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Development of economic analysis models for woody biomass to biofuels in central Appalachia

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**DEVELOPMENT OF ECONOMIC ANALYSIS MODELS FOR WOODY BIOMASS TO
BIOFUELS IN CENTRAL APPALACHIA**

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**Dissertation Submitted to the
Davis College of Agriculture, Natural Resources, and Design
at West Virginia University
in partial fulfillment of the requirements
for the degree of**

**Doctor of Philosophy
in
Forest Resources Science**

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Division of Forestry and Natural Resources

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programming, Logistics.**

ABSTRACT

DEVELOPMENT OF ECONOMIC ANALYSIS MODELS FOR WOODY BIOMASS TO BIOFUELS IN CENTRAL APPALACHIA

Jinzhao Wu

Concerns about volatile crude oil prices, energy security, and environmental issues are driving the production and use of renewable energy in the United States. Woody biomass can be used as feedstock for solid or liquid fuels or electricity generation. An economic analysis model was developed to estimate the delivered cost of woody biomass using different woody biomass handling systems. The model was designed to minimize the total annual delivered cost of woody biomass and applied to the central Appalachian region. Six forest districts were used to represent the destination of woody biomass supply. When demand is 900 metric tons (990 short tons) of dry woody biomass per day, for that base case scenario, the average delivered cost per unit of woody biomass ranged from \$2.77 to \$3.01 per GJ (\$44.07 to \$47.77 per short ton) among the different handling systems. The delivered cost was found to be mostly affected by woody biomass demand, mill residue availability, and mill residue purchase price, while skidding distance had the least impacts on the delivered cost.

The economic feasibility of a woody biomass-based ethanol facility was analyzed using a mixed integer programming model. The model is designed to maximize the net present value (NPV) of a facility over its economic life. A case study was conducted in the central Appalachian hardwood region. Eleven feasible plant locations were identified based on the requirements of site selection. Results showed that the optimal plant location was in Buckhannon, West Virginia. The NPV of the plant, with a demand of 1,814 metric tons/day of woody biomass and plant life of 20 years, varied from \$17.28 million to \$35.54 million among different systems. Ethanol production cost averaged approximately US¢ 50.85 – 52.38 per liter (\$1.92-\$1.98 per gallon). Factors such as biomass availability, mill residue purchase price, plant investment and capacity, ethanol yield, and financing are sensitive to ethanol production cost. Findings suggest that a woody biomass-based ethanol facility in central Appalachia could be economically feasible under certain operational scenarios.

Liquid fuels from coal and biomass have the potential to reduce petroleum fuel use and CO₂ emission. West Virginia is a heavily forested state and also rich in coal reserves. A multi-equation model was developed to assess the economics of a coal/biomass-to-liquids (CBTL) fuel plant in West Virginia. Specifically, the objective was to minimize the total annual cost subject to a series of regional supply, demand, and other constraints. The results indicated that the required selling price (RSP) of Fischer-Tropsch (FT) diesel for a 40,000 barrel-per-day CBTL plant with coal/biomass ratio of 85/15 varied between \$79.30 and \$79.57 per barrel using the different biomass handling systems. The RSP of FT diesel heavily depended upon plant capacity, capital cost, coal price, and liquid fuel yield. The crude-oil-equivalent price of FT fuels must be above \$62/bbl for a CBTL plant to be profitable and a feasible long-term option in central Appalachia.

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CHAPTER 1: INTRODUCTION

The increasing volatility of crude oil prices, the heavy dependence of the U.S. on imports for foreign oil, and environmental issues have together sparked strong national interest in the production and use of renewable energy in the United States. Biomass is regarded as a key renewable resource in future energy systems and can be upgraded to solid or liquid fuels, or used for electricity generation. Benefits of using biomass as feedstock for biofuels include reduced use of nonrenewable fuels, less dependency on foreign oil, stabilization of income in rural areas, and reduced carbon dioxide emissions to the atmosphere (Office of Technology Assessment 1993). Furthermore, linking biomass collection and transportation to economically generate raw material for bioenergy can create new, high-skilled jobs for people specializing in engineering systems, computers, economics, and international trade while providing new opportunities for forest managers, biologists, and engineers (Vogt et al. 2005).

Woody biomass (Figure 1.1), which includes residues produced during timber harvesting, fuelwood extracted from forestlands, and residues generated at primary and secondary wood processing facilities, is a potentially important feedstock for bioenergy (Kaylen et al. 2000, Bridgwater et al. 2002, Thek and Obernberger 2004, Caputo et al. 2005). To date, energy from woody biomass has played a relatively small role in terms of the overall U.S. energy use, making up only 3 percent of the total consumed (Duncan 2004). Demand for bioenergy in the U.S. is growing due to a concerted effort to reduce the nation's dependence on fossil fuels.

