Demand Curve Estimation of Locally Produced Woody Biomass Products

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Abstract. *The goal of the Waste-to-Wisdom project is to produce and sell value-added products derived from post-harvest forest residues including wood briquettes, torrefied briquettes, and biochar. The consumer demand for these products (i.e., market size) determines the success of manufacturers especially when the location of production is far away from a population center and the producer is a price taker. Consumers are often scattered and transportation costs from the factory to retail stores lower the net sales revenue at the plant. The objective of this study was to estimate the demand curves and the associated revenue functions of the bioenergy products in five case locations applying a market-based analysis. We first estimated the size of the potential market for the products in each location and then assumed a market penetration rate to estimate consumer demand. This information was used to develop a set of mathematical functions based on deductive logic. Plugging presumable values based on scenario assumptions into the models contributes to the economic feasibility studies.*

Keywords. *, Biochar, Forest products marketing, Market penetration rate, Price skimming strategy, Wood briquette.*

One of the challenges associated with timber harvesting and forest thinning operations in the western United States is the disposal of the slash and woody biomass left over following forest operations. Typically these unmerchantable forest residues are collected into slash piles and burned (Malmsheimer et al., 2008). While forest residues could be used to produce bioenergy products, the economic, technological, and logistic challenges associated with utilizing forest residues has prevented their widespread utilization (Han et al., 2004). Newly developed in-woods, mobile biomass conversion technologies (BCTs) can lower the production costs of manufacturing value-added bioenergy products. The mobile production system described in this article will be referred to as the "Waste-to-Wisdom" (W2W) process. The bioenergy products most often produced by these mobile technologies include: wood briquettes, torrefied wood briquettes, and biochar. Wood briquettes are produced from dried wood chips that are fed into a hopper and extruded under high pressure to form a briquette. Torrefied wood briquettes can be produced by using torrefied wood chips as the feedstock in the briquette forming process. Torrefaction is a slow thermochemical process that occurs at very high temperatures and drives off both the moisture and the low energy volatile organic compounds contained within the wood chips. As a result, torrefied wood briquettes are much more energy dense than basic wood briquettes. Finally, biochar is produced via pyrolysis (thermal degradation) in a high temperature system devoid of oxygen (Spokas et al., 2012). Biochar's highly porous structure allows it to retain large amounts of water and water-soluble nutrients, making it ideal for improving the fertility of acidic soils and thereby increasing agricultural productivity (Page-Dumroese et al., 2010). Biochar is often mixed with compost to reduce treatment costs and help maintain soil fertility over a longer period of time. However, transportation of forest residues is the largest barrier to the increased utilization of forest residues due to the high cost and inefficiencies associated with trucking high moisture, low energy density forest residuals (Stidham and Simon-Brown, 2011). By taking advantage of in-woods BCTs, bioenergy products can be produced closer to the forest resource, thereby reducing transportation costs and the capital investment associated with large centralized processing facilities. The economics of the in-woods BCT production system are described in this article.

In the forest products literature, transportation costs are often a key issue and much research has shown how transportation costs affect the economics of the forest resource utilization (e.g., Han et al., 2004; Zamora-Cristales, 2013; Berry and Sessions, 2018). However, the demand-side analysis for bioenergy products derived from residual biomass that takes into consideration transportation cost is often lacking in the literature because researchers focus on supply-side issues while oversimplifying the demand-side context. Thus, applying a market-based analysis to understand the consumer demand for value-added bioenergy products is critically important (Sasatani and Eastin, 2017). Estimating consumer demand for these bioenergy products requires understanding the

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relationship between product features and price (Kotler and Keller, 2009). In the W2W project, we are planning to produce value-added bioenergy products for sale in local markets. Adding value to forest residues results in higher returns as producers take advantage of niche markets that support higher prices and higher profit margins (Sasatani, 2013). However, targeting local markets with a high volume of products can easily exceed local demand and drive down product prices. In order to understand the dynamics in local markets, we considered the transportation costs from factory to retail stores and estimated the demand curves for wood briquettes, torrefied wood briquettes and biochar produced using BCTs situated in five locations across the Pacific Northwest. Consumer demand for the bioenergy products is dependent on the size of the local market, the population distribution, the estimated rate of market penetration, and competition from substitute products.

MARKET BACKGROUND

WOODY BIOMASS-BASED ENERGY PRODUCTS

Over the past century, developed economies have switched from using wood as a fuel source, transitioning instead towards capital-intensive fossil fuels, including oil and natural gas. The development of densified wood energy products, including wood pellets and wood briquettes, as well as the more recent development of torrefied pellets/briquettes, has increased the efficiency of using wood as a source of renewable energy and as a substitute for fossil fuels. In addition, new energy policies, particularly in the EU, are mandating significant reductions in carbon emissions within the energy sector by favoring the use of carbon-neutral energy sources, including wood and woody-biomass, for energy production. Given continued growth in the demand for bioenergy products in Europe, as well as in Asian markets, particularly Japan and South Korea, the outlook for the market for woody biomass-based bioenergy products is promising.

The use of wood for residential heating in the United States has generally been confined to firewood. However, as the cost of fossil-based energy has risen, and as concern about global climate change and the carbon emissions associated with heating and power generation from fossil-based fuels has increased, interest in using woody biomass-based energy has increased within both the residential heating and industrial/commercial energy sectors (Mendell and Lang, 2012). U.S. households generated 580 trillion BTU from woody biomass in 2014, which accounted for 2.7% of total energy consumption within the residential sector [U.S. Energy Information Administration (EIA), 2016]. In addition, 4.8% and 0.7% of total energy consumption within the industrial and commercial sectors, respectively, was derived from biomass including wood and biomass-based waste (EIA, 2016). In recent years, the production and consumption of wood pellets in the United States has been highly influenced by international markets. The EU 2020 Renewable Energy Directive (2009/28/EC) set a binding target of deriving 20% of energy consumption from renewable resources by 2020, with each member country setting their own national goals. The recently adopted EU 2030 Energy Strategy increased that target to 27% by 2030. The EU renewable energy mandates have resulted in a huge increase in the demand for wood pellets, far exceeding the domestic EU supply. As a result, the growing international demand for U.S. wood pellets has transformed the wood pellet sector in the southeastern United States and made the United States a global player in the wood pellet market. U.S. pellet exports jumped from 332,426 tons in 2011 to 4.7 million tons in 2016 while the United States share of global pellet exports increased from 2.1% to 29.7% over the same period. The vast majority of U.S. wood pellet exports went to the United Kingdom (over 90%) in 2016. The average F.O.B. export value for U.S. wood pellets was $146.28 per metric ton in 2015 and $130.06 per metric ton in 2016 [U.S. International Trade Commission (USITC), 2017].

