.46} \quad (2)$$

TRANSPORTATION AND LOGISTICS

Potential cost savings in transportation logistics drive the financial case for mobility. Biomass (e.g. tops, branches or mixed) when transported in its raw form can be cumbersome, inefficient and subsequently costly when compared to the final product. In raw form, forest residues are less compact, have a higher moisture content, and are in a form less organized for moving and handling. The transportation cost depends on the form of biomass (type, moisture content), truck/trailer the biomass is transported in (capacity, operating cost) and overall transportation

Table 2. Effective plant scale as a function of the number of relocations in a year.[a]

		Number of Moves and Effective Plant Scale (BDMTyr^{-1})[b]						
Base Scale	Base BDMT	1	2	3	4	5	6	% Diff/Move
Large	45,400	47,200	49,000	50,800	52,600	54,400	56,200	4%
Medium	27,200	28,000	28,800	29,700	30,500	31,300	32,100	3%
Small	13,600	13,900	14,200	14,400	14,700	15,000	15,200	2%

[a] Downtimes of 1 week (small scale), 1.5 weeks (medium scale), and 2 weeks (large scale) are assumed. The percentage column indicates effective incremental scale adjustment per mobilization.

[b] BDMT $yr^{-1}$is a function of the duration of downtime with respect to each scale observed, where BDMT yr^{-1}= Base Scale + No. of moves×(weeks per move) ×weeks per $year^{-1}$

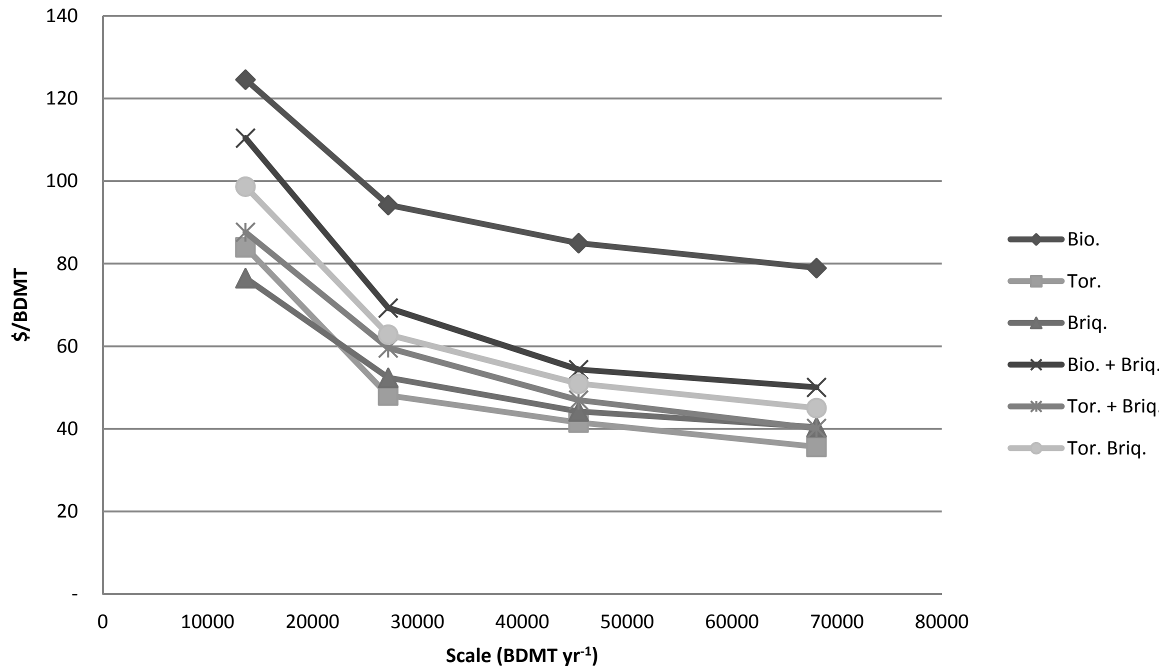

Figure 1. Core operational expenses [plant labor costs, power, insurance, supplies, maintenance, etc. (less conversion technology operating expenses beyond labor)] vs. plant scale (BDMT yr^{-1}). As plant scale increases operational expenses (per unit input) decrease.

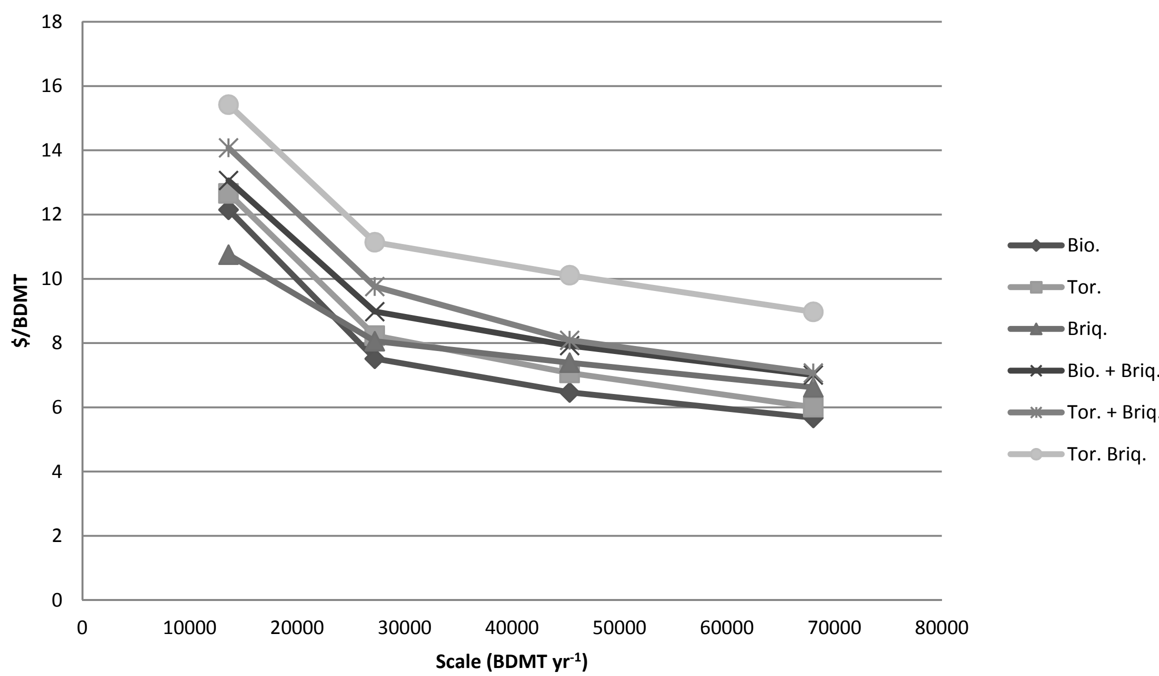

Figure 2. Core capital expenses [site prep, technology, MRS&R, mechanical installs (less conversion technology capital costs)] vs. plant scale (BDMT yr^{-1}). As plant scale increases capital expenses (per unit input) decrease. A 10-year facility service life is assumed.

distance. Analysis for the cost of transportation assumed a 30% moisture content (wet basis), and several raw and converted transportation options [short log truck, hook lift truck, chip van (traditional and rear-steer), bale truck, and on-highway conventional flatbed trailers] and pathways corresponding to typical Pacific Northwest operation logistics (table 3). Assumptions for truck loading and supporting equipment utilization are embedded within this framework and are accounted for via variable and fixed costs along the route/pathway selected.