Figure 1.1. Wood residues: (a) logging residue, (b) mill residue.

The state of West Virginia, located in the central Appalachian region, is one of the most heavily forested states in the U.S., and produces an estimated 2.41 million dry tons of woody biomass per year (Wang et al. 2006). Even with this significant and low cost resource, limited economic value is generated. West Virginia is also the nation's second largest coal-producing state, and produced approximately 161 million tons of coal in 2007, about 13% of the U.S. total (West Virginia Coal Association 2007). To date, no commercial-scale facility is operating to convert woody biomass or coal and woody biomass into bioenergy or bioproducts in the state. Industries that could use wood as a feedstock, such as biorefining, biochemicals, and biopolymers, have limited start-up potential due to a lack of financial capital and economic related information. Research on the economic feasibility of using woody biomass as feedstock for biofuels (i.e., bioethanol, biodiesel) in the state is a critical need.

Previous studies (e.g., Wooley et al. 1999, Kaylen et al. 2000) have evaluated the economics of converting lignocellulosic biomass (e.g., crop residues, woody biomass, energy crops, or municipal solid waste) into bioenergy or bioproducts. However, these studies mainly focused on the Midwestern U.S. and the results were either site specific or assumption dependent. For example, most studies assumed the price paid for “as-received” feedstock

(woody biomass or agricultural residue) was constant. However, this price may vary depending on plant location, biomass density and availability, and other market factors. A guaranteed supply of woody biomass at a competitive price within a reasonable radius of a potential bioenergy plant is critical for profitability, and viability, of the plant. Information on delivered cost of woody biomass was not well documented in the region. Systematic economic models that are suitable for woody biomass to biofuels are critically needed to help investors/developers identify biomass opportunities. The risk of operating a woody biomass-based bioenergy plant is uncertain in view of dynamic technology, government policies, business opportunities, and markets; therefore, detailed analyses are necessary to estimate the sensitivity levels of production and profitability.

Specifically, the objectives of this dissertation are to: (1) develop a mathematical model to evaluate the delivered cost of woody biomass from stump to a woody biomass utilization plant, (2) assess the economic feasibility of a woody biomass-based ethanol facility in West Virginia, and (3) estimate the production cost of liquid fuels from local coal and biomass resources in the central Appalachian region.

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CHAPTER 2: AN ECONOMIC ANALYSIS MODEL OF WOODY BIOMASS UTILIZATION FOR BIOENERGY*

* Submitted to Canadian Journal of Forest Research.

Abstract

An economic model was developed to estimate the delivered cost of woody biomass which included the costs associated with biomass stumpage, harvesting/bundling, extraction, storage, loading and hauling, and chipping/grinding under different woody biomass handling systems. Seven woody biomass handling systems were considered based on extraction methods and forms of biomass delivered, including cable skidder-loose residue, cable skidder-chips, grapple skidder-loose residue, grapple skidder-chips, forwarder-loose residue, forwarder-chips, and forwarder-bundle. The model was designed to optimize a woody biomass-based biofuel facility's location with the objective of minimizing the total annual delivered cost of woody biomass under resource and operational constraints. The model was applied in the central Appalachian region within the state of West Virginia. Results showed that the optimal plant location would be at Addison (Forest District 3) in West Virginia when demand is 900 metric tons of dry woody biomass per day. For that base case scenario, the average delivered cost per unit of woody biomass ranged from \$2.77 GJ⁻¹ to \$3.01 GJ⁻¹ across the different handling systems. Extensive sensitivity analysis was performed under different resource and operational scenarios, such as woody biomass availability and purchase (stumpage) price, demand level, extraction distance, and fuel pricing. It was found that the delivered cost was mostly affected by woody biomass demand, mill residue availability, and mill residue purchase price. Skidding distance had the least impacts on the delivered cost. Due to the importance of the stabilization of the woody biomass supply chain, finding niche supply markets through long-term contracts or collaborative relationships with landowners and major forest products companies is recommended. The results would be useful to facilitate the research and economic development of woody biomass utilization for bioenergy in the region.

2.1 Introduction

Concerns about increasing volatility of crude oil prices, energy security, and environmental issues are driving the production and use of renewable energy in the United States. Woody biomass is a renewable energy source and can be used as feedstock for solid or liquid fuels or electricity generation (Kaylen et al. 2000, Bridgwater et al. 2002, Tembo et al. 2003, Thek and Obernberger 2004, Caputo et al. 2005). Wood-based biomass includes residues produced during timber harvesting, fuelwood extracted from forestlands, residues generated at primary and secondary wood processing facilities, and biomass from fuel reduction treatments (Wang et al. 2006). The delivered cost of woody biomass from forest to utilization plants includes the costs associated with a stumpage fee (if any), harvesting/bundling (if needed), extraction, storage, loading and hauling, chipping/grinding, and a return for profit and risk (Walsh et al. 1999). It varies spatially and is often the largest single cost component of a biomass derived fuel product (SRI 2007). Therefore, efficient harvesting, extraction, and transportation would be essential to the economic success of woody biomass utilization.

