A FOREST-TO-PRODUCT BIOMASS SUPPLY CHAIN IN THE PACIFIC NORTHWEST, USA: A MULTI-PRODUCT APPROACH

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ABSTRACT. *A comprehensive biomass supply chain landscape model is presented to provide an analysis of transportable biomass conversion facility design and evaluate its potential economic viability. This study focuses on the generation of a tactical-based landscape model to optimize biomass extraction, transportation, conversion and product production within a market system. The model considers various pathways including supply options at landings (burn, grind, chip, bale), centralized landings (grind/chip), biomass conversion facilities (biochar, briquettes, torrefied wood) and delivery to final market. The model solves a multi-period, multi commodity, multi-echelon combinatorial problem to maximize net present value using a genetic algorithm. The landscape is evaluated over a one year planning horizon with monthly time steps simulating a transportable conversion facility mobilization cycle. A hypothetical biochar facility located in Lakeview, Oregon was used as a case study. A sequence of scenarios are used to vary system inputs (logistics, product pricing and moisture management strategies) to put bounds around system viability. The results provide an economic framework to view the Pacific Northwest forest harvest residues processing, conversion and transportation supply chain options. System viability is largely dependent on market pricing, plant assumptions and conversion estimates while processing and transportation logistics are smaller, but important contributors for small scale biomass conversion faculty design configurations.*

Keywords. *Biomass supply, Biomass products, Facility location, Tactical planning, Transportable plants.*

Modern societal trends focusing on sustainability, efficient use of resources, and domestic energy independence have translated into new initiatives and public mandates for today's forestland owners. Historically, forest harvest residues (branches, tops and other un-merchantable wood left after regeneration harvest or thinning) have been an underutilized resource. Usually this biomass is burned on-site either as part of site preparation or to reduce fire risk, because it was the least cost alternative. In the last decade, there has been a sustained interest and research surrounding the effective use of forest residues for the generation of biofuels, bioenergy and biobased products [Northwest Advanced Renewables Alliance (NARA, 2016), DOE Billon Ton Study Update (USDOE, 2016)]. In a broad sense, there has been a paradigm shift in viewing biomass as a potentially valuable resource that can be used to produce marketable products and potentially benefit rural economies.

The goal of this article is to help evaluate biomass conversion technologies and systems to support the development of bio-based products. This article studies the operational logistics and plant design that will help support the development of an economical supply chain system for the production of bioproducts in the Pacific Northwest. We focus on the generation and analysis of a landscape model to characterize and optimize biomass recovery, transportation, conversion, and product production within a market system. This article focuses on the transportable conversion facility concept which can be transported using multiple trailer loads distinguishing it from a mobile design (single trailer load) or a relocatable facility which may require considerably more time to initialize (Polagye et al., 2007).

Biomass processing, conversion and transportation technologies, methods and limitations are generally well known (e.g., Anderson et al., 2012; Johnson et al., 2012; Zamora-Cristales et al., 2015; Bisson et al., 2016). Typically, supply chain options center around differing locations for processing biomass whether that is at the landing, at a centralized location, or at an industrial conversion faculty.

Johnson et al. (2012) highlighted the different potential transportation options when collecting biomass. They illustrate the concept that material can be processed at the landing, a central landing or handled loose and moved to a conversion site for processing. Their findings indicate that comminution at the landing is generally most cost effective while in certain circumstances it may be more cost

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effective to grind and shuttle the material to a central conversion site. Zamora-Cristales et al. (2015) describes the range of transportation (hook lift trucks, truck trailers, doubles, etc.) and processing options (landing, centralized yard, facility) and the sensitivities of their interactions in their analysis concluding centralized yards and high capacity trucks are generally most cost effective but this depends on processing utilization, truck interactions and site specific considerations. Harrill and Han (2010) further evaluate central landing processing with hook lift trucking options suggesting their applicability and cost effectiveness but highlight challenges related to planning, logistical arrangements, slash pile arrangement and their significant impacts on productivity and viability. Other logistic considerations that can further reduce the cost of collecting and transporting biomass include the use of modified dump trucks, densification, baling and other methods (Rawlings et al., 2004; Dodson, 2010; Bisson et al., 2016; Zamora-Cristales et al., 2014).

Anderson et al., 2016 provides a summary of the novel applications related to moisture management, densification, baling systems and equipment noting the problem complexity and circumstantial nature. Additionally, Kizha and Han (2015) studied the costs associated with processing and sorting residuals into different commodity classes (slash, tops) demonstrating its ability to produce high quality feedstock, enable low cost chipping and suggested it may also enable economically feasible biomass recovery. Ghaffariyan et al. (2017) review of the technologies and supply chains concluding appropriate equipment are generally specific to the terrain in question, comminution costs are sensitive to transportation logistics and delays, equipment sizing, and harvest technology. Additionally, their review summarizes anticipated logistics costs generally range from $45-66 per bone dry metric tonne (BDMT) [$40-60/bone dry ton (BDT)] depending on technology, assumptions, and location.

Moisture content of the biomass feedstock impacts both logistics and conversion processes. Truck transportation costs are determined by maximum load capacity which is limited by weight or volume (Acuna et al., 2012; Sessions et al., 2013; Zamora-Cristales and Sessions, 2015; Belart et al., 2017a). Feedstock drying costs have been found to be a potentially significant part of the overall energy cost structure. In stationary sawmill operations, dry kilns are utilized for drying which is often the most intensive energy requirement at the plant (Bond, 2008; Pirraglia et al., 2010; Loeffler et al., 2016). In particular, drying costs for pellets can be nearly 20% of product cost at industrial-scale operations (Mani et al., 2006; Ortiz et al., 2011). Given the challenges of transportable designs of small-scale and off-grid operations, moisture management may be an even more important element in resource planning.

Studies have analyzed and optimized supply chain systems with competing factors including economic, environmental, social, and spatial issues (e.g., Yue et al., 2014; Cambero and Sowlati, 2014). Supply chain characteristics, goals, and approaches to model formation and solution generation vary greatly among projects. Cambero et al. (2014) present a multi-period MIP model optimizing the biomass supply chain for forest residues and bioproducts. The model maximizes NPV over a 20-year horizon accounting for integrated production and conversion technologies options while simplifying logistic costs. The authors note the case-specific nature of supply chain optimization and the need for full supply chain integration. Van Dyken et al. (2010) presents a LP and MIP model for biomass supply chain optimization incorporating supply, process, storage, and demand of different types of biomass. In their work, they considered 12 weekly time steps, three products, and variable drying rates with an objective function of minimizing total costs for energy production, however core operational logistics are not considered.

Overall, supply chain optimization models are generally developed to characterize a unique set of parameters and often not transferable to different problems (Sharma et al., 2012; Shabani et al., 2013; Meyer et al., 2014). In general, from these studies, there is a trend towards methods that have higher processing utilization rates (i.e., equipment having less idle and more productive time with centralized processing versus distributed processing) given the advantages in economies of scale and high processing costs though it is site dependent and highly contingent on associated transportation costs. The main gaps within the literature are a lack of a systems view (interdependent operations), a lack of genericity, limited scalability, limited time horizon, failure to include uncertainty, and a lack of real world integration.

Shabani et al. (2013) provides an overview and synthesis of approaches currently utilized in optimization of forestry supply chain networks. The discussion around mathematical and optimization techniques used in the design and management of these supply chains was of particular relevance – here both heuristic and mathematical programming techniques were highlighted with various objective functions. The authors also discussed deterministic and stochastic methods and the value of incorporating uncertainty in models. Sharma et al. (2012) reviewed mathematical programming models used for biomass supply chain design and modeling. This article synthesizes energy trends, feedstock, and conversion technologies in addition to modeling methodologies and supply chain structure. Their exhaustive literature review concluded that most work is being done using mixed integer programming, with strategic decisions related to plant location/network design and tactical operational decisions generally include material flow and inventory management. Additionally, the authors noted that most models are designed to minimize cost for biofuel production and include case studies. Other issues discussed include developing models that can be easily used by stakeholders, incorporating uncertainty, and the lack of system-wide modeling.