We assume the forest residues have been previously sorted at roadside during harvesting operations into log-like material (i.e., tops, non-commercial species, breakage) and branches in order to maximize biomass transportation and processing efficiencies. In general, forest residues could be processed at the roadside landing, at a central landing, at the BCT, or burned on site (fig. 3). Central landings function as hubs that serve as transshipment or switching points for transportation networks. The purpose of the centralized landing is to provide an opportunity to increase product density while minimizing mobilization costs for the comminution equipment and are located where large trailers can access the site. Campbell (1994) solves the general hub location problem using integer programming. At the strategic level, we assume each central landing serves four supporting harvest units at an average distance of 2.4 km (1.5 miles) from the originating harvest unit following results from Bisson et al. (2015). Each logistic configuration is assigned an associated pathway/route and transportation option (tables 3 and 4).

The estimated cost of transportation of these biomass classes by system are based on volumetric and weight capacities as well as a 30% assumed moisture content (wet basis) (table 4). In this study we assume self-loading log trucks, rear-steer chip vans, bale trucks (flatbed truck), and bin trucks can access any landing whereas traditional chip vans can only access centralized yards. Converted product transport consists of products being transport on a flatbed truck by super sack (biochar) and pallets (briquette and torrefied briquette) or in bulk with a chip an (torrefied wood).

The highest cost raw material transport options are from the local harvest unit (via bin truck) to the central landing at nearly \$3/BDMT-km (\$4/BDT-mile), however these high costs may be offset by savings in mobilization costs due to collective processing at centralized locations, improvements in grinder/chipper utilization, and reductions in landing-to-landing equipment moving costs. The selected transportation option also depends on the volume of biomass at each landing, loading/unloading efficiencies and haul distance. Transportation cost by product are more than an order of magnitude lower than transporting loose branches and tops, varying from (\$.06 to \$.13 per BDMT-km) (\$.08 to \$.19 per BDT-mile) when considered on an equivalent forest residue dry tonne basis (table 4).

ELECTRICAL ENERGY COSTS

A major component of the overall cost structure is the energy required to run a conversion facility (plant).Using the Facility Costing model and core BCT technology specifications, energy requirements for production were evaluated. Energy demands, which vary based on the technology employed, were examined for on-grid versus off-grid power assumptions. The BCT units themselves consume power but the system as a whole needs a variety of additional supporting conveyors and systems that require

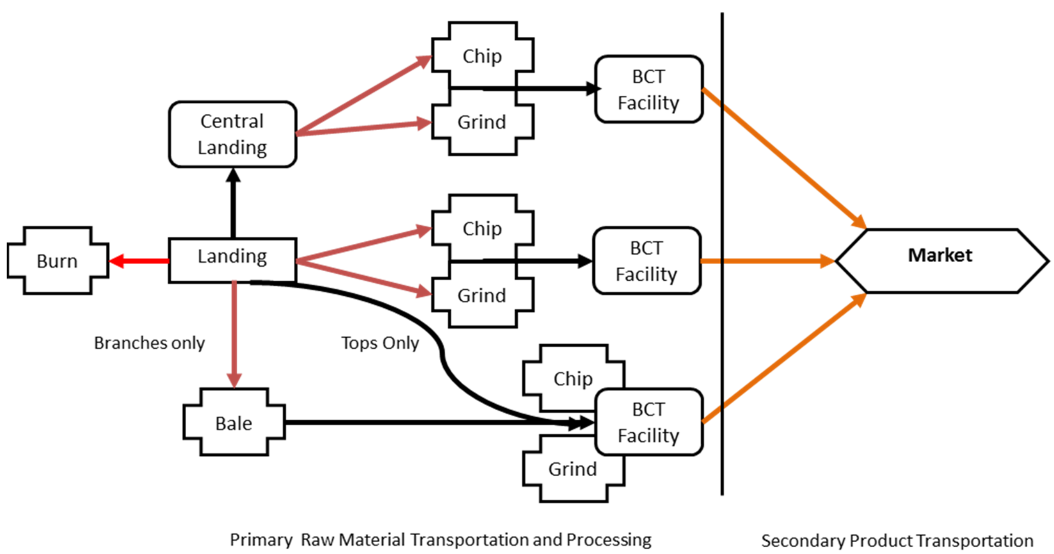

Figure 3. Supply chain pathways originating from landing (LX), converted at the biomass conversion facility (BCT) and sent to market. Black lines indicate raw material transportation options, red indicate processing options and orange lines indicate product transportation.

Table 3. Pathways originating from landing per commodity class (logs, branches) along with associated transportation options.

Commodity	Logistic Configuration	Primary/Secondary Transportation
Logs/Tops	T1: Chipped/ground at the site then transported to BCT	Chip van
	T2: Sent to Central Landing (CL) for processing then to BCT	Bin truck/Chip van
	T3: Hauled to biomass conversion facility (BCT)	Self-loading short log truck
	Burned on site	
Branches	B1: Ground at the site then transported to BCT	Chip van
	B2: Sent to Central Landing (CL) for processing then to BCT	Bin truck/Chip van
	B3: Baled on site then sent to BCT for processing	Bale truck
	Burned on site	

Table 4. Transportation characteristics and costs for transport. Table includes raw material transport (branches, chips, grindings) and converted product transport (biochar, briquettes, torrefied wood) corresponding to route (pathway) selected.

