SUBREGIONAL COMPARISON FOR FOREST-TO-PRODUCT BIOMASS SUPPLY CHAINS ON THE PACIFIC WEST COAST, USA

M. D. Berry, J. Sessions, R. Zamora-Cristales

ABSTRACT. *Transportable biomass conversion facilities producing biochar, briquettes, and torrefied wood are modeled and optimized for five different sub-regions within the Pacific Northwest. Subregional case studies in Quincy, California; Lakeview, Oregon; Oakridge, Oregon; Port Angeles, Washington; and Warm Springs, Oregon, are evaluated to characterize the potential economic viability of these novel transportable designs. A mixed integer program is used to characterize the supply chain from residue extraction to market optimizing transportation, production, and plant mobility in order to minimize the supply chain costs. Regional variations including log specifications, energy rates, trucking, and logistic capacities are considered within the model and supporting analyses to differentiate regional costs and market viabilities. It was found that the optimal transportable design included facility movement on a 1 to 2.5 year frequency depending on product and region with biochar being the most likely to be economically viable. Regional feedstock composition and availability was the biggest indicator of lower cost production. Supply chain costs varied by 5%-10% depending on product and region being produced. Transportation and mobilization were found to account for 15%-30% of the overall supply chain cost. Quincy, California, and torrefied wood were found to have the lowest of these costs due to low move frequency and high wood availability while Port Angeles, Washington, with briquettes was the highest. With regards to fuel price sensitivity, torrefied wood was the most sensitive as its conversion process was most energy intensive (±12%-13%) and biochar least sensitive (±3-5%).Transportation accounted for 5% to 30% of the fuel price variation due to diesel prices depending on product and region. When including grid-connectivity, cost reductions were approximately 6%-7% for biochar, 27%-29% for briquettes and 33%-38% for torrefied wood. These findings indicate biochar as the most likely candidate for a transportable conversion system given its relatively low power consumption, high allowable moisture content, and low product transportation cost. Quincy, California, was found to be the most desirable sub region with the lowest overall production costs attributed to its high input quality feedstock and relative accessibility; its higher grid-connected power cost also makes transportable options relatively more attractive than other off-grid locations. Port Angeles, WA had the highest production costs and lowest grid-energy costs. Our results indicate that a rise in diesel price, while incentivizing transportable conversion facilities due to more cost effective transportation, would be more than offset by the higher cost energy consumption during the conversion process when compared with grid-power with the potential exception of biochar. Overall, we see a transportable operation with grid-power would likely be the difference between an economically viable supply chain and one that is not.*

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

There are nearly 1.3 million bone dry metric tonnes (bdmt) per year [1.4 million bone dry tons (bdt) per year] of recoverable logging residuals in the Pacific Northwest, USA, and some 33 million bdmt (36 million bdt) of material throughout the United States (Walsh et al., 2000; Perlack et al., 2005; Gan and Smith, 2006). This quantity of material equates to nearly 68,000 GWh of energy or almost 15 million tonnes (17 million tons) of carbon displaced making it a large underutilized resource pool with economic and environmental motivations for its consumption (White, 2010 after Gan and Smith 2006). In the Pacific Northwest most of this material is piled and burned on site as it is too costly to extract for alternative uses (White, 2010). The main economic challenge with regards to utilizing biomass residuals is its overall high handling and transportation costs (low density, low quality) making it too costly to extract at marketable rates (Wolfsmayr and Rauch, 2014). It has been estimated that the transportation costs alone are 20%-50% of the supply chain costs in the bio-energy sector (Browne et al., 1998).

In order to enable residue utilization at scale there must either be a higher valued product to produce (increased revenue) or a reduction in transportation costs (reduced cost) or both. Proposed solutions to make this material

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economical through value-added products and lowering of transportation and logistics costs, include the use of mobile or transportable biomass conversion facilities, bio-refineries, or depots. These concepts and their implications to lower transportation and handling costs have been highlighted by Mirzaie (2013), Wolfsmayr and Rauch (2014), and Mirkouei et al. (2017). Lamers et al. (2015) suggested the benefits from incorporating biomass processing facilities (biomass depots) into the overall feedstock supply chain outweigh the costs and should be aggressively pursued. Chai and Saffron (2016) reviewed optimal capacity for pellet and torrefied wood depot facilities highlighting the dependence of moisture (drying energy) with optimal depot ranges between 60-100 MW [450,000-815,000 bdmt yr^{-1}(500,000-900,000 bdt yr^{-1}) of feedstock] while others have suggested 63,000-135,000 bdmt yr^{-1} (70,000-150,000 bdt yr^{-1}) may be optimal for fixed placement pellet depots (Sultana et al., 2010).

There has been much interest in recent years in mobile or transportable biomass facilities, particularly among bio-refinery researchers, at scales ranging from 13-90+ bdmt d^{-1} (15-100+ bdt d^{-1}) (Badger and Fransham, 2006; Polagye et al., 2007; Dumroese, 2009; Badger et al. 2010; Keefe et al., 2014). Transportable facilities are characterized by a modular design and transported by multiple trailer loads. Studies have typically not looked at a wide range of regional variations in supply chain costs of mobile systems, though portions of the biomass supply chain have been studied including trucking capacities and supply implications (Zamora-Cristales and Sessions, 2015; Jacobson et al., 2016). The study of transportable facility design to produce higher value wood products (biochar, torrefied wood, briquettes, pellets) is less studied (Chai and Saffron, 2016; Berry and Sessions, 2018a, b). Berry and Sessions (2018a) take this concept a step further by optimizing strictly transportable facilities [13,500-45,000 bdmt yr^{-1}(15,000-50,000 bdt yr^{-1})] for a biochar facility finding optimal time between moves being 1 to 2.5 years. While suffering from economies of scale issues due to low production and low efficiency plant operations, the transportable system may yield a viable supply chain. However, this largely depends on landscape biomass characteristics, access to power and market prices.

While many studies evaluate intermediate depots, only a few studies examine mobile or transportable biomass facility design in general (Polagye et al., 2007) and very few evaluate higher value wood products in the context of transportable facilities. Additionally, few studies seek to examine the regional variability (market, cost, logistic constraints) and their impact on the potential viability of a proposed marketplace (Lamers et al., 2015). It is also unknown whether the additional costs of off-grid power sources for conversion, drying, and facility operations may exceed the benefit of reduced transportation costs for mobile rather than stationary facilities. No identified studies combine both a transportable facility design and a multi-product regional assessment using forest biomass, although Jacobson et al. (2016) does consider a large but localized multi-product facility. In this analysis, we evaluate transportable biomass conversion economic viability at five study locations that vary log specifications, energy rates and trucking capacities. Since the premise of transportable design relies on reduced transport costs, we evaluate system cost sensitivities due to energy prices. Furthermore, we analyze the relative advantage and disadvantage of transportable facilities when compared to stationary modular plants within the context of energy costs and transportation distances to determine which design may be more desirable in the regions reviewed. The analysis considers three facility technology configurations that would produce biochar, briquettes or torrefied wood as previously outlined in Berry and Sessions (2017b).

The article is organized by (1) mobility description and methods, (2) mathematical description, (3) regional variations and differences, (4) a results section, and (5) an economic analysis and sensitivity to fuel prices section.

Problem Description and Methods

Methods

This research extends the logic proposed by Berry and Sessions (2018a) for biomass conversion technologies and transportable facility design and optimization. We apply the mathematical model logic, logistic pathways and supporting architecture to different regional settings. Biomass availability source data is from the University of Washington Rural Technology Initiative Group (RTI) as outlined within Berry and Sessions (2018a). The basic methods are illustrated within this text but the reader is encouraged to review Berry and Sessions (2018a,b) for additional detail.

The raw material are forest harvest residuals that are processed into chips or grindings at roadside, at a centralized location or at a conversion facility and then converted into a product (biochar, briquettes, torrefied wood) (fig.1).

Mobility Concept

Transportable facility design relies on the movement of a plant to optimize material availability, transportation and logistics costs. At its simplest, we are moving the facility around the landscape finding different equivalent zones of low cost production where the costs are primarily a function of both the raw material transport (raw and or processed) and the product transport (post conversion processing). Graphically, this can be represented by different ‘zones’ of influence surrounding each facility location; as the processing facility location extends farther

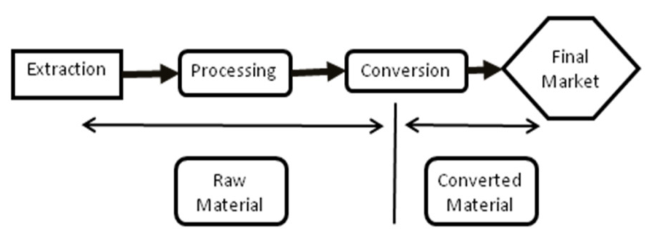

Figure 1. Material flow diagram. Material is extracted in its raw form, chipped/ground, converted into a product, and then sent to a final market.

from the market location (conversion transport costs increase), thus the raw material transportation costs must decrease (and its extraction zone decreases) to maintain the same overall average cost structure (fig. 2).

Logistics

Material flowing through the network can be handled and processed at several points along the supply chain including at the roadside landings (burn, grind, chip, bale), centralized landings (grind/chip) and biomass conversion facilities eventually making its way to final conversion at the Biomass Conversion Technology Facility (BCT) location (biochar, briquette, or torrefied wood) and ultimate delivery to a final market (fig. 3). Residuals are assumed to be sorted into log-like material (tops) and branches. These governing supply chain options are well studied (e.g., Anderson et al., 2012; Johnson et al., 2012; Zamora-Cristales et al., 2015; Bisson et al., 2016) with the model's specific supply chain discussed in Berry and Sessions (2018b).

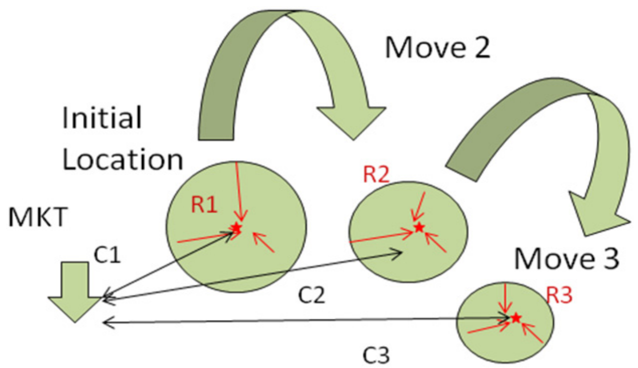

Figure 2. Transportable facility movement illustrating one market location and three facility locations corresponding to different raw material transport costs (R1-3) and different conversion transportation costs (C1-3). As C (converted material transport) increases, R (raw material transport) must decrease.