In response to the huge surge in international demand, the production capacity within the wood pellet sector in the United States has grown from less than one1 million short tons in 2006 to over 10.5 million short tons in 2016, while wood pellet production rose to 10.4 million short tons in 2016 (Walker and Pilla, 2016). Growth in the pellet industry has largely taken place in the US south, where the share of US production capacity grew from 37.8% in 2009 to 69.4% in 2015. In contrast, the US share of wood pellet production capacity in the north dropped from 44.4% to 18.1% while the west saw its share drop from 17.8% to 12.4% over the same period (Walker and Pilla, 2016). Retail prices for wood pellets sold into the residential market in the United States have been stable with little seasonal variability. Despite the strong international demand, the retail price for wood pellets in the U.S. residential market was about $260 per ton in 2016 (Walker and Pilla, 2016). In addition to pellets, wood biomass is sold as densified wood briquettes, although there is little information on the volume of wood briquettes produced in the United States annually. Anecdotal price information suggests that wood briquettes sell for about 10% less than wood pellets in the northeastern United States, where demand for wood briquettes is strongest.

While wood pellets (also called white pellets) have achieved a strong position in the marketplace within a very short period, some industry analysts think that torrefied wood pellets may be the future of the industry. Torrefaction, also known as mild pyrolysis/carbonization, is a thermal pretreatment process that can upgrade lignocellulosic biomass into a higher-quality, more energy dense product that can be co-fired with coal (Mendell and Lang, 2012). The torrefaction process subjects the biomass to temperatures ranging from 200°C to 300°C in the absence of oxygen for up to 30 min. The slow heating process roasts the biomass, releasing volatile compounds and breaking down the hemicelluloses. Following the torrefaction process, the torrefied biomass can be densified into pellets or briquettes. Another type of energy product, black pellets, are very similar to torrefied pellets. Black pellets are produced using a steam explosion process that softens the lignin and allows it to act as a natural binder during the pellet forming process. Torrefied and black pellets have properties that are superior to white pellets and are very similar to coal. Torrefied or black pellets/briquettes can be ground up using the same equipment that is used in coal-fired plants and can be substituted for coal in ratios up to 90% in coal burning boilers with no change in boiler technology (Mendell and Lang, 2012). Transportation costs for torrefied pellets/briquettes are substantially lower than for white pellets/briquettes on an energy density basis due to their much lower moisture content. The calorific content of white pellets ranges from 15 to 16 MJ/kg whereas it is 20 to 24 MJ/kg for torrefied and black pellets (Kleinschmidt, 2011). In addition, torrefied pellets/briquettes are hydrophobic; so that they can be stored in the open similar to coal and do not need to be covered, thereby reducing infrastructure costs. Technical and economic challenges have hampered full commercial scale production of torrefied pellets (Mendell and Lang, 2012). In 2015, Zilkha Biomass in Selma, Alabama supplied black pellets to the French power company, Compagnie Parisienne de Chauffage Urbain (CPCU), which provides about a third of the heat for Paris. The F.O.B. unit price for the black pellets exported to France in 2015 was $204.66 per metric ton while the unit price of white pellets exported to the U.K. in 2015 was $147.84 per metric ton (USITC, 2017). This price difference implies that black pellets commanded a 38.4% price premium over white pellets in 2015. However, most market experts think that the price premium for black pellets will decline to about 20% over time as the supply of black pellets increases.

The Market for Biochar as a Soil Amendment Product

In contrast to the wood-based bioenergy market, the global biochar market is extremely fragmented and localized; and all biochar is not created equal. The diversity in feedstocks (softwoods, hardwoods, bamboo, coconut shells, palm kernel shells, and other agricultural by-products) and production technologies makes it impossible to compare biochar products based on price. Even more confusing is the fact that most biochar is sold as a soil amendment where it is mixed with a wide variety of other organic and inorganic materials to produce a final (often proprietary) product. The International Biochar Initiative has documented the state of the global biochar sector since 2013. Based on a survey of 23 biochar producers in the Unites States in 2013, the wholesale price of pure biochar was approximately $0.27/kg ($244.94/ST), while the average retail price was $2.74/kg ($2,485.69/ST) (Jirka and Tomlinson, 2014). A follow-up survey of 28 biochar producers in the United States, administered in 2014, found that the average wholesale price of pure biochar was $1.50/kg ($1,360.78/ST) while the average retail price of pure biochar was $4.26/kg ($3,864.61/ST) (Jirka and Tomlinson, 2015). While the biochar industry is still small, it has been growing in response to strong demand within the organic farming sector. Recent market research suggests that many biochar companies see the lack of market awareness of the benefits of biochar as a major obstacle to growth [International Biochar Initiative (IBI), 2016]. Another challenge to market growth is the high transportation and shipping costs of biochar (IBI, 2016). Despite these challenges, the outlook for biochar appears to be bright, with about 65% of companies surveyed agreeing that the demand for biochar will continue to increase in the near future (IBI, 2016).

The objective of this research was to estimate the demand curves and the associated revenue functions for three bioenergy products in five target markets (referred to as case locations). Since the relationship between price and demand for each product in each market is unknown, we first estimated the size of the potential market for each product in each market. Next, we assumed a market penetration rate in order to estimate consumer demand. This information was used to develop a set of mathematical functions that were used to develop the demand curve and net sales revenue function for each product in each market.

Methodology

Before describing the methodology, it is important to distinguish between the "factory price" and the "delivery price." Figure 1 illustrates the "price" for bioenergy products at different stages along the supply chain. The factory price includes a producer profit that is added to the cost of production. The delivery price is the factory price plus the cost of transporting the product to the retail location. The retail price is considerably higher than the delivery price because the retailer includes both their cost of operation as well as their profit. The goal of this study

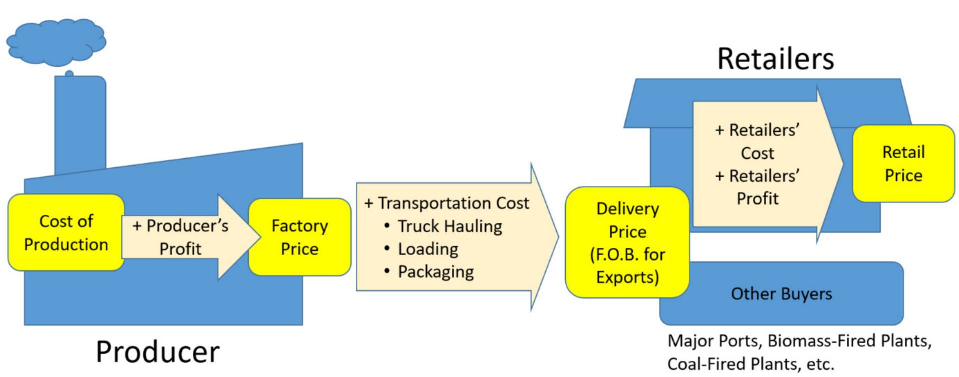

Figure 1. Definition of prices at the different stage on the supply chain.

was to estimate the demand curve for the factory prices for the three bioenergy products (i.e., pellets, torrefied pellets, and biochar) under consideration.