Objectives

The goal of this article is to help solve the biomass-product market viability problem by evaluating transportable conversion facilities to determine if this concept can initiate a profitable business model to convert forest harvest residuals into wood products. Additionally we seek to identify operational system design components which are a barrier to a sustainable marketplace for forest residues using the flexible transportable biomass facility implementation strategy. This research provides a framework that evaluates the prerequisite conditions of a viable market-based biomass products industry. The model framework is designed to be a platform that can be used to analyze the sensitivity of the system, product parameters and assumptions to develop a broader set of guidelines for economic utilization of biomass. The main objective is to develop and evaluate a comprehensive landscape model to characterize the Pacific Northwest biomass supply chain components and costs and optimize the net present value of the supply chain.

Many approaches evaluate and optimize biomass extraction but usually after narrowing down the possible pathways. A few studies attempt to incorporate moisture control, inventory management at the landscape spatial scale due to the overall supply chain complexity. Coupling logistic systems with realistic conversion and facility costing, market pricing and conditions for a set of proposed transportable conversion technologies and plant designs has not yet been completed. This research contributes to the literature by providing a model characterization and evaluation of a biomass-to-product supply chain for smaller scale transportable conversion facility design including sensitivity to product, plant configuration and logistical system utilization strategies. We focus on a Lakeview, Oregon case study with proposed biochar plant and then extend the analysis to include other products.

METHODS

LOGISTIC OPTIONS

The boundaries of any biomass supply chain logistic system are an important element to determine logistics, transportation costs, and subsequent biomass product market viability. For this research we assume forest biomass has been previously sorted at the landing level allowing distinct commodity pathways for the two different material types (log-like material and branches). Within the context of this project, a pathway is considered an option (potential solution route) or pathway that material can follow.

BIOMASS SUPPLY CHAIN COMPONENTS | SOLUTION PATHWAYS

In its generalized form, the problem contains four main pathway decision nodes: landings (LX), central landings (CL), Biomass Conversion Facilities (BCT), and Final Markets (fig. 1). For brevity, the term BCT is sometimes used synonymously to refer to the specific biomass conversion technology and to the biomass conversion facility. The framework includes the potential for a power plant to illustrate other potential biomass market destinations, however in our specific regional studyit is not an available option.

The problem includes various pathways promoting different options for material handling at landings (burn, grind, chip, bale), centralized landings (grind/chip), biomass conversion facilities (to biochar, briquette, or torrefied wood) and delivery to final markets (product distribution centers). These available pathways vary spatially (various landings) and temporally (various periods) within the case study, depending on the landing and context. The system itself contains two commodity classes (logs, branches) with their separate potential solution pathways. Each material type is handled, transported, and processed differently, while being able to be converted into a specific group of products based on product feedstock requirements. It is assumed that biocharring and briquetting can use chipped or ground material while torrefied conversion requires chips or upgraded ground feedstock.

Pathways from Landings

Material at a given landing can be burned, baled, ground, and chipped, sent to a central landing via bin/dump trucks, or sent to a biomass conversion facility via bale truck, chip van or log truck (fig. 2, table 1).

Pathways from Central Landings

Unprocessed material at central landings can be chipped or ground. Processed material from landings or central landings can be sent to a BCT facility or powerplant via Chip Van (fig. 3, table 2).

Pathways from the Biomass Conversion Facility

Processed material sent to a biomass conversion facility is converted into a market product. Unprocessed material is processed (chipped or ground) on site and then converted into a market product or utilized for combustion at a cogeneration plant (figs. 4 and 5, table 3). Market products are transported with specialized on-highway trucks (high capacity, highway legal, product storage customization). In this study Lakeview, Oregon, is considered the market location.

MODEL DESCRIPTION

The tactical landscape model encompasses an interconnected set of forest to product biomass supply chain cost and revenue structures including inventory management, and decisions on supply, demand, processing, conversion, and distribution. The multi-period nature of the problem recognizes the seasonality of logging schedules and road access. Little or no field operations are possible during

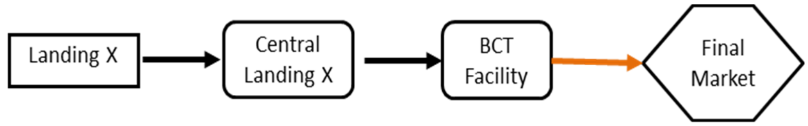

Figure 1. Conceptual figure of supply chain decision nodes where pathway options are generated.

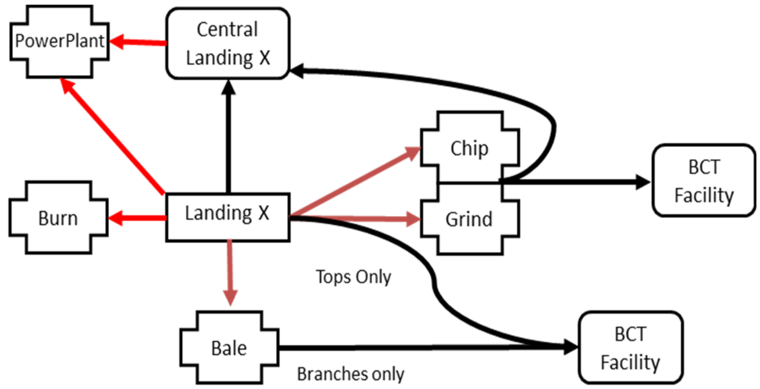

Figure 2. Conceptual diagram of pathways originating from landing (LX) decision node. Residues (tops and branches) originate at the landing while products are produced at the BCT Facility.

Table 1. Detailed description of pathways originating from landing site per commodity class (tops, branches) along with associated transportation options.

Commodity	Pathway	Transportation
Tops	Hauled to Biomass Conversion Facility (BCT) or PowerPlant (PP)	Log truck
	Sent to Central Landing (CL) for processing	Bin truck
	Chipped/Ground at the site then transported to BCT, CL, or PP	Bin truck/Chip Van
	Burned on site	
Branches	Ground at the site then transported to BCT, CLX, or PP	Bin truck/Chip Van
	Baled on site then sent to CL or BCT for processing	Bale truck
	Burned on site	

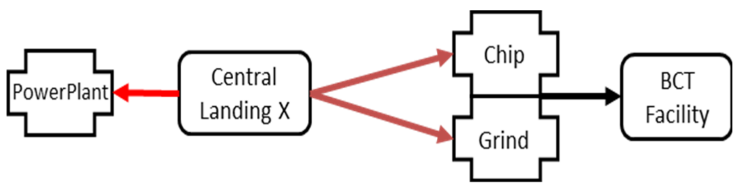

Figure 3. Diagram of pathways originating from central landing (CL) decision nod.

Table 2. Pathways originating from CL site and associated transportation options.

Commodity	Pathway	Transportation
Any	Chipped/Ground at the CL then transported to BCT or PP	Chip Van
	Previously processed material is sent to BCT or PP	Chip Van

winter, the model assumes accessibility during a 5-month operational window consistent with regional practice.

Moisture Management

Biomass moisture content varies with time since harvest and affects transportation, inventory management, and conservation of mass and energy at the conversion facilities. Material is assumed to dry from 50% moisture content (wet basis) when initially harvested to a 30% moisture content after two months of in-woods drying, and 25% after 6 months based on work by Belart et al. (2017b). These curves are embedded within both the transportation and conversion facility modeling to inform transportation costs and feedstock drying costs in preparation for conversion (table 4).

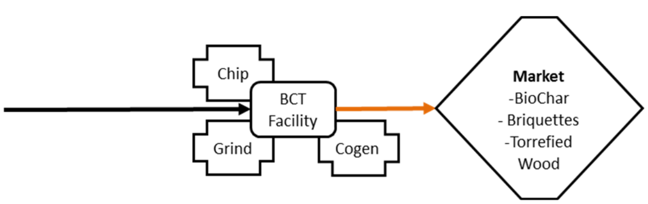

Figure 4. Diagram of pathways originating from biomass conversion facility (BCT) supply chain component.

