Economic Modeling of Woody Biomass Utilization for Biofuels: A Case Study in West Virginia

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Abstract: West Virginia is the third most heavily forested state in the U.S. and produces 2.41 million dry tons of wood residues annually. These wood wastes can be used as feedstock for biofuels, bio-gas and green electricity. Efficient harvesting, extraction, and transportation of woody biomass are the key to the economic success of wood residue utilization. The cost components of collecting, processing, and delivering woody biomass are not well documented, which hinders further research on the economic feasibility of woody biomass-based biorefineries in West Virginia. An economic analysis model was developed to evaluate woody biomass utilization for biofuels, including the costs for woody biomass harvesting/extraction, storage, loading/unloading, transportation, and wood chipping under different harvesting system configurations. A mix integer programming (MIP) model was specifically developed using General Algebraic Modeling System (GAMS) to optimize potential woody biomass-based biorefinery locations with the objective of minimizing the total annual delivered cost of available woody biomass and resource constraints. The model was applied in West Virginia and analyzed in terms of sensitivity analysis under different resource and operational scenarios, such as woody biomass availability, demand levels, and inventory at plant. The results would be useful to facilitate the research and economic development of woody biomass for biofuels in the region.

Keywords: Woody Biomass, System Modeling, Cost Analysis, Bioenergy.

1. Introduction

West Virginia has abundant woody biomass resources and produces 2.41 million dry tons of wood residues yearly. Even though 68% of mill residues were utilized in 2006, most of the logging residues, the largest proportion of wood residues, were underutilized (Wang et al. 2006). In recent years, the interest of using woody biomass as feedstock of bioenergy in the U.S. has been increasing due to the concerns of reducing energy dependence on foreign oil. Ethanol as one of the products made from wood residues has attracted much attention. The utilization of abundant wood residues as feedstock for ethanol or other biofuels or bioproducts may provide West Virginia a significant opportunity in economic development and energy independence. Efficient harvesting, extraction, and transportation of woody biomass are the keys to the economic success of woody biomass utilization. However, the optimized costs for collecting, processing, and delivering woody biomass under different resource constraints and operational circumstances are not well addressed, which hinders further research on the economic feasibility of woody biomass-based biorefineries. The purpose of this paper is to develop a MIP model to analyze the woody biomass utilization for biofuels in West Virginia.
2. Model development

The objective of the model is to minimize the total annual delivered cost of woody biomass from the supply locations to demand locations, which is expressed as follows:

\[
\min \ z = \sum_{m=1}^{M} \left[ \sum_{i=1}^{I} \sum_{h=1}^{H} (\alpha_h + sc)x_{ihm} + \sum_{i=1}^{I} \sum_{j=1}^{J} mp_{ijh} + \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{h=1}^{H} (cs_h + \tau_{ijh} + cp_h)x_{ijhm} \right] + Lct
\]

Five cost components were modeled including logging residue extraction cost, on-site storage cost, hauling and loading cost, chipping cost in the field or at mill, mill residue purchased cost and stumpage cost of logging residue. Logging residue was assumed available all the year, thereby ready for collection at any time. Seven woody biomass handling systems which included extraction, storage, transportation and comminution activities were considered in the model based on extraction methods and forms of biomass delivered, including cable skidder-loose material, cable skidder-chip, grapple skidder-loose material, grapple skidder-chip, forwarder-loose material, forwarder-chip, and forwarder-bundle. The notations for variables and symbols in the model are explained in the Appendix. Except for forwarder-bundle system, logging residues can be shipped out either immediately after collection or stored in the field for a period of time. The storage assumption for forwarder-bundle system was described in the later constraints.

Several constraints were considered in the model. It was assumed that there was one extraction system at each supply location (Equation 2). The handling system index \( h \) ranged from 1 to 7. Here, it was set to 1, which means that cable skidder-loose material system was selected in the model.

\[
\begin{cases} 
\sum_{h=1}^{H} Alfa_{ih} = 1, \forall i, \\
Alfa_{ih} = 1, \forall i, \text{where } h = 1.
\end{cases}
\]