In order to develop supply curves for the five case locations, we needed to make several assumptions to help estimate the model parameters. Given that some market data, such as prices, can fluctuate widely, we chose conservative deterministic reference points based on a review of the literature. Since some information is not available because the bioenergy products being considered are new to market, we applied the Delphi technique to estimate this information (Dalkey and Helmer, 1963). A questionnaire was sent to select industry experts with relevant real-world information. We summarized their information and then asked for their feedback regarding the information obtained. We then incorporated their comments into the summary and sent the revised summary back to the same group of experts, asking them to revise their previous responses in light of the new information provided by the other experts. We repeated this process one final time when their responses converged and they had reached consensus.

Market Size Estimation

The five case locations used in this research were: 1) Port Angeles, Washington; 2) Warm Springs, Oregon; 3) Lakeview, Oregon; 4) Oakridge, Oregon; and 5) Quincy, California. Since the primary end-users of wood briquettes and biochar are local consumers, producers sell their products to local retail stores, such as neighborhood hardware stores and local nurseries. As distance from the production site to the retail outlet increases, so too does the transportation cost. This study used the population distribution by path distance from the central production location as the base to estimate the market size. First, by using ArcGIS (ESRI, 2011), road layers for the network service area within 10 miles of the production facility for each case location were created. Next, the population located within the range of buffers between each service area was estimated. Exponential regressions were used to smooth the shape of the original population distributions. Since there is adequate demand within major metropolitan areas, the domain of the regression (i.e., distance) is from zero to the closest major metropolitan area.

Wood Briquette Market Size Estimation

Wood briquettes can be marketed towards two markets; the local residential heating market or the local commercial biomass energy market. The first market to target for wood briquettes is the local residential heating market because wood briquettes can substitute for firewood when the price is competitive. According to the U.S. Census Bureau (2012), 7% of Oregon's households and 4.4% of Washington's households use firewood as their main energy source for heating. Based on State Energy Data (EIA, 2016), California households burned 42.9 trillion BTU of wood for energy, Washington households burned 20.2 trillion BTU of wood and Oregon households burned 18.3 trillion BTU of wood and wood-derived fuel in 2014. The estimated population of California, Washington and Oregon was 38.8 million, 7.1 million and 4.0 million, respectively, in 2014 (U.S. Census Bureau, 2017). Thus we can estimate that the per capita consumption of wood fuel by residents in California, Washington and Oregon was 1.1 million BTU, 2.96 million BTU and 4.6 million BTU, respectively. Although the heating value of wood briquettes varies based on the type of feedstock used (e.g., wood species, moisture content, etc.), for this analysis we assume that wood briquettes generate 16.4 million BTU per short ton (Bear Mountain Forest Products, 2017). Thus, the annual average consumption of wood briquettes for heating was estimated to be 0.068, 0.174 and 0.281 short tons per person in California, Washington, and Oregon, respectively. Combining the wood briquette consumption estimates with the population estimates for each case location allows us to estimate the potential residential demand for wood briquettes in each location.

In the second evaluation, we considered the potential demand for wood briquettes by local commercial biomass-fired plants, such as combined-heat-and-power (CHP) facilities, commercial electricity-only plants, commercial heat-only plants and commercial boilers. While there are many commercial biomass-fired plants and boilers in the Pacific Northwest, their numbers tend to fluctuate in response to changes in policy, energy prices and feedstock supplies. In this analysis, we assume that the demand for wood-biomass by commercial plants is proportional to the population distribution in each study location. The commercial energy sectors in California Washington, and Oregon consumed 17.1 trillion BTU, 2.6 trillion BTU and 2.4 trillion BTU of biomass in 2014 (EIA, 2016). Therefore, the average annual biomass consumption per capita within the commercial sector was estimated to be 0.441 million BTU in California, 0.368 million BTU in Washington, and 0.605 million BTU in Oregon. This equates to a per capita consumption of 0.027, 0.022 and 0.037 short tons of wood briquettes for California, Washington and Oregon, respectively. Combining the wood briquette consumption estimates with the estimated population in each case location allows us to estimate the potential commercial demand for wood briquettes in each location.

As previously mentioned, the F.O.B. price of wood pellets was about $146/MT or $132/ST in 2015 (USITC, 2017). Since the price of wood briquettes is about 10% less than that of wood pellets, the F.O.B. price of wood briquettes was estimated to be approximately $119/ST. Our survey of industry experts estimated that there is a 20% price premium for wood briquettes sold into the residential market relative to the commercial market, which suggests that the residential delivered price for wood briquettes is approximately $143/ST. These are very conservative estimation of the delivered price (i.e., wholesale price), but they are considered to be useful for the W2W study since wood briquettes are made from forest residues. Transportation costs include both fixed (loading and packaging) and variable (truck hauling) costs. For residential use, wood briquettes are packaged, put on pallets and delivered to retail outlets using 25 ton single trailers. Loading and packaging costs were estimated to be $13.83 per short ton while the truck hauling costs were estimated to be $0.21 per short ton-mile (round trip) for residential markets. In contrast, since there is no need to package wood briquettes for commercial use, the loading costs were estimated to be $0.72 per short ton while the truck hauling costs (bulk) were estimated to be $0.23 per short ton-mile (round trip) for commercial markets (Berry and Sessions, 2018). The analysis included deliveries to nearby metropolitan areas in order to ensure adequate demand. Although the season for residential heating generally runs from October to April, we ignored the seasonal fluctuation in demand and the associated inventory costs to simplify the estimations.

Adoption is the process by which a consumer begins and continues to use a product and diffusion is a measure of the rate of adoption (Rogers, 2003). The market penetration rate refers to sales of a product into a potential target market over time. This rate can be influenced by many factors, including price, product quality, advertising, type of supply chain, and the sales efforts of retailers (Kotler and Keller, 2009). Since this is difficult to determine for a new product, we conservatively assumed that W2W wood briquettes could achieve a 1% rate of substitution for firewood in the residential heating market and a 2% rate of substitution for wood in the commercial heating market as a bench mark. This assumption will be relaxed for the sensitivity analyses.

