Woody Biomass Sustainability for Bioenergy Production 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 are sustainable and can be used as feedstock for biofuels, bio-gas and green electricity. Biomass sustainability, 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. A mix integer programming (MIP) model was 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. The model was applied in West Virginia and analyzed in terms of sensitivity analysis under different resource and operational scenarios, such as proportion of woody biomass availability, demand levels at plant, and others. The results would be useful to facilitate the research and economic development of woody biomass for biofuels in the region.

1. Introduction

The interest of using woody biomass as feedstock for bioenergy in the U.S. has been increasing due to the concerns of reducing energy dependence on foreign oil. Biomass sustainability, 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. This study develops an economic analysis model to address the sustainability and estimate the delivered cost of woody biomass as bioenergy feedstock. The results can be very helpful in determining the economic feasibility of woody biomass utilization for bioenergy. The utilization of abundant wood residues as feedstock for ethanol could provide West Virginia a significant opportunity in rural economy development.

1.1 Woody Biomass Sustainability in West Virginia

West Virginia contains 12 million acres of forestland (USDA 2000, Griffith and Widmann 2003). Of this acreage there were 226,838 acres harvested in West Virginia during 2006, which is consistent with recent years (WVDOF 2006). The 2005 Forest Inventory and Analysis (FIA) data for West Virginia showed a net annual growth to removal ratio of 1.08:1 for all species combined (USDA Forest Service 2008), which means that the annual growth is greater than the annual removals of growing stock. The state produces approximately 2.41 million dry tons of wood residues per year including 1.34 million dry tons of logging residue, 941,868 dry tons of mill residues, 118,590 dry tons of urban tree residues and 12,716 dry tons of pallet residues (Wang et al. 2006). 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). The consistency of the harvested acreage notes a sustainability of woody biomass production in West Virginia.

1.2 Economic Feasibility

A small percentage of primary and secondary wood residues are being used for pulp chips, composite production, and pellet fuel for energy production. The vast majority of wood residues are left unutilized and therefore potentially available for bioenergy production. Currently there is no large-scale commercial facility operating in the state to utilize this significant and low cost resource. New opportunities for the development and adaptation of technologies have been limited due to a lack of solid economic and business related information and analysis. The wood industry is active in each of the 55 counties in WV and therefore woody biomass utilization has the opportunity to create employment in each county. West Virginia has the benefit of being in close proximity to several major cities and borders the Ohio River, which is a major source of river transportation. Therefore, there are several opportunities for biofacility placement in the state. To expand the productivity and viability of the forest products, new uses and products focused on wood residues are critically needed.

2. Economics of Woody Biomass Utilization in West Virginia

2.1 Model Development of Woody Biomass Delivered Cost

The inputs of the mixed integer programming model include woody biomass availability, woody biomass-based plant locations, extraction cost, storage cost in the field, transportation cost, and chipping cost. Seven woody biomass utilization systems which are identified by extraction machine used and form of woody biomass delivered are optional: Cable skidder-loose material, Cable skidder-chip, Grapple skidder-loose material, Grapple skidder-chip, Forwarder-loose material, Forwarder-chip, and Forwarder-bundle. Logging residue was assumed available all the year round, thereby ready for collection at any time. Logging residue in the systems except forwarder-bundle system can be moved out either immediately after collection or stored in the fields for a period of time. All the harvested bundles in forwarder-bundle system are assumed to enter into storage.

The objective of the model is to minimize the total annual delivered cost of woody biomass from supply locations to demand locations (Equation (1)). The highlighted cost components include logging residue extraction cost, on-site storage cost, hauling/loading cost, chipping cost in the field or at the plant, purchased cost of mill residue and stumpage cost of logging residue.

$$Min \quad z = \sum_{m=1}^{M}\left[\sum_{i=1}^{I}\sum_{h=1}^{H}(\alpha_h + sc)xh_{ihm} + \sum_{i=1}^{I}\sum_{h=1}^{H}\varphi xsp_{ihm} + \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{h=1}^{H}(cs_h + \tau_{ijh} + cp_h)xt_{ijhm} \right.$$
$$\left. + \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{r=1}^{R}(mc_r + mt_{ij})xm_{ijrm}\right] + Lct \tag{1}$$