Inventory Management

Biomass operations are designed to operate, produce and sell product throughout the entire year while logging and biomass recovery operations are often seasonal and related to weather, site access and operating conditions. Inventory is built during the field season to maximize system efficiency and keep the conversion operation running near capacity.

Table 3.Pathways originating from central landing site and associated transportation options.

Commodity	Pathway	Transportation
Any	Chipped/ground at the BCT then made into product and sent to market or used for cogeneration	Market truck
	Previously processed material is made into product and sent to market or used for cogeneration	Market truck

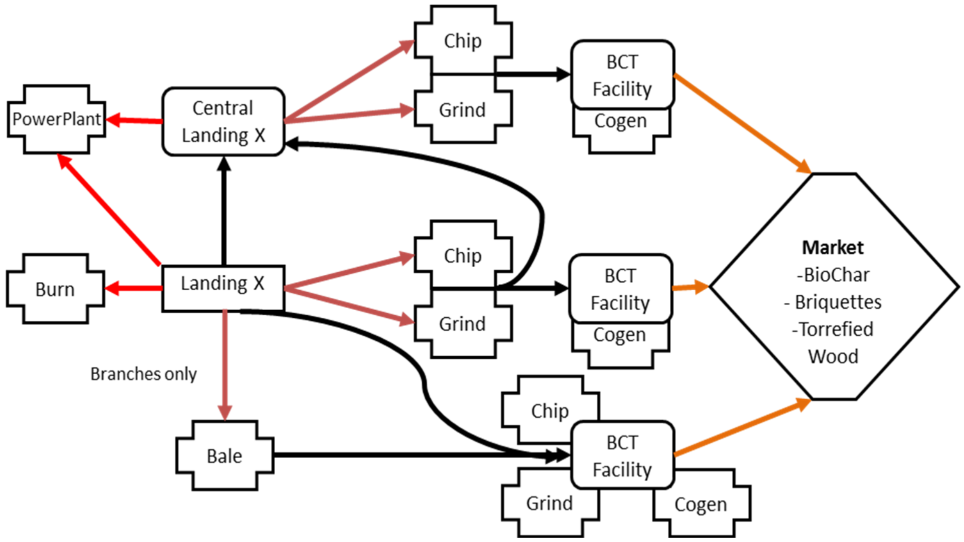

Figure 5. Complete conceptual diagram of biomass supply chain and associated pathways. Landing, central landing, and BCT locations are in-woods.

The importance of inventory management and the general inventory routing problem has been illustrated by many authors (e.g., Kleywegt et al., 2002; Shen et al., 2003).

CENTRAL LANDINGS

Central landings are potential hubs where biomass can be densified prior to transport to the conversion facility. The economics of central landings are dependent on the material quantity and source locations being used to feed the centralized facility and mobilization costs (Harrill and Han, 2010; Anderson and Mitchell, 2016; Bisson et al., 2016). In this study, we estimate central landing cost savings by pooling possible mobilization costs between extracted parcels over the time horizon and increase anticipated utilization rates to simulate the system efficiency compared to handling at the individual landing or BCT facility level. Basic processing technology and utilization costs are described in table 5. Utilization rates for processing equipment are assumed highest for BCT operations (stable supply and controlled environment) and lowest for distributed in-woods landing locations (frequent movement and less efficient) based on previous studies (Anderson et al., 2012; Johnson et al., 2012; Zamora-Cristales et al., 2015).

PLANT AND FACILITY MODELING

Within this study we focus on six transportable plant configurations representing likely technology combinations. The underlying rationale for the transportable plant is to reduce raw material transportation costs by periodically moving the conversion facility closer to the supply. Different operating configurations were reviewed to illustrate the impact of inventory, moisture content, investment costs, and anticipated revenue streams. In this study we focus on a proposed scale of 45,000 BDMT yr^{-1} (50,000 BDT yr^{-1}) which is thought to be the most likely scenario given its relative economies of scale but still able to be efficiently transportable and fit within a reasonably sized footprint [<1.6 ha (<4 acres)] (Berry and Sessions, 2018). Biochar, torrefied wood, and briquettes are assumed to be stand-alone plants and products, similarly torrefied briquettes are assumed to be produced using in-line processing. Two other configurations of hybrid plants are also evaluated and assumed to capitalize on thermal and drying efficiencies and moisture management handling. The two hybrid systems (biochar and briquettes, as well as torrefied chips and torrefied briquettes) are designed to utilize waste heat in thermal processing where the biochar or torrefied process excess heat is used to dry the briquetting feedstock input and reduce subsequent drying requirements.

Within the model framework, conversion costs are handled separately to allow for unique allocation of costs for each respective parcel/logistical system over time. Conversion costs (labor, time, drying) were estimated using data for the individual conversion technology used and facility type with direction provided by Humboldt State University Schatz Energy Research Center. An overview of the biomass conversion technology (BCT) is presented below (table 6).

Table 4. Transportable biomass dryer assumptions.[a]

Drying Cost Structure[b]		
Base[c]	Base + Fuel[d]	
445.28	1120.70	$/Evaporative Tonne

[a] Prices per evaporative ton based on re-circulated heat and/or external fuel consumption required. Biochar and torrefied wood are assumed to use re-circulated waste heat, dryer would not need fuel to operate.
[b] Belt-o-matic 123B Biomass Dryer.
[c] Equipment running costs (excluding labor and fuel).
[d] Equipment running costs (excluding labor).

FACILITY COSTING MODEL AND MOBILIZATION COST

A Facility Costing Model was developed to represent the operational and capital required for the transportable system. This model was adapted from the Biomass Enterprise Economic Model developed by the Oregon Wood Innovation Center (OWIC, 2017) and modified to represent transportable conversion facility design considerations and adaptations for varying core

Table 5. Processing costs and assumptions based on logistics pathway.

Process	Model Class	Capital Cost	Productivity (BDMT/PMH)	Utilization Rates Landing (50%)	Central Landing (65%)	BCT (85%)	
Grinder	Peterson 1050 hp	$650,000	334.51	449.45	376.42	319.14	$/PMH
Chipper	Morbark 875 hp	$500,000	437.73	346.73	272.85	214.91	$/PMH

technologies. Additionally, this model, coupled with conversion technology handling and relocation estimates, was used to estimate the initial mobilization cost for the conversion facility assuming 45,000 BDMT yr^{-1} (50,000 BDT yr^{-1}) operation. The biomass facility is built from modular units assuming no economics of scale whereas the supporting infrastructure and operating labor have decreasing unit costs with increases in scale. We separate the capital costs between those with economies of scale and those without. A product conversion rate that includes amortization and operating costs is used for the core biomass technologies (table 7).

Energy required for conversion and drying is derived from diesel generators to help support the off-grid mobility aspect of the problem. Mobile wood-fired gasification units are an alternative to diesel electric generation but are not considered in this analysis.

PRODUCTION CAPACITIES

For the Lakeview, Oregon, case study the assumed minimum monthly conversion facility production capacity is 2,700 BDMT $month^{-1}$ (3,000 BDT $month^{-1}$) of input biomass feedstock being converted into product (allowing for some flexibility). This provides an approximate even work load and utilization capacity. We cap the input biomass flow that can enter the facility to 12,700 BDMT $month^{-1}$(14,000 BDT $month^{-1}$) to recognize biomass delivery operations during the five-month field season so as to not overload facility supporting systems.