The amount of logging residues annually extracted using system \( h \) at supply location \( i \) should be no greater than the available logging residues at that location (Inequality 3). The slope constraint was also considered for cable skidder, grapple skidder, and forwarder extraction systems to further limit logging residue availability. All the extraction machines and slash bundler were assumed to be able to operate on sites with slope 35% or less. Besides this constraint, the amount of logging residues extracted is also subject to the availability of logging residue for a specific time period (or a month) (Inequality 4) and extraction ability of loggers (Inequality 5). An average rate was applied to logging residue availability in each month. For instance, we assumed the logging residue extracted can not exceed 1/12 of the total available if extracted in January. The working time of each extraction machine was assumed as 6 hours per day and 5 days a week, therefore a total of 120 working hours per machine was assumed in a month. The amount of mill residues shipped out of each county is also subject to the total mill residues available in that county (Inequality 6).
The total logging residue extracted using system \( h \) at supply location \( i \) in month \( m \) plus the usable parts of stored logging residue should balance with the sum of logging residue shipped to demand locations and stored in the field (Equation 7). Tembo et al. (2003) indicated that the amount of biomass shipped out plus biomass lost in field storage balance with total biomass produced in the year. Then, the logging residue storage balance in one year can be derived. If summing equation (7) for one year, we get equation (8). Rearranging this equation, we get equation (9). Equation (10) was used to model the relationship among logging residues extracted, logging residues entering storage and removed from storage, and logging residues transported to demand locations. The storage for logging residue was to balance the whole logistics of logging residue handling process.

\[
\begin{align*}
\sum_{m=1}^{M} x_{ihm} - \text{Ext}_{m} \cdot \text{BPVS}_{i} & \leq 0, \quad \forall i, h, m. \\
\sum_{m=1}^{M} x_{ihm} - \text{Ext}_{m} \cdot \text{BPBVS}_{i} & \leq 0, \quad \forall i, h.
\end{align*}
\]

\[
x_{ihm} - \text{Ext}_{m} \cdot \text{BPBIV}_{i} \leq 0, \quad \forall i, h, m.
\]

\[
x_{ihm} - 120P_{h} \cdot NL_{1} \cdot NM_{h} \leq 0, \quad \forall i, h, m.
\]

\[
\sum_{j=1}^{J} x_{mijr} - MP_{r} \cdot MIV_{ir} \leq 0, \quad \forall i, r, m.
\]

The total logging residue extracted using system \( h \) at supply location \( i \) in month \( m \) plus the usable parts of stored logging residue should balance with the sum of logging residue shipped to demand locations and stored in the field (Equation 7). Tembo et al. (2003) indicated that the amount of biomass shipped out plus biomass lost in field storage balance with total biomass produced in the year. Then, the logging residue storage balance in one year can be derived. If summing equation (7) for one year, we get equation (8). Rearranging this equation, we get equation (9). Equation (10) was used to model the relationship among logging residues extracted, logging residues entering storage and removed from storage, and logging residues transported to demand locations. The storage for logging residue was to balance the whole logistics of logging residue handling process.

\[
x_{ihm} + \theta_{1} x_{s_{ihm-1}} - \sum_{j=1}^{J} x_{t_{ijm}} - x_{s_{ihm}} = 0, \quad \forall i, h, m.
\]

\[
\sum_{m=1}^{M} \sum_{h=1}^{H} x_{ihm} + \theta_{1} \sum_{h=1}^{H} x_{s_{ih12}} + (\theta_{1} - 1) \sum_{m=1}^{M} \sum_{h=1}^{H} x_{s_{ihm}} - \sum_{h=1}^{H} \sum_{m=1}^{M} x_{s_{ihm}} - \sum_{j=1}^{J} \sum_{i=1}^{I} \sum_{r=1}^{R} x_{t_{ijm}} = 0, \quad \forall i.
\]

\[
\sum_{m=1}^{M} \sum_{h=1}^{H} x_{ihm} - (1 - \theta_{1}) \sum_{m=1}^{M} \sum_{h=1}^{H} x_{s_{ihm}} - \sum_{j=1}^{J} \sum_{m=1}^{M} x_{t_{ijm}} = 0, \quad \forall i.
\]

\[
x_{ihm} - \text{Ext}_{m} \cdot \text{BPBIV}_{i} = 0, \quad \forall i, h, m.
\]

Regarding forwarder-bundle system, residue bundles are assumed to deliver to a storage site for drying and transportation (Equation 11). The quantities of slash bundles (in tons) transported to demand locations should be no greater than the usable portion of bundles stored before current month in the field.