Woody biomass can be removed from the forest using different methods. Transporting loose residue, in-woods chipping, and bundling are all viable options (Spinelli et al. 2007). The collection of woody biomass can either be accomplished after harvesting activities or incorporated with the harvest of roundwood or other products. Woody biomass, in the form of branches, tops, etc. can be extracted to landings by a skidder or forwarder. The loose residue can then be delivered to consumers via truck or truck-and-trailer units. This system is constrained by the difficulty of fully utilizing vehicle payload and is preferable only over a short hauling distance (Spinelli et al. 2007). Chipping and grinding process can improve bulk volume, homogeneity, and handling characteristics of the raw material from forest (Johansson et al.

2006). In-woods chipping as part of conventional logging or thinning is the most cost-effective system to recover forest residue for biomass (Hartsough et al. 1997). Bundling is a possible alternative to improve forest fuel-logistics (Spinelli et al. 2007). Biomass bundlers collect, compress, and bind forest residue into cylindrical bundles approximately 3 meters in length and between 0.6 and 0.8 meters in diameter (Rummer et al. 2004). The bundles can allow full load capacity if compression is enough and make handling, such as loading and processing, more efficient.

The total supply costs of various logging residue recovery systems have been studied extensively, especially in Scandinavian countries. Johansson et al. (2006) calculated the transport cost of fuel chips and bundles from stump to consumer and reported that bundles were cheaper to transport than fuel chips in road transport bins. Transportation cost was also affected by moisture content, which decreased until moisture content reached critical levels, below 40.9% for chips and below 44.7% for bundles. Spinelli et al. (2007) simulated three logging residue recovery alternatives (in-woods chipping, bundling, and transporting loose residue) and identified the conditions that make one preferable to the others. The relationship between delivered cost and transportation distance showed that the bundling system was the least efficient option. Transporting loose residue was the cheapest alternative when the transportation distance was within 40 km. Kärhä and Vartiamäki (2006) studied the supply costs of roadside chipping, loose residue, and standard bundling chains and derived similar results as Spinelli et al. (2007). If the bundling supply chain was optimized, it could be competitive with the loose residue supply chain when the transportation distance exceeded 60 km.

Some efforts for estimating woody biomass delivered cost have been made in the U.S. (Kerstetter and Lyons 2001, Jensen et al. 2002, Grushecky et al. 2007, Pan et al. 2008, Galik et

al. 2009). For example, Kerstetter and Lyons (2001) developed a logging residue supply curve for the U.S. Pacific Northwest, which can be used to derive the average cost of delivering a certain amount of logging residue to a specific location. They concluded that the in-woods cost of recovering logging residue was high, starting at \$33 per dry metric ton for the most accessible materials. Jensen et al. (2002) developed a program to estimate the cost of transporting residue on a county-by-county basis or a statewide basis. This program was specifically designed for mill residue, thus the costs associated with collection and handling of logging residue were not considered. Grushecky et al. (2007) estimated the costs of extraction and trucking of logging residue in West Virginia and found that the extraction and trucking cost ranged from \$1.55 GJ⁻¹ to \$5.09 GJ⁻¹ under different truck type and road conditions. Comparisons across studies are difficult because of differences in assumptions and methods. However, none of these studies considered both logging and mill residues as a biomass feedstock for biofuel plants, nor did they take into account optimization techniques to derive the supply cost of woody biomass and the logistics of woody biomass handling activities and working schedules.

The optimization of a woody biomass supply chain which involves all the handling activities as described above and is subject to supply and demand constraints can be realized through mathematical programming techniques. There are three types of static mathematical programming models including linear programming (LP), nonlinear programming (NLP), and integer or mixed integer programming (IP or MIP). Mixed integer optimization models have received increased attention in the area of forest logistics (Weintraub et al. 1994, 1995). MIP models have been used widely in many fields such as facility location, resources allocation, and scheduling problems (Mapemba 2005). Tembo et al. (2003) developed a multi-region, multi-period MIP model encompassing alternative feedstock, feedstock production, delivery, and

processing. The most economically efficient source of agriculture-based biomass, timing of harvest and storage, inventory management, and biorefinery size and location were determined in the model.