Where, I -Set of woody biomass locations;
J -Set of feasible plant locations;
M - Month of the whole year;
H -Woody biomass extraction system;
R -Mill residue types, r = {bark, chips, sawdust};
α_h -Logging residue extracting cost ($/ton);
sc -Stumpage cost of logging residue ($/ton);
φ -Logging residue storage cost on the field ($/ton);
cs_h -Chipping cost on the field corresponding to extraction system h ($/ton);

τ_{ijh} -Round trip transportation cost from supply location i to plant location j corresponding to extraction system h (\$/ton);

cp_h -Chipping cost at plant corresponding to extraction system h (\$/ton);

mc_r -Purchased cost of mill residue type r (\$/ton);

mt_{ij} - Mill residue transportation cost from location i to location j (\$/ton);

Lct -Within-county transportation cost (\$);

xh_{ihm} -Quantity of logging residues extracted in month m at location i using system h (tons);

xt_{ijhm} -Quantity of logging residue extracted using extraction system h delivered from supply location i to plant location j in month m (tons);

xsp_{ihm} -Quantity of logging residue extracted using extraction system h entered into storage at supply location i in month m (tons);

xm_{ijrm} -Quantity of mill residue r delivered from supply location i to plant j in month m (tons);

The constraints of the model include number of woody biomass utilization systems used, woody biomass availability including logging residue and mill residue, logging residue extracted from the same location each month, extraction ability of loggers at supply locations, storage system balance in the field, woody biomass demand at the plant, minimum inventory at the plant and the number of woody biomass-based plant being built. To compare the difference of woody biomass utilization system, only one system is assumed in the model. Besides common availability constraints, a slope constraint was added considering the slope impacts on the woody biomass availability and extraction machine used. The constraints for storage balance of logging residues in the field are modified on Tembo's models (Tembo et al 2003). For the woody biomass-based plant, the upper bound of the number of plants being built was set to one. The total woody biomass delivered to the plant plus the usable biomass stored last month at the plant should be no less than the storage at the plant and plant demand for the current month. Since the total supply of woody biomass is assumed to be greater than the total demand of woody biomass, a $\geq$ sign can ensure the MIP model to get an optimal solution.

Since the transportation cost of woody biomass is site specific, further calculation is necessary to avoid impractical estimation. Jensen et al (2002) developed an analysis tool Wood Transportation and Resource Analysis System (WTRANS) in spreadsheets to aid users to calculate woody biomass transportation cost. In this paper, a trucking cost model incorporating road networks will be developed based on Jensen's WTRANS and Miyata's (1980) machine cost rate. The model consists of fuel cost, driver wages, and overhead and maintenance costs, which is a function of deliver distance from supply to demand locations. Considering the difference of forms of woody biomass delivered such as loose residues, wood chips, etc., transportation cost rate (\$/ton) including loading/unloading cost corresponding to each utilization system will be calculated by diving the trucking cost per load by the truck loads in tons.

Since the supply counties are represented by the centroids of counties in the trucking cost model, the transportation cost within supply counties are not fully considered especially when the supply location and demand location are in the same county, which may result in underestimating the total delivered cost. The within-county transportation cost will be included in the total delivered cost in case of the distance between supply location and demand location no greater than a half of the longest straight-line distance of the supply county, which is calculated by equation (2). The maximum amount of logging residue moved out of each location per month in West Virginia was defined as 75,000 green tons. The breakpoints were defined at 0, 1,000, 3,000, 5,000, 10,000, 20,000, 30,000, 40,000, 50,000 and 75,000 green tons. 9 variables (xtl_{ijh1} , xtl_{ijh2} , xtl_{ijh3} , xtl_{ijh4} , xtl_{ijh5} , xtl_{ijh6} ,

xtl_{ijh7}, xtl_{ijh8}, xtl_{ijh9}) represent the amount of separated ranges over the entire logging residues moved out of each supply location. The average woody biomass density in West Virginia was estimated as 56.45 tons/mile^2 assuming 65% of logging residues available. The separable linear functions over the domain of total logging residues shipped out of location i each year are derived. Substitute the linear functions into equation (2), we get equation (3).