Modeling Architecture

The model integrates a sequence of cost components that is then optimized with mixed integer mathematical programming (MIP). Three distinct models are blended in this framework including a machine rate model, facilities costing model, and logistics framework. A machine rate model with costs, throughputs, and efficiencies for each respective piece of equipment from trucking, to technology choices to processing is incorporated. A separate facility model was also developed to represent a systems view of the modular plant (overhead, combined labor, siting, mechanical and electrical install, shipping and receiving, utilities). This model incorporates the core technology related operational expenses and is also used to estimate mobilization and re-establishment of facility costs. Three facility configurations were modeled, each producing a single product (biochar, briquettes, torrefied wood). The logistics model consists of distinct pathways for material processing, handling and transport (figs. 3 and 4), largely using machine rate data developed by the U.S. Forest Service Forest Products Laboratory (W2W 2017).

The architecture and modularity is designed to allow flexibility of equipment used, technologies evaluated and logistics options enabling it to be used as a more general supply chain optimization framework.

Mathematical Model

Following the logic of Berry and Sessions (2018a), the optimization problem is to minimize supply chain costs given facility scale, feedstock availability, and cost of plant movement.

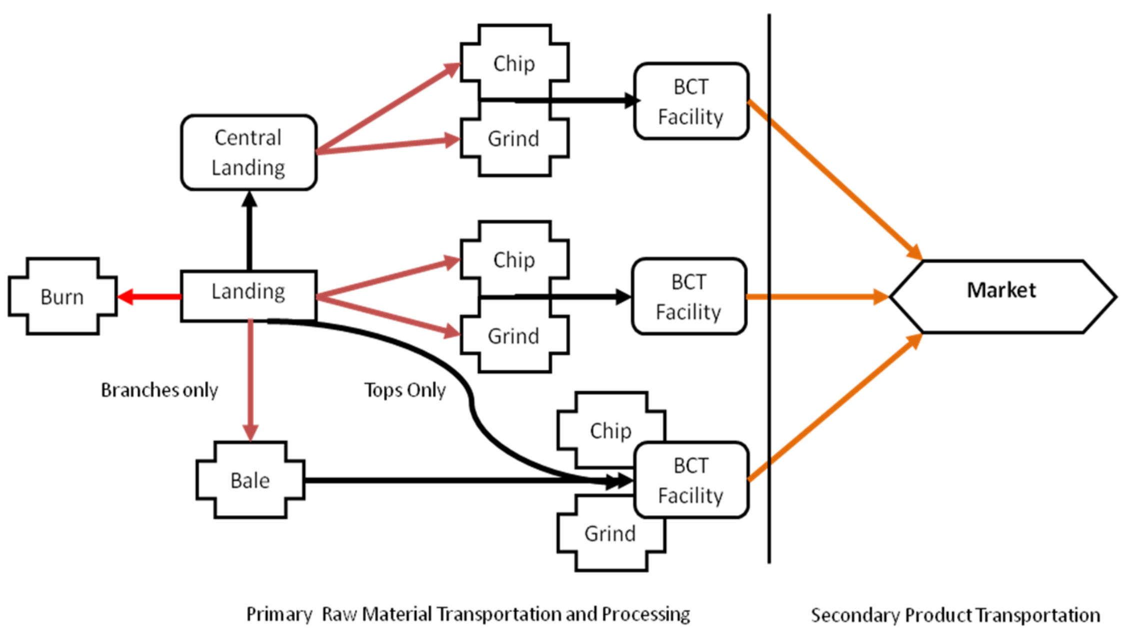

Figure 3. Biomass supply chain and associated pathways (from Berry and Sessions, 2018a). Black lines indicate raw material transportation options, red indicate processing options and orange lines indicate product transportation.

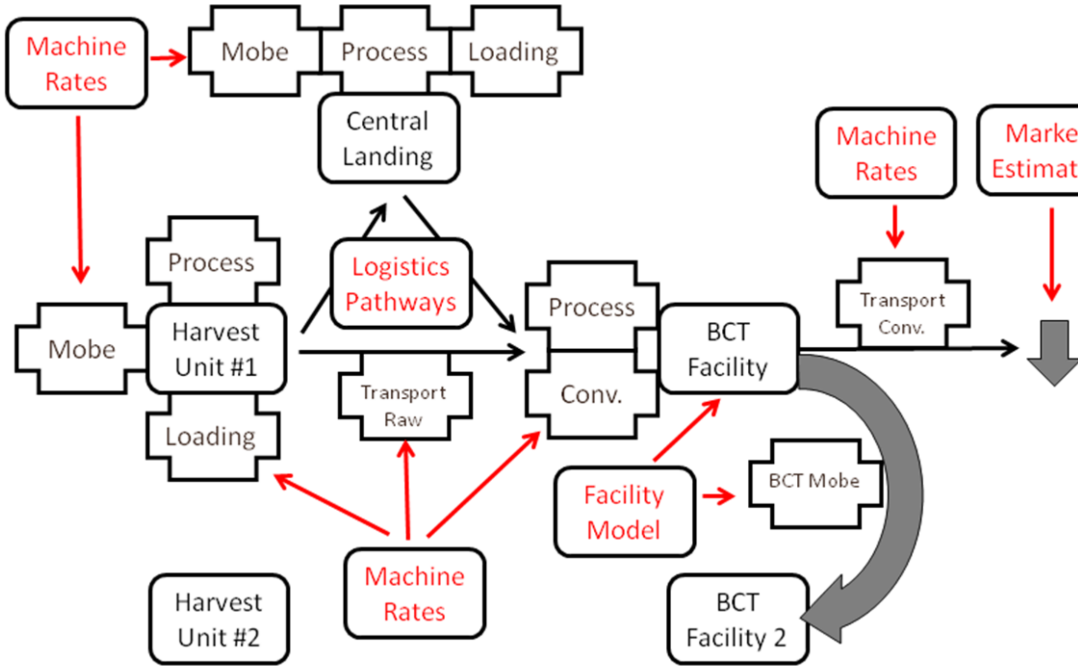

Figure 4. Modeling architecture, cost modules, and model components. Material from harvest unit is modeled through to market and includes elements of processing, mobilization, transportation, loading, conversion and plant mobilization, key model components in red (after Berry and Sessions, 2018a).

$$\text{MIN}\sum_{a}\sum_{i}\sum_{j}\sum_{k}\sum_{m}\left(C_{aijkm} * X_{aijkm}\right) + \sum_{a}\sum_{i}\sum_{j}\sum_{k}\sum_{m}\left(CONST_{ik} * XBIN_{aijkm}\right) + \sum_{j}\left(BCTmobe * JBIN_{j}\right) \qquad (1)$$

Subject to:

$$C_{aijkm} = TRAW_{aij} + TCONV_{jm} + CC_{j} + SEC_{ak} + PRO_{ak} + PRE_{ak} + TLC_{ak} \quad \forall a \in A, \forall i \in I, \forall j \in J, \forall k \in K, \forall t \in T \qquad (2)$$

$$M * XBIN_{aijkm} \geq X_{aijkm}, \quad \forall a \in A, \forall i \in I, \forall j \in J, \forall k \in K, \forall m \in M \quad XBIN(0,1) \qquad (3)$$

$$M * JBIN_{j} \geq FLOWJ_{j}, \forall j \in J \qquad JBIN(0,1) \qquad (4)$$

where

$$\sum_{a}\sum_{i}\sum_{j}\sum_{k}\sum_{m} X_{aijkm} = FLOWJ_{j}, \forall j \in J \qquad (5)$$

$$\sum_{j} FLOWJ_{j} \leq Q \qquad (6)$$

$$\sum_{j} JBIN_{j} = Nmoves \qquad (7)$$

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 (*$/bdmt)
TRAW(*a*,*i*,*j*)	Raw or processed material transportation costs of residual *a* from node *i* to BCT*j* ($)
TCONV(*j*,*m*)	Converted material transportation costs from BCT *j* to market *m* ($)
CONST(*i*,*k*)	Construction and mobilization costs associated with node *i* taking route *k* ($)
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.) associated with each residual *a* along route *k* ($/bdmt)
PRE(*a*,*k*)	Pre-Sorting and arranging cost associated with each residual *a* along route k ($/bdmt)
TLC(*a*,*k*)	Transportation loading and 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

Regional Variations and Assumptions

Regional Landscape Characteristics

For each study area, we simulate a 5-year planning horizon with approximately 1850 harvested parcels incorporating 10 potential mobile conversion locations. Individual parcels likely to be harvested in the next 5 years were identified and delineated by ownership class, likely harvest system, probable management approach to develop spatial explicit biomass data (residue quantity and quality) for each parcelas outlined in Berry and Sessions (2018a). The transportable facility is assumed to be sized at 45,000 bdmt yr^{-1} (50,000 bdt yr^{-1}). Each regional landscape was represented using spatially explicit parcels (known feedstock quantity and composition available at roadside) and average transportation distances (table 1). Specific regional assumptions were generated systematically using watershed centroids as potential conversion plant locations, with these filtered down to ten that were also in close proximity to roads and biomass concentrations enabling efficient transport. The 'market' is assumed to be in a town where a market or access to other forms of long-distance transport (rail, barge) exist. The regions around Quincy (Calif.), Lakeview (Ore.), Oakridge (Ore.), Warm Springs (Ore.), and Port Angeles (Wash.) were chosen to illustrate the feedstock, energy markets, and logistical considerations within the Pacific Northwest (fig. 5).

Log Specifications | Regional Markets

Available biomass quantity and quality available for extraction are a function of the specific regional landscape, forest land area, harvesting operations, infrastructure, local species, utilized harvest systems, regional market conditions, and specific time horizon. A key differentiator between regions is whether or not an active pulp market exists. In this study, we consider pulp material to be stem wood biomass from 15 to 10 cm (6 to 4 in.) small end diameter, inside bark, while tops are assumed to be stem biomass less than a 10 cm (4 in.) diameter, inside bark, for all cases.In high pulp markets, top diameters as low as 5 cm (2 in.) may be utilized.Where a local pulp market exists, it is often economical to extract this log-like residual material during harvesting operations thus changing the amount and character of the residual material available for biomass to product conversion. In this analysis we assume that if a pulp market exists, pulp material is not available, however tops would still be available for extraction. The available biomass also informs transport and processing options as log-like material (pulpwood and tops) can be transported on short log truck trailers and later chipped, where branches need to be ground and transported by chipvan, or in bales as discussed by Berry and Sessions (2018a). Table 2 summarizes the material available within each region.