PRODUCT PRICING AND MARKET ASSUMPTIONS

Product prices (table 8) were obtained from a University of Washington College of the Environment survey with industry experts, industry representatives, and consumer reports. For our modeling base case, wood briquettes for residential/retailer delivery are estimated at $131/tonne ($119/ton), Torrefied wood and torrefied briquettes were assumed to be priced as a coal substitute at $163/tonne ($148/ton), and biochar pricing was estimated to range from $110 to $3,300/tonne ($100 to $3,000/ton) depending on market (Sasantani and Eastin, 2017). Market prices are assumed to be delivered prices to retailers inclusive of transportation costs, FOB costs. Biochar is still immature market with a wide array of anticipated pricing levels depending on process, feedstock, regional and product end user and thus pricing sensitivity is very important to the ultimate viability. The potential U.S. biochar market is estimated to reach $5 billion yr^{-1} in the near term (Delaney, 2015) with speculation that wholesale price at commercial production levels would be near $1,650/tonne ($1,500/ton) (*Biofuels Digest*, 2017). We conservatively use an estimate of $1,100/BDMT ($1,000/BDT) in this study. We also assume an inelastic demand curve for the products with flat rate market pricing assumed at the product distribution center in Lakeview, Oregon. Additionally, within this study we model the supply chain as if one entity were doing all of the activities. We do not account for company profit or the marginal profit and overhead an individual actor or subcontractor may exert on the supply chain in order to streamline the analyses and exemplify break-even pricing.

MODEL LOGIC AND METHODS

MODEL AND NETWORK LOGIC

The model is designed as a network flow problem with the decision variables being pathways through the supply chain network. Within this framework, pathways represent supply options at landings, centralized landings, biomass conversion technologies, and final markets including different transportation options for the three commodity classes (tops, branches, tops/branches). Pathways can originate in any one of 12 monthly periods. Time variations and pathway selection inform commodity usage, moisture content values, and inventory levels at each time step in the supply chain (table 9).

Table 6. Biomass conversion technology specifications and requirements.

Conversion	Model No.	Capital Cost	Conversion Rate Dry Basis	Input Rate BDMT h^{-1}	Conversion Cost[a] $/BDMT of Product	Bulk Density kg m^{-3}	Input Moisture Content Required (wet basis)	Input Class
Biochar Machine	Unique	$400,000	0.159	0.45	$293.93	107.32	25%	Chipped/ground
Torrefier	CM600	$600,000	0.85	0.61	$199.06	224.26	30%	Chipped
Briquetter	RUF 400	$105,000	0.98	0.34	$34.40	913.05	15%	Chipped/ground

[a] Conversion cost excludes labor.

Table 7. Facility costing model: plant capital expenses and operational expenses per BDMT based on a 45,000 BDMT yr^{-1} (50,000 BDT yr^{-1}) plant.

	Bio.	Tor.	Briq.	Bio. + Briq.	Tor. + Briq.	Tor. Briq.	Unit
Mobilization	340,632	209,306	162,096	314,270	226,131	243,195	$/Each
CAPEX	6.46	7.05	7.37	7.91	8.07	10.09	$/BDMT
OPEX	84.81	41.47	44.13	54.24	46.89	50.85	$/BDMT

[a] Capital costs exclude core biomass conversion technology costs and assume a 10-year lifecycle. Mobilization values are based on estimates of loads, labor and site preparation required for transportable conversion facility move and establishment.

Table 8. Base product/market pricing assumptions.[a]

	Bio.	Tor.	Briq.	Tor. Briq.
$/tonne product delivered	110-3,300	163	131	163

[a] Prices based on $/Tonne of product delivered to final or intermediate market (FOB).

OBJECTIVE FUNCTION AND CONSTRAINTS

The objective function maximizes net system present value (revenue less associated costs) given discrete pathways and time period. The pathways and time periods are generated by the heuristic solver based on the input constraints and the requirements that inventory levels maintain BCT facility productivity. Biomass is assumed available at no cost at roadside. Minimum inventory levels are required to ensure plant operability all year, not just during the seasonal feedstock delivery period. Key decision variables include which time period and pathway will be utilized for each landing site (table 10). The pathways represent routes between origins and destinations, an approach commonly used (Strome and Sullivan, 1979; Patriksson, 1994; Karlsson et al., 2006; Henningsson et al., 2007).

SOLUTION TECHNIQUE

The problem becomes assigning biomass from parcels to supply pathways subject to supply, inventory, and production constraints in a way that maximizes net present value to the supply chain. This can be characterized as a combinatorial problem. A number of solution techniques have been used including linear programming (LP), mixed-integer programming (MIP), and heuristic techniques (Shabani et al., 2013; Meyer et al., 2014). These methods differ in how they construct, define, and solve the problem. A LP can find the optimal solution if the objective function and constraints are linear. MIP uses one of several heuristics that solves the LP as a subprogram if the constraints are linear with the only source of nonlinearity being that the decision variables must be integer. A number of other solution methods utilize an iterative approach based on criteria to create new solutions and have rules to attempt to avoid local optima. In some heuristics, constraints are brought into the objective function and penalized (Richards and Gunn, 2000). Other approaches prune the number of decision variables that enter the MIP and then solve the smaller problem to optimality (Strome and Sullivan, 1979). When solving large or difficult to formulate combinatorial problems, the use of mathematical programming or exact solution finding becomes time-intensive and difficult to achieve (Meyer et al., 2014). Many of the alternative heuristic approaches draw from physical or biological analogies such as simulated annealing, harmony search, ant colony, genetic algorithms, and particle swarm techniques to approximate the optimal solution (Bettinger et al., 2002).

This study uses a genetic algorithm (GA) to identify the approximate optimal solution as generally described within Reeves (1993). The GA approach has been used successfully to solve a range of complex problems (Thompson et al., 2009) including forest harvest scheduling (Ducheyne et al., 2004; Falcao et al., 2001 and others). Studies have also indicated its particular utility in complex supply chain problems (Jauhar and Plant, 2015; Jeong et al., 2002; Altiparmak et al., 2006).

A coupling of GIS spatial data files, Excel input files, MatLab programming logic, and Palisades Evolver Optimization and @Risk Optimizer engines are used to construct and run the optimization program and associated simulations.

Table 9. Key model inputs.

Key Model Inputs	Details/Clarifiers
Site Characteristics	Feedstock quantity, quality, moisture content
Available Pathways	Available destinations to/from LX, CL, BCT
Road Network	Distances, times
Trucking Options	Log truck, chip van, dump truck, bin truck, bale truck, market truck
Machine Data	Grinder/chipper/loader/dryer costs, utilization, throughput, etc.
Logical Triggers	Large truck access, minimum volumes to truck/process
Plant Data	Site size & required production, cost, capability, available products to produce
Market/Product Data	Desired moisture content, grain size, market pricing

Table 10.Key decision logic parameters, variables, and concepts.

Concepts:	Moisture/Inventory Management, Transportation/Processing Options
Decisions:	Extraction Period, Pathway Selection, Market Period, BCT Type
Response Variable/Objective Goal: Maximize NPV	

MATHEMATICAL FORMULATION

The objective is to maximize NPV:

$$\sum_{a}\sum_{p}\sum_{j}\sum_{t}\left(W_{apjt} * Y_{apjt}\right) - \sum_{a}\sum_{i}\sum_{j}\sum_{k}\sum_{t}\left(C_{aijkt} * X_{aijkt}\right) - \sum_{k}\sum_{t}\left(KIN_{kt} * RI_{kt}\right) - \sum_{p}\sum_{j}\left(PIN_{pj} * PI_{pj}\right) \quad (1)$$

WITH DECISION VARIABLES:

-*X(a,i,j,k,t)* – BDMT flow of residue a, from LXX i, to BCT j, using route k, in time period t

-*Y(a,p,j,t)* – BDMT of residue a, into product p, from BCT j, in period t

USING THE NOTATION OF:

A = Forest residues
I = Node
J = BCT
K = Route taken (option/pathway)
T = Time period
P = Product produced

SUBJECT TO:

Inventory levels

$$INV_{ajt} = INV_{ajt-1} + \sum_{i}\sum_{k} X_{aijkt} - \sum_{p} Y_{apj}, \forall t \in T, \forall j \in J, \forall a \in A$$

Investments (fixed costs)

$$M * PIN_{pj} \geq \sum_{a}\sum_{t} Y_{apjt}, \forall p \in P, \forall j \in J \qquad PIN(0,1)$$

$$M * KIN_{kt} \geq \sum_{i}\sum_{i}\sum_{j} X_{aijkt}, \forall k \in K, \forall t \in T \qquad KIN(0,1)$$