TORREFIED BRIQUETTE MARKET SIZE ESTIMATION

The use of torrefied briquettes would primarily be as a replacement for coal since it is unlikely that they would be used in biomass fueled energy plants or by residential households given their substantially higher price. There are currently three domestic coal-fired power plants located near our case locations that could provide demand for torrefied briquettes; the Centralia Big Hanford power plant in Centralia, Washington, the Boardman Coal Plant in Boardman, Oregon, and the North Valmy Generating Station in Valmy, Nevada. In addition, there is a potential international market for torrefied wood briquettes if they can be delivered at a competitive price. In this analysis, we assume that W2W producers will target the closest market to minimize transportation costs. Market experts estimate that the price premium for torrefied wood briquettes would be approximately 20% to 25% over traditional wood briquettes. Based on this estimate, the F.O.B price of torrefied briquettes used in this analysis was $148/ST (a 25% price premium), and we assumed that this would be the delivered price at the domestic coal-fired power plants as well as at major ports. Loading costs for wood briquettes are $0.68 per short ton and transportation costs are $0.20 per short ton-mile (round trip) in bulk truck shipment (Berry and Sessions, 2018). Finally, it is important to note that we assumed that there would be adequate demand for torrefied briquettes in the market.

BIOCHAR MARKET

There is an immature, but potentially profitable, market where biochar can be sold to retail garden and landscaping firms as a packaged consumer product. Biochar can also be sold to wholesalers, to landscape companies, or for special horticultural uses (T. Miles, personal communication, 1 February 2017) within the Pacific Northwest (PNW) region. The price of biochar will vary significantly depending on the target market (e.g., retail vs. wholesale). For this analysis, we assumed that W2W producers would adopt a “price skimming strategy” that targets local niche markets located within 150 miles of the biochar production facility. The delivery price for biochar used in gardening and landscaping applications ranges between $4,950/ST (M. Severy, personal communication, 10 February 2017) at the high-end down to $250/ST (Jirka, S., & Tomlinson, 2014; U.S. minimum wholesale price) at the low-end. The production of organic compost in Washington, Oregon, and California are 1.2, 0.2, and 5.9 million tons per year, respectively (Platt and Glodstein, 2014). Most of the organic compost producers in the PNW use waste collected from organic disposal facilities which helps to keep their biochar prices low (e.g., $37.5-62.5/ST). The state of Washington only consumes about 70,000 tons of biochar per year, primarily in gardening and landscaping applications with some being used within the agricultural sector (T. Miles, personal communication, 25 February 2017). We assumed that the per capita consumption of compost is 0.01 ST (20 lb) within the PNW region. While there may be some niche market opportunities to sell to organic farmers or horticultural growers, the great majority of these potential customers were deemed unlikely to purchase biochar at 10 times the price of compost. Assuming that biochar could be priced at $100/ST, there would be sufficient demand in the local agricultural markets for these types of high-end compost products. Thus, for our model we utilized prices for biochar products that ranged between $100/ST and $250/ST. Biochar can be packaged in supersacks and delivered by a 25 ton single trailer. The loading and packaging costs were estimated to be $2.11/ST while the truck hauling costs (round trip) were estimated to be $0.50 per short ton-mile (Berry and Sessions, 2018). While it is very difficult to forecast the appropriate market penetration rate, we assumed that biochar will gain a 1% to 2% share of the local soil amendment market, based on our consultations with local experts.

MATHEMATICAL FORMULATION

The parameters of the supply models are summarized in table 1. First, the demand curve function for wood briquettes was developed. Equations for the price and quantity of wood briquettes in the residential market are shown as follows:

$$Q_{WB}^{R} = g(d)\ a_{WB}^{R}\ p_{WB}^{R}, \tag{1}$$

$$FP_{WB}^{R} = DP_{WB}^{R} - TCF_{WB}^{R} - d\ TCV_{WB}^{R}, \tag{2}$$

$$Q_{WB}^{C} = g(d)\ a_{WB}^{C}\ p_{WB}^{C}, \tag{3}$$

$$FP_{WB}^{C} = DP_{WB}^{C} - TCF_{WB}^{C} - d\ TCV_{WB}^{C}. \tag{4}$$

In order to represent the total quantity of wood briquettes, we add equations 1 and 3 and combine the

Table 1. Parameters (variables and constants) used to develop the supply curves for W2W products.

Parameters	Assumption	Unit	Description
Products Quantity			
Q_{WB}^{R}		ST	Production quantity of wood briquettes for residential use
Q_{WB}^{C}		ST	Production quantity of wood briquettes for commercial use
Q_{WB}		ST	Total production quantity of wood briquettes
Q_{TB}		ST	Production quantity of torrefied briquettes
Q_{BC}		ST	Production quantity of biochar
Products Price			
FP_{WB}^{R}		\$/ST	Factory price of wood briquettes for residential use
FP_{WB}^{C}		\$/ST	Factory price of wood briquettes for commercial use
FP_{WB}		\$/ST	Factory price of total wood briquettes
FP_{TB}		\$/ST	Factory price of torrefied briquettes
FP_{BC}		\$ST	Factory price of biochar
DP_{WB}^{R}	143	\$/ST	Delivery price of wood briquettes for residential use
DP_{WB}^{C}	119	\$/ST	Delivery and fob price of wood briquettes for commercial use
DP_{TB}	148	\$/ST	Delivery and fob price of torrefied briquettes
DP_{BC}^{high}	4950	\$/ST	Highest delivery price of biochar for gardening and landscaping @ 1st
DP_{BC}^{low}	250	\$/ST	Lowest delivery price of biochar for gardening and landscaping
DP_{BC}^{min}	100	\$/ST	Minimum willingness-to-pay for high-end compost
Transportation Costs			
d		miles	Distance from the central location
TCV_{WB}^{R}	0.207	\$/ST-mile	Truck hauling costs for wood briquettes for residential use
TCV_{WB}^{C}	0.228	\$/ST-mile	Truck hauling costs for wood briquettes for commercial use
TCV_{TB}	0.199	\$/ST-mile	Truck hauling costs for torrefied briquettes
TCV_{BC}	0.504	\$/ST-mile	Truck hauling costs for biochar
TCF_{WB}^{R}	13.828	\$/ST	Loading and packaging for wood briquettes for residential use
TCF_{WB}^{C}	0.722	\$/ST	Loading and packaging for wood briquettes for commercial use
TCF_{TB}	0.675	\$/ST	Loading and packaging for torrefied briquettes
TCF_{BC}	2.152	\$/ST	Loading and packaging for biochar
Market Size Parameter			
a_{WB}^{R} WA	0.174	ST/person	Per capita annual consumption of firewood in Washington
a_{WB}^{R} OR	0.281	ST/person	Per capita annual consumption of firewood in Oregon
a_{WB}^{R} CA	0.068	ST/person	Per capita annual consumption of firewood in California
a_{WB}^{C} WA	0.022	ST/person	Per capita annual consumption of commercial biomass in Washington
a_{WB}^{C} OR	0.037	ST/person	Per capita annual consumption of commercial biomass in Oregon
a_{WB}^{C} CA	0.027	ST/person	Per capita annual consumption of commercial biomass in California
a_{BC}	0.01	ST/person	Per capita annual consumption of compost for gardening
g(d)		Persons	Population in a marketing range
p_{WB}^{R}	1	%	Market penetration rate of wood briquettes for residential use
p_{WB}^{C}	2	%	Market penetration rate of wood briquettes for commercial use
p_{BC}	1-2	%	Market penetration rate of biochar for gardening
Net Sales Revenue			
R_{WB}		\$	Factory's net sales revenue from selling wood briquettes
R_{TB}		\$	Factory's net sales revenue from selling torrefied briquettes
R_{BC}		\$	Factory's net sales revenue from selling biochar