	Raw Material Transport					Converted Product Transport				
	Self-Loading Log Trk	Chip Van	Chip VanRS[a]	Bin Truck	Bale Truck	BioChar	Torrefied	Briquette	Torr. Briq.	
Route	LX-BCT	LX-BCT	LX-BCT	LX-CLX	LX-BCT	BCT-MKT	BCT-MKT	BCT-MKT	BCT-MKT	Units
Load/unload time[b]	0.5	0.5	0.5	0.1	0.5	0.3	0.3	0.3	0.3	hours
Speed avg.	32	32	32	16	32	72	72	72	72	km h^{-1}
Capacity, GT	22.7	22.7	22.7	13.6	22.7	22.7	22.7	22.7	22.7	Green tonnes
Capacity, BDMT	15.9	15.9	15.9	3.8	15.9	8.0	20.4	20.4	20.4	BDMT
OP. cost	108.4	89.0	106.8	80.3	94.2	100.0	110.0	100.0	100.0	$/h[c]
Transp. cost:	0.43	0.35	0.42	22.62	00.37	00.06	00.12	00.13	00.10	$/BDMT-km (round-trip)

[a] ChipVan Rear Steer trailer assumed to be a 20% premium over a conventional truck tractor chip van.
[b] Route: From - To, where: Landing (LX), Central Landing (CL), and Biomass Conversion Facility (BCT).
[c] Raw material transport modeled as $/SMH to best account for utilization, converted material transport modeled with an estimated $/PMH assuming 85% utilization.

electrical power. The composite electrical power requirements vary greatly by BCT configuration and scale. Additionally, the cost of electrical power varies with source (grid, diesel, biomass gasifier) as well as by State. Electric power costs are considered separately from other costs as grid access is tied specifically to a BCT location. Portable wood gasifiers, with a lower carbon footprint than diesel, are an alternative to diesel generation, but have a higher kWh cost and are not considered in this study.

Assuming an industrial electrical energy cost of $0.058/kWh in Oregon, fuel prices and using rental rates for a diesel generator we can calculate the approximate electricity costs for on-grid vs. off-grid operations (Professional Engine Systems, 2017; U.S. EIA, 2017) (table 5). Off-grid generator costs were assumed to range from $0.33/kWh if diesel fuel prices were $0.53/L ($2.00/gal) to $0.52/kWh with fuel prices of $1.06/L ($4.00/gal) (table 5).

Based on these assumptions coupled with our core BCT technologies and auxiliary power requirements from the plant itself, we developed costs/BDMT for electricity based on the different plant configurations in Oregon assuming 24 h d^{-1} facility operations (table 6).

The electricity costs vary significantly depending on plant configuration and the assumed fuel costs. In particular, we see that the base torrefaction technology considered in this study (utilizing an electrically heated screw) would likely be inappropriate for a mobile setting given its high power consumption when compared to a similar-size combustion unit [up to an additional $110/BDMT ($100/BDT) over installed electricity]. For a large-scale biochar plant in Lakeview, Oregon, with an assumed diesel price of $0.87/L ($3.27/gal) we can expect a cost savings of around $11/BDMT ($10/BDT) in energy costs for a stationary plant connected to the grid as compared to a diesel generator (interpolated from table 6). The overall range of potential energy savings due to a grid-connection depends on configuration and fuel price and can vary from $9/BDMT to $110/BDMT ($8/BDT to $100/BDT). Thus, electrical energy availability needs to be part of the calculus in considering alternative BCT locations, whether stationary or transportable.

Table 5. Electricity costs: on-grid electric vs. off-grid diesel generator ($/kWh) using a low and high cost for off-highway diesel fuel.

	Grid Industrial	Off-Grid Diesel (low) $0.53/L	Off-Grid Diesel (high) $1.06/L
Energy Price ($/kWh)	0.058	0.33	0.52

MATHEMATICAL MODEL

The problem is a multi-commodity, multi-facility problem where material can flow from a parcel (harvest unit) to any number of conversion facility locations (BCTs) and then to a single final market for distribution (figs. 4 and 5) that would most likely represent a railhead or port. In this study we assume the final market to be the town of Lakeview, Oregon which has access to both a local market and rail transportation. Incoming material is processed and converted along the network through a range of simplified most likely pathways (fig. 3). The network is solved using mixed integer linear programming (MILP) to identify the optimal set of pathways from harvest units to market. To address the nonlinear impacts of costs on scale, the MILP is solved at alternative scales and a post solution adjustment is used to take into account the number of facility moves over the planning horizon. Alternative BCT configurations are evaluated in separate runs. Some researchers have used disjunctive programming introducing additional binary

Table 6. Total electricity cost: on-grid electric vs. off-grid diesel generator ($/kWh) assuming a large facility operating at 45,000 BDMT (50,000 BDT) of feedstock input/year.

	Throughput (tonnes/h)	h/yr	Units Req	kWh/ unit [a]	BCT Power Req mWh	Aux kWh Req	Aux PowerReq mWh	Total Power Req	$/BDMT Low- Grid	$/BDMT Low Off-Grid	$/BDMT High-Off Grid	$/BDMT Per 10¢/kWh[b]
BioChar	0.45	6000	17	6.0	612	140	840	1,452	1.92	10.62	16.51	3.20
Briq.	0.34	6000	23	18.9	2,608	135	810	3,418	3.45	25.00	38.87	7.93
Torr.	0.61	6000	13	129.0	10,062	165	990	11,052	13.31	80.83	125.66	24.85

[a] Electrical power required for each conversion technology modular unit.
[b] Relative cost (per input BDMT of input feedstock) of an additional $.10/kWh paid for electricity.

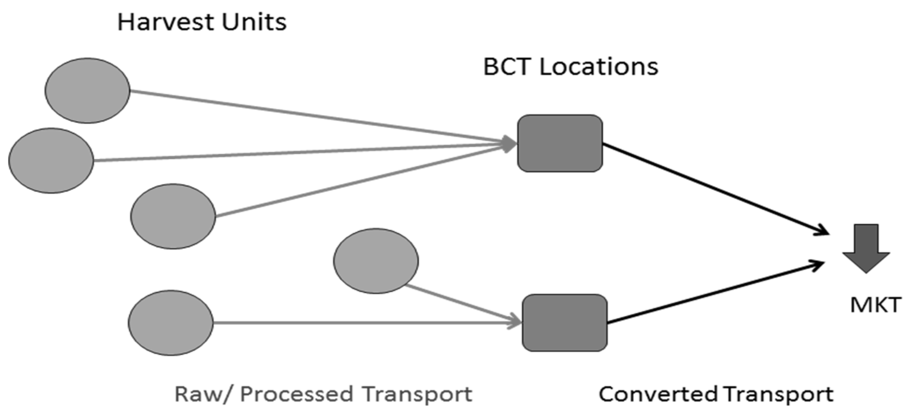

Figure 4. Overview of supply chain. Multiple harvest units service each potential BCT location.

variables to trigger costs by scale or configuration (Bowling et al., 2011; Rodriguez et al., 2016). The mathematical model uses biochar as its example product due to recent high interest in the potential U.S. biochar market which is estimated to reach $5 billion/year in the near term (Delaney, 2015) with speculation that wholesale price at commercial production levels would be near $1650/tonne ($1,500 per ton) (*Biofuels Digest*, 2017). Other biomass conversion technologies were modeled similarly but not presented in this article.