Located in the central Appalachian region, West Virginia (Figure 2.1) is the state with the third highest percentage of land area that is forested in the U.S. containing 4.8 million ha (12 million acres) of forest land (Griffith and Widmann 2003). The state produces 2.19 million dry metric tons of wood residues per year including 1.22 million dry metric tons of logging residue, 856,243 dry metric tons of mill residues, 107,809 dry metric tons of urban tree residues and 11,560 dry metric tons of pallet residues (Wang et al. 2006). Wood residues represent a significantly under-utilized source of biomass feedstock in the state, which could be used for biofuels production. However, industries that could use the woody biomass as feedstock for biofuels have limited information on potentials and economics of handling these biomass resources. This under-utilized resource has the potential to improve the economy of West Virginia. Given the fact that the median household income for West Virginia over the last three years was more than 25 percent lower than the national average (US Census Bureau 2008), this resource could play a major role in boosting the state economy. Therefore, the objectives of this paper were to: (1) develop an economic model to assess the cost of woody biomass utilization for bioenergy, and (2) apply the model in the central Appalachian region to facilitate rural economic development, and conduct sensitivity analyses under different resources and operational scenarios in the region.

Figure 2.1. The geographical location of West Virginia, USA.

2.2 Model Development

2.2.1 Objective Function

A mixed integer programming (MIP) model was developed and solved using General Algebraic Modeling System (GAMS)/CPLEX. The objective of the MIP model was to minimize the total annual delivered cost of woody biomass from supply locations to demand locations, which was expressed as:

$$\begin{aligned}
Min\ z = & \sum_{m=1}^M \left[\sum_{i=1}^I \sum_{h=1}^H (hc_h + bc_h + sp) \cdot xh_{ihm} + \sum_{i=1}^I \sum_{h=1}^H sc \cdot xps_{ihm} + \sum_{i=1}^I \sum_{j=1}^J \sum_{h=1}^H (\tau_{ijh} + lc_h + cs_h + cp_h) \cdot xt_{ijhm} \right. \\
& \left. + \sum_{i=1}^I \sum_{j=1}^J \sum_{r=1}^R (mc_r + mt \cdot d_{ij}) \cdot xm_{ijrm} \right] + lct
\end{aligned} \tag{2.1}$$

The notations for variables and symbols in the model are explained in Appendix 2.A. The unit, metric ton, refers to green metric ton if not specified. The cost components considered in the objective function include a stumpage fee paid to land owners, logging residue harvesting/bundling (if any) and extraction, on-site storage, loading and hauling, in-woods chipping or grinding at a processing plant, and mill residue purchase and transportation.

Seven woody biomass handling systems that perform bundling (if any), extraction, storage, hauling, and chipping/grinding activities were included in the model based on extraction methods and forms of biomass delivered. These systems are cable skidder-loose residue (S1), cable skidder-chips (S2), grapple skidder-loose residue (S3), grapple skidder-chips (S4), forwarder-loose residue (S5), forwarder-chips (S6), and forwarder-bundle (S7). Except for the forwarder-bundle system, logging residues were assumed to be shipped out either immediately after collection or stored in the field for a period of time. It was assumed that there was one handling system employed at each supply location (Equation 2.2). The index of handling system h ranges from 1 to 7. To evaluate each system separately, the variable α_{ih} can be specified. For example, $\alpha_{ih} = 1$ when $h = 1$, which means that the handling system cable skidder-loose residue (S1) will be evaluated.

$$\sum_{h=1}^H \alpha_{ih} = 1, \quad \forall i, \tag{2.2}$$

The woody biomass was assumed to be delivered to one of the potential plant locations (Equation 2.3) at the minimum delivered cost. β_j is a binary variable related to plant j . If β_j equals 1, woody biomass would be delivered to plant j , and 0 otherwise.

$$\sum_{j=1}^J \beta_j = 1 \quad (2.3)$$

The woody biomass supply locations were represented by counties in West Virginia. A city located near the geographic center of each county was used to represent the supply location for that county. The demand locations, or optional woody biomass-based utilization plants were selected based on a series of criteria depending on the types of the facilities. For instance, locating a woody biomass-based biorefinery may consider the proximity to feedstocks, utilities, infrastructure accessibility, and other factors.