equations given the equal factory price of wood briquettes, FP_{WB}:

$$Q_{WB} = Q_{WB}^{R} + Q_{WB}^{C} = g\left(\frac{DP_{WB}^{R} - TCF_{WB}^{R} - FP_{WB}}{TCV_{WB}^{R}}\right) a_{WB}^{R}\ p_{WB}^{R} + g\left(\frac{DP_{WB}^{C} - TCF_{WB}^{C} - FP_{WB}}{TCV_{WB}^{C}}\right) a_{WB}^{C}\ p_{WB}^{C}, \quad (5)$$

which is the demand curve of wood briquettes. Equation 5 can be simplified in terms of the quantity as the only variable:

$$FP_{WB} = f\left(Q_{WB}\right), \quad (6)$$

though, the shape of the distribution, f(▪), is determined by the shape of g(▪). In this study, we plug a set of numbers in FP_{WB} and calculate the associated Q_{WB}. Then, we apply the most appropriate regression model to specify f(▪). The cumulative distribution function of the equation 6 is the total net sales revenue. The cumulative price (i.e., net sales revenue) of the factory from selling Q_{wb}^{*} short tons of wood briquettes can be expressed as:

$$R_{WB} = \int_{0}^{Q_{WB}^{*}} f\left(Q_{WB}\right) dQ_{WB}. \quad (7)$$

The estimated price of wood briquettes is uncertain and the variations are wide. In addition, as already discussed, the market penetration rate is extremely difficult to project, and the variations are wide as well. Hence, a sensitivity analysis of factory prices on the demand and price curve is necessary and critical. The above equations assume two different markets; residential and industrial. In order to reduce the complexity, it is assumed that a new wood briquette producer in a given location would only target the residential market. In this case, equation 5 can be simplified as:

$$Q_{WB}^{R} = g\left(\frac{DP_{WB}^{R} - TCF_{WB}^{R} - FP_{WB}^{R}}{TCV_{WB}^{R}}\right) a_{WB}^{R}\ p_{WB}^{R}\,. \qquad (8)$$

Equation 8 can be expressed in terms of the factory price of wood briquettes, FP_{WB}^{R}. The net sales revenue of the factory from selling Q_{wb}^{R*} short tons of wood briquettes can be expressed as:

$$R_{WB}^{R} = \int_{0}^{Q_{WB}^{R*}} f\left(Q_{WB}^{R}\right) dQ_{WB}^{R}\,. \qquad (9)$$

We will use two sensitive input parameters; p_{WB}^{R} and DP_{WB}^{R}, while all other variables are constant.

Second, the supply curve function for torrefied briquettes was developed. The factory price of torrefied briquettes can be expressed as:

$$FP_{TB} = DP_{TB} - TCF_{TB} - d\ TCV_{TB} \qquad (10)$$

where d is the distance from the central location to the closest coal plant facility or major port. The net sales revenue derived from selling torrefied briquettes at a given production quantity Q_{TB} is:

$$R_{TB} = Q_{TB}\left(DP_{TB} - TCF_{TB} - d\ TCV_{TB}\right). \qquad (11)$$

Finally, the demand curve function for biochar was developed. The delivery price high is the price when the factory only produces 1 short ton of biochar while the delivery price low is the price when the factory saturates the potential residential gardening market (which is the product of the total compost consumption and the penetration rate). Assuming the supply curve has an exponential function, the delivery price at the retail store can be expressed as:

$$DP_{BC} = \exp\left\{\frac{ln\left(DP_{BC}^{low} - DP_{BC}^{min}\right) - ln\left(DP_{BC}^{high} - DP_{BC}^{min}\right)}{p_{BC}\ a_{BC}\ g(d) - 1}\left(Q_{BC} - 1\right)\right\} + DP_{BC}^{min} \qquad (12)$$

By simplifying equation 12 in terms of two variables, this can be expressed as $h(g(d), Q_{BC})$. In order to calculate the factory price, transportation costs have to be subtracted from the delivered price, and the equation can be written as:

$$FP_{BC} = h\left(g(d),\ Q_{BC}\right) - TCF_{BC} - d\ TCV_{BC} \qquad (13)$$

The net sales revenue of factory from selling biochar at a given production quantity, Q_{TB}, is:

$$R_{BC} = \int_{0}^{Q_{BC}^{*}} \left\{h\left(g(d),\ Q_{BC}\right) - TCF_{BC} - d\ TCV_{BC}\right\} dQ_{BC} \qquad (14)$$

The biochar revenue equation will be very complex if distance remains in the equation as a variable. In this study, we assume that the W2W producer's marketing range is within a 150 mile radius of their production location, so g(*d*) becomes a constant value for each location and quantity is the only variable needed to determine the price level in equations 12-14.

RESULTS

POPULATION

In order to estimate the population distribution in terms of d as the path distance from the case locations with reference to the nearest metropolitan area, we use the following equations: 1) *g*(*d*) = 11,411 × *exp*(0.0685 × d) *as* {d < 105 *miles* [*Tacoma*]} in Port Angeles, Washington; 2) *g*(*d*) = 2,600 × *exp*(0.0739 × d) *as* {d < 95 *miles* [*Portland*]} in Warm Springs, OR; 3) *g*(*d*) = 128,643 × *exp*(0.023 × d) *as* {d < 105 *miles* [*Portland*]} in Oakridge, OR; 4) *g*(*d*) = 13,684 × *exp*(0.0226 × d) *as* {d < 350 *miles* [*Portland*]} in Lakeview, Oregon; and 5) *g*(*d*) = 83,728 × *exp*(0.0300 × d) *as* {d < 220 *miles* [*Richmond*]} in Quincy, California. Based on these population estimates, plugging the assumed numbers into parameters in table 1 provides the following results in table 2. The factory price of wood briquettes at each location is estimated by the equation in terms of x as the production quantity in short tons. The equation works until the production threshold is reached, at which point the threshold quantity is constant at each location.