Capacity considerations

$$\sum_{a}\sum_{p} Y_{apjt} \leq Q_{jt} \qquad \forall j \in J, \forall t \in T$$

$$\sum_{a}\sum_{p} Y_{apjt} \leq Q_{jt} \qquad \forall j \in J, \forall t \in T$$

Main cost calculator(s)

$$C_{aijkt} = CONST_{ik} + TC_{ik} + PC_{ik} + MOBE_{ik}$$
$$\forall a \in A, \forall i \in I, \forall j \in J, \forall k \in K, \forall t \in T$$

$$W_{apjt} = pvalue_{p} * pdiscountfactor_{pj}$$
$$\forall a \in A, \forall p \in P, \forall j \in J, \forall t \in T$$

Where key parameters and values include:

Parameter	Description
available(*i*)	Forest residue available at node *i*, BDMT
mci(i)	Initial moisture content at node *i*
pvalue(*p*)	Value of product *p* produced per incoming BDMT
mcfactor(*i,t*)	Moisture content of material from node *i* if extracted in period *t*
pvalue(*p*)	Time value discount of product *p* in time period *t*
pdsctfactor(*p,t*)	Infrastructure investment to make product *p* at BCT *j*
pinvestment(*p,j*)	Time value discount of product *p* in time period *t*
routeinvestment(*k,t*)	Investments to make route *k* in time *t*
TC(*i,k*)	Transportation costs from node *i* taking route *k* to BCT ($/BDMT)
CONST(*i,k*)	Construction costs from node *i* taking route k ($/EA)
MOBE(*i,k*)	Mobilization costs from node *i* taking route *k* to BCT ($/EA)
PC(*i,k*)	Processing costs from node *i* taking route *k* to BCT ($/BDMT)
Q*(j,t*)	=BCTcapacity(j,t) – capacity of BCT in period *t* (BDMT)
W(*a,p,j,t*)	(function of pvalue, pdsctfactor)
Inv(*a,j,t*)	Inventory levels of residue a, at BCT *j*, in time period *t*
PIN(*p,j*)	Binary Value – investment in product *p* at BCT *j*
KIN (*k,t*)	Binary Value – investment in route *k*, in period *t*

CASE STUDY

STUDY AREA

Lakeview, Oregon, was chosen for the case study. Located in southeast Oregon, the Lakeview area has a large forest land base. It is isolated from pulpwood markets, and generally relies on burning forest residues that result from commercial timber harvest or forest restoration activities. Conversion of forest residues to products such as briquettes, biochar, pellets, or hogfuel offer opportunities to utilize this currently unutilized resource while generating economic activities in rural communities. There has been interest in mobile, transportable, and fixed production facilities to utilize forest residues. Previous research in the Lakeview area has suggested the potential for a transportable supply chain system with 1-2 years likely between each respective move for a transportable system at the 45,000 BDMT yr^{-1} (50,000 BDT yr^{-1}) input scale (Berry and Sessions, 2018). In this study we assume a single transportable facility scale [45,000 BDMT yr^{-1} (50,000 BDT yr^{-1})], a one-year planning horizon, a single market location (Lakeview, Ore.) and six unique conversion facility designs (biochar, briquettes, torrefied wood, torrefied briquettes, biochar, and briquettes) to evaluate the system likely financial viability.

The underlying biomass data for this analysis was provided by the University of Washington Rural Technology Initiative (RTI) which estimated the residual composition of branches and tops for managed forest land that is likely to be harvested in the next 5 years in the Lakeview, Oregon, area. Estimated per parcel biomass availably at roadside is calculated based on assumed harvest system, management approach, recovery values, allowances for defects and breakage and local markets as described by Berry and Sessions (2018). In particular, we assume there is no pulp market within the Lakeview area with stems (log-like material) less than 15 cm (6 in.) diameter available for extraction. For this region the base case raw material is roughly 50% branches, 47% pulpwood composition, and 3% tops. The pulpwood tops are log-like material as opposed to the branches that are generally less than 3 in. in diameter. A randomized harvest scheduler was developed to further refine the 5-year parcels assumed to be harvested and used to set estimate a harvest schedule (monthly time periods) which would provide the forest residue pool following harvest. Consistent with regional practice, a 5-month operating season is assumed (1 June through 31 October). Biomass within a 80-km (50-mile) radius of the proposed BCT location was considered for biomass delivery providing a pool of 150 parcels with approximately 225,000 BDMT (250,000 BDT) of residual biomass available at roadside. We model a single BCT facility location approximately 175 km (110 miles) from the Lakeview, Oregon, market (fig. 6).

RESULTS

A base case (Case 1) using a single product (biochar) is presented followed by several additional cases: different logistical considerations (Case 2), different facility designs/ configurations (Case 3), market revenue assumptions (Case 4), and impacts of moisture management (Case 5). The base case provided the optimal set of pathways, recovery periods, and production periods for the model. The biomass supply pathways were then utilized to inform the six different BCT configurations and supporting analysis. We use these values and inferences to determine breakeven points for each respective configuration case.

CASE 1: BIOCHAR FACILITY

Base Case Material Flow

Biomass delivery tends to be delayed (offset into the fall months) in an effort to minimize associated product drying costs while allowing the buildup of inventory to enable winter production (fig. 7). The results of the base case indicate that the primary material class for recovery is the log-like pulpwood/top material due to lower transport and

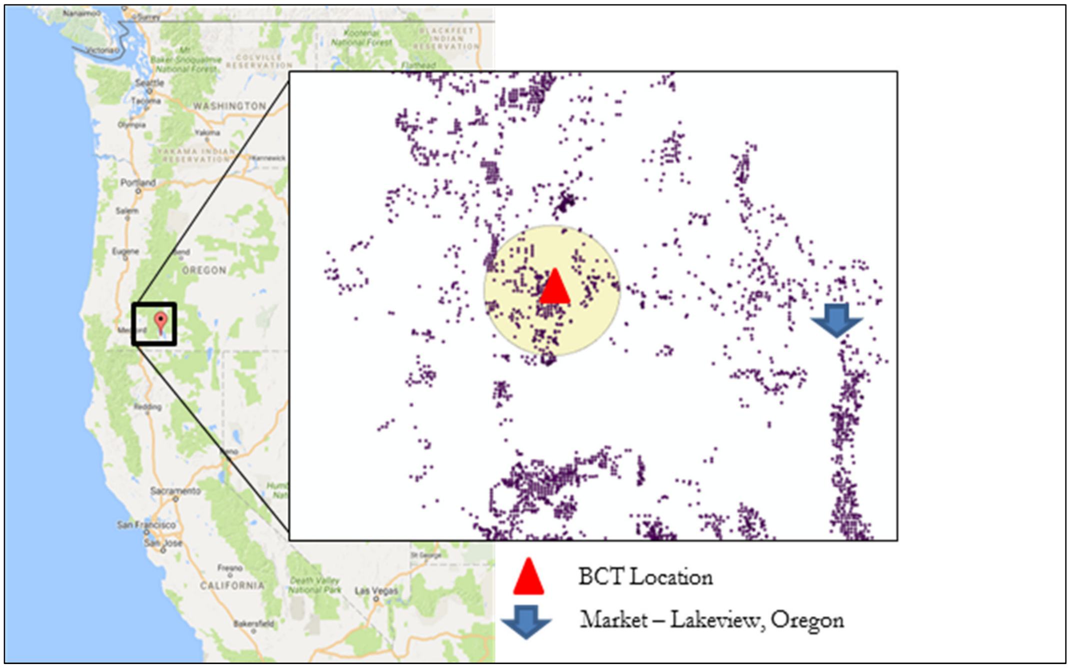

Figure 6. Spatial location of proposed conversion facility and 150 harvested parcel locations within a 80-km (50-mile) driving radius contributing up to 225,000 BDMT (250,000 BDT) of material over the time horizon.

chipping cost. Logs (pulpwood/tops) were transported by self-loading log truck and trailer (fig. 8). Central landings were used for some locations with a shuttle truck system used to move top material to the central landing for distribution, allowing decreased overall transportation costs to the BCT facility. A small amount of branches were recovered associated with grinding at the landing or central landing depending on the source material location, these locations were limited to those in close proximity to the BCT facility (fig. 8).