Woody biomass transportation cost can be affected by hauling distance, fuel price, payload size, biomass dimension and density (loose residue, chips, bundles). The trucking cost component incorporating road networks was modeled based on the Wood Transportation and Resource Analysis System (WTRANS) (Jensen et al. 2002) and machine rate method (Miyata 1980) (Equation 2.4). The trucking cost per load from supply location i to plant j consists of fuel cost, driver wages, overhead and maintenance costs. In consideration of the different forms of woody biomass delivered (loose residues, wood chips, or bundles), the transportation cost rate (τ_{ijh}) associated with each woody biomass handling system was computed by dividing the total cost per truck load from supply location i to plant j (t_{ij}) by the weight hauled ($load_h$) (Equation 2.5).

$$t_{ij} = \frac{2d_{ij}}{kpl} fpl + \frac{2d_{ij}}{kph} dwh + \frac{\frac{(tp-ts)}{n} + \left(\frac{(tp-ts)(n+1)}{2n} + ts \right) iitr}{smh \cdot ut} \frac{2d_{ij}}{kph} + \frac{(tp-ts)mr}{n \cdot smh \cdot ut} \frac{2d_{ij}}{kph} \quad (2.4)$$

$$\tau_{ijh} = \frac{t_{ij}}{load_h} \quad (2.5)$$

The variable lct is a cost component that is used to compute the under-estimated transportation cost (Equation 2.1). When the supply and demand locations are located in the same county or in adjacent counties, the assumed hauling distance of logging residue d_{ij} could be less than the actual delivery distance, thus the total delivered cost of woody biomass could be underestimated. Transportation cost is related to the spatial distribution of logging residue. A mathematical model by Dornburg and Faaij (2001) was modified to determine lct . Assuming that the distribution of logging residue within a county was constant, expressed as biomass distribution density, the logging residue was transported over a marginal transport distance that was the radius of a circle in which the logging residue was spread within the given distribution density. Then we derive the total amount of ton-km to transport a certain amount of logging residue within a county:

$$sm_i = \frac{2}{3} \left(\sum_{j=1}^J \sum_{h=1}^H \sum_{m=1}^M xt_{ijhm} \right)^{1.5} (D_b \pi)^{-0.5}, \forall i. \quad (2.6)$$

Where, sm_i is the average turnover (metric ton-km) for delivering biomass at supply location i , and D_b is biomass spatial density (metric tons km^{-2}). If we assumed one woody biomass handling system is used at one supply location (Equation 2.2) and one optimal plant location is selected (Equation 2.3), Equation (2.6) can be rewritten as:

$$sm_i = \sum_{j=1}^J \sum_{h=1}^H \frac{2}{3} \left(\sum_{m=1}^M xt_{ijhm} \right)^{1.5} (D_b \pi)^{-0.5}, \forall i. \quad (2.7)$$

The nonlinear function (Equation 2.7) was approximated by a piecewise linear function using the Separable Programming approach (Taha 2006). A finite number of breakpoints were

defined over the entire range of the quantity of logging residue annually shipped out from the supply county i by a_s , where $s = 0, 1, \dots, S$. It is noted that as the number of breakpoints defined increases, the efficiency of the linear approximation will increase. However, the computation time will increase accordingly. Thus, a reasonable number of breakpoints should be used. Let xtl_{ijhs} be the increment of annual amount of logging residue delivered from supply county i to plant j associated with system h in the range (a_{s-1}, a_s) , and subject to the following constraints:

$$\sum_{s=1}^S xtl_{ijhs} = \sum_{m=1}^M xt_{ijhm}, \forall i, j, h. \quad (2.8)$$

$$0 \leq xtl_{ijhs} \leq a_s - a_{s-1}, s = 1, 2, \dots, S \quad (2.9)$$

So Equation (2.7) is transformed to:

$$sm_i = \sum_{j=1}^J \sum_{h=1}^H \sum_{s=1}^S fc_s xtl_{ijhs}, \forall i. \quad (2.10)$$

Where, fc_s is the slope of the s^{th} line segment corresponding to $\frac{2}{3} \left(\sum_{m=1}^M xt_{ijhm} \right)^{1.5} (D_b \pi)^{-0.5}$.

Multiplying the average turnover (sm_i) by the transportation cost rate (t_h) for the different woody biomass handling systems and summing up all the counties together, the under-estimated transportation cost can be derived (Equation 2.11). A necessary constraint ($d_{ij} \leq rs_i$) was set to ensure that the cost was only computed for the supply counties when the supply and demand locations are in the same county or adjacent counties.

$$lct = \sum_{i=1}^I \sum_{j=1}^J \sum_{h=1}^H \sum_{s=1}^S t_h fc_s xtl_{ijhs}, \text{ where } d_{ij} \leq rs_i \quad (2.11)$$

2.2.2 Constraints

The objective function (Equation 2.1) is also subject to a series of resource and operational constraints. The amount of logging residue annually extracted using system h at supply location i should be no greater than the available logging residue produced at that location (Equation 2.12). In terms of biomass accessibility, a terrain slope constraint was considered for the cable skidder, grapple skidder, and forwarder extraction systems to further limit logging residue availability. All the extraction machines and the slash bundler were assumed to be able to operate on forest sites with a slope of 35% or less. The amount of logging residue extracted was also subject to the availability of logging residue within a specific time period (or a month) (Equation 2.13) and extraction capability of local loggers (Equation 2.14). Wet or other extreme weather can limit loggers' ability to operate their harvesting equipment due to site accessibility safety and environmental concerns (Cusack 2008). There are certain times of the year when harvesting is limited due to wet or other extreme weather. An average rate of logging residue availability was evenly assigned for each month within a year. For instance, the logging residue extracted cannot be more than 1/12 of the total available amount if extracted in January. Then, this rate was adjusted based on historical production data and monthly precipitation in the study region. Local loggers' capability of extracting logging residue was defined by $\lambda p_h nl_i nm_h$.