$$Lct = \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{h=1}^{H}\sum_{n=1}^{N} t_h\, fc_n xtl_{ijhn}, \;\; where\ d_{ij} \le rs_i \qquad (2)$$

$$Lct = \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{h=1}^{H}\sum_{n=1}^{N} t_h \begin{pmatrix} 2.55xtl_{ijh1} + 5.35xtl_{ijh2} + 7.63xtl_{ijh3} + 10.42xtl_{ijh4} + 14.74xtl_{ijh5} \\ +19.08xtl_{ijh6} + 22.60xtl_{ijh7} + 25.63xtl_{ijh8} + 30.17xtl_{ijh9} \end{pmatrix}, where\ d_{ij} \le rs_i \qquad (3)$$

Where, N -Number of sections divided over the total logging residue delivered from one supply county per year, and n is segment index;

fc_n -Coefficient of linear function at section n;

t_h -Within-county transportation cost rate for extraction system h (\$/ton/mile);

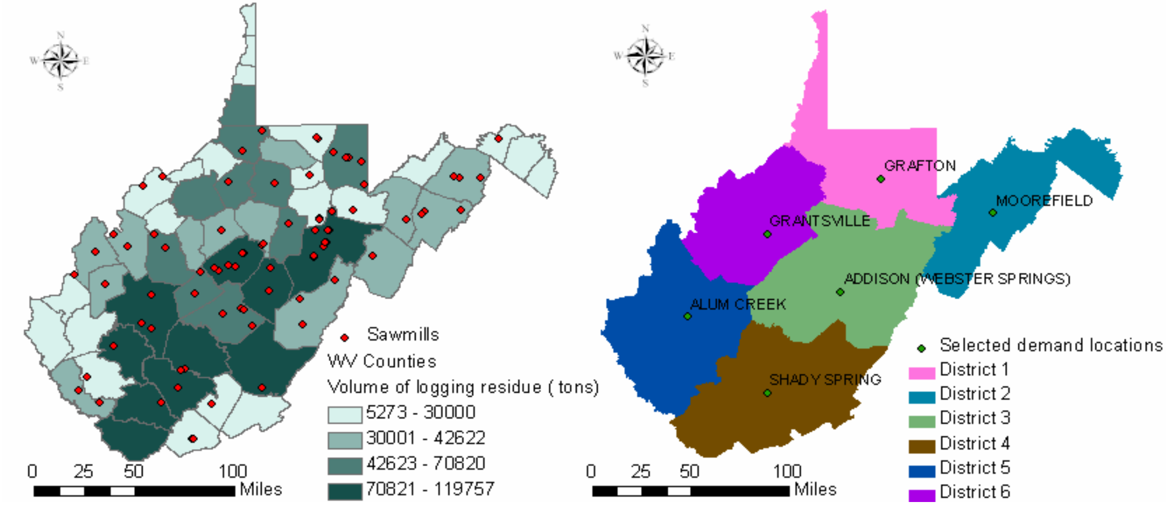
d_{ij} -Transportation distance between supply location i to plant j (miles);

rs_i - A half of the longest straight-line distance of supply county i (miles);

xtl_{ijhn} -Amount of annual delivered logging residue that are extracted using system h from location i to plant j at section n.

2.2 Model Application and Results

The model was applied in the state of West Virginia. Thirty three out of 55 counties are chosen as woody biomass supply locations based on logging residue yields $\ge$30,000 tons/year. Six woody biomass demand locations located in the center of each district in West Virginia are selected. Figure 1 shows the woody biomass supply and demand locations in West Virginia.



(a) Logging residue and sawmills. (b) Woody biomass demand locations.

Figure 1. Woody biomass supply and demand locations.

2.2.1 Model Inputs

The volume of logging residue in West Virginia was from Logging Sediment Control Act

(LSCA) 2005 statistics. Considering the terrain constraints and environment protection, the recovery rate of logging residues was estimated as 65% in the base case. The volume of mill residue was from Bragonje et al. (2006). Wood chips and sawdust are considered as feedstock for biofuels. The mill residue is assumed non-available in the counties such as Braxton, Gilmer, Fayette, Randolph, Raleigh, Upshur and Webster due to the competitiveness from pellet companies. 90% of mill residue in the other counties is available at the cost of $10/ton.