Each model instance incorporates a single five year period, a fixed scale and a single product type (biochar). Additional underlying assumptions are that the forest residues have been previously sorted, log-like material is be chipped, branches ground and there are four potential pathways for each material class from each parcel (also see fig. 3). These pathways generally include 1) burning the material, 2) grinding/chipping/baling at the parcel level with transport of the densified material to BCT, 3) grinding/chipping at a central landing (transport raw material from LX to CL then transport processed material to BCT), and 4) transport biomass from landing LX to BCT with processing at the BCT.

The objective is to minimize operational expenses:

$$\sum_a \sum_i \sum_j \sum_k \sum_m (C_{aijkm} * X_{aijkm}) + \sum_a \sum_i \sum_j \sum_k \sum_m (CONST_{ik} * XBIN_{aijkm}) + \sum_j (BCTmobe * JBIN_j) \tag{3}$$

Subject to:

$$C_{aijkm} = TRAW_{aij+}TCONV_{jm} + CC_j + SEC_{ak} + PRO_{ak} + PRE_{ak} + TLC_{ak} \quad \forall a \in A, \forall i \in I, \forall j \in J, \forall k \in K, \forall t \in T \tag{4}$$

$$M * XBIN_{aijkm} \geq X_{aijkm}, \quad \forall a \in A, \forall i \in I, \forall j \in J, \forall k \in K, \forall m \in M \quad XBIN(0,1) \tag{5}$$

$$M * JBIN_j \geq FLOWJ_j, \forall j \in J \qquad JBIN(0,1) \tag{6}$$

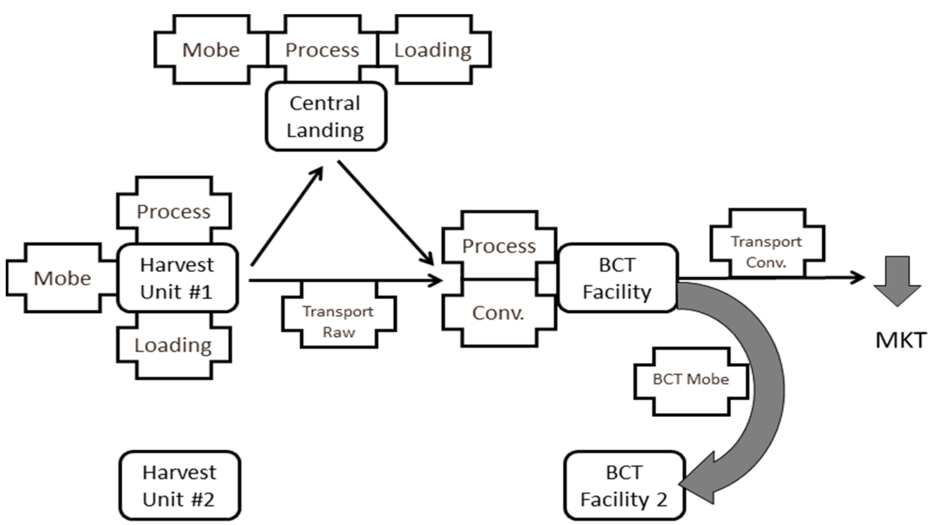

Figure 5. Overview of cost and process structure embedded within the optimization solver. Material from harvest unit is modeled through to market and includes elements of processing, mobilization, transportation, loading, conversion, and BCT mobilization. Each BCT location draws from multiple harvest units with BCT locations moving throughout the landscape.

where

$$\sum_a \sum_i \sum_j \sum_k \sum_m X_{aijkm} = FLOWJ_j, \forall j \in J \quad (7)$$

$$\sum_j FLOWJ_j \le Q \quad (8)$$

$$\sum_j JBIN_j = Nmoves \quad (9)$$

Where key parameters and values include:

X(*a,i,j,k,m*)	Decision Variable – Allocation of residual *a*, from node *i*, to BCT *j*, along route *k*, to market *m* (BDMT)
C(*a,i,j,k,m*)	Total cost for residual *a*, from node *i*, to BCT *j*, along route *k*, to market *m* ($/BDMT)
TRAW(*a,i,j*)	Raw/processed material transportation costs of residual *a* from node *i* to BCT *j* ($)
TCONV(*j,m*)	Converted material transportation costs from BCT *j* to market *m* ($)
CONST(*i,k*)	Construction/mobilization costs associated with node *i* taking route *k* ($)
BCTmobe(*j*)	Mobilization costs of setting up BCT *j* ($/each)
PRO(*a,k*)	Processing cost (grind/chip) for each residual *a* along route *k* ($/BDMT)
SEC(*a,k*)	Supporting equipment cost (loader, etc.) as sociated with each residual *a* along route *k* ($/BDMT)
PRE(*a,k*)	Pre-Sorting/arranging cost associated with each residual *a* along route k ($/BDMT)
TLC(*a,k*)	Transportation loading/waiting cost for residual *a* along route *k* ($/BDMT)
CC(*j*)	Conversion costs of producing material at BCT *j* ($)
M	Large number for logical trigger
material(*i*)	Material available at node *i* (BDMT)
XBIN(*a,i,j,k,m*)	Binary value –unique route
JBIN(*j*)	Binary value –conversion facility location
FLOWJ(*j*)	Sum of material to each BCT *j* (BDMT)
Q	Plant scale capacity over time horizon (BDMT)
Nmoves	Number of BCT *j* locations utilized

Equation 4 sums the costs along each pathway. Equation 5 sets the binary variable equal to one if a pathway is used. Equation 6 sets the binary variable equal to one each time a conversion facility is used. Equation 7 sums the flow to each conversion facility. Equation 8 limits the flow at any conversion facility. Equation 9 sets the number of mobilizations made over the time horizon. The model is run for a range of mobilizations. Lost production during facility mobilization is accounted for with a post-solution facility capacity cost adjustment (fig. 8).

APPLICATION AND STUDY AREA

The model was applied to a case study in Lakeview, Oregon, with a range of 13,500-45,000 BDMT yr^{-1} (15,000-50,000 BDT yr^{-1}) assuming a biochar facility. Estimated harvest schedule (and associated biomass availability) unique to the Lakeview region was generated for this study. For this particular instance of the problem, the base scenario used 1850 unique parcels, 15 potential BCT locations, and a single market location (Lakeview, Ore.). Four cases are analyzed: Case 1 the base case transportable plant, Case 2 varying scale, Case 3 varying biomass availability, and Case 4 a comparison to a permanent BCT facility with grid electrical power.