Where, λ is monthly productive time per machine in hours, p_h is productivity of extraction machine associated with system h , nl_i is the number of loggers in supply location i , and nm_h is the average number of extraction machines that a logging crew owns.

$$\begin{cases} \sum_{m=1}^M xh_{ihm} - \alpha_{ih} bp_i biv_i \leq 0, & \forall i, h. \\ \sum_{m=1}^M xh_{ihm} - \alpha_{ih} bp_i bvs_i \leq 0, & \forall i, h. \end{cases} \quad (2.12)$$

$$\sum_{h=1}^H xh_{ihm} - ext_m bp_i bvs_i \leq 0, \quad \forall i, m. \quad (2.13)$$

$$xh_{ihm} - \lambda p_h nl_i nm_h \leq 0, \quad \forall i, h, m. \quad (2.14)$$

Mill residue was considered to be another source of woody biomass for the plant, which would be delivered from mills to plant j directly. The amount of mill residue shipped out of each location was also limited to the total mill residue available at that location (Equation 2.15).

$$\sum_{j=1}^J xm_{ijrm} - mp_{ir} miv_{ir} \leq 0, \quad i, r, m. \quad (2.15)$$

Storage of logging residue at landings may occur when seasonal timber harvesting is conducted. The total logging residue extracted using system h at supply location i in month m plus the usable portion of stored logging residue should balance with the sum of logging residue shipped to demand locations and stored in the field (Equation 2.16). For each supply county, the amount of biomass shipped out plus biomass lost in field storage should balance with the total biomass produced in a year (Tembo et al. 2003). The storage balance of logging residue for one year can be expressed as Equation (2.17).

$$xh_{ihm} + \theta_i xs_{ihm-1} - \sum_{j=1}^J xt_{ijhm} - xs_{ihm} = 0, \quad \forall i, h, m. \quad (2.16)$$

$$\sum_{m=1}^M \sum_{h=1}^H xh_{ihm} + \theta_i \sum_{h=1}^H xs_{ih12} + (\theta_i - 1) \sum_{m=1}^{11} \sum_{h=1}^H xs_{ihm} - \sum_{h=1}^H xs_{ih12} - \sum_{j=1}^J \sum_{h=1}^H \sum_{m=1}^M xt_{ijhm} = 0, \quad \forall i. \quad (2.17)$$

Rearranged Equation (2.17) as

$$\sum_{m=1}^M \sum_{h=1}^H xh_{ihm} - (1 - \theta_i) \sum_{m=1}^M \sum_{h=1}^H xs_{ihm} - \sum_{j=1}^J \sum_{h=1}^H \sum_{m=1}^M xt_{ijhm} = 0, \quad \forall i. \quad (2.18)$$

The interrelationship among logging residue extracted, logging residue entered into storage and removed from storage, and logging residue transported to demand locations is

described in Equation (2.19), which is used to balance the whole logistics of the logging residue handling process.

$$\sum_{h=1}^H xh_{ihm} - \sum_{h=1}^H xps_{ihm} + \sum_{h=1}^H xsn_{ihm} - \sum_{h=1}^H \sum_{j=1}^J xt_{ijhm} = 0, \quad \forall i, m. \quad (2.19)$$

Loose residue can either be shipped out immediately after collection or stored in the field for a period of time (Equation 2.20). Since it is not appropriate to store fresh wood chips at landings, the quantity of wood chips entered into onsite storage for the chipping systems (S2, S4, and S6) were assumed to be zero (Equation 2.20). Regarding the forwarder-bundle system (S7), slash bundles were assumed to be forwarded to a landing (storage site) for drying and transportation (Equation 2.20).

$$\begin{cases} xps_{ihm} - xh_{ihm} \leq 0, & \forall i, m, \text{ where } h = 1, 3, 5 \\ xps_{ihm} = 0, & \forall i, m, \text{ where } h = 2, 4, 6. \\ xps_{ihm} - xh_{ihm} = 0, & \forall i, m, \text{ where } h = 7. \end{cases} \quad (2.20)$$