Costs of logging residue extraction machines were calculated by machine rate method (Miyata 1980). Fixed/ownership costs, variable or operating costs and labor costs are the cost components of machine cost. The assumptions are summarized in Table 1.

The fuel (diesel) price is assumed to be $3.259/gallon. Lubricant cost is estimated as 36.77% of fuel cost. Scheduled machine hours are 2000 hours per year for all the machines. Thus, the hourly cost estimation are: cable skidder: $82.54/PMH; grapple skidder: $96.49/PMH; forwarder: $104.85/PMH; loader: $67.11/PMH. The cost for the slash bundler is calculated as $190.60/PMH, but twine cost is also included in the operating 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 can be up to $195.60/PMH.

Li et al's hourly productivity models (2006) for extraction machines were used to approximate the productivity of extraction machines for logging residue. In the base case, average extraction distance is assumed to be 750 feet. The payload size for extraction machines are: cable skidder: 106 ft^3; grapple skidder: 107.87 ft^3; and forwarder: 304.62 ft^3. The payload size for forwarding bundles is 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 (Wang 2007). The models fitted for saw log and pulp wood were used to estimate loading productivity for forest bundles and loose residues, respectively. The extraction/loading cost of logging residues can be calculated dividing machine cost by productivity rate.

Table 1. Assumptions for machine cost

Items	*Cable skidder*	*Grapple skidder*	*Forwarder*	*Slash bundler*	*loader*
Purchased price ($)	150,000	190,000	220,000	450,000	130,000
Savage value (% of price)	25	25	25	25	25
Economic life (years)	5	5	5	5	5
Interest, insurance, and tax (%)	20	20	20	20	20
Labor cost ($/hour)	10	10	10	10	10
Labor fringe (% of labor cost)	35	35	35	35	35
Maintenance and repair (% of depreciation)	90	90	90	90	90
Mechanical availability (%)	65	65	65	65	80
Horse power (hp)	100-110	110-120	110	182	140-150
Fuel consumption (gal/hp.hr)	0.028	0.028	0.0248	0.027	0.0217
Lubricant (% of fuel cost)	36.77	36.77	36.77	36.77	36.77
Scheduled machine hours/year	2000	2000	2000	2000	2000

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 1.52Euro/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 gives the similar estimation for the lower chipping cost. In the base case, the chipping costs under different systems are estimated as follows: chipping at plants at $3.57/ton, chipping at landings at $7.14/ton and crushing bundles at $2.84/ ton.

Trailer truck and chip van were used as transportation tools for loose residue and chips, respectively. The purchased costs were $135,000. The economic life was assumed to be 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 $3.259/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 assumed to be 20% of yearly investment. Considering woody biomass density in different forms, the loads under different systems are assumed: loose residues shipped to plant: 16 tons, chips to plant-20 tons and forest bundles-25 tons assuming that the truck capacity is 25 tons.

2.2.2 Results

The demand of 1,000 dry tons of wood chips per day was assumed. An inventory of zero is assumed for all the systems. The demand location in Addison, District 3, is the optimum location with minimum cost in all the systems. The total delivered cost ranged from $13,387,698 for forwarder-loose material system to $16,694,441 for cable skidder-chip system. The average cost was calculated by dividing the total delivered cost by the annual demand. Figure 2 shows the composition of average delivered cost. The transportation cost and purchased cost are the major cost parts, accounting for 39.81% and 31.01% of the average cost, respectively. Extraction cost accounts for 20.54% of the total average. The chipping cost is a small part. No storage cost is shown because of zero cost rate of storage assumed in the base case. If logging residue could be extracted with saw timber production, the average cost could be reduced to $28.78/dry ton, a very competitive price for woody biomass utilization.