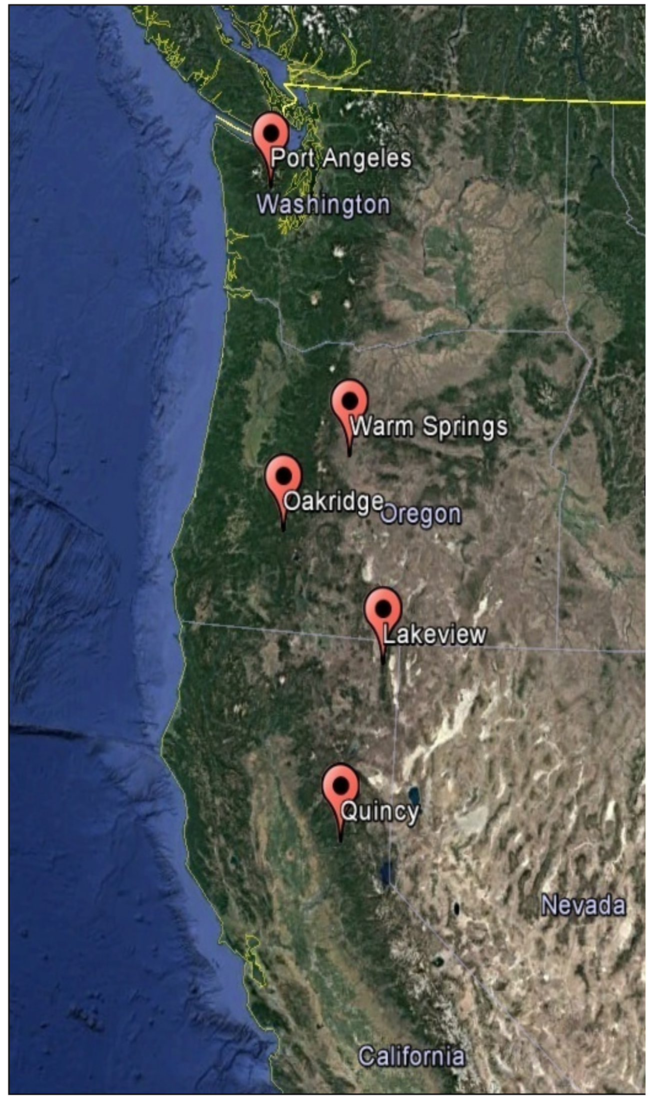

Figure 5. Pacific Northwest setting highlighting five case studies (Quincy, Lakeview, Oakridge, Warm Springs, Port Angeles).

Table 1. Regional landscape characteristics.[a]

	Landscape Area[b] (km^2)	Harvested Area[c] (km^2)	Avg. Harvest Unit (ha)	Avg. Distance to Harvest Unit (km)
Quincy, Calif.	12,447	396	21.4	87.8
Lakeview, Ore.	45,302	394	21.3	149.9
Oakridge, Ore.	6,493	181	9.8	49.9
Warm Springs, Ore.	10,875	223	12.0	89.0
Port Angeles, Wash.	3,675	101	5.5	85.1

[a] where each landscape includes 1850 unique harvested parcels with biomass estimates over a 5-year time horizon
[b] Total subregional area included in model encompassing the geographic area supporting the market
[c] Total area of harvested parcels over the five year time horizon within the subregion reviewed

Large differences in available log-like material (tops) between study areas are directly correlated to the existence of a regional pulp market (table 2). Biomass on a per hectare basis varies depending on individual harvested site characteristics (parcel level) and regional forested land allocation (landscape level). We see the greatest amount of biomass available on the parcel and landscape levels in Quincy and Port Angeles. Quincy, California, is characterized by close proximity high productivity forests without a pulp market (high percentage of tops and biomass/ha) and Port Angeles, Washington, has high productivity mixed-species forests consisting of a large quantity of western

Table 2. Parcel and landscape level biomass composition.[a]

	At Parcel Level		At Landscape Level	
	Biomass Tonnes/ha	% Tops	Biomass Tonnes/ha	Active Pulp Market?
Quincy, Calif.	78.16	51%	2.48	
Lakeview, Ore.	48.20	53%	0.43	
Oakridge, Ore.	38.52	8%	1.06	☑
Warm Springs, Ore.	47.30	52%	0.99	
Port Angeles, Wash.	67.80	5%	1.87	☑

[a] Biomass density at the parcel level refers to average biomass density within the harvest unit. Biomass density at the landscape level refers to total available biomass divided by total landscape area.
Note:5-year time horizon.

hemlock (high crown/bole ratio) within a relatively confined coastal region with a pulp market (low percentage of tops and high biomass/ha). The Oregon landscapes are also variable with the lowest per parcel material availability in Oakridge (due to pulp market) and the lowest spatial availability of biomass within Lakeview due to material composition and a more scattered forested land allocation. Overall, these distinct regional biomass differences provide the logical spatial backdrop for the following analysis with wide variation of conditions to review transportable system viability.

Logistics - Truck Capacities & Costs

Truck capacity on public roads can vary depending on state regulations. These regulations directly affect cost of transporting raw material-to-plant and from plant-to-market. In Oregon and Washington, higher maximum gross vehicle weights are allowed compared to California [47,900 vs. 36,300 kg (105,500 vs. 80,000 lb) gross load]. Loaded trucks were assumed to use public roads at some point along their route.For this analysis, three truck configurations are considered for raw material transport with a forest residues having a 30% moisture content, wet basis (table 3). Plant-to-market transport costs are product dependent with biochar being transported in super-sacks on a flatbed, torrefied chips in a chipvan, and plastic-wrapped briquettes on a flatbed.All plant-to-market trailers were assumed to be volume limited.Transport costs were \$0.06 bdmt^{-1} km^{-1} for biochar, \$0.12 bdmt^{-1} km^{-1} for torrefied chips, and \$0.13 bdmt^{-1} km^{-1}for briquettes.

ENERGY PRICES

Regional energy prices play a role in determining costs and incentives for mobility by 1) informing relative conversion costs and 2) dictating transportation costs and logistics costs (table 4). If electricity prices are low, then conversion costs and plant operational expenses are lower providing less of an incentive for a mobile facility. Similarly, if diesel prices increase, the effective cost of a mobile conversion and facility operations would increase and thus a stronger case for a grid-connected stationary plant could be made. On the other hand, as diesel prices increase, relative transportation costs of a transportable system would decrease compared to a grid-connected stationary plant (shorter average haul distances) thus making the mobile system appear more desirable. In this analysis we use the following regional industrial electricity rates for Oregon, Washington and California based on EIA (2017) data: \$0.061/kWh, 0.045/kWh, and 0.107/kWh, respectively.

RESULTS AND DISCUSSION

We present optimal results for each region including move frequency, raw material extraction characteristics, transportation distances and overall supply chain costs to obtain an informed financial perspective of the implementation of the proposed system. Results and supporting commentary are followed by a discussion of overall economics and energy sensitivities that can potentially change the cost structure influencing the economic viability of the system.

We model the supply chain as if it was a vertically integrated enterprise controlling all aspects of the supply chain, as such we do not include marginal profit for any individual supply chain element. Additionally, we do not include company profit in order to determine break-even pricing, and highlight potential viability. Variability in supply chain costs was modeled using upper and lower bounds on cost inputs.Additional sources of uncertainty, not taken account within the model or analysis, include biomass (quantity and composition) on a per parcel basis, and market prices, but are discussed more fully by Berry and Sessions (2018b) and Sasantani and Eastin (2018).

Table 4. Regional energy price assumptions.[a]

	Base	Low	High	Unit
Diesel for power generation & transport	0.86	0.53	1.19	\$/L
Propane price for drying	0.66	0.4	1.06	\$/L
Natural gas for drying	159	106	530	\$/1000 m^3

[a] The same energy price(except electricity) is assumed for all regions.

Table 3. Raw material transportation capacities and costs.

	Oregon and Washington			California			
	Self-Loading Log Truck	Chip Van-15m	Chip Van_RS-15m[a]	Self-Loading Log Truck	Chip Van-14m	Chip Van_RS-14m[a]	Unit
Truck-trailer weight	17.7	16.3	18.1	16.3	14.5	16.3	tonnes
Maximum legal weight	44.5	43.5	43.5	36.3	36.3	36.3	tonnes
Maximum payload	26.8	27.2	25.4	20	21.8	20	green tonnes
Volume	-	107	107	-	99.4	99.4	m^3
Limiting Capacity[b]	18.7	18.5	17.7	14	15.2	14.1	bdmt
Limiting Factor	Weight	Volume	Weight	Weight	Weight	Weight	
Operating Cost	108.4	89	106.8	108.4	89	106.8	\$/SMH
Transp. Cost	0.36	0.3	0.38	0.48	0.37	0.47	\$/bdmt-km (round trip)[c]

[a] RS indicates 6x6 truck with rear-steer trailer capable of accessing more remote parcel locations.
[b] Capacity limited by either weight or volume.
[c] Assuming average vehicle speed of 32 km h^{-1} (25 mi h^{-1}).

MOVE FREQUENCY

A key consideration for transportable system design is the appropriate frequency of plant movement within any given region, this mobility is the primary advantage and tool to reduce logistics costs and support economic viability. Move frequency is a function of three factors: 1) mobilization cost to dismantle, move and re-establish a plant location, 2) the transportation costs of moving biomass from a specific harvested parcel to the plant, and 3) the cost of moving converted material from a conversion site to a market. Optimal mobilization frequency varies by region and product (table 5).

Movement frequency depends largely on both the product type (specific mobilization and transportation costs) and the specific landscape/ regional plant placement, material availability). This is a function of the tradeoff between mobilization cost and transportation cost, where at some point it is lower cost to move the entire plant then incur incremental increases in raw material transportation costs.Movement distances were generally less than 80 km (50 miles).Because the cost of transporting and re-establishing a biochar plant was the highest cost of the three products (and its associated converted transportation cost was low), we see the lowest move frequency. Additionally, we see that as a region's biomass availability [bdmt ha^{-1}(bdt $acre^{-1}$)] decreases and average distance to market increases, so does the move frequency (Lakeview and Warm Springs) (tables 1 and 5). Similarly, locations with either a low average distance to market or high biomass availability, move frequency tends to be lower (Oakridge, Quincy, and Port Angeles) (tables 1 and 5). While there are key differences in both production values and regions, movement frequency is on the order of every 1-2.5 years with biochar being the least frequent to move while briquetting and torrefaction facilities move more frequently.

RAW MATERIAL EXTRACTION

Supply chain costs are sensitive to the material being handled [tops vs. branches (table 2)], with tops being the least costly to transport and convert and thus favored for biomass utilization. Regions without a pulp market (Quincy, Warm Springs, Lakeview) are sourced almost solely by top material leveraging lower transportation and processing costs, whereas the other locations must utilize both tops and branches due to lack of accessible lower cost top material within the landscape (table 6).

TRANSPORTATION DISTANCES (PARCEL TO BCT, BCT TO MARKET)

Economic viability of the transportable system design relies on savings as a result of reduced transportation costs. Transportation costs and associated haul distances are directly related to product mobility and associated mobilization costs. For a given facility configuration, these two cost structures are linked when solving for optimal movement frequency. While a lower average raw transportation distance might be expected as the plant move frequency increases, this depends on the specific product and associated raw and converted transportation costs. It is also a function of the regional landscape (spatial availability and material composition) and the tradeoff between the more expensive raw material transport [up to \$3 $bdmt^{-1}$ km^{-1}(\$4 bdt^{-1} $mile^{-1}$)] and product transport [<\$0.13 $bdmt^{-1}$ km^{-1}(<\$0.20 bdt^{-1} $mile^{-1}$)] when taking into account vehicle speed, operating costs, and tonnage as outlined in Berry and Sessions (2018a). Logically, when product transport costs are lower (BioChar<Torr.<Briq.), we can 'afford' to travel farther from the market to BCT locations that may enable lower raw material transportation costs (tables 7 and 8). This generally is the case with biochar having the highest product transport distance and lowest raw transport distance while torrefied wood generally has lower product distance and higher raw material transport distances. In the case of biochar, the lower product transportation costs enabled the BCT to be located farther away from the market allowing access to more concentrated biomass locations resulting in lower raw material transport costs. Of course, this depends on the specific regional landscape, facility locations, transportation costs and material availability within the vicinity.