Where Pathway Notation is:

Notation	Description
LXCH_CL_BCT	Chip residues at landing, shuttle material to central landing then transport to conversion facility for product production
CLCH_BCT	Shuttle material from landing to central landing for centralized chipping then transport to BCT for product conversion
BCT_CH	Transport material directly to conversion facility then chip and convert into product
LXGR_BCT	Grind at landing then transport to conversion facility for product production
LXGR_CL_BCT	Grind at landing, shuttle material to central landing then transport to conversion facility for product production
CLGR_BCT	Shuttle material from landing to central landing for centralized grinding then transport to BCT for product conversion

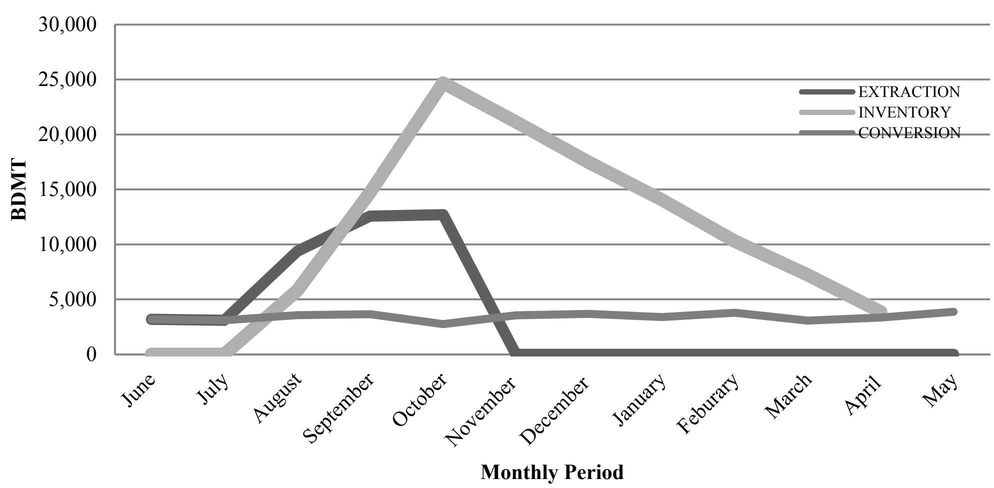

Figure 7. Material flow per period. All values in BDMT of raw feedstock. Product production is nearly even flow, the model favors delayed biomass recovery to permit drying before transport while still being able accumulate the necessary inventory for winter product production.

Figure 8. Base case logistics optimized. Tops were the primary biomass extracted with top material typically moved with a self-loading log truck directly from the landing and sent to the BCT for processing and conversion. A small portion of branches were sent to centralized yards for processing before delivery to the BCT for conversion.

Base Case Suply Chain Cost Structure

For an average biochar product value of $1,100/BDMT ($1,000/BDT) there is a strong disincentive for plant operation with a negative net present value of nearly $900,000 (fig. 9). More than 75% of the total cost is associated with product conversion at the facility (phase 2) while extraction, transportation and mobilization (phase 1) costs account for less than 25% (table 11). In this case, one would not invest in this plant operation, but rather continue with the current practice of burning forest residues. At a burning cost of $396/ha ($160/acre) over the nearly 3,230 ha (8,000 acres) treated, total costs would be $1.2 million, a $300,000 greater loss. This tradeoff depends on local silviculture practices and management costs.

Cash flows are negative in the first 5 months beginning with the initial mobilization cost and continuing with the buildup of inventory (fig. 9). Cashflows turn positive as inventory is being drawn down with production costs lower than conversion costs over the remainder of the time horizon (November-May). Inherently the model and cashflows are correlated to revenue assumptions, sensitivities due to product pricing, and conversion rates on profitability are discussed in Case 3.

Table 11. Optimized supply chain cost structure.[a]

Phase	Cost	$/BDMT Feedstock	% of Whole
Phase #1: Extraction & Mobilization	Plant mobilization	7.57	4%
	Pre-sort cost	4.46	2%
	Baler	0.00	0%
	Raw material transport	17.07	8%
	In-woods mobilization	0.54	0%
	Loader	4.22	2%
	Processing	6.43	3%
Phase #2: Production Conversion	Conversion	47.03	23%
	Drying	8.77	4%
	Plant OPEX	84.81	41%
	Plant CAPEX	6.46	8%
	Market loading & packaging	0.37	0%
	Market transportation	9.54	5%
	TOTAL:	1197.26	

[a] Phase 1 (Biomass delivery) components account for roughly 20% of the overall cost.

CASE 2: PATHWAY ANALYSIS AND LOGISTIC CONFIGURATIONS

Given the base set of optimal conditions, we see the relatively low cost of biomass delivery (~20%) when compared to plant operations, biomass drying, and facility capitalization. However, logistics will inevitably play an important role as plant operational and capital expenses are streamlined in order to provide the lowest cost product. We provide a sequence of logistic scenarios to determine the relative importance and bounds on competing biomass delivery systems within the supply chain (table 12, fig. 10). The same feedstock base (same parcels and same timing) is assumed for each configuration in order to make a comparison among systems and extraction conditions.

From this study, the optimized logistics provides up to $20/BDMT ($18/BDT) savings when compared to concentrating all operations at a roadside landing, a central landing, or at the conversion facility (fig. 10). This largely has to do with use of the lower cost self-loading log trucks for hauling log-like material. This configuration alleviates the need for mobilization of supporting equipment to the landing, alleviates the need for more extensive material handling and minimizes transportation costs. Potential logistics savings compares with Johnson et al. (2012) who found a variation of $32/BDMT ($21/BDT) between systems at 30% moisture content with grinding at the landing being least costly ($54/BDMT [$49/BDT]) and grinding at a central landing being the most costly [$77/BDMT ($70/BDT)] in the Inland West, United States. On the other hand, Bisson et al. (2016) found grinding at the central landing to be about $60/BDMT ($54/BDT) (25% moisture content) in Northern California. Costs are highly dependent on landscape and assumed travel distances.

CASE 3: FINANCIAL VIABILITY OF ALTERNATIVE PRODUCTS

Using the same feedstock stream as that for biochar and assuming market prices from a University of Washington study (Sasantani and Eastin, 2017), all four main biomass products: biochar, torrefied chips, briquettes, and torrefied briquettes were not financially viable (table 13). On the

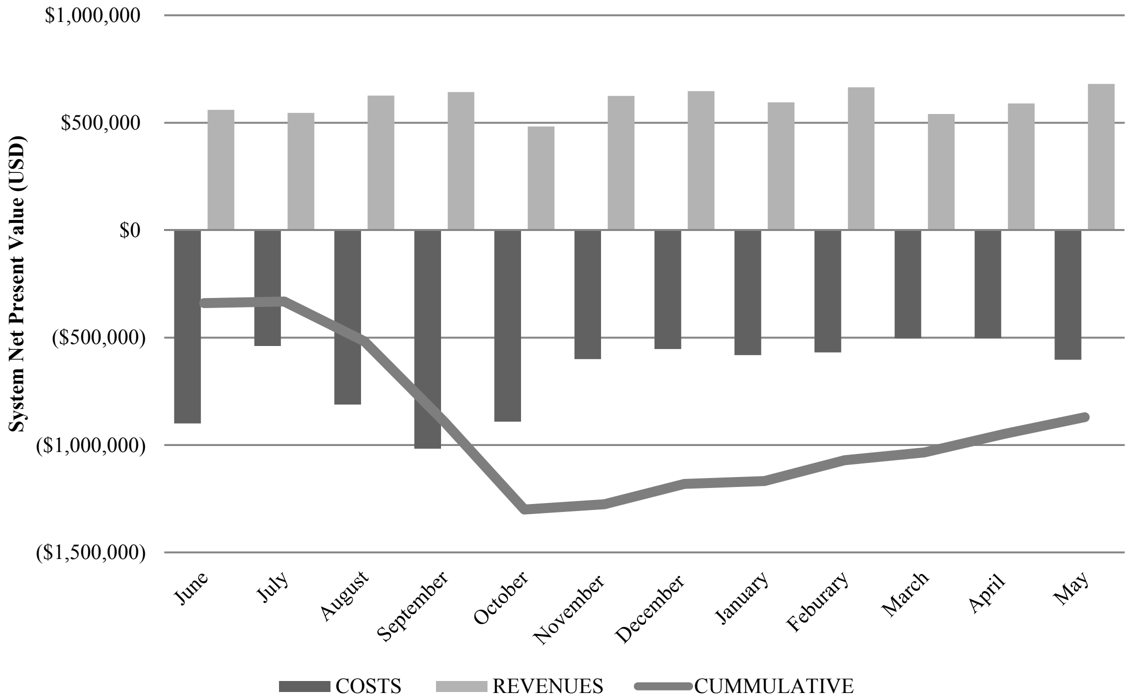

Figure 9. Monthly cashflows related to costs (extraction/conversion) and revenues assuming $1,100/BDMT ($1,000/BDT) of biochar produced.