WOOD BRIQUETTES

The graphical representation of the demand curves for each case location are presented in figure 2. The factory prices for wood briquettes in Port Angeles and Warm Springs remain relatively high across the production horizon since they are located close to large metropolitan areas. On the other hand, since Lakeview is located far away from a major metropolitan area, the higher transportation costs reduce the factory price of wood briquettes produced at Lakeview.

The net sales revenue generated from manufacturing wood briquettes at each of the case locations is presented in

Table 2. Factory price and net sales revenue of wood briquettes in five case locations.

Locations	Factory price ($/ST) when x<threshold	Production threshold (ST)	Factory price ($/ST) when threshold<x
Port Angeles, Wash.	$FP_{WB} = -3.024\,ln(x) + 138.24$	26,526	$FP_{WB} = 107.44$
Warm Springs, Ore.	$FP_{WB} = -2.802\,ln(x) + 134.17$	6,647	$FP_{WB} = 109.51$
Oakridge, Ore.	$FP_{WB} = -9.059\,ln(x) + 183.29$	12,114	$FP_{WB} = 98.12$
Lakeview, Ore.	$FP_{WB} = -9.154\,ln(x) + 162.74$	109,280	$FP_{WB} = 56.72$
Quincy, Calif.	$FP_{WB} = -6.939\,ln(x) + 164.33$	112,517	$FP_{WB} = 83.63$

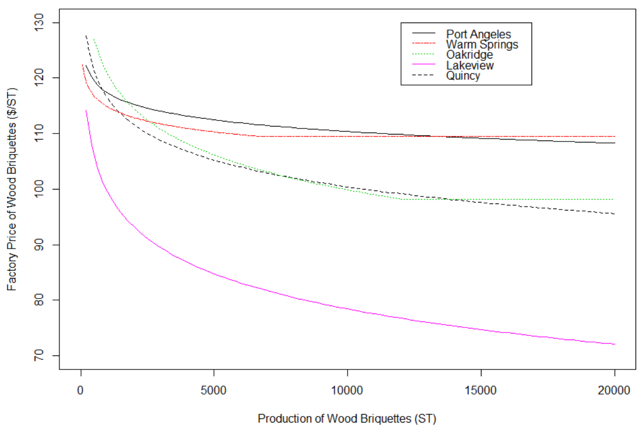

Figure 2. Factory price of wood briquettes versus production quantity in five case locations.

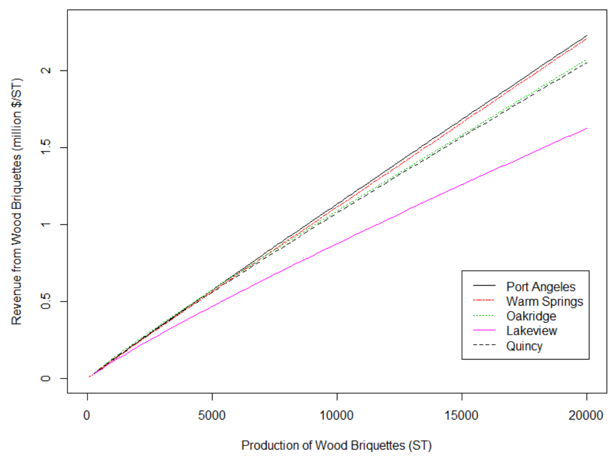

Figure 3. Net sales revenue of factory from selling wood briquettes versus production quantity in five case locations.

figure 3. The results show that if each factory were to produce the same volume of wood briquettes, Port Angeles and Warm Springs would generate the highest revenue, followed by Oakridge and Quincy. Lakeview would generate the lowest amount of revenue among the five case study locations.

The estimated equations for the sensitivity analyses are shown in table 3. In the sensitivity analyses, two input parameters, the market penetration rate and the delivery price (p_{WB}^{R} and DP_{WB}^{R}), were varied while all other variables were held constant. The delivery price was varied from \$140/ST to \$180/ST while the market penetration rate of wood briquettes into the residential firewood market was varied from 1% to 5%. Based on the results of the sensitivity analysis, the estimated sales revenues at Port Angeles are shown in figure 4. The results of the sensitivity analysis show that as the delivery price is increased from \$140/ST (the left figure in fig. 4) to \$180/ST (the right figure in fig. 4), the net sales revenue also increases assuming that all other conditions are equal. In contrast, varying the market penetration rate from 1% to 5% does not have much of an influence on the net sales revenue. The estimated sales revenues at Quincy are show in figure 5. Similarly, as the delivery price increased from \$140/ST (the left figure in fig. 5) to \$180/ST (the right figure in fig. 5), the net sales revenue increases, assuming that all other conditions are equal. However, in this case the market penetration rate does significantly impact the total net sales revenue at Quincy. The results of the sensitivity analyses suggest that since there is a high population density around the Port Angeles area, there is a higher potential sales opportunity in this area and the net sales revenue is less dependent on achieving a high market penetration rate. In contrast, the lower population density around the Quincy area means that with fewer potential customers in the area, net sales revenue is much more dependent on increasing the market penetration rate. One implication of the sensitivity analyses is that it would be a good idea for a manufacturer located in an area with a lower population density to invest in marketing activities (e.g., advertising) to increase demand for their product to help increase the market penetration rate.

Table 3. Estimated net sales revenue function of wood briquettes for sensitivity analyses at each location.

Locations	Net Sales Revenue at Factory (\$)
Port Angeles, Wash.	$R_{WB} = -Q_{WB}^{*}\left[3.021\left\{ln\left(Q_{WB}^{*}\right)-ln\left(p_{WB}^{R}\right)\right\}-DP_{WB}^{R}-12.134\right]$
Warm Springs, Ore.	$R_{WB} = -Q_{WB}^{*}\left[2.801\left\{ln\left(Q_{WB}^{*}\right)-ln\left(p_{WB}^{R}\right)\right\}-DP_{WB}^{R}-6.852\right]$
Oakridge, Ore.	$R_{WB} = -Q_{WB}^{*}\left[9.009\left\{ln\left(Q_{WB}^{*}\right)-ln\left(p_{WB}^{R}\right)\right\}-DP_{WB}^{R}-89.639\right].$
Lakeview, Ore.	$R_{WB} = -Q_{WB}^{*}\left[9.158\left\{ln\left(Q_{WB}^{*}\right)-ln\left(p_{WB}^{R}\right)\right\}-DP_{WB}^{R}-70.924\right]$
Quincy, Calif.	$R_{WB} = -Q_{WB}^{*}\left[6.897\left\{ln\left(Q_{WB}^{*}\right)-ln\left(p_{WB}^{R}\right)\right\}-DP_{WB}^{R}-62.496\right]$

Torrefied Briquettes

The factory price and net sales revenue estimation results for torrefied briquettes produced at each of the case locations are presented in table 4. The results show that Warm Springs has the highest factory price, followed by Port Angeles and Oakridge. The factory price of torrefied briquettes produced at Quincy and Lakeview were the lowest among the five locations, primarily due to the longer transportation distance.