Table 5. Move frequency by product and region.

	Quincy, Calif.	Port Angeles, Wash.	Warm Springs, Ore.	Oakridge, Ore.	Lakeview, Ore.	Unit
Landscape biomass availability	2.48	1.87	0.99	1.06	0.43	bdmt ha^{-1}
Biochar	2.5	2.5	2.5	2.5	2.5	Years/Move
Briq.	1.7	1.7	1.3	2.5	1.3	Years/Move
Torr.	1.7	1.7	1.0	2.5	1.3	Years/Move

Table 6. Composition of landscape feedstock (% Tops) compared with the optimal feedstock utilization (% Tops).[a]

	Quincy, Calif.	Port Angeles, Wash.	Warm Springs, Ore.	Oakridge, Ore.	Lakeview, Ore.
Landscape[b]	51%	5%	52%	8%	53%
Biochar[c]	100%	11%	100%	19%	96%
Briq. [c]	100%	12%	100%	20%	85%
Torr. [c]	100%	12%	99%	20%	88%

[a] Top material is disproportionally used in the optimal solution due to lower transportation and production costs.
[b] Landscape feedstock composition (% Tops).
[c] Feedstock composition (% Tops) utilized in the optimized solution.

Table 7. Regional raw material transportation values.

	Unit to BCT Raw Transportation Distance (km)[a]				
	Quincy, Calif.	Port Angeles, Wash.	Warm Springs, Ore.	Oakridge, Ore.	Lakeview, Ore.
Biochar	11.2	20.0	25.8	14.2	17.3
Briq.	14.6	21.4	21.8	17.1	20.8
Torr.	14.6	20.6	24.3	17.1	19.4
Approximate load (bdmt of feedstock)	14.0	18.5	18.7	18.5	18.7

[a] Distances are based on approximate roadway distances.

Table 8. Regional product transportation and production conversion quantities.

	BCT to Market product (conversion) transportation distance (km)[a]							
	Quincy, Calif.	Port Angeles, Wash.	Warm Springs, Ore.	Oakridge, Ore.	Lakeview, Ore.	Approx.Load (bdmt of product)	Production/Year (tonnes of product)	Approx.Load (bdmt of feedstock)
Biochar	65.0	57.3	119.8	43.0	148.2	8.1	7,250	50.2
Briq.	28.8	38.2	92.6	34.6	96.2	20.4	44,500	21.2
Torr.	28.6	36.5	94.9	34.6	89.3	20.4	38,500	26.6

[a] Distances are based on approximate roadway distances

PRODUCTION COST (LOGISTICS, CAPEX, OPEX, CONVERSION)

Logistics and mobilization costs account for between 15% and 30% of the overall cost structure with the lowest cost being in Quincy, California, with torrefied wood production due to material quality and proximity combined with lower plant mobilization costs (fig. 6). The largest logistics and mobilization costs are associated with briquetting operations in Port Angeles, Washington, due to high raw (primarily branches) and product transportation costs. Additionally, related to the model formulation, if a

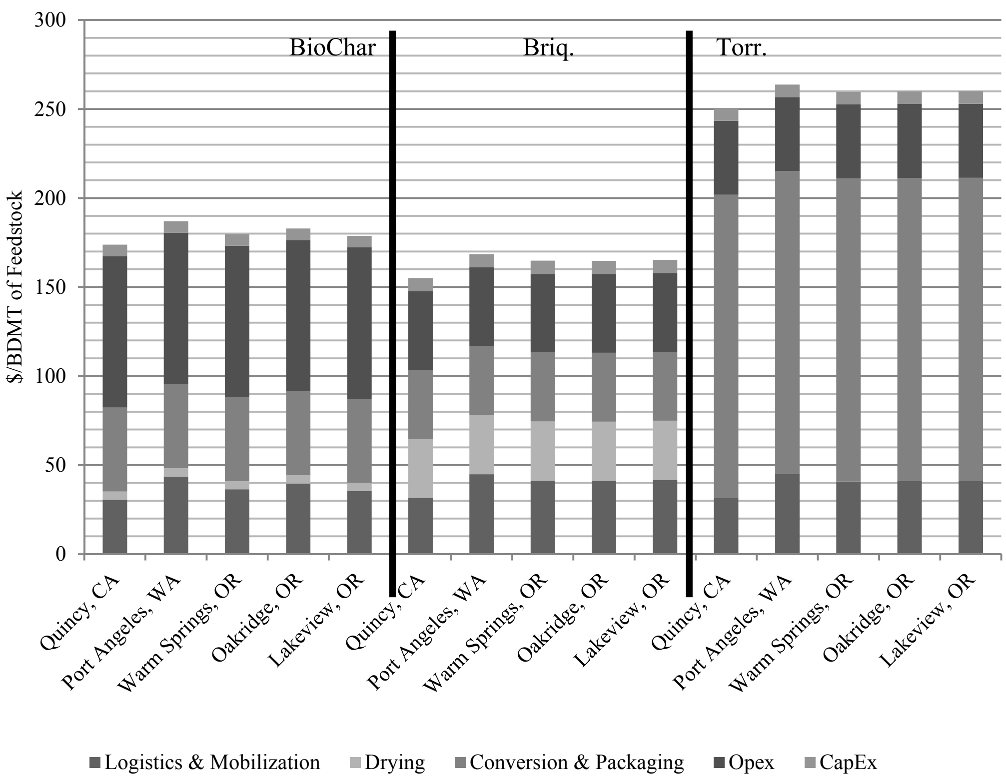

Figure 6. Base production cost of product ($/bdmt of input feedstock), where

Cost Component	Description
Logistics & Mobilization	Includes costs associated with transport, processing, and facility mobilization
Drying	Cost incurred when reducing moisture residue moisture content to processing specifications.
Conversion & Packaging	Conversion cost of producing biochar including cost of the core technology amortized over a ten-year period - excludes labor component [within Plant OPEX]. Packaging and loading truck costs from plant to market are also included.
Plant OpEx	Plant operational expenses of conversion facility - includes plant labor costs, power, insurances, supplies, maintenance [less conversion technology operating expenses beyond labor]
Plant CapEx	Plant capital costs related to facility - includes site prep, technology, MRS&R, mechanical installs [excludes conversion technology capital costs]

suitable location for the BCT cannot be found at the centroid of a watershed, then the residue transport distances in table 7 would likely be larger. A sensitivity analysis suggested that the maximum error would be in the range of 3-6% of the total supply chain cost and the expected error would be smaller.

More significantly we see the plant OpEx Cost being the main cost for biochar (~45%), a fairly significant drying cost for briquetting (~20%), and high primary conversion costs for the torrefaction operations (~65%). These not only indicate main sources of potential cost reduction but highlight the nature of the transportable plant problem. The problem becomes: 1) it can be difficult to achieve high levels of economies of scale with modular operations, 2) handling moisture is expensive off-grid, and 3) equipment selection is very important to the overall cost structure and potential viability. For example, within this study, we examine an electrically heated screw-type torrefaction unit with subsequently high energy costs whereas a differentpiece of equipment (one headed through a thermal process) would likely yield a lower conversion and drying cost.

Analysis and Sensitivities

We frame the analysis around a series of questions a manager might ask when considering a transportable system design within the Pacific Northwest:

1) Are transportable conversion facilities initially profitable?
2) How sensitive are product costs to diesel fuel prices? (Diesel fuel sensitivity)
3) What are the energy savings associated with a grid-connected modular facility?(Energy sensitivity)
4) How much farther can you transport with grid-connected energy savings? (Transportation sensitivity, transportable vs. stationary)

Question #1: Are Transportable Conversion Facilities Profitable?

Profitability is a function of production costs and a market willingness to pay for a product. As discussed in Berry and Sessions (2018b) and Sasantani and Eastin (2018) market values are difficult to estimate for immature product-market conditions and effective product costs largely depend on assumed technology utilized (highly variable) and conversion rates. These contributing factors make it difficult to judge profitability. From the base results, we concluded the overall product costs depend largely on product type, plant operational expenses and technology utilized with a relatively minor component related to logistics and mobilization providing limited regional variability. Quincy, California, generally has the lowest cost structure due to high quality feedstock close to potential conversion locations and market even though transportation costs are higher than in other regions (lower maximum truck legal weights). Port Angeles, Washington, with the largest costs given the high percentage of branches and its relatively long product transportation distance. There is a relatively small variation between regions with biochar, briquetting, and torrefied wood varying by 8%, 9%, and 5%, respectively (fig. 7).

From these results, the likely best candidate for profitable operation is the implementation of a biochar plant where current estimates of product valuerange from $110-3300/bdmt ($100-3000/bdt) and thus may exceed the anticipated production cost. If we assume a market value of $132/bdmt ($120/bdt) for briquettes and $165/bdmt ($150/bdt) for torrefied wood (Sasantani and Eastin, 2018) there is a deficit of nearly 22% for briquettes and 55% for the torrefied wood product on the base cost. Markets prices are assumed to be inelastic with fixed product prices in this study.

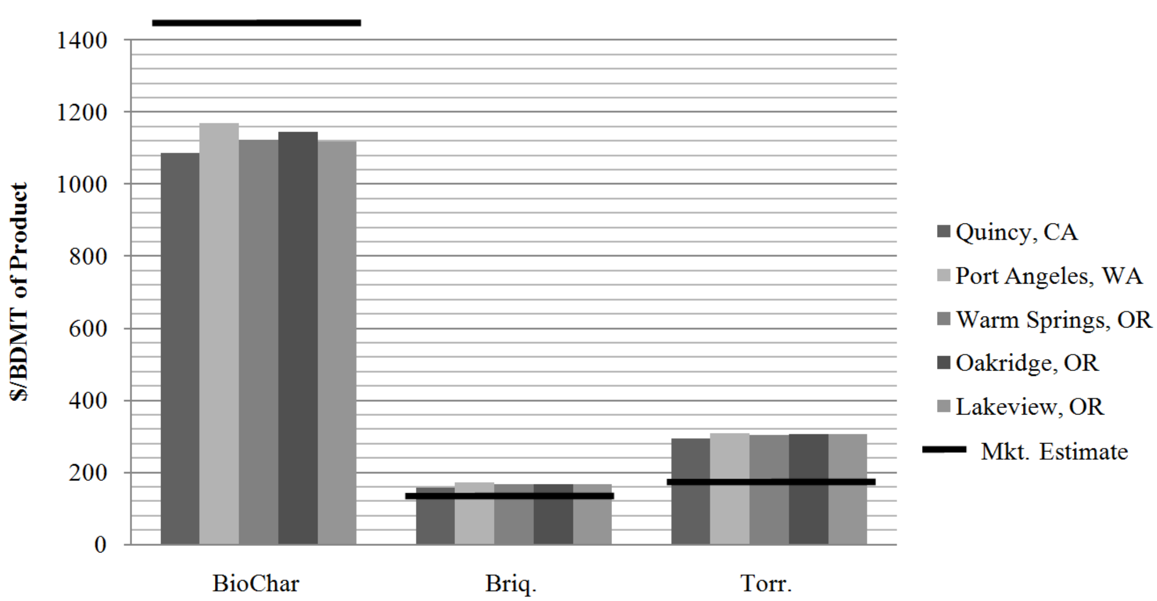

Figure 7. Production cost of product ($/bdmt of product produced). Conversion rates are assumed to be 16% for biochar, 85% for torrefied wood, and 98% for briquettes. Market line indicates anticipated market price for each product.