\[
\begin{align*}
\text{xs}_{ihm} - x_{ihm} &= 0, \quad \forall i, h, m, \text{where } h = 7.
\text{xs}_{ihm} - x_{s_{ihm-1}} &\leq 0, \quad \forall i, h, m, \text{where } h = 7.
\end{align*}
\]

The total woody biomass delivered to a plant plus the usable biomass stored in previous month at the plant should be no less than the storage and feedstock demand at the plant (Inequality 12). We also assumed plant scheduled working days per month as 30 days and 50% moisture content of woody biomass. Therefore, the monthly feedstock demand in wet tons will be 60 times of daily demand in dry tons.

\[
\sum_{i=1}^{I} \sum_{h=1}^{H} (1 - tloss) x_{t_{ijh}} + \sum_{i=1}^{I} \sum_{r=1}^{R} x_{m_{ijr}} + \phi xss_{jm-1} - xss_{jm} - 60 \cdot CP \beta_{j} \geq 0, \quad \forall j, m.
\]
The minimum inventory of woody biomass at a plant was defined to ensure smooth production and zero inventory was assumed in the base case (Mapemba 2006):

\[ \text{xs}_j \cdot \text{ss}_m \cdot \text{MNBI}_j \cdot \beta_j \geq 0, \forall j, m. \]  

(13)

The number of plants that can be built was also considered as a constraint (Mapemba 2006). It was set to one in the base model.

\[ \sum_{j=1}^{J} \beta_j = 1 \]  

(14)

2.1 Woody biomass transportation

Transportation cost of woody biomass can be affected by hauling distance, payload size, biomass dimension and density. The trucking cost model incorporating road networks were based on Wood Transportation and Resource Analysis (WTRANS) (Jensen et al. 2002) and machine rate (Miyata 1980). The trucking cost model (Equation 15) consists of fuel cost, driver wages, and overhead and maintenance costs, which is also a function of payload and hauling distance from supply to demand locations.

\[ T_{ij} = \frac{2d_{ij}}{\text{mpg}} \cdot \text{fpg} + \frac{2d_{ij}}{\text{mph}} \cdot \text{dwh} + \frac{(tp-ts)}{N} + \frac{(tp-ts)(N+1)}{2N} \cdot \text{ITR} + \frac{2d_{ij}}{\text{mph}} \cdot \frac{(tp-ts)\cdot \text{MR}}{N \cdot \text{SMH} \cdot \text{UT}} \]  

(15)

Where, \( T_{ij} \) - total trucking cost per load from location \( i \) and demand location \( j \) ($); \( d_{ij} \) - hauling distance between location \( i \) and demand location \( j \) (miles); \( \text{mpg} \) - truck miles per gallon (miles/gal); \( \text{mph} \) - truck miles per hour (miles/h); \( \text{fpg} \) - fuel (diesel) price per gallon ($/gal); \( \text{dwh} \) - driver’s wages per hour, including a fringe of benefit rate of 40% ($/h); \( tp \) - purchased price of truck ($); \( ts \) - truck salvage value, calculated as a percentage of truck purchased price (%); \( N \) - economic life of trucks (years); \( \text{SMH} \) - scheduled trucking hours per year, assumed 2000 hours/year (hours); \( \text{ITR} \) - Interest, insurance, and taxes rate (%); \( \text{MR} \) - maintenance & repair rate, expressed as a percentage of depreciation (%); \( \text{UT} \) - average annual utilization rate of trucks (%).

Considering different forms of woody biomass delivered (loose residues, wood chips, bundles), transportation cost rate ($/ton) including loading/unloading cost corresponding to each extraction system was computed by dividing trucking cost per load by truck loads.

2.2 Within-county transportation

Since woody biomass supply counties are represented by centroids of the counties in the general transportation cost model (Equation 15), the transportation cost within supply locations are not fully considered especially when the supply location and demand location are in the same county, which results in underestimating the total delivered cost. We calculated the total ton-mile to transport woody biomass for supply location \( i \) given the density of biomass as Dornburg and Faaij (2001):

\[ \text{sm}_i = 1.073 \left( \sum_{j=1}^{J} \sum_{h=1}^{H} \sum_{m=1}^{M} x_{ijhm} \right)^{1.5} (D_b \pi)^{-0.5} \]  