revenue side, either market price needs to increase or the conversion yield needs to increase since gross revenue is equal to product yield multiplied by market price.

where Gross Revenue =

$$\text{Input Feedstock} \times \text{Conversion Yield} \times \text{Market Pricing} \quad (2)$$

The anticipated market price of the product (or effective product conversion rate) drive the resource and economic balances required for biomass recovery. For every ton of raw material input we expect a certain fraction of a ton ending up as product output, this is the conversion yield (or conversely percent mass loss). The anticipated market price is also reflected in product quality and characteristics. The conversion yield is dependent on how the raw material is being manipulated (in our case thermal or mechanical processes) in order to create a market ready product. This yield is variable depending on process, likewise the equipment and feedstocks used for production of the product will also impact this value. For example, for every ten BDMT of input if we assume a 10% conversion yield we will anticipate one BDMT of product. If conversion yield was 20% we would expect two BDMT of product. Therefore, any variation in conversion percentage will directly affect the anticipated revenue for the raw material (fig. 11).

Conversion yields for biochar and torrefied chips are particularly variable. Some of the variation is due to conversion processes that produce products of different characteristics. For biochar, there are different 'blends' or characteristics the biochar can yield for different markets and different market prices. Conversion yields for feedstock to product can vary from 10% to nearly 35%. The yield depends on the pyrolysis process, temperature, furnace or other technology employed with each process producing a different biochar blend, with different physical and chemical characteristics, each a different corresponding market price (Mohan et al., 2006; Laird et al., 2008; WDNR, 2011; Anderson et al., 2013).

Case 4: Economic Impacts of Moisture Management

Plant Configuration vs. Drying Costs

For the biochar base, drying costs can be a substantial cost driver within the overall system and motivator for in-field drying prior to transport to the BCT facility. The average drying costs were approximately $9/BDMT ($8/BDT) of input feedstock for the biochar case. Corresponding drying costs for torrefied wood using the

Table 12. Summary of supply chain configurations outlined.[a]

Scenario	#1 – Burned	#2 – Process at Landing	#3 –Process at Central Landing	#4 –Process at Conversion Facility	#5 – Configuration C (Optimized)
Tops	BURNED	Tops and branches ground/ chipped at landing	Processed tops chipped at CL	Processed tops trucked out	Trucked, baled, burned, chipped/ ground at (LX, CL, BCT)
Branches			Branches ground at CL	Baled and transported	
Destination		BCT conversion	BCT conversion	BCT conversion	BCT conversion

[a] Comparisons are completed on material treated.

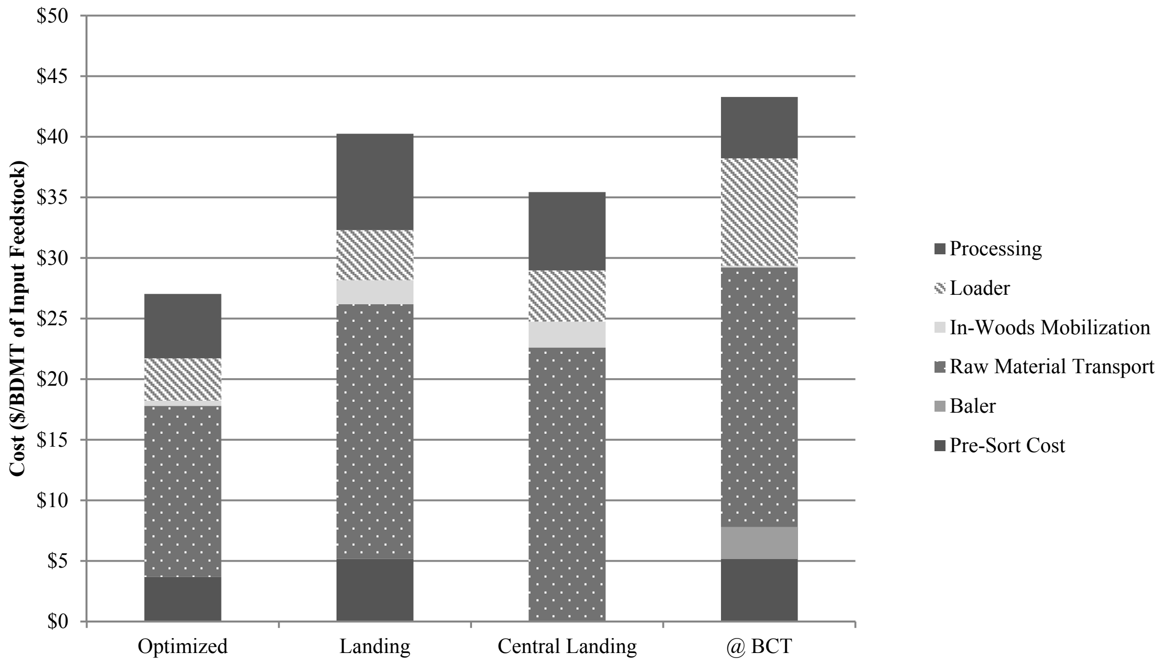

Figure 10. Cost allocation for biomass recovery. Costs increase due to inefficiencies in processing, transportation, mobilization and the need for additional sorting.

Table 13. Derived system break-even pricing based on alternative biomass products.

Biochar	Torrefied Chips	Briquettes	Torr. Briquettes	
$1,102	$163	$131	$163	Product Pricing ($/BDMT Product)
($876,192)	($5,862,762)	($2,978,355)	($8,053,118)	System NPV
$1,236	$332	$206	$400	Break Even Pricing - Market Product ($/BDMT)

same feedstock delivery schedule is approximately $5.5/BDMT ($5/BDT) and briquette needed nearly $33/BDMT ($30/BDT) of drying in order to bring the feedstock to a moisture content suitable for the biomass conversion process (fig. 12). Biochar and torrefied wood processes yield surplus heat that can be utilized in the moisture reduction process where the briquetting process does not. Optimized schedules for torrefied wood and briquetting would increase the importance of moisture management.

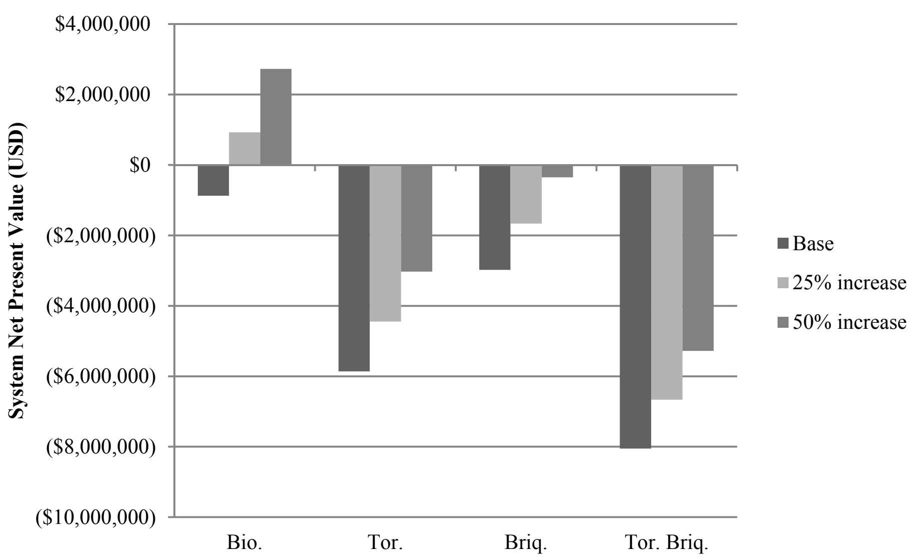

Figure 11. Net revenue for alternative products as a percentage change in market price × conversion yield. A clear linear relationship emerges. Tor. Briq. is found to be least viable given its redundant BCT core technologies and operations without any assumed market premium.