Question #2: How Sensitive Are Product Costs to Diesel Fuel Prices?

For transportable systems, nearly all the processes (conversion technology, trucking, processing) are assumed to be powered from diesel engines or diesel generators. Their respective consumption coupled with possible price fluctuations are important criteria to judge costs and subsequent flexibility of the system.We first provide a sensitivity analysis to diesel prices and its impact on the supply chain costs of each product. The analysis is first segmented by cost component (facility and conversion costs, processing/loading, transportation), and then are compiled to interpret sensitivity to product cost and potential viability considerations (composite cost variations). Off-road diesel fuel prices are assumed to be $0.86/L ($3.24/gal) as a baseline with a low of $0.53/L ($2.00/gal) and a high of $1.19/L ($4.50/gal).

Facility and Conversion Costs vs. Diesel Prices

Conversion and facility costs are a large component of the overall cost structure and the fuel consumed to power these processes can be substantial. The range of costs associated with diesel generator power consumption to support the facility and conversion processes are presented in figure 8. The horizontal bars represent the high/low values for a range of fuel prices on cost [i.e. $0.53/L ($2/gal) low bar, $0.86/L ($3.24/gal) bar graph, and $1.19/L ($4.50/gal) high bar].

The biochar facility consumes the least amount of fuel for input feedstock and is therefore least subject to fuel price volatility [<$11/bdmt (<$10/bdt) of input, ±3-5% of supply chain costs] while torrefaction consumes the most and is most sensitive [> $55/bdmt (>$50/bdt), ±12-13% of costs] (fig. 8). This difference in fuel consumption is largely because the biochar technology uses a combustion chamber and recirculated heat whereas the torrefaction technology employs an electrically heated process consuming greater amounts of power per unit input.

Processing and Supporting Equipment

Comminution and loading of material in-woods consumes diesel fuel in the process. Relative to the overall supply chain cost structure, these costs are relatively minor (<5%) though they are heavily dependent on fuel prices and vary by product and region (fig. 9).

Overall variability ranges from ±$1.1/bdmt (±$1/bdt) to upwards of ±$3.5/bdmt (±$3/bdt) depending on product and region. Additionally, Quincy, Warm Springs, and Lakeview are least sensitive to fuel prices given their high percentage of tops enabling chipping operations, while Port Angeles and Oakridge are more sensitive due to higher degrees of grinder utilization. Grinding generally consumes more fuel per ton than chipping (Zamora-Cristales et al., 2015; W2W, 2017).

Transportation Costs

Transportation costs become the base argument for whether or not a transportable facility is economical. As diesel prices increase there is progressively less incentive to travel farther out from a centralized location to extract material. Within the optimized sequence of transportable design scenarios, the fuel prices vary on the order of ±$1.1-3.5/bdmt (±$1-3/bdt) (fig. 10). This would increase for additional raw material or product transport distances.

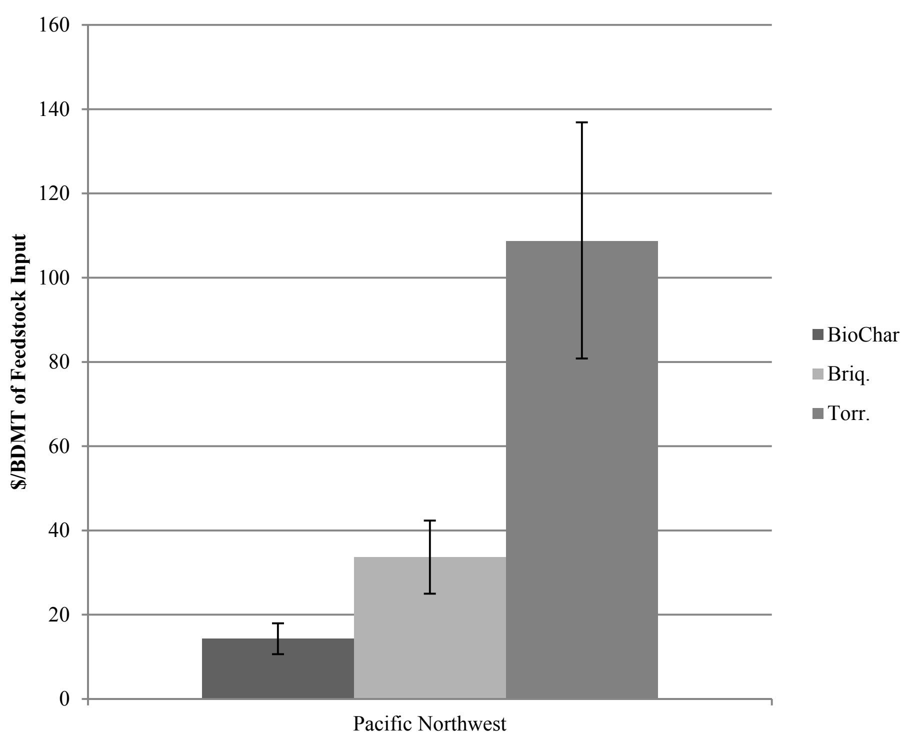

Figure 8. Cost of generator power consumption for biochar, briquettes and torrefied wood. The sensitivity to fuel prices are described by the range where the baseline is $0.86/L ($3.24/gal) with a low of $0.53/L ($2.00/gal) and a high of $1.19/L ($4.50/gal).

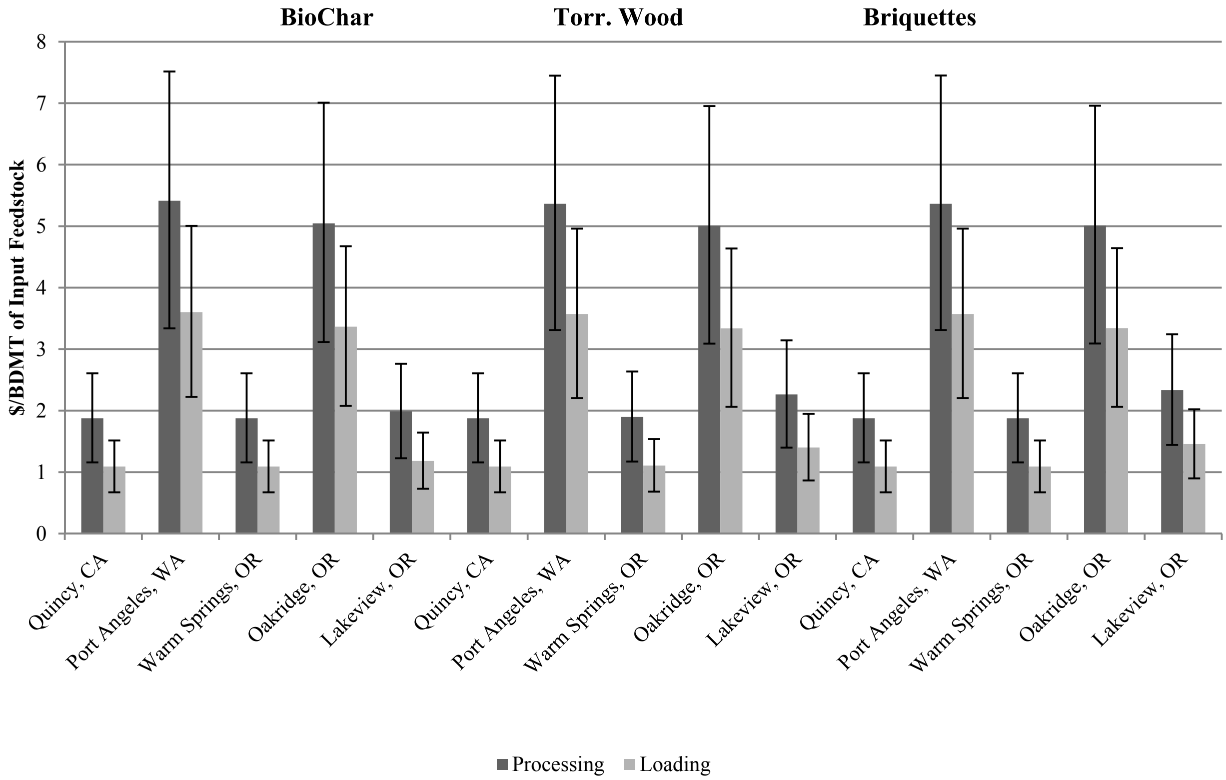

Figure 9. Cost of processing and loading operations in the supply chain. The sensitivity of cost to diesel fuel price is shown by the range between horizontal bars where the base is $0.86/L ($3.24/gal) with low of $0.53/L ($2.00/gal) and a high of $1.19/L ($4.50/gal).

Composite Cost Variations to Product Pricing

Facility operational and conversion fuel costs account for the major share of potential fuel consumption variability accounting for roughly 40-60% of biochar cost variability, 80-90% of torrefied wood variability, and 60-80% of briquetting variability depending on region and feedstock conditions. Furthermore overall fluctuations from biochar, briquettes and torrefied wood translated into ±$5.5-10/bdmt (±$5-9/bdt), ±$10-13/bdmt (±$9-12/bdt), and ±$30-35/bdmt (±$27-32/bdt) of raw feedstock input respectively (up to 15% of the supply chain costs).