All model scenarios use the same base regional harvest schedule which included 1850 parcels [within a roughly 225 km (140 mile) aerial radius of Lakeview, Ore., identified to be likely harvested within the next five years] representing almost 1.9 million tonnes (2.1 million tons) of potential residual forest biomass. The average parcel size is roughly 21 ha (52 acres) averaging 60 dry tonnes ha^{-1} (22 dry tons $acre^{-1}$) of biomass available at roadside. Roughly 49% of this material is log-like, 45% is branches and 6% are small tops and breakage. Fifteen potential BCT locations were identified based on site access and biomass availability in the Lakeview area with the market at Lakeview, Oregon (fig. 6).

RESULTS AND DISCUSSION

The underlying mobility logistics (i.e., mobilization costs, move frequency, transportation costs and assumed distances) were analyzed along with comparisons of energy costs, economies of scale and the impact of differing levels of biomass availability that would impact economic viability of a transportable versus stationary facility.

CASE 1: BASE CASE SCENARIO

For the base case scenario, the optimal solution extracts only pulp/top wood from the landscape. Given the previous material sorting coupled with the relative large quantity of biomass available [~60 tonnes ha^{-1} on average (~22 tons $acre^{-1}$)] the most cost-effective solution leaves branches to be disposed of by burning. The optimal number of times to move the BCT (given a large-scale facility assumption and our assumptions for potential BCT site locations), would be four times over the five year time horizon (one initial move in and then three subsequent moves) or a frequency of moving once every 15 months.

The optimized cost structure for producing a biochar product (including all components and plant/technology investment) at the 45,000 tonne level (50,000 ton) is $182/BDMT ($165/BDT) (table 7) of woody biomass input or approximately$1140/dry tonne (1035/dry ton) of biochar product produced (assuming a 16% product conversion). The main cost drivers are associated with the supply chain operations are plant capital and operating costs, along with conversion unit costs followed by a suite of the associated costs including processing material, pre-sorting material, mobilizing the facility as well as transporting raw material

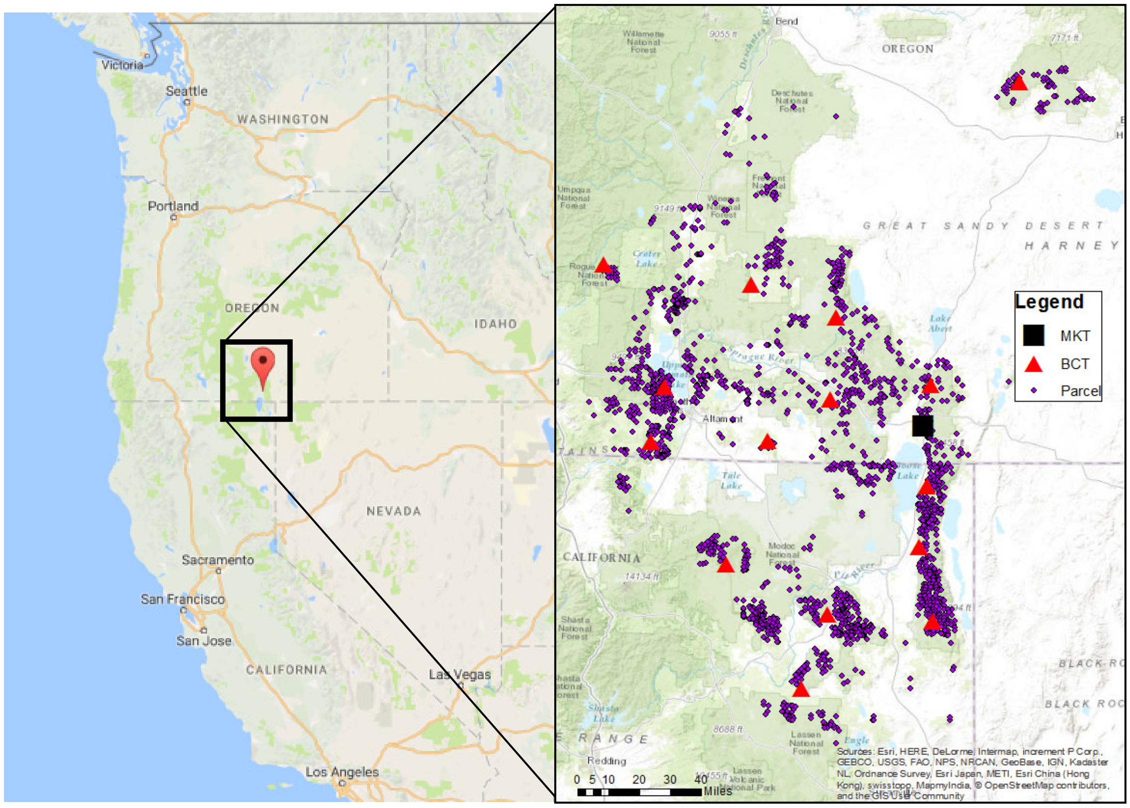

Figure 6. Vicinity map of Lakeview, Oregon (left), Geo-Referenced parcels, BCT and market locations in the Lakeview, Oregon area (right).

to the BCT facility and converted material to the market itself (fig. 7). For the optimal number of four transportable plant moves, the effect on scale due to move time is small, but becomes more significant should the number of moves increase potentially amount to \$3.3/BDMT (\$3/BDT) for 15 moves during the time horizon (fig. 8).

Transportable facility movement cost structure changes due to mobilization cost, scale efficiencies, raw material transport, and biochar product transport alterations. In this example, the tradeoff between these costs resulted in nearly \$11/BDMT (\$10/BDT) of input feedstock (fig. 7). For the optimized case 45% of the mobilization and transportation cost of biochar production cost was associated with raw material (log) transportation at an average of 16 km (10 miles), 30% of the cost being biochar product transport at an average of almost 180 km (110 miles) and the four mobilizations accounted for roughly 25% of this cost (fig. 8). The overall cost structure is largely dependent on the landscape and logs/branches) which dictates which transportation pathway can be used.

CASE 2: EFFECTS OF FACILITY ASSOCIATED TRANSPORTATION COSTS AS WELL AS THE MATERIAL COMPOSITION (SCALE)

The base case is for a plant size of 45,000 BDMT yr^{-1}(50,000 BDT yr^{-1}). This required an average raw material transport of approximately 16 km (10 miles) with four moves over the planning horizon of five years. A smaller plant would reduce transportation distancesbut would initiate higher production per unit cost due to scale inefficiencies (figs. 1 and 2). For biomass availability in the study area, lower biomass transportation costs and mobilization yield a cost savings of \$3-7/BDMT (\$3-6/BDT) (fig. 9) due to shorter transportation distances to

Table 7.Transportable plant costs for base case including facility relocations.