Biochar

The relationship between the delivered prices of biochar versus the production quantity based on the two market penetration rates are presented in figure 6. Given the large urban populations located in Northern California that are located within 150 miles of the Quincy case location, our analysis suggests that this might be the best location for biochar production. Warm Springs and Oakridge share very similar supply curves since the population within 150 miles of each of these locations is pretty similar. Port Angeles, located at the tip of Olympic Peninsula, has a lower population density within the 150 delivery radius unless you deliver products across the Puget Sound or target the Canadian market. Finally, the Lakeview case area is located far away from any major metropolitan areas, giving it a substantial market disadvantage because of the high transportation costs and low local demand.

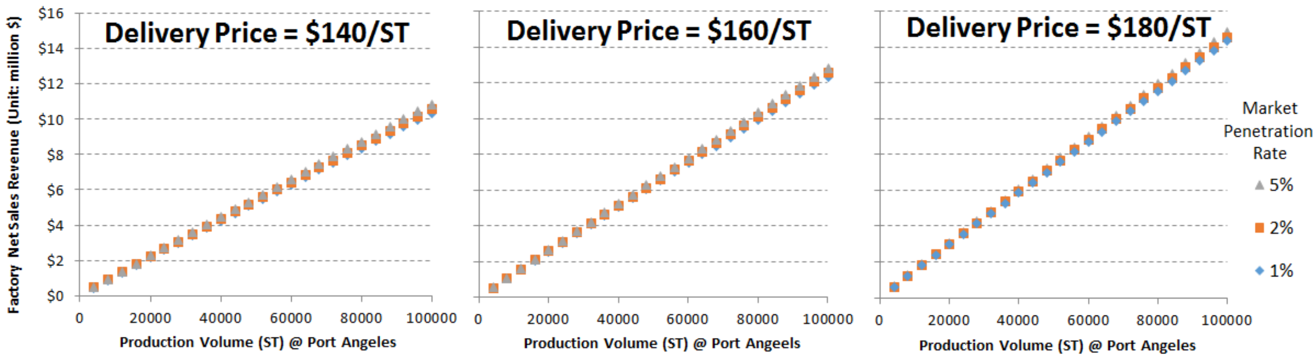

Figure 4. The estimated net sales revenues from wood briquettes at Port Angeles, Washington: sensitivity analysis.

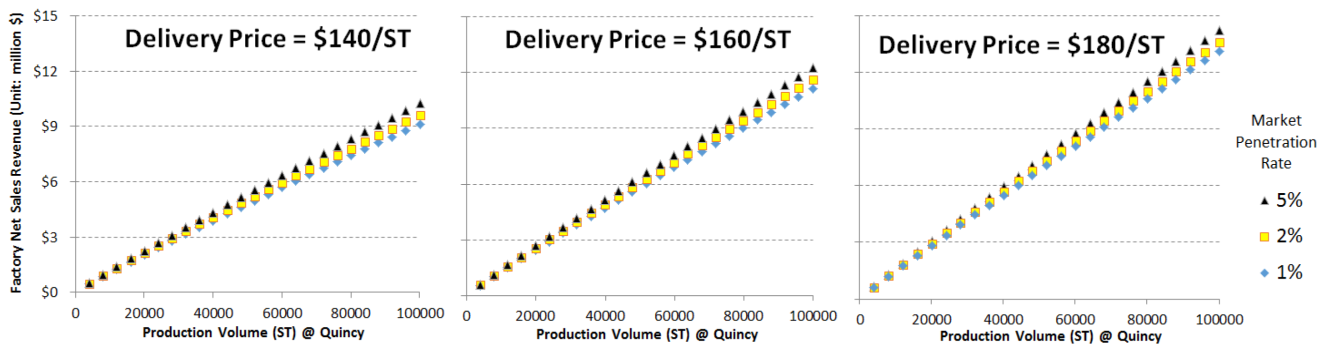

Figure 5. The estimated net sales revenues from wood briquettes at Quincy, California: sensitivity analysis.

Table 4. Factory price and net sales revenue of torrefied briquettes in five case locations.

Locations	Closest Market	Distance (miles)	Factory Price	Net Sales Revenue
Port Angeles	Port of Tacoma	110	$125.44/ST	125.44 × Q_{TB}
Warm Springs	Port of Portland	102	$127.03/ST	127.03 × Q_{TB}
Oakridge	Port of Portland	154	$116.68/ST	116.68 × Q_{TB}
Lakeview	North Valmy	250	$ 97.58/ST	97.58 × Q_{TB}
Quincy	Port of Richmond	220	$103.55/ST	103.55 × Q_{TB}

If you assume that the distance to local markets averages 70 miles for each of our case locations, then the transportation costs will be approximately $37.43. If the production costs for biochar are estimated to be $900/ST and we use a market penetration rate of 1%, the break-even production volume for Port Angeles is 176.1 ST, for Warm Springs is 214.8 ST, for Oakridge is 204.4 ST, for Lakeview is 31.6 ST, and for Quincy is 291.6 ST (fig. 6).

Estimates of the net sales revenues derived from selling biochar relative to the production quantities are presented in figure 7. As noted previously, if the market penetration rate is 2%, the quantity that the factory produces doubles and the associated revenue also doubles (fig. 7).

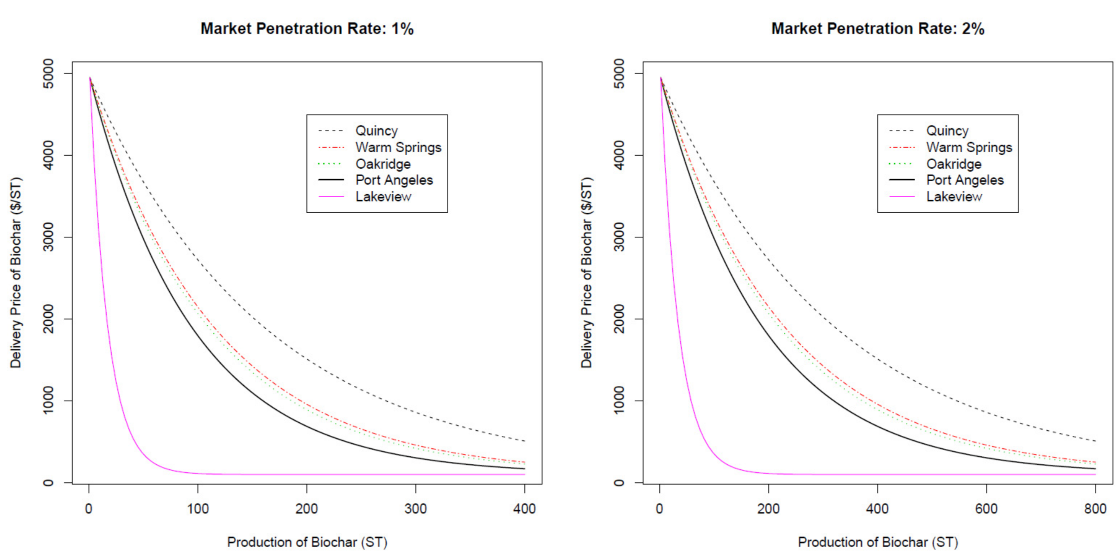

Figure 6. Factory price of biochar versus production quantity in five case locations.