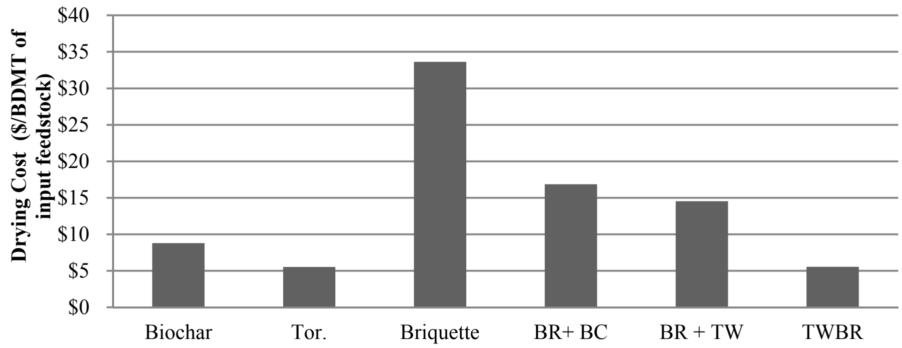

Figure 12. Drying cost for biomass conversion technologies ($/BDMT) for a transportable biomass dryer. All technologies assume to benefit from using process heat except briquette production, note potential cost savings in drying alone when using a thermal process along with briquetting [up to nearly $27/tonne ($25/ton)].

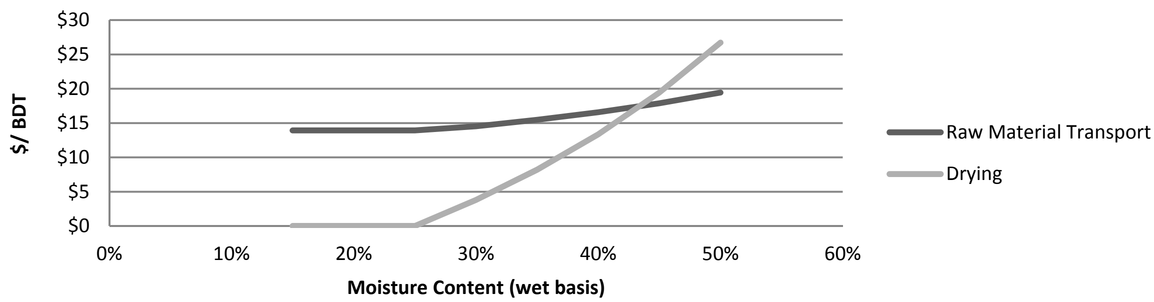

Figure 13. Raw material transport and drying costs vs. incoming feedstock moisture content.

Part 2: Moisture Content vs. Supply Chain Costs and Product Pricing

Using the optimal supply chain pathways, at a fixed moisture content, transportation costs vary from $15/BDMT ($14/BDT) to $23/BDMT ($20/BDT) for moisture content over the range from 30% to 50% (figs. 13 and 14). Increasing moisture content has an even greater effect on drying costs, adding up to $30/BDMT ($27/BDT) at 50% moisture content for biochar. For briquettes the cost would be nearly $100/BDMT ($90/BDT) of feedstock input. Figure 14 illustrates the full supply chain cost structure, in which the greatest proportion of costs come from product conversion and facility infrastructure.

CONCLUSIONS

From this analysis, the proposed transportable system largely depends on product revenue assumptions, the ability to convert material in a cost-effective manner, and limiting facility costing and operational expenses. Supply chain costs appear to be most sensitive to plant, conversion, and revenue assumptions. To a lesser degree, biomass delivery costs including transportation, logistics, material handling, and comminution impact the overall bottom line. The framework provided can be useful for exploring transportable biomass conversion facility design viability. For the case study, the difference between having the full set of supply chain pathways available as compared to restricting pathways to use either landings, or central landings, or direct delivery to BCT amounted to a difference of about $20/BDMT ($18/BDT). Moisture management could reduce transportation costs up to an additional $5.5/BDMT ($5/BDT). However, the sensitivity of feedstock delivery costs on total costs are much lower than the sensitivity of product conversion costs to drying costs related to biomass moisture [$55/BDMT+ ($50/BDT+)] or the impact of market pricing or conversion yield [$110/BDMT + ($100/BDT+)] on economic viability. A major challenge to biomass product viability is development of a conversion facility to improve economics of scale and improve conversion yield. Additionally, this research highlights the importance of accurate revenue models when determining economic viability of a proposed plant design especially when reviewing novel or emerging products.

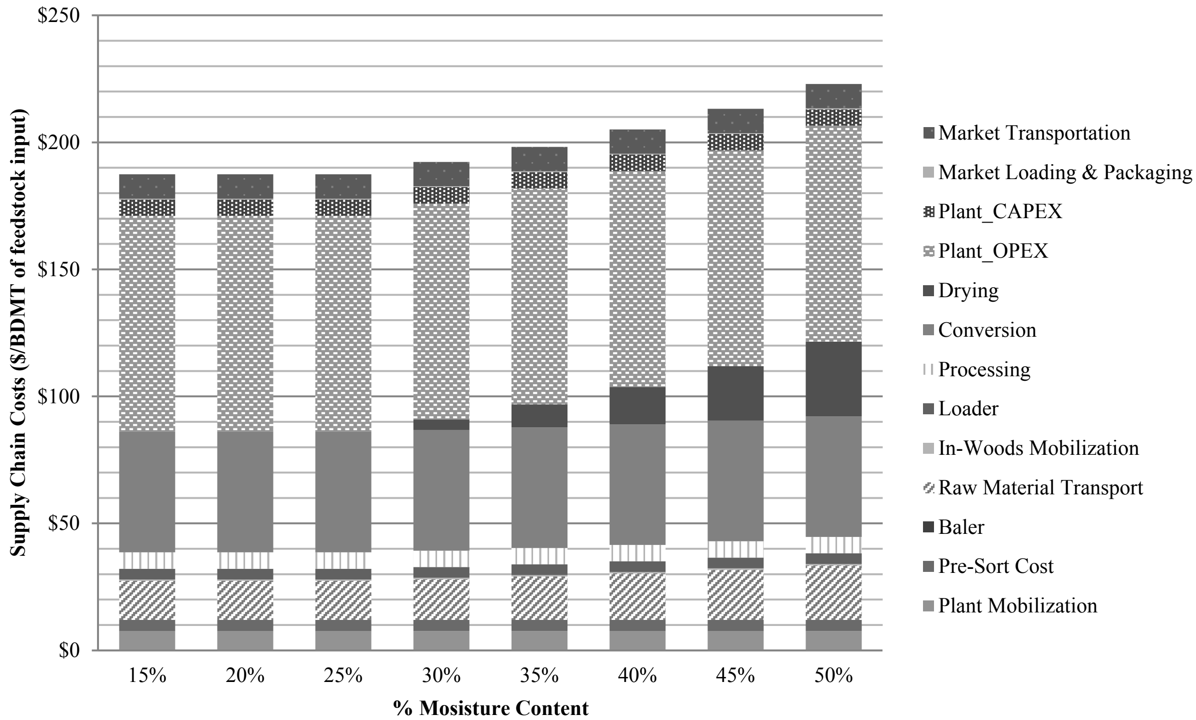

Figure 14. Supply chain cost structure with varying moisture content.

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