Cost Component	$/BDMT	Description
Pre-Sort	$5.38	Costs associated with forest harvest residue pre-sorting prior to extraction and transportation
Plant Mobilization	$5.46	Mobilization Cost of the Conversion Facility during periodic relocation
Raw Transport	$6.67	Transportation of Raw Material (tops, branches) from the landing to the conversion facility
Truck Loading	$3.83	Truck loading cost
Loader	$3.42	Supporting Equipment Costs (in-woods loader operation)
In-Woods Mobilization	$0.00	Mobilization Cost of equipment to either a landing or a centralized yard to enable collection and processing
Processing	$5.82	Grinding and/or Chipping at landing, central landing, or conversion facility
Plant OpEx	$87.44	Plant Operational Expenses of Conversion Facility - includes BCT Core technology labor costs
Plant CapEx	$7.02	Plant Capital Costs related to facility - excludes BCT Core Technology
Conversion	$46.84	Conversion cost of producing biochar including cost of the core technology amortized over a ten year period - excludes labor component (within Plant OPEX)
Package/Loading	$0.36	Packaging and Loading Truck from BCT to Market
Conversion Transport	$9.47	Transportation cost of Converted Material (biochar) from conversion facility to market
Total Cost:	$181.72	

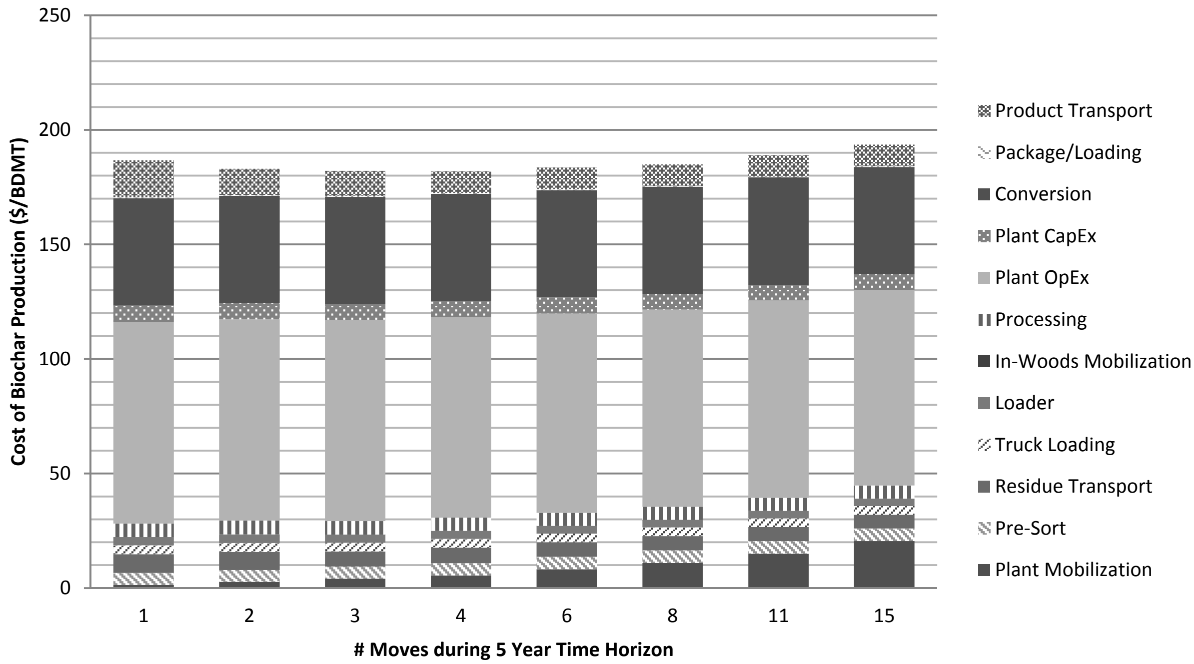

Figure 7. Supply chain costs as a function of the number of plant moves over a 5-year time horizon for a large-scale biochar plant. Costs include increases in plant scale to accommodate down time due to moving the BCT facility. Total costs range from $182-193/BDMT ($165-175/BDT).

the plant, however the additional per unit plant costs expressed on a $/BDMT basis may increase up to eight times this amount due to infrastructure and labor inefficiencies (fig. 10). The large-, medium-, and small-scale plant required four, three, and nine moves, respectively, due to varying mobilization costs. The effect of scale makes a small plant very unattractive to operate in nearly any condition except in cases where either a small locally-produced premium market or high value niche market exists (fig. 10).

CASE 3: IMPACT OF BIOMASS CHARACTERISTICS

Optimization results are sensitive to forest residue characteristics and availability. Residue quantity and composition can vary due to any number of reasons including different logging systems utilized, management

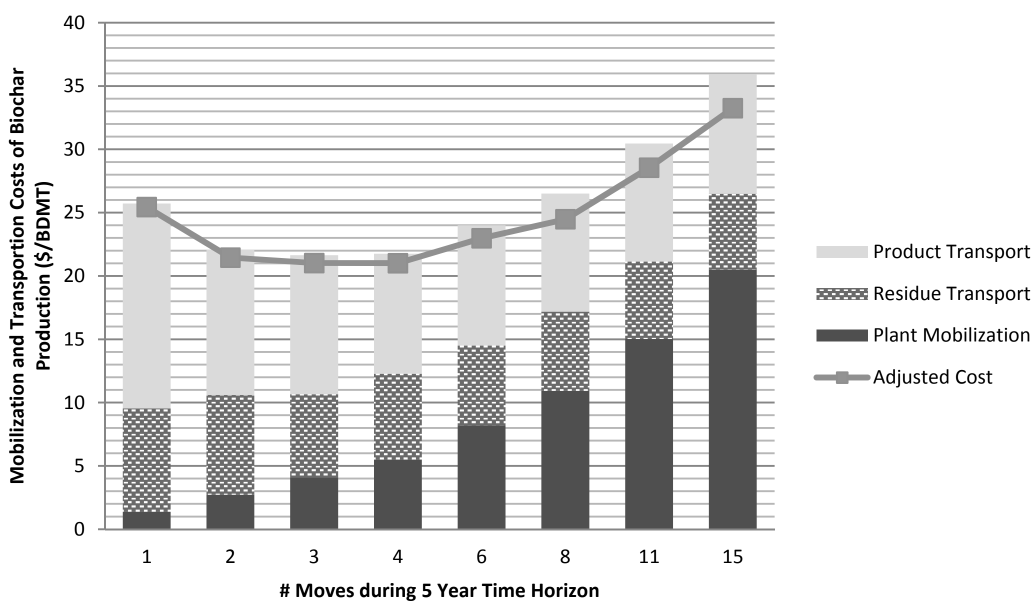

Figure 8. Mobilization and transportation (raw and converted) and plant mobilization cost as a function of the plant moves over a 5 year time horizon to high transportation logistics impacts of transportable design. Figure includes relative plant scale efficiencies (savings due to gains in economy of scale) represented as an adjusted cost (line), these efficiencies vary up to $3.5/BDMT ($3/BDT). As the number of moves increase, operational and capital efficiencies increase.