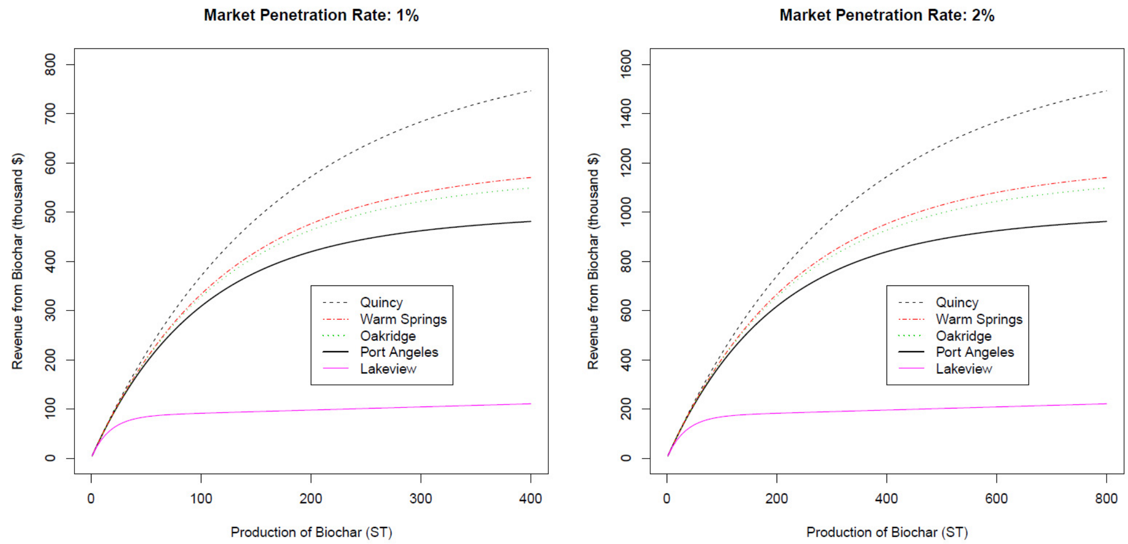

Figure 7. Net sales revenue of factory from selling biochar versus production quantity in five case locations.

Discussion and Conclusions

This study attempted to develop a set of economic models for the bioenergy and soil amendment products manufactured in the W2W project to provide the demand-side perspective. Demand curves and the associated net sales revenue functions were estimated at five different locations in the PNW. Comparing the demand curves with the supply curves allows one to identify the equilibrium points, where the volume of production is the most efficient. This analysis provides several interesting results.

First, the results clearly show that distance from market is a critical factor to be considered in locating a bioenergy production facility. The main customers for bioenergy products are residential households and as delivery costs rise, they substantially reduce profitability (i.e., net sales revenue per short ton of products) of these operations. Among the five case locations considered, the Lakeview location is the most problematic because of the lack of a nearby market. On the other hand, Port Angeles, Warm Springs, and Quincy are close to large urban areas and they can access those markets with lower transportation costs. Even though Port Angeles is close to large metropolitan areas, the Port Angeles location on the Olympic peninsula is problematic because the transportation dynamic is more complicated. In the case of biochar, where smaller volumes of higher margin products can be sold directly to consumers, using the internet may help to overcome market access problems.

Not surprisingly, we found that increasing the market penetration rate also increases the net sales revenue. Market penetration is a measure of the volume of sales of a product relative to the total theoretical market for the product and competing products. According to the sensitivity analysis, if the production facility is located in a less populated area, it would be better to promote the bioenergy products in nearby markets in order to increase the market penetration rate. Some marketing techniques, such as advertising, price, convenience and product quality, can encourage consumers to switch from competing products (e.g., firewood, wood pellets, compost) to W2W products (e.g., wood briquettes and biochar). Considering the return on marketing, the models we developed would help to evaluate the effectiveness of budgeting for marketing activities. In addition, there were some potential markets for the W2W products that were not included in the study. For example, torrefied wood briquettes could be sold into the residential heating market. Market development and market penetration require appropriate marketing investment. Since the production costs are different in each location, it is very important for W2W producers to evaluate the return on marketing investment in assessing the profitability of W2W products in each location.

Wood briquettes and torrefied briquettes producers would be price takers since there are a lot of substitute energy products and producers cannot easily influence prices, although the sensitivity analysis showed that the price of energy products significantly influences the sales revenue. Improving the quality of the bioenergy products could increase the consumers' willingness to pay and therefore offset potentially higher delivery prices. However, improving the quality and the production costs represent a trade-off. Our models can help manufacturers to understand the economic feasibility of product development, for example to find out the break-even point of the production costs. It is important to note that high retail prices for biochar, wood briquettes and torrefied briquettes would not guarantee the profitability of these products, especially in those locations where market access and market size are low. In addition, the production volume in areas where the market size is low needs to be taken into consideration as large volumes of production will likely result in market saturation and reduced profitability and growth potential. W2W producers in rural locations need to be aware of, and sensitive to, this oversupply issue.

There are several limitations in this study. The mathematical models used in this analysis were based on several simplifying assumptions because of a lack of market data.

For example, we only used a limited numbers of variables to estimate the models while the population distributions were oversimplified. Improving the data used for these variables would enhance the accuracy of the mathematical models. Also, competition between products was not considered in this model. There are some very lucrative niche markets with high profit margins for high quality biochar products where competition would be an important factor in introducing a new product. Similarly, if W2W producers manufacture wood briquettes in multiple locations, market ranges may overlap, creating a more competitive market environment. Also, most of the prices and parameters were fixed in this study and we did not consider the risk and uncertainty associated with these parameter inputs. For example, the fluctuation of crude oil prices will substantially impact transportation costs and production costs as well as the competitive relationship between substitute energy products, which in turn will change the shape of the demand curves. To address this uncertainty, we provided a set of mathematical functions that allow the use of different parameters or random variables to take into account a variety of different scenarios.

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