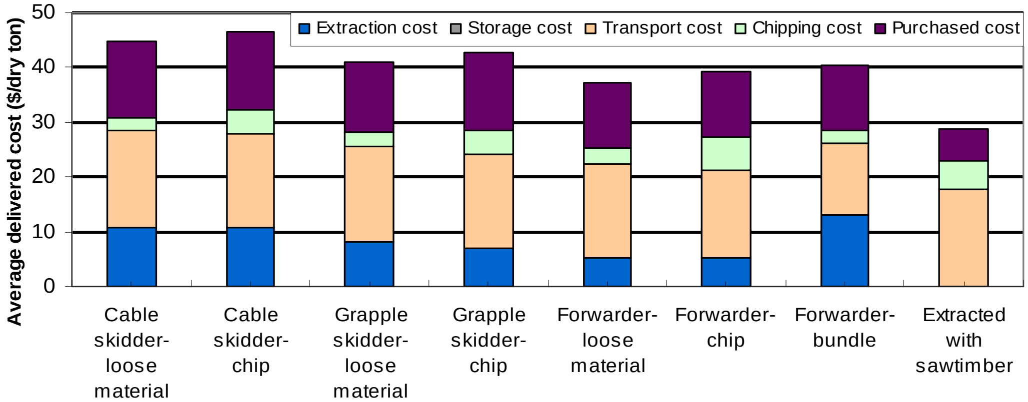


Figure 2. Delivered cost composition for demand of 1,000 dry ton/day.

2.3 Sensitivity analysis

(1) Effects of woody biomass availability on delivered cost.

Figure 3 show that the larger the proportion of logging residue available, the lower the delivered cost is. However, the magnitude of cost changes is not significantly different among different proportions. The proportion of logging residue has greater impact on the average cost if logging residue were extracted with saw timber. The delivered cost at 20% of logging residue available increase $5.80/dry ton compared with base case, accounting for 20.15% of the original.

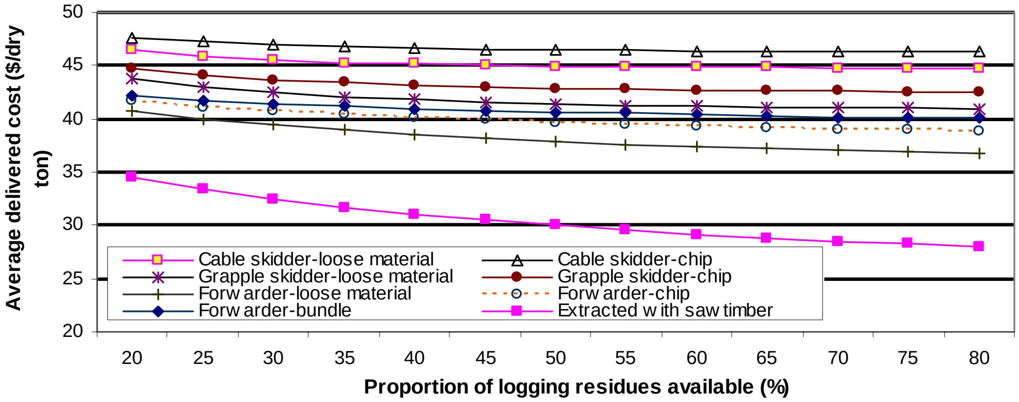


Figure 3. Average delivered cost vs. logging residues availability (1,000 dry tons/day).

Sensitivity analysis shows that the average delivered cost is very sensitive to the variation of mill residue available proportion. As the mill residue available proportion decreases, the average delivered cost increases at an increasing rate. This situation is due to the large share of mill residue in the lower demand level. Without sufficient mill residue, more logging residue should be extracted from forests even at higher cost in order to satisfy the demand. Figure 4 also shows that there are little impacts of mill residue available proportion on the average delivered cost when logging residue extraction could be combined with timber production.