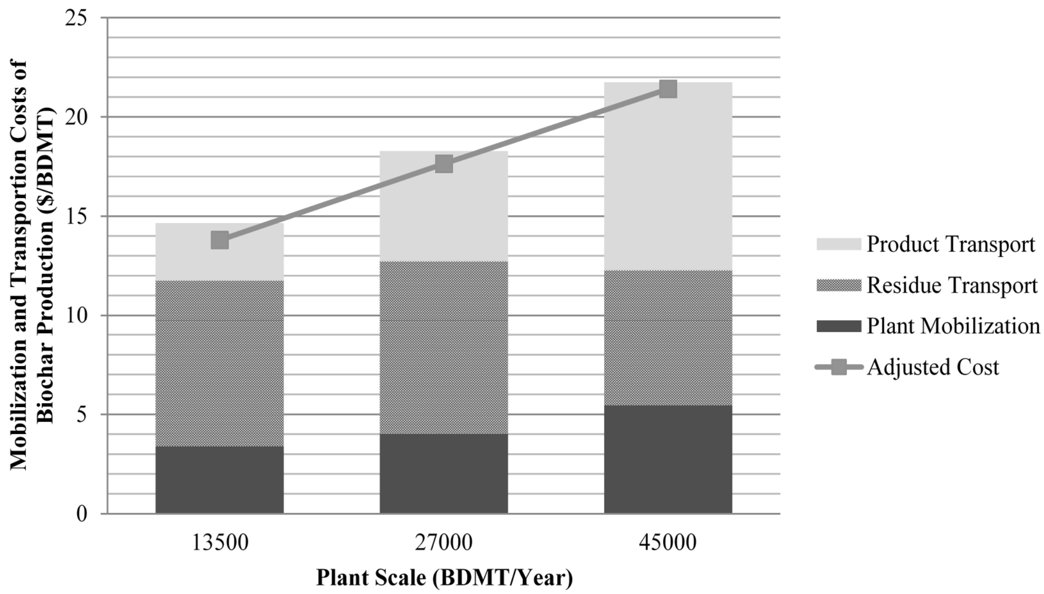

Figure 9. Transportation (raw and converted) and plant mobilization costs as a function of plant scale. Move frequency decreased with increasing plant scale.

approach, species composition and changes in local markets. In order to analyze the impact of material availability on mobilization for the case study, the following suite of conditions were evaluated (fig. 11):

1. Base = No pulp market, all slash available [60 tonnes ha^{-1}(22 tons $acre^{-1}$) - 54% tops]
2. Pulp Market A = No pulp material, all slash available [30 tonnes ha^{-1}(11 tons $acre^{-1}$) - 10% tops]
3. Pulp Market B = No pulp or tops available - only slash [27 tonnes ha^{-1}(10 tons $acre^{-1}$) - 0% tops]
4. Pulp Market C = No pulp material, all slash available at 50% [15 tonnes ha^{-1}(5.5 tons $acre^{-1}$) - 10% tops]
5. No Pulp market = All material available at 50% [30 tonnes ha^{-1} [11 tons $acre^{-1}$) - 54% tops]

Under these conditions, costs ranged from $182/BDMT ($165/BDT) to roughly $204/BDMT ($185/BDT) in the case with no pulpwood market and limited material

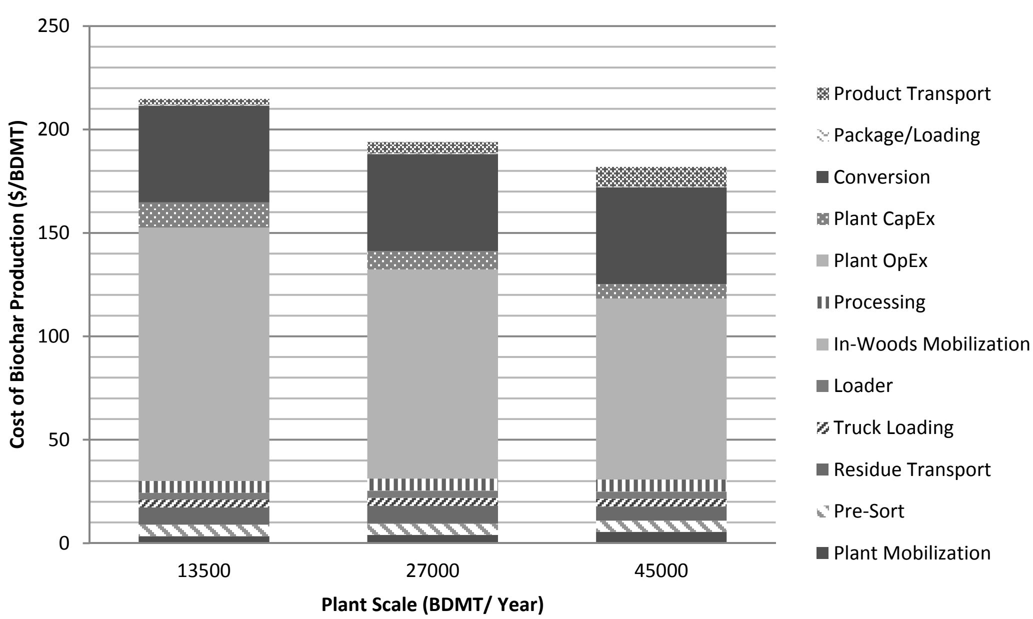

Figure 10. Supply chain costs as a function plant scale. As scale increases, overall costs rapidly decrease due to plant scaling efficiencies.