The total woody biomass delivered to a plant plus the usable biomass stored in the previous month at the plant should balance with the storage and feedstock processed at the plant for the current month (Equation 2.21). The moisture content of logging residue (lmc) and mill residue (mmc_r) would be specified for the study region.

$$\sum_{i=1}^I \sum_{h=1}^H (1 - \delta)(1 - lmc)xt_{ijhm} + \sum_{i=1}^I \sum_{r=1}^R (1 - mmc_r)xm_{ijrm} + \phi xss_{jm-1} - xss_{jm} - xpp_{jm} = 0, \forall j, m. \quad (2.21)$$

The quantity of woody biomass processed each month was subject to the monthly feedstock demand at a plant (Equation 2.22). The feedstock needed for plant j per month was $\rho \cdot capacity \cdot \beta_j$. If $\beta_j=1$, $xpp_{jm} = \rho \cdot capacity$, otherwise the processing capacity at plant j would be zero.

$$xpp_{jm} - \rho \cdot capacity \cdot \beta_j = 0, \forall j, m. \quad (2.22)$$

The minimum inventory of woody biomass at a plant was defined to ensure uninterrupted production as Mapemba (2005) described, and zero inventories were assumed in the model.

$$xss_{jm} - mnbin \cdot \beta_j \geq 0, \forall j, m. \quad (2.23)$$

Finally, the following decision variables should be nonnegative

$$xh_{ihm}, xt_{ijhm}, xm_{ijrm}, xs_{ihm}, xps_{ihm}, xsn_{ihm}, xss_{jm}, xpp_{jm} \geq 0 \quad (2.24)$$

2.3 Model Application

The model was applied in the central Appalachian region within the state of West Virginia. Approximately 68 percent of mill residue was utilized in 2006, and most of the logging residue, which makes up the largest proportion of wood residue, was underutilized according to Wang et al. (2006). The utilization of abundant wood residue as feedstock for ethanol or other biofuels or bio-products may provide West Virginia a significant opportunity in economic development and energy independence. All the counties in West Virginia were chosen as potential woody biomass supply locations (Figure 2.2a). Six woody biomass demand locations were selected, one for each forest district in West Virginia (Figure 2.2b). A medium size bioenergy plant with a demand of 900 metric tons of dry woody biomass per day, combined with the following assumptions was used as the base case for assessing the delivered cost of woody biomass.

Figure 2.2. Modeled woody biomass supply and demand locations in West Virginia. (a) Annual logging residue production and mill residue distribution. (b) Selected woody biomass demand locations.

2.3.1 Woody Biomass Availability and Accessibility

The production of wood residues has been surveyed several times over the last 10 years in West Virginia (Wang et al. 2006). The annual harvested acreage was obtained from the West Virginia Logging Sediment Control Act (LSCA) 2006 statistics (WVDOF 2006). The annual harvested acreage averaged approximately 100,000 ha (250,000 acres) over the last 10 years, which is about two percent of the total forest land in the state. The amount of logging residue in each county was derived by multiplying the harvested acres by the logging residue density from previous surveys (Grushecky et al. 2006). Subject to the operational accessibility, harvesting techniques, economic and environmental constraints, the recovery rate of logging residues was assumed to be 65 percent on the forest lands with a slope of 35 percent or less. The availability of logging residue by month in percent was assumed as $ext_m = \{8.3, 8.3, 8.3, 8.3, 7.5, 7.5, 7.5,$

7.5, 9.2, 9.2, 9.2, 9.2} based on the harvesting time and monthly precipitation in West Virginia (USDS 2009).

Logging residue has been promoted as an under-utilized resource with limited value and a stumpage price of \$1 metric ton⁻¹ was assumed for logging residue in the study (Galik et al. 2009). Data from an annual report by the West Virginia University Appalachian Hardwood Center (Bragonje et al. 2006) were used to estimate the annual production of mill residue in the region. Forty percent of mill residue in the supply counties was assumed to be available at an average cost of \$25 metric ton⁻¹ for bark and chips, \$30 metric ton⁻¹ for sawdust, \$20 metric ton⁻¹ for slabs and planer shavings, and \$10 metric ton⁻¹ for other mill residues (T. Goff, personal communication, 2009). Feedstock competition from other uses (such as pellet fuel, boiler fuel, paper, charcoal, and others) was also considered in the cost estimate process. The usable proportions of logging residue stored at landings and at plants were assumed to be 95% and 99%, respectively (Richardson et al. 2002). The average moisture content of logging residue was assumed at 43 percent (wet basis) while the moisture content of mill residue was assumed as 30 percent for sawdust and chips, 20 percent for planer shavings, and 42 percent for bark, slabs and others (Wang et al. 2006). Hardwood logging residue density was 0.77 metric ton m⁻³ (47.8 lb ft⁻³) (Appalachian Hardwood Center 2006).