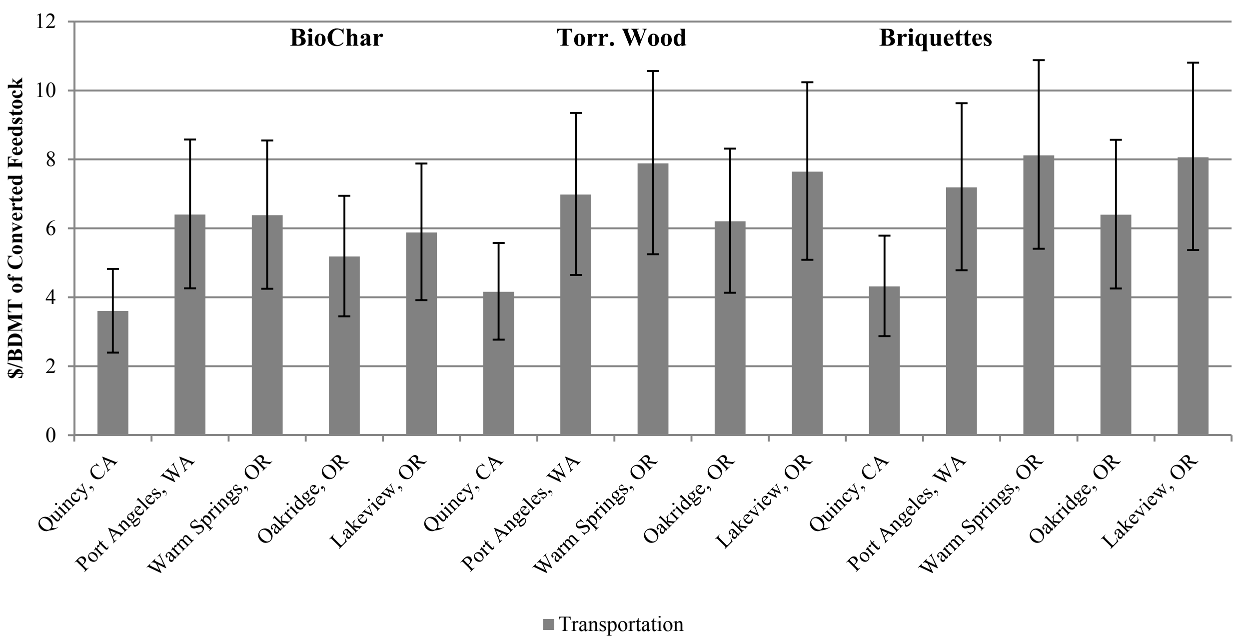

Figure 10.Total transportation cost (raw and converted product) in the supply chain. The sensitivity of cost to diesel fuel price is shown by the range between horizontal bars where the base is $0.86/L ($3.24/gal) with low of $0.53/L ($2.00/gal) and a high of $1.19/L ($4.50/gal).

Product production price depends on diesel price assumptions (fig. 11). This variation depends more on the product that is being produced (due to the high influence of plant design and conversion costs) than the region itself. Biochar is likely the only product to which a transportable facility design would make sense, though briquettes could approach this break-even point.

Question #3: What Are the Energy Savings Associated with a Grid-Connected Modular Facility?

Within the regional context, varying energy prices can provide either an incentive or disincentive to adopt the transportable conversion facility design concept. As electricity prices decrease (or diesel prices increase) the effective incentive for a stationary plant increases when compared to a transportable facility due to lower conversion and facility costs. Conversely, if diesel prices fall, than the relative energy cost 'gap' decreases and thus there is less incentive for a stationary plant when compared to a transportable operation. To illustrate this concept and relative grid-connected advantage, we developed an energy cost differential matrix (grid-connected energy cost less off-grid energy cost) for Oregon, Washington, and California. The grid-connected advantages of using electrical energy when compared to diesel fuel and grid-connected dryer natural gas usage versus transportable propane usage are highlighted. We then extend this analysis to look at equivalent transportation distances relative to these effective energy savings within the following section.

Facility and Conversion Costs (Electricity and Diesel)

Incentives for a grid-connected power source (when looking at conversion and facility energy consumption) vary widely depending on the state and product being produced (fig. 12). This varies from ±\$3.5/bdmt (±\$3/bdt) to over ±\$28/bdmt (±\$25/bdt) of feedstock input. California and biochar provide the least incentive to move to a stationary facility due to higher energy costs and relatively low energy consumption for producing biochar while Washington and torrefied wood have the largest incentive due to low energy costs and high energy consumption for producing torrefied wood.

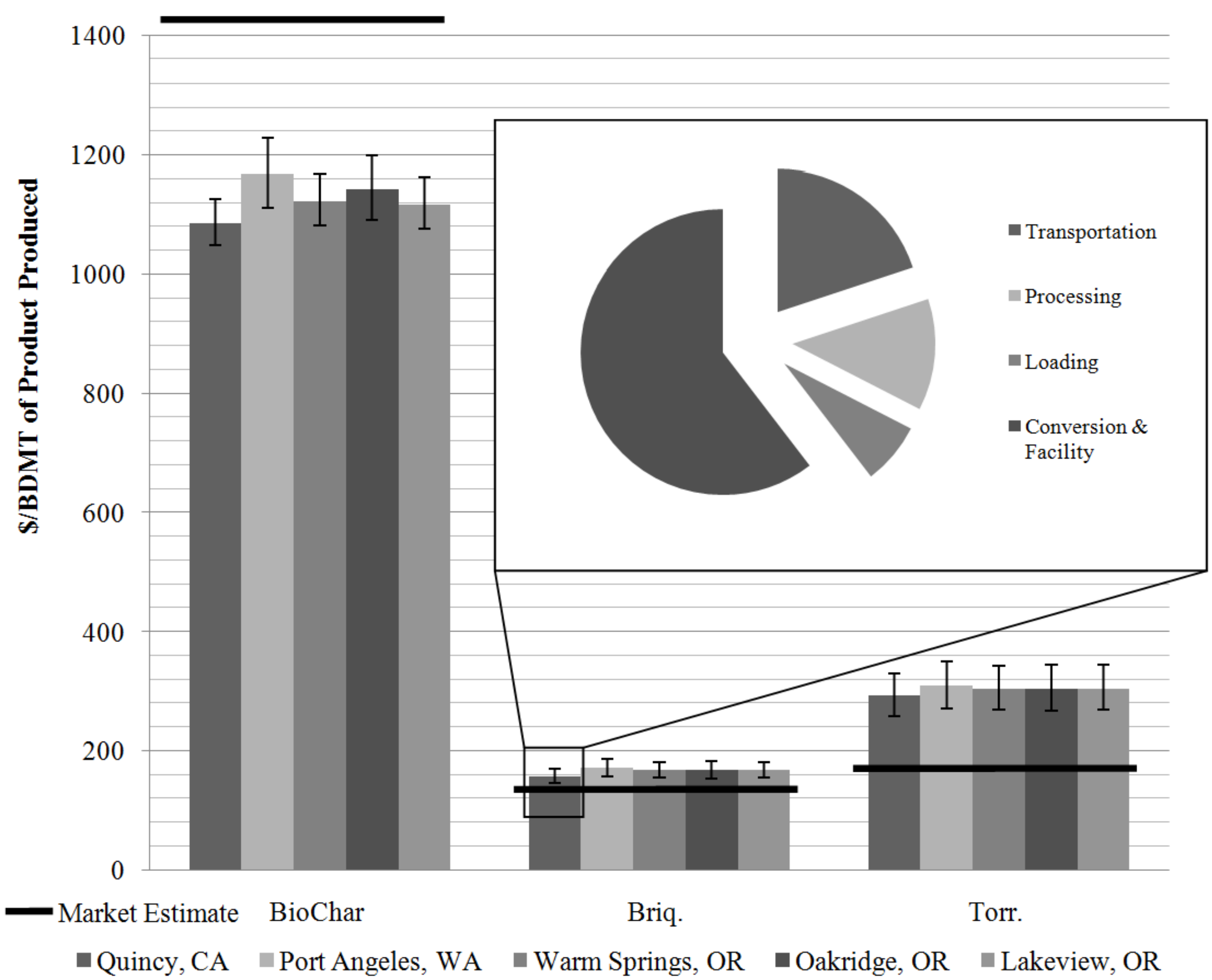

Figure 11. Variation in production cost of product (\$/bdmt of product produced). Conversion rates are assumed to be 16% for biochar, 85% for torrefied wood, and 98% for briquettes. Market line indicates anticipated market price for each product. Ranges indicate costs with high/low energy prices. Inset chart indicates the proportion of variation within each cost category due to fuel prices for the Quincy, California, briquetting case.

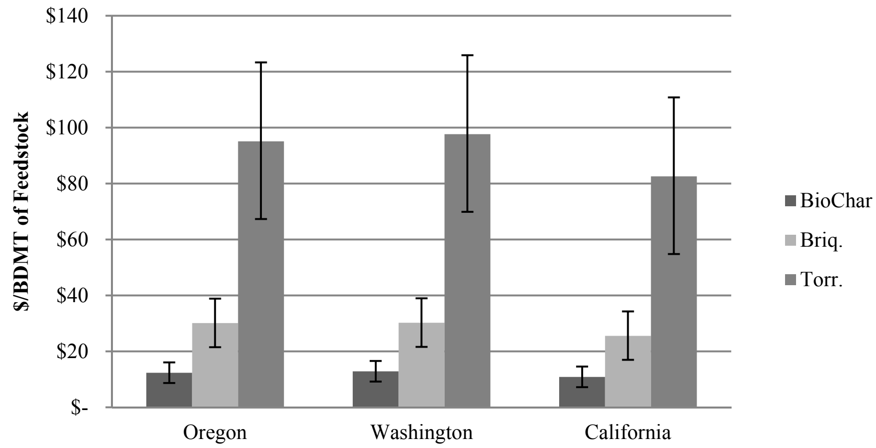

Figure 12. Potential facility cost savings due to grid-connected power supply while still implementing a modular conversion technology design (same equipment and plant design). Cost reductions are generated from a change in energy prices and overall energy consumed (conversion technology and auxiliary systems). Ranges indicate the potential change in anticipated cost reductions due to variable diesel prices where low is \$0.53/L (\$2.00/gal) and high is \$1.19/L (\$4.50/gal). Electricity prices are assumed constant at \$.061/kWh, \$.045/kWh, and \$.107/kWh for Oregon, Washington, and California, respectively.

Drying Costs (Propane vs. Natural Gas Usage)

Drying costs can also be a large portion of the overall cost structure depending on the product produced, acceptable moisture content, raw material moisture content, and equipment utilized in drying. The base model assumes a Belt-O-Matic dryer and propane as the primary fuel, whereas in a stationary grid-connected facility, similar belt drying techniques can be used (at potentially more efficient scales) with more cost effective natural gas as the fuel. In this study, we assume biochar conversion does not require external fuel for drying (uses re-circulated heat) and the torrefied wood conversion technology does not require drying for the 30% moisture content biomass input. Briquettes, on the other hand, require an incoming moisture content of about 15% thus requiring drying from the incoming 30% moisture content to the desired 15% moisture content (wet basis) with an external fuel source. Figure 13 illustrates the range of anticipated cost savings for briquetting with a range of propane and natural gas market prices.