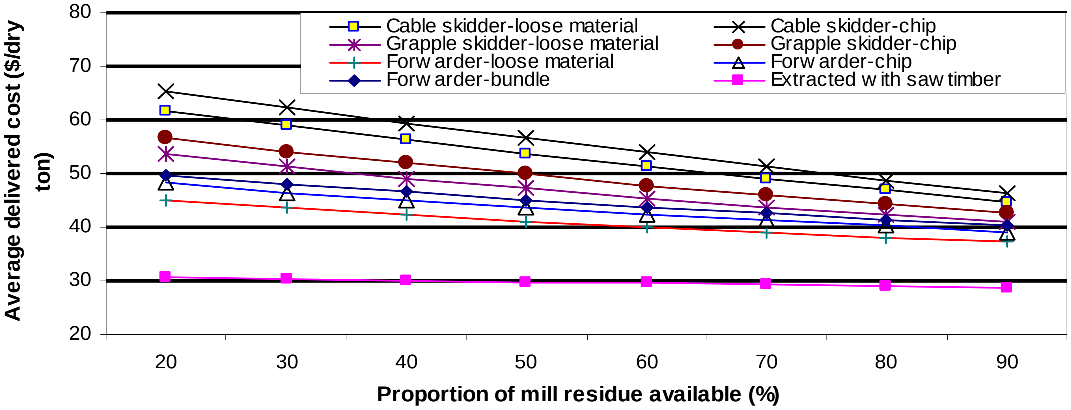


Figure 4. Average delivered cost vs. mill residues availability (1,000 dry tons/day).

(2) Effects of woody biomass demand on delivered cost.

Figure 5 shows that the average delivered cost increase at a decreasing rate as the demand increases in all the systems. The cost in grapple skidder extraction systems and forwarder extraction systems are lower than those in cable skidder extraction systems. Also, it is noted that the delivered cost for demand, no less than 1, 800 dry tons /day, is only shown in cable skidder extraction systems. This is because of the limitation of woody biomass availability. Besides the common resource constraints of 65% of logging residue available and 90% of mill residue available, the slope constraints for grapple skidder and forwarder extraction systems make the woody biomass less than that for cable skidder extraction systems, and the insufficient feedstock supply make the MIP model infeasible. Even though grapple skidder extraction systems and forwarder extraction systems can reduce the average delivered cost, the demand is limited to 1,800dry tons/day.

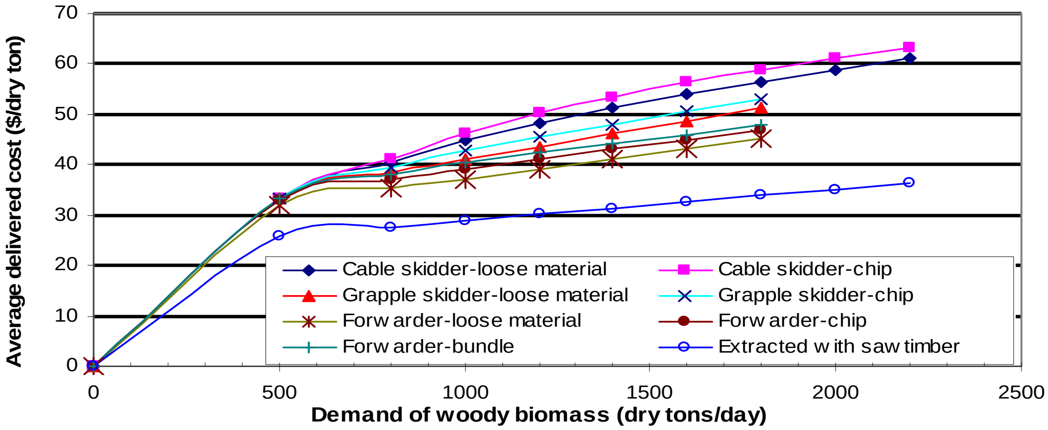


Figure 5. Woody biomass delivered cost vs. feedstock demand.

(3) Effects of inventory at plant on delivered cost.

The inventory level of woody biomass at a plant is critical to ensure the smooth production of biofuels, especially at seasons when the woody biomass collection is difficult. However, it is costly to maintain a higher level of inventory. Another three levels of inventory by weeks were analyzed in terms of average cost. Figure 6 shows that the average cost increases as the inventory at plant increases in all the extraction systems. The highest cost increase occurs in cable skidder extraction systems, followed by grapple skidder extraction systems. For the extracted with sawtimber system, the delivered cost increase is up to $1.16/dry ton on average if one more week inventory was assumed.