(16)
Here, \( sm_i \) is the average ton-mile for delivering biomass (tons mile per year) in supply location \( i \), and \( D_b \) is biomass density (tons mile\(^{-2}\)). If there is only one woody biomass handling system and one optimal plant location, equation (16) is equivalent to:

\[
sm_i = \sum_{j=1}^{J} \sum_{h=1}^{H} sm_{ijh} = \sum_{j=1}^{J} \sum_{h=1}^{H} 1.073 \left( \sum_{m=1}^{M} x_{ijhm} \right)^{1.5} (D_b \pi)^{-0.5}
\]

(17)

The nonlinear function (Equation 17) was approximated by a piecewise linear function using a separable programming approach. The range of the amount of logging residue annually shipped out of each supply location should be determined, over which the breakpoints were defined at \( a_n, n = 0,1,\ldots,N \). Let \( x_{ijhn} \) be the increment of amount of logging residue annually shipped out of supply county \( i \) in the range \((a_{n-1}, a_n)\), and subject to the following constraints:

\[
\sum_{n=1}^{N} x_{ijhn} = \sum_{m=1}^{M} x_{ijhm}
\]

(18)

\[
0 \leq x_{ijhn} \leq a_n - a_{n-1}, \quad n = 1,2,\ldots,N
\]

(19)

Then, equation (17) is transformed to:

\[
sm_i = \sum_{j=1}^{J} \sum_{h=1}^{H} \sum_{n=1}^{N} f_{c_n} x_{ijhn}
\]

(20)

The transportation cost within supply counties was considered in the total delivered cost if the distance between supply location and demand location \( (d_{ij}) \) was no greater than one half of the longest straight-line distance of the supply county \( (r_{s_i}) \). The within-county transportation cost can be calculated as:

\[
Lct = \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{h=1}^{H} \sum_{n=1}^{N} t_{ijhn} \left( \sum_{m=1}^{M} x_{ijhm} \right), \quad \text{where} \quad d_{ij} \leq r_{s_i}
\]

(21)

3. Model application

The model was applied in the central Appalachian region within the state of West Virginia. Thirty three out of 55 counties were chosen as woody biomass supply locations based on logging residues yields \( \geq 30,000 \) tons/year. Six woody biomass demand locations located in the center of each forest district in West Virginia were selected (Figure 1). A medium size of woody biomass-based plant with demand of 1,000 dry tons of wood chips per day together with the following assumptions were assumed as base case for comparison of delivered cost among woody biomass handling systems and further sensitivity analysis.
3.1 Woody biomass availability and accessibility

The production of wood residues has been surveyed for several years in West Virginia (Wang et al. 2006). The annual harvesting acreage was derived from West Virginia Logging Sediment Control Act (LSCA) 2005 statistics. Considering the terrain constraints and environment protection, the general recovery rate of logging residues was assumed at 65% in the base case. Zero stumpage cost was assumed. The mill residue is assumed non-available in some of the counties such as Braxton, Gilmer, Fayette, Randolph, Raleigh, Upshur and Webster due to the competitiveness from pellet companies. Ninety percent mill residues in the other counties were assumed available at an average cost of $10/ton.

3.2 Logging residue handling productivities and costs

Based on the productivity models for logging residue extraction developed in the region (Li et al. 2006, Grushecky et al. 2007), in the base case, we assumed average extraction distance to be 750 feet. The payload size was 106 ft$^3$ for cable skidder, 107.87 ft$^3$ for grapple skidder, and 304.62 ft$^3$ for forwarder. The payload size for forwarding slash bundles was assumed to be 480.39 ft$^3$ per cycle (Rummer et al. 2004).

Wang (2007) reported that loading productivity varied from 3.40 MBF/PMH for loading pulp logs, to 7.56 MBF/PMH for peeler logs, and to 12.24 MBF/PMH for sawlogs. The models fitted for saw log and pulp wood were used to estimate loading productivity for forest bundles and loose residues, respectively.

Costs of logging residue extraction were calculated by using machine rate method (Miyata 1980), which include fixed or ownership costs, variable or operating costs, and labor costs (Table 1).
Table 1. Assumptions for logging residue extraction/handling machines.