Overall Potential Savings

For the base case, we would anticipate a potential cost savings of roughly \$11-13/bdmt (\$10-12/bdt) for biochar, between \$42-46/bdmt (\$38-42/bdt) for briquettes, and between \$83-99/bdmt (\$75-90/bdt) for torrefied wood depending on the region if a grid-connection was available. Furthermore, when the full range of variability (with fuel price adjustments) is considered, the sum of the variations

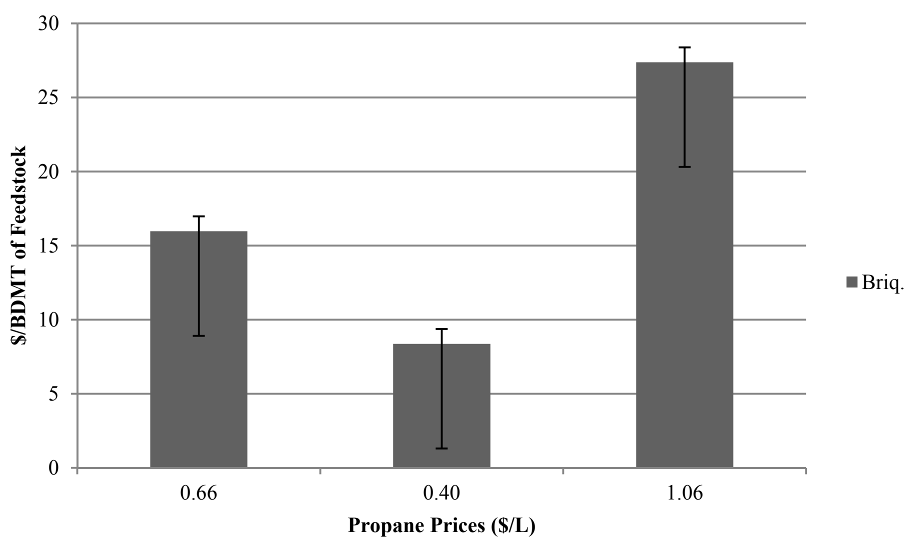

Figure 13. Potential drying cost savings during briquetting operations due to grid-connected power supply. For a given propane value, an estimated cost reduction by switching to natural gas is estimated. The horizontal bars indicate the range of likely natural gas prices [\$106-530/1000 m^3(\$3-15/1000 cf) with the base being \$159/1000 m^3(\$4.5/1000 cf)].

can approach$17/bdmt ($15/bdt) for biochar,$62/bdmt ($56/bdt) for briquettes, and $127/bdmt ($115/bdt) of feedstock input for torrefied wood (fig. 14).

The ‘energy cost differential’, expressed as a percentage of the overall supply chain cost structure for a modular transportable facility illustrates the importance of fuel prices and the strong incentive to connect the facility to the grid (table 9).

If grid-connected energy is available for each facility location, briquetting becomes economically feasible while torrefaction likely continues to be unprofitable (fig. 15).

Overall, this indicates, in a substantial way, that the energy cost is a primary driver in economic viability given the conversion technologies considered. Grid-connections are unlikely in many mobile locations, but realizing their importance can affect the choice of location.

Additional Cost Savings of Stationary Facilities

Extending this logic to a singular permanent facility, scale we would not be limited to a modular installation and could choose technology based on purely efficiency, throughput, and power consumption rather than being limited to transportable options. It has been suggested that next generation biochar machines are commonly scaled at three-times the throughput of our selected machine indicating a reduction in inherent operational expenses (Smith and Holloman, personal communication). Additionally, with the inclusion of permanent buildings, concrete pads and other infrastructure we would anticipate more efficient storage, movement and transport processes within the plant, though land acquisition costs would be higher. These factors are not included in this analysis, rather a comparison among modular transportable designs is presented.

Table 9. ‘Energy cost differential’ as a percentage of overall supply chain cost for a transportable facility for facility type and region.

	Quincy, Calif.	Port Angeles, Wash.	Warm Springs, Ore.	Oakridge, Ore.	Lakeview, Ore.
BioChar	6%	7%	7%	7%	7%
Briq.	27%	28%	28%	29%	28%
Torr.	33%	37%	37%	38%	37%

QUESTION #4: HOW MUCH FARTHER CAN YOU TRANSPORT WITH GRID-CONNECTED ENERGY SAVINGS?

After having developed a realistic operational incentive for grid-connected operations by region, we can pair this with fuel prices by region to develop a set of scenarios to compare a transportable system with a stationary grid-connected modular plant (fig. 16). The breakeven point is where the raw material and product transport costs of the transportable system plus mobilization costs are equal to the raw material and product transport costs of the stationary facility reduced by cost savings due to energy efficiencies (energy cost differential) (eq. 8).

where

$$(Ravg \times \$\ km^{-1}bdmt^{-1} \times bdmt + Cavg \times \$\ km^{-1}bdmt^{-1} \times bdmt) + Mobilization\ Cost = Rs \times \$\ km^{-1}bdmt^{-1} \times bdmt + Cs \times \$\ km^{-1}bdmt^{-1} \times bdmt - Energy\ Incentive \quad (8)$$

This can be partitioned into two parts 1) How much farther can we transport raw material or 2) how much farther can we transport products?

Equivalent Raw Distance Transportation (Haul Distance)

From figure 17 we can see that for biochar the relative grid-connected stationary plant advantage equates to an additional 22 to 42 raw material haul km (14-26 miles) where briquettes can be upwards of 160 km (100 miles) and torrefied wood can exceed 280 km (175 miles) depending on location and material being moved. Additionally, the

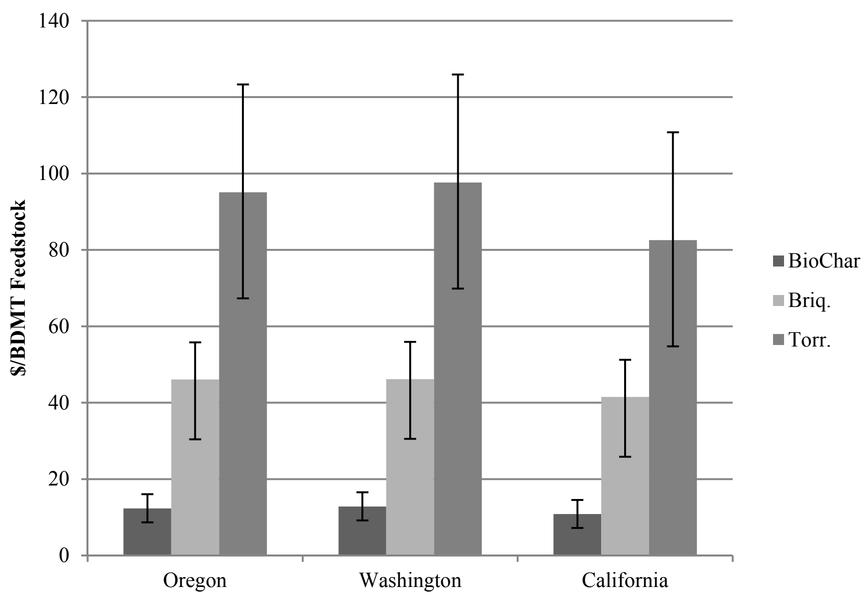

Figure 14. Overall potential transportable facility cost savings due to grid-connected power and fuel supplies. Values reflect effective energy cost differential with the horizontal bars representing the high/low values of diesel, propane and natural gas prices over the three state region.

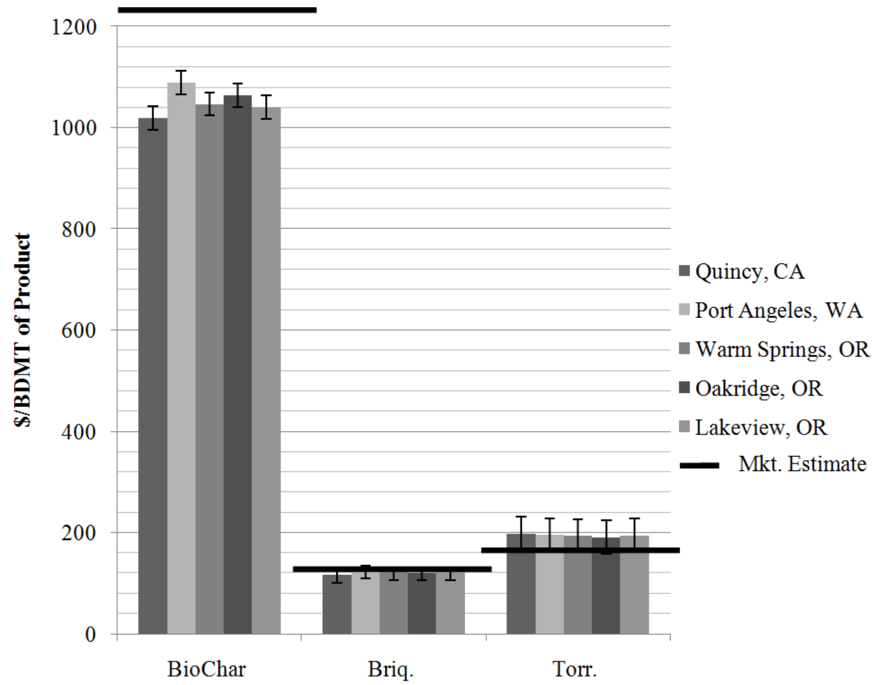

Figure 15. Product cost if the transportable plant is grid-connected. Market line indicates anticipated market price for each product. Ranges indicate costs with high/low energy prices.

stationary grid-connected advantage with respect to fuel prices and travel distances vary only minimally for biochar while most significant [~80 km (~50 miles)] for briquettes (when incorporating propane price fluctuations) and up to 50 km (30 miles) for torrefied wood (fig. 17).

Compared to the base transportation data (table 8), this additional distance equates to roughly 2-15 times that of the base raw material transportation distance, indicating a potentially large incentive to move to a grid-connected stationary facility. Comparing our average regional landscape distance from harvest unit to market (table 1) to the 'additional' equivalent raw material transportation distance (fig. 17), we would conclude that energy cost savings from a grid connection would 1) favor a stationary plant for torrefaction in all regions, 2) likely favor a stationary plant for briquetting in all regions except possibly at Lakeview and Quincy (as this additional transportation distance is less than the average unit to market distance) and 3) probably favor a transportable biochar plant due to the lower benefits of a grid-connection. Results of course depend on specific stationary plant placement, plant operational efficiencies and local road network.

Equivalent Converted Distance Transport (Plant to Market)

When equating these savings to additional converted product transport there is also a large incentive to move to a grid-connected stationary site. In this case, a grid-connected stationary biochar plant equates to roughly 197-

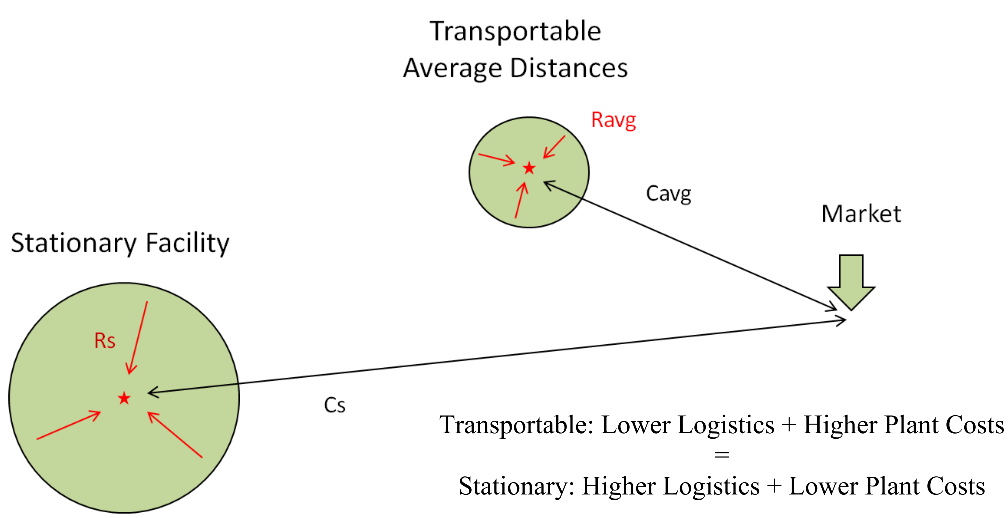

Figure 16. Transportable vs. stationary facility transportation logistics. A transportable system with lower transport distances (raw and/or converted) can be equated to a stationary facility depending on its respective 'energy gap' (lower plant costs) and transportation costs.