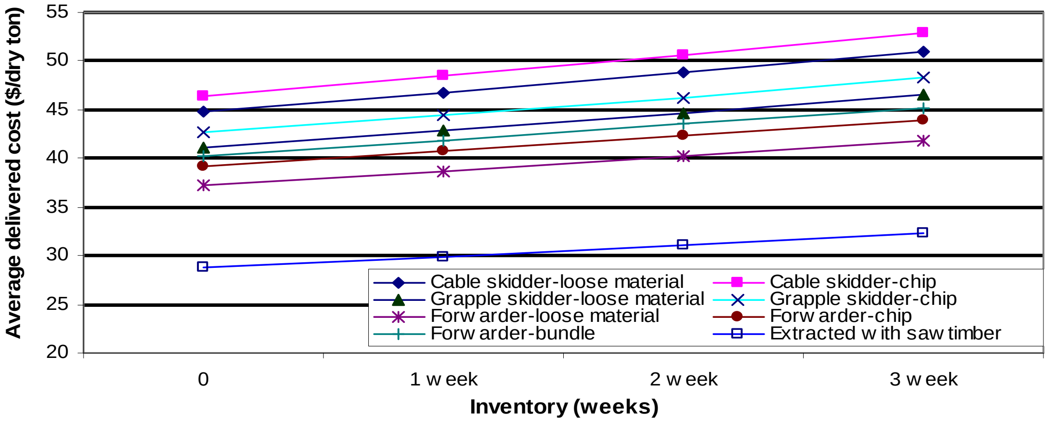


Figure 6. Woody biomass delivered cost vs. inventory at plant.

3. Conclusions

The 2005 Forest Inventory and Analysis (FIA) data for West Virginia showed a net annual growth to removal ratio of 1.08:1 for all species combined (USDA Forest Service 2008). It simply indicates that the annual growth is greater than the annual removals of growing stock and the state of West Virginia is practicing sustainable forest management. West Virginia's total energy consumption reached 793.9 trillion Btu in 2005 (EIA 2008a). The majority of the energy consumed was produced from coal. Biomass only accounted for about a half percent of energy produced (EIA 2008a). McCann (2005) estimated that West Virginia has the potential to produce 5.4 billion kWh of electricity from biomass, which would be enough to supply power to 543,000 average homes, or 61 percent of the state's residential needs. Ethanol is also one of the potential biofuel products made from wood residues. With a conversion factor of 66 gallons of ethanol from one dry ton of wood chips, West Virginia could produce up to 159 million gallons of ethanol per year. Even if a small fraction of woody biomass were used, a significant amount of bioenergy can be produced. Therefore, the utilization of wood residues as feedstock for bioenergy may provide West Virginia a significant opportunity in economic development and energy independence. West Virginia is a moderate ethanol consumer, but future trend of ethanol consumption is inevitably increasing. The most current ethanol consumption in West Virginia is about 126,000 gallons (EIA 2008b). The bordering states such as Ohio, Virginia, and Pennsylvania consume more ethanol than West Virginia. Currently, West Virginia and Virginia has no ethanol production. If the woody biomass in West Virginia can be converted into ethanol, the ethanol produced can not only supply its own needs but also supply markets in the neighboring states.

The results of the economic model for woody biomass utilization as bioenergy feedstock show that the average delivered cost of woody biomass for the demand of 1, 000 dry tons/day ranged from $37-$46/dry ton in all the extraction system, which is a little higher than the DOE (Department of Energy) target cost of $35/dry ton at which level the production of biofuels from woody biomass could be profitable. Note that zero inventories are assumed in the base case. The sensitivity analysis on inventory shows that increasing inventory can dramatically increase the average delivered cost of woody biomass. Without considering the extraction cost of woody biomass, the average cost could be reduced to $27.78/dry ton, which is a very competitive cost.

Sensitivity analysis also shows that the availability of mill residue and demand levels at plant, have great impacts on the average delivered cost. Since the stabilization of feedstock supply is really important, finding niche markets for mill residue is the key point to ensure the supply stabilization. The average delivered cost of woody biomass varies significantly as different demand increases. The larger the demand and the more diffuse the woody biomass, the greater the impact on the transportation cost, and thereby the average delivered cost.

The research that is taking place at WVU will prove to be beneficial when developing demonstration facilities and disseminating experience to new facilities. The WVU Biomaterials Center plans to host workshops in order to educate the public about the research taking place. These workshops will be adapted in order to apply them to groups who have an interest in developing facilities in our state. Information will also be made available through the center's website. Through extension services such as these WVU will be able to focus research on current issues concerning bioenergy and biofuels production.

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