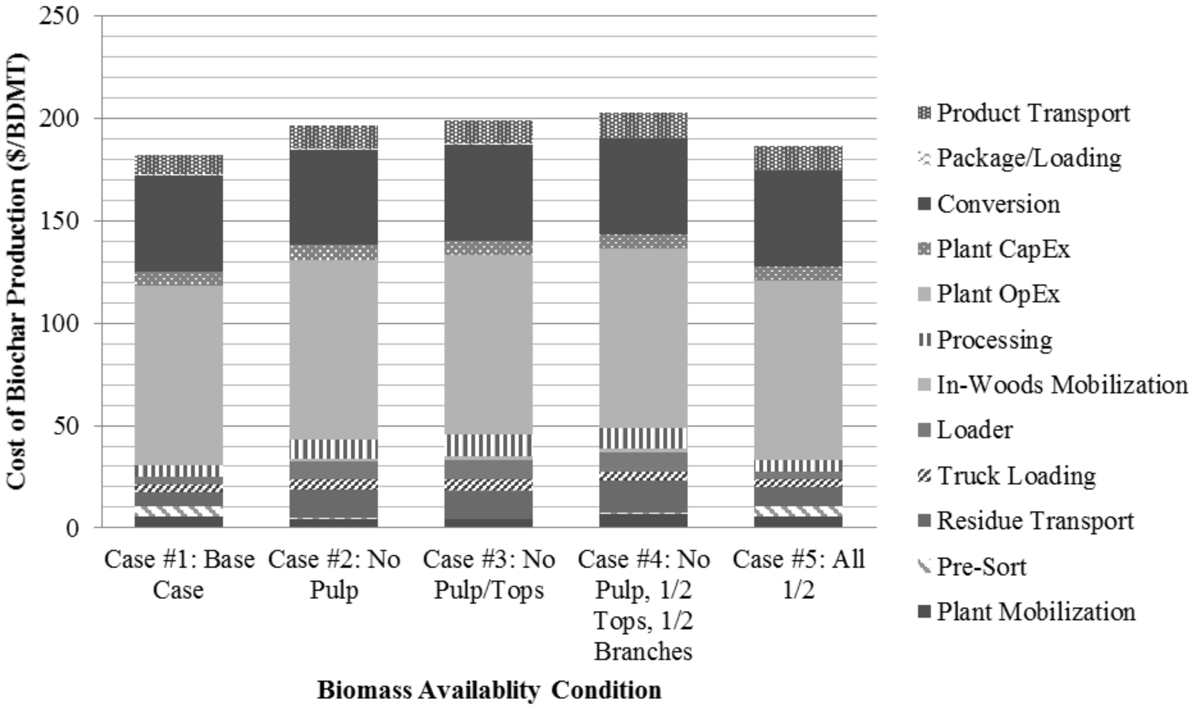

Figure 11. Full supply chain cost structure (transportation, mobilization, processing, conversion, OPEX, CAPEX, sorting, etc.) for five different feedstock conditions. As the availability of low cost extraction material (pulp/tops) decreases overall supply chain costs increase.

availability (Case 4), a nearly 13% cost adjustment over the base case. This increase in cost was mostly influenced by increase in transportation costs along with additional higher processing costs associated with the handling of branch material. Additionally, move frequency varied from three to five moves. The impact on overall biochar product cost delivered to market at Lakeview would be $110-165/BDMT ($100-150/BDT) (when assuming a 16% conversion yield). Furthermore, when compared to a stationary plant, the relative advantage of movement ranged from $5.5/BDMT ($5/BDT) in the base case to $11/BDMT ($10/BDT) in the most limited feedstock condition.

Case 4: Energy Costs and Grid Energy Comparison

From the table of energy costs (table 6), cost savings due to a grid-connected plant vary between $9-$110/BDMT ($8-100/BDT) depending on plant configuration. The large biochar facility had an energy cost that was about $11/BDMT ($10/BDT) lower when using electrical installed energy as opposed to diesel sources. The base case involving four moves with a transportable facility operating on diesel power had a combined transportation (raw and converted) plus mobilization cost of approximately $4.5/BDMT ($4/BDT) less than a stationary modular facility. The stationary facility had an unconverted residue transport of 19 km (12 miles) and product transport of 288 km (180 miles). This suggests there is a roughly $7/BDMT ($6/BDT) cost savings if a stationary transportable facility is connected to grid energy when compared to an optimized transportable off-grid system. Additionally, benefits of a stationary non-modular plant likely include not only access to grid power but greater production scale efficiencies, more advanced inventory management systems and better access to supporting equipment and technicians. However, this facility concept is not considered in this study.

Summary and Conclusions

The larger scale plant was more efficient than the smaller scale plant. From figure 12, we see the disadvantages of a small scale operation with increased OPEX and CAPEX costs exceeding the cost savings of lower transportation $33/BDMT ($30/BDT) vs. $11/BDMT ($10/BDT) savings. Additionally, there is a financial incentive for grid-connected power supply at a $0.058/kWh rate. This conclusion could vary with other geographic areas. California, for example, has an industrial power rate of almost $0.15/kWh and truck weight limits are considerably lower than in Oregon and Washington [36,300 kg (80,000 lb) compared to 47,600 kg (105,500 lb) gross load] which would affect weight-limited vehicles. For the base case, move frequency affected cost primarily through relocation costs and secondarily through reduced productive time. In situations where moves are more frequent, reduced lost productivity through moving the facility will be more significant.

Biomass availability and characteristics are important. The log-like component of forest harvest residues are lower cost to transport and convert. Bark percentage and dirt vary with residue diameter with log-like material being of larger diameter than branches. As feedstock conditions become limited, the economic advantage of a transportable facility

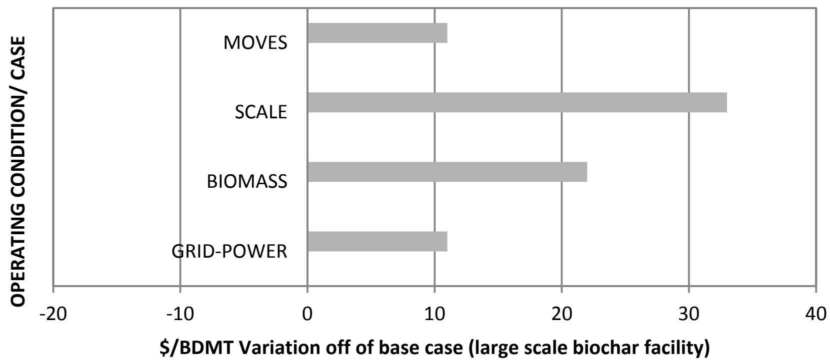

Figure 12. Summary of operational cases observed, effects measured in $/BDMT (of input feedstock) compard to base case. Additional plant scale costs due to small scale plant inefficiencies (up to an additional $33/BDMT[$30/BDT]) and biomass availabilty [up to an additional $22/BDMT ($20/BDT)] have the largest potential negative effect on supply chain costs while the base effect of mobility (transportation and mobilization) is affected by number of moves [up to $11/BDMT ($10/BDT)] while installed electrical costs can save nearly $11/BDMT ($10/BDT).

are increased. Biomass moisture content was not varied in this case, but moisture content can impact product conversion and logistics costs.

For the assumed biochar production technology, feedstock costs were a much smaller component of the total costs than the product conversion costs suggesting that future work examine alternative biomass conversion technologies. The modular technology, although convenient, has limited scale efficiencies. The only economy of scale realized was through more efficient use of labor and supporting infrastructure and equipment.

This work represents a novel evaluation of the tradeoffs of mobility and scale of transportable conversion facilities that has previously been lacking in the literature. Even though the setting and technology was different, our case study supports the conclusions of Polagye et al. (2007) that a stationary conversion plant, with access to grid electrical power and scale efficiencies, likely has a cost competitive advantage over a transportable plant.

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