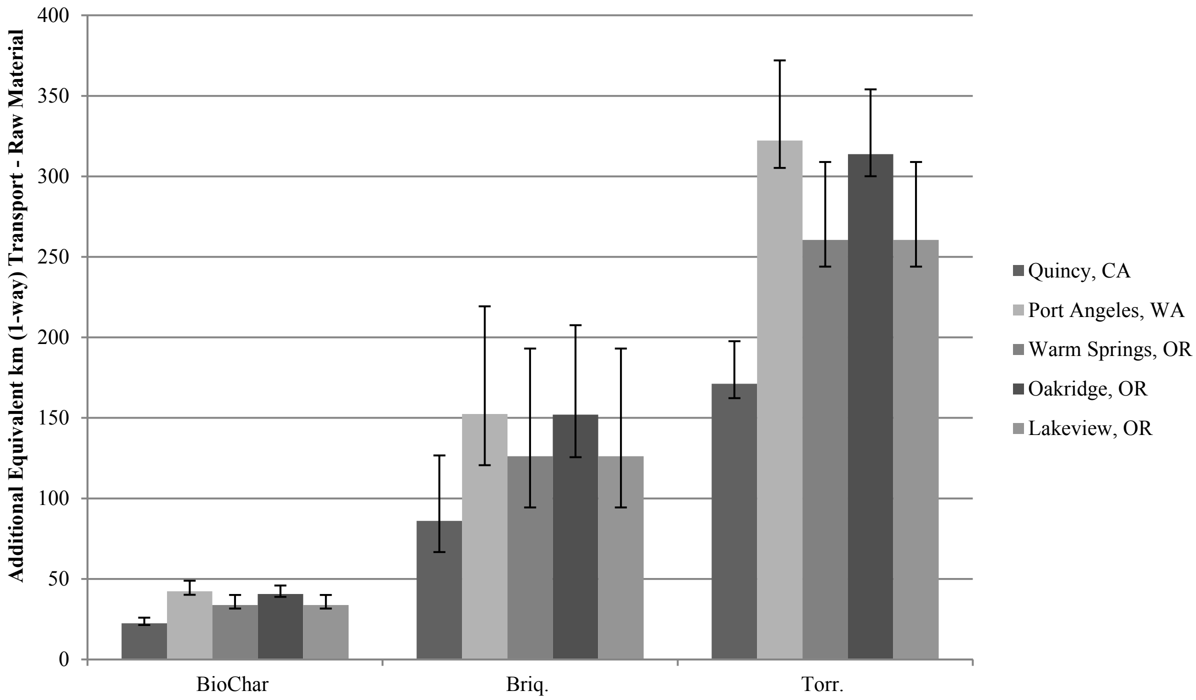

Figure 17. Transportable vs. grid-connected facility: break-even point (additional transport km). Additional km are the 1-way distance to travel to the stationary plant for raw material transport. The horizontal bars indicate the high and low transportation distances with respect to varying fuel prices.

233 increased product transport km (123-146 miles) where briquetting can be upwards of 350 km (220 miles) and torrefaction can exceed 800 km (500 miles) of product transportation. Additionally, variations due to fuel prices can vary that advantage by 40, 240, and up to 160 km (25, 150, and 100 miles), respectively (fig. 18).

Thus, the grid-connected plant could offset an additional product transportation distance that is 2-25 times the base transportation distance, reinforcing the financial incentive to move to a stationary facility on a cost basis.

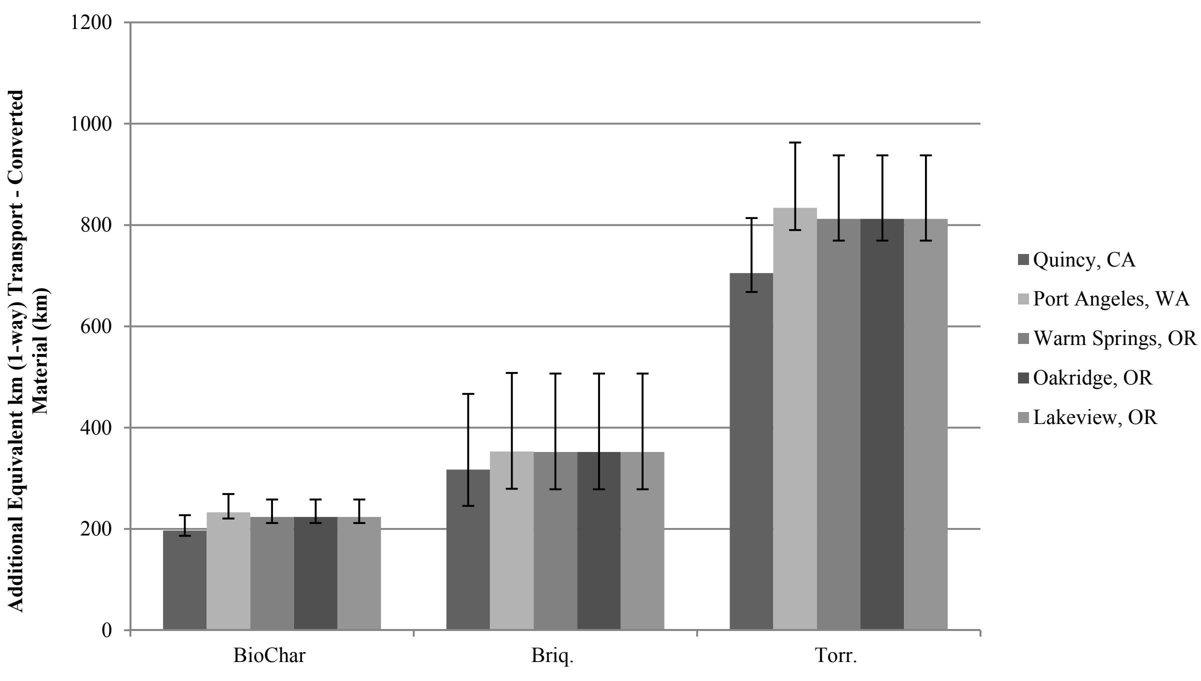

Figure 18. Transportable vs. grid-connected facility: break-even point (additional converted product transport km). Additional km are 1-way distance to travel to stationary plant for product transport. The horizontal bars indicate the high and low transportation distances with respect to varying fuel prices.

CONCLUSIONS

We examined the cost structure of three transportable plant configurations with five regional landscape settings within Washington, Oregon, and California. These settings included variable feedstock composition, harvest unit and spatial biomass per land area values, different log markets, truck configurations and energy markets, which allowed examination of how a transportable biomass conversion facility would operate and itssupply chain cost structure. From the base regional results a transportable biomass conversion plant of a 45,000 bdmt yr^{-1} (50,000 bdt yr^{-1}) production would optimally move every 1.0-2.5 years where a biochar plant moves least frequently and a torrefied wood plant moves most frequently. All operations predominantly use log-like feedstock, where available, rather than branches to support lowest cost operations. Additionally, transportation distances (raw and product) depend largely on the regional landscape features with the shortest material transport distances associated with regions of higher spatial biomass material availability (Quincy and Oakridge) and the longest plant-to-market distance associated with biochar (lowest per km cost). While there were regional differences, these amounted to a less than 10% of product cost with biochar being the only product that isviable under the assumed market conditions. Torrefied wood was the least likely profitable unless a high market premium can be achieved (Question #1).

The logic behind transportable biomass conversion facilities is that the logistics and associated hauling costs would begreatly reduced due to near-woods conversion yield costs savings in transportation. To test this logic we evaluated a sequence of additional questions highlighting first the transportable system design sensitivity to energy and fuel prices, and then a comparison to a grid-connected power supply in each region. The diesel price sensitivity analysis (Question #2) determined the product cost was sensitive to diesel fuel prices by ±3-5% for biochar, ±7-9% for briquettes, and ±12-13% for torrefied wood. The lower end of the fuel price range was not enough to move briquettes and torrefied wood to viability. Transportation's share of the total cost change caused by fuel price sensitivity was 5-30% depending on product and region with the conversion process absorbing the remainder.Grid-connected access (Question #3) including diesel, electrical, propane and natural gas price would reduce baseline costs on the order of 6-7% for biochar, 27-29% for briquettes and 33-38% for torrefied wood. Overall, Quincy had the lowest incentive for a grid-connected plant (high electricity costs) and Port Angeles with the highest incentive. With a grid connection, both biochar and briquetting appear potentially viable.

As it is unlikely to have grid-connected mobile locations, we analyzed transportation sensitivity to grid connectivity (Question #4) to determine what equivalent transportation distances would offset the calculated grid-connected incentives. We found that the energy cost incentives allowed for 2-15 times the base raw material transport distances or roughly 2-25 times the base product transport distances with biochar on the low end and torrefied wood on the high end. The overall viability depends on the specific market price and the specific landscape reviewed. When comparing energy incentives and equivalent increased raw material transportation distance in the five regions we conclude a transportable biochar facility is likely preferable to a stationary grid-connected location (depending on landscape). For briquettes, a transportable facility within Quincy or Port Angeles maybe more economical compared with a stationary facility, but will likely remain unprofitable. A torrefied plant would likely not be viable even with grid-connected power.

In summary, these findings indicate a favorability towards biochar as the most likely candidate for a transportable system given its low reliance on power, high allowable moisture content for conversion, and low product transportation costs. Additionally Quincy, California, is the preferred region given its high quality feedstock allocation, relative accessibility, and higher grid-connected power cost making transportable options more attractive while Port Angeles, Washington, yielded the highest production costs and lowest grid-energy mobility incentives. These results provide the analytical framework and results generally support the conclusions hypothesized by Polagye et al. (2007) that transportable designs are generally uneconomical, although the Polagye et al. analysis was in a different landscape setting, concentrating on thinning of overstocked forests for wildfire reduction. This said, our analysis points to situations where a transportable system could be economical (namely biochar within any region and briquetting depending on grid connectivity). Additional research into the other advantages (cost, social, auxiliary) of a stationary plant beyond grid-connected power when compared to transportable designs would further highlight viability potential.

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