<table>
<thead>
<tr>
<th>Items</th>
<th>Cable skidder</th>
<th>Grapple skidder</th>
<th>Forwarder</th>
<th>Slash bundler</th>
<th>loader</th>
</tr>
</thead>
<tbody>
<tr>
<td>Purchased price ($)</td>
<td>150,000</td>
<td>190,000</td>
<td>220,000</td>
<td>450,000</td>
<td>130,000</td>
</tr>
<tr>
<td>Savage value (% of price)</td>
<td>25</td>
<td>25</td>
<td>25</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Economic life (years)</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Interest, insurance, and tax (%)</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Labor cost ($/hour)</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Labor fringe (% of labor cost)</td>
<td>35</td>
<td>35</td>
<td>35</td>
<td>35</td>
<td>35</td>
</tr>
<tr>
<td>Maintenance and repair (% of depreciation)</td>
<td>90</td>
<td>90</td>
<td>90</td>
<td>90</td>
<td>90</td>
</tr>
<tr>
<td>Mechanical availability (%)</td>
<td>65</td>
<td>65</td>
<td>65</td>
<td>65</td>
<td>80</td>
</tr>
<tr>
<td>Horse power (hp)</td>
<td>100-110</td>
<td>110-120</td>
<td>110</td>
<td>182</td>
<td>140-150</td>
</tr>
<tr>
<td>Fuel consumption (gal/hp.hr)</td>
<td>0.028</td>
<td>0.028</td>
<td>0.0248</td>
<td>0.027</td>
<td>0.0217</td>
</tr>
<tr>
<td>Lubricant (% of fuel cost)</td>
<td>36.77</td>
<td>36.77</td>
<td>36.77</td>
<td>36.77</td>
<td>36.77</td>
</tr>
</tbody>
</table>

The fuel (diesel) price was assumed to be $3.26/gallon. Lubricant cost was estimated at 36.77% of fuel cost. Scheduled machine hours were 2000 hours per year for all the machines. Thus, the hourly cost estimation were: cable skidder: $82.54/PMH; grapple skidder: $96.49/PMH; forwarder: $104.85/PMH; loader: $67.11/PMH. The cost for the slash bundler was calculated as $190.60/PMH without considering twine cost. Each bundle uses about 270 feet of baling twine (Rummer 2004). Baling twine cost was estimated as $5/PMH given the productivity of 20 bundles per hour. So the cost for slash bundler was estimated as $195.60/PMH.

The extraction/loading cost of logging residues in dollar per ton was computed dividing machine cost by productivity rate.

Johansson et al. (2006) estimated that the chipping cost of loose material at landing and forest bundles at plant as 4.23 Euro/MWh (megawatt hour) and 1.52 Euro/MWh, respectively. Converted to US dollars, the chipping cost will be $7.60/ton for loose material and $2.73/ton for forest bundles assuming that one bundle (0.4-0.7 dry ton) with 50% moisture content contains 1MWh energy. EECA (2007) also presented a similar estimation for chipping cost. In our case, the chipping costs under different systems were assumed as follows: chipping at plants at $3.57/ton, chipping at landings at $7.14/ton and crushing bundles at $2.84/ton.

Regarding to the general transportation, the following assumptions were assumed. Tractor-trailer and chip van were used for transporting loose residue and chips, respectively. Both of the purchased costs were $135,000. The economic life was 8 years with salvage value as of 20% of the purchased cost. MPG and MPH were assumed to be 8 miles/gallon and 35 miles/hour for intercounty transportation and 5 miles/gallon and 25 miles/hour for intracounty transportation. Fuel price was $3.26/gallon. Driver wages plus fringe benefits were $14 per hour. Scheduled operating hours were 2000 hours per year and utilization rate was 90%. Maintenance and repair was 90% of depreciation. Interest, insurance and taxes were 20% of yearly investment. The truck capacity was assumed to be 25 tons. Considering woody biomass density in different forms, the loads under different systems were assumed: loose residues shipped to plant: 16 tons, chips to plant: 20 tons and forest bundles: 25 tons.

Considering the difference of logging residue availability in different supply counties, the amount of logging residue that can be shipped out of each supply county per year was assumed ranging from 0 to 75,000 tons, over which a total of ten breakpoints were defined at $a_n$. 