The number of licensed loggers in each county was obtained from the West Virginia Division of Forestry. A logging firm in the state owns, on average, 1.5 cable skidders and 1.6 grapple skidders (Milauskas and Wang 2006). Forwarders are not as commonly used as cable and grapple skidders in this region. We assumed the average number of forwarders per firm to be one. The productive time of each extraction machine was assumed to be 6 hours per day and 5 days a week. Therefore, there would be a total of 120 productive hours per machine in a month.

It was assumed that there were enough transportation vehicles to deliver woody biomass from stands (or mills) to a woody biomass-based plant in the study region.

2.3.2 Logging Residue Handling Productivities and Costs

The assumptions for the woody biomass handling machines were presented in Table 2.1. Hourly machine costs were calculated by using the machine rate method (Miyata 1980), which includes fixed or ownership costs, variable or operating costs, and labor costs (Table 2.2). The productivities of woody biomass extraction by the cable skidder, grapple skidder, and forwarder were calculated using the existing models developed in the region (Wang et al. 2004, Li et al. 2006, Grushecky et al. 2007). Average extraction distance of logging residues was assumed as 300 m for all systems (Li et al. 2006). The payload size was 3 m³ for the cable skidder, 3.05 m³ for the grapple skidder, 8.5 m³ for the forwarder (loose residue), and 12 m³ for the forwarder (bundles) (Rummer et al. 2004; Grushecky et al. 2007). Loading productivity varied among different products: 15.30 m³ h⁻¹ for loading pulp logs, 34.02 m³ h⁻¹ for peeler logs, and 55.08 m³ h⁻¹ for sawlogs in West Virginia (Wang 2007). The models developed by Wang (2007) were employed to estimate loading productivity for forest slash bundles and residues in consideration of the physical properties (length, diameter, and weight). The productivities for other machines were based on literature (Leinonen 2004, Kärhä and Vartiamäki 2006). The unit cost for each individual handling machine was computed by dividing hourly machine cost by hourly production rate (Table 2.2).

Tractor-trailers, quad bunk short-log trailers, and chip vans were used for transporting loose residue, slash bundles, and chips, respectively. Fuel consumption was assumed to be 2.12 km l⁻¹ on average and the average speed of a fully loaded vehicle was 56.32 km h⁻¹ for inter-county transportation and 40.23 km h⁻¹ for intra-county transportation (M. Adams, personal

communication, 2008). The maximum loaded capacity of the truck and chip van was limited by legislation in West Virginia and the vehicle capacity, assumed as 23 metric tons. Considering the density and form of woody biomass, the loaded capacity (wet basis) was assumed as: 12.73 metric tons for loose residue, 19.09 metric tons for chips, and 18.18 metric tons for forest slash bundles (Spinelli et al. 2007). Hauling distances between the supply and plant locations were determined using the ArcGIS Network Analyst, Origin-Destination (OD) cost matrix. The detailed street dataset was from the 2003 Tele Atlas Dynamap Transportation version 5.2 product. An Excel spreadsheet was used to store the 55×6 distance matrix and was called by the GAMS program when implemented.

Table 2.1. Assumptions for the woody biomass handling machines^a.

Items	CD	GD	FL	FB	SD	LD	CP	GL	GB	HV
Purchase price (\$1,000)	130	200	265	310	450	150	330	350	350	140
Salvage value (% of price) ^b	20	25	20	20	20	30	20	20	20	20
Economic life (yr) ^b	5	5	5	5	5	5	5	5	5	8
Interest, insurance, and tax (%) ^{c, d}	20	20	20	20	20	20	20	20	20	20
Labor cost (\$ h ⁻¹) ^c	10	10	10	10	10	10	10	10	10	10
Labor fringe (% of labor cost) ^c	35	35	35	35	35	35	35	35	35	40
Maintenance and repair (% of depreciation) ^{c, d}	90	90	90	90	90	90	90	90	90	90
Mechanical availability (%) ^b	65	65	65	65	65	65	75	80	80	90
Horse power (hp)	117	117	115	161	182	170	500	700	875	-
Fuel price (\$ l ⁻¹)	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94
Fuel consumption (l hp ⁻¹ h ⁻¹) ^b	0.11	0.11	0.09	0.09	0.12	0.08	0.11	0.11	0.11	-
Lube and oil (% of fuel cost)	36.7	36.7	36.7	36.7	36.7	36.7	36.7	36.7	36.7	-
Scheduled machine hour (h yr ⁻¹) ^{c, d}	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000

^a CD-cable skidder, GD-grapple skidder, FL-