The average density of logging residue in West Virginia was estimated as 56.45 tons/mile$^2$ assuming 65% of logging residues available. Then, the separable linear functions over the domain of total logging residues shipped out of location $i$ each year can be derived. Substitute the parameters into equation (21), we get the applied within-county transportation cost model as:

$$L_{ct} = \sum_{i=1}^{t} \sum_{j=1}^{t} \sum_{h=1}^{t} t_{ijh} \left(2.55 x_{tl_{ijh1}} + 5.35 x_{tl_{ijh2}} + 7.63 x_{tl_{ijh3}} + 10.42 x_{tl_{ijh4}} + 14.74 x_{tl_{ijh5}} + 19.08 x_{tl_{ijh6}} + 22.60 x_{tl_{ijh7}} + 25.63 x_{tl_{ijh8}} + 30.17 x_{tl_{ijh9}}\right), \text{where } d_{ij} \leq r_{s_{ij}}$$

(22)

4 Results

4.1 Base case

The results indicated that the optimum location for a plant with minimum delivered cost in all the systems was near Addison in Forest District 3. The total delivered cost increased from forwarder-loose material system to cable skidder-chip system. The averaged cost was calculated by dividing the total delivered cost by the annual demand (Figure 2). The transportation cost and purchased cost (including mill residue purchased cost and logging residue stumpage cost) were the major cost components, accounting for 39.90% and 30.97% of the total cost, respectively. Extraction cost accounted for 20.50% of the total and followed by the chipping cost. The comparisons among handling systems demonstrated that chipping cost at mills was cheaper than that in the field. No storage cost was incurred because we assumed that there was either no storage cost or no storage needed.

![Figure 2. Delivered cost composition by handling systems.](image)

4.2 Sensitivity analyses

(1) Woody biomass availability

The effects of wood residue availability on the average delivered cost of woody biomass were analyzed (Figures 3 and 4). The cost varied slightly as logging residue available proportion changed. Compared to the base case (65% of logging residue available), the delivered cost at 20% of logging residue available increased $1.93/dry ton for forwarder-bundle handling system, $2.08/dry ton for cable skidder and grapple skidder-chip systems, $2.61/dry ton for cable skidder and grapple skidder-loose material systems, $2.60/dry ton for forwarder-chip system, and
$3.56/dry ton for forwarder-loose material system. However, the average delivered cost of woody biomass was sensitive to the variation of mill residue availability. If the available proportion of mill residue decreased from 90% to 20%, the cost increased $20.35/dry ton for cable skidder-based handling systems, $13.17/dry ton for grapple skidder-based handling systems, and $8.76/dry ton for forwarder-based handling systems. Among all the woody biomass delivered, about 59-69% were mill residues and the rest was logging residues. Mill residue availability had great impacts on the average delivered cost at current demand level in comparisons with logging residue.

![Figure 3. Average delivered cost vs. logging residues availability.](image)

![Figure 4. Average delivered cost vs. mill residues availability](image)

(2) Woody biomass demand

The average delivered cost increased dramatically as the demand at a plant increased among woody biomass handling systems (Figure 5). As shown in the previous figures, the costs for grapple skidder and forwarder-based handling systems were relatively lower than that for cable skidder-based handling systems. Due to the biomass resource constraints defined such as 65% of logging residue available and 90% of mill residue available and slope constraints for extraction machine operation, the available woody biomass can satisfy the feedstock demand at plant up to 1,800 dry tons/day. Compared to the base case, the average delivered cost corresponding to the demand of 1,800 dry tons/day increased $14.46/dry ton for cable skidder-
based handling systems, $10.37/dry ton for grapple skidder-based handling systems, and $7.82/dry ton for forwarder-based handling systems.

![Figure 5. Woody biomass delivered cost vs. feedstock demand](image5)

(3) Woody biomass inventory at plant
The inventory level of woody biomass at a plant is critical to ensure the smooth production of biofuels or bioproducts, especially in some seasons when woody biomass collection is not possible. However, it is costly to maintain a higher level of inventory. Even though the inventory cost at plant was not a part of delivered cost, the inventory level would indirectly impact all the activities involved in woody biomass handling. In addition to the base case for comparison, three different levels of inventory by weeks were analyzed. The average delivered cost increased as the inventory level at plant increased among woody biomass handling systems (Figure 6). The highest cost occurred with cable skidder handling systems followed by grapple skidder handling systems. At current demand level of 1,000 dry tons/day, the inventory at plant should be no more than 3 weeks in terms of available woody biomass resources.

![Figure 6. Woody biomass delivered cost vs. inventory at plant](image6)

5. Conclusion and discussion
The economic model developed can be used to facilitate woody biomass handling cost analysis and locating potential woody biomass utilization plant under certain supply, demand and other factors. The base case study indicated that the optimum plant location with different woody biomass handling systems was coincidently near Addison, in Webster County (Forest District 3), which is located near the center of West Virginia and surrounded by abundant woody biomass. It is noticed that all the potential plant locations were given by forest districts in the application. Actually, many factors could affect location of a woody biomass-based plant, such as possibility of utilizing existing facilities, accessibility to road networks and utilities, target market for biofuels or bioproducts, and others. All these factors will be considered in the future research and the derived feasible plant locations will be plugged into the model to achieve more accurate and reasonable results.

The average delivered cost of woody biomass for a medium size plant with demand of 1,000 dry tons/day of wood chips ranged from $37.19 to $46.58/dry ton with different woody biomass handling systems, which was a little higher than DOE (US Department of Energy) target cost of $35/dry ton at which level the production of biofuels from woody biomass could be profitable. In addition, zero inventories were assumed in the base case. If the inventory at plant were increased, the average delivered cost of woody biomass will be higher.

Sensitivity analysis also showed that the availability and purchased cost of mill residues, and demand levels had great impacts on the average delivered cost. Since the feedstock supply stabilization is really important, it is necessary to find niche supply markets for wood residues either by signing long-term contracts or developing cooperation relationship with landowners and major forest products companies. The average delivered cost varied significantly as the demand at plant changed. To determine a reasonable demand, factors such as available funds, plant investment, industrial lands availability, feedstock supply stabilization also need to be addressed.

References


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Appendix: Nomenclature

\( I \) - Set of woody biomass locations;
\( J \) - Set of feasible plant locations;
\( M \) - Month of the whole year, \( m = 1, 2, 3, \ldots, 12 \);
\( H \) - Woody biomass handling system;
\( R \) - Mill residue types, \( r = \{ \text{bark, chips, sawdust} \} \);
\( \alpha_h \) - Logging residue extracting cost ($/ton);
\( sc \) - Stumpage cost of logging residue ($/ton);
\( \varphi \) - Logging residue storage cost in the field ($/ton);
\( \tau_{ijh} \) - Round trip transportation cost from supply location \( i \) to plant \( j \) for system \( h \) ($/ton);
\( l_h \) - Loading cost of woody biomass corresponding to system \( h \) ($/ton);
\( cs_h \) - Chipping cost in the field corresponding to handling system \( h \) ($/ton);
\( cp_h \) - Chipping cost at plant corresponding to system \( h \);
\( t_h \) - Within-county transportation cost for system \( h \) ($/ton/mile);
\( mc_r \) - Purchased cost for mill residue type \( r \) ($/ton);
\( mt_{ij} \) - Mill residue transportation cost from location \( i \) to location \( j \) ($/ton);
\( BP_i \) - Proportion of logging residue available for extraction at supply location \( i \);
\( BIV_i \) - Volume of logging residue at supply location \( i \) (tons);
BVS_i - Volume of logging residue on sites with slope 35% or less at supply location i (tons);
Ext_m - Limitation of logging residue extracted in month m as a percentage of the total year (%);
MP_r - Proportion of mill residue r available at supply location i;
MIV_r - Volume of mill residue r at supply location i;
tloss - Loss rate of woody biomass due to transportation (%);
CP - Woody biomass demand at plant (dry tons/day);
Lct - Within-county transportation cost ($);
NL_i - Number of loggers in supply location i;
NM_i - Average number of extraction machines that each logger owns;
n - Breakpoint index;
a_n - Breakpoints over the value of annually delivered logging residue from supply location i;
fc_n - Slope of the line segment in the range \( (a_{n-1}, a_n) \);
xh_{ihm} - Quantity of logging residues extracted in month m at location i using system h (tons);
xt_{ijhm} - Quantity of logging residue that are extracted using system h delivered from location i to plant j in month m (tons);
xps_{ihm} - Quantity of logging residue that are extracted using system h entered into storage at supply location i in month m (tons);
xm_{ijm} - Quantity of mill residue r delivered from location i to plant j in month m (tons);
xs_{im} - Quantity of logging residue that are extracted using system h stored at location i in month m (tons);
xsn_{ihm} - Quantity of logging residue that are extracted using system h removed from storage at location i in month m (tons);
xss_{jm} - Quantity of woody biomass stored at plant j in month m (tons);
xtl_{ijn} - The increment of logging residue annually shipped out of location i in the range \( (a_{n-1}, a_n) \);
\beta_j - A binary variable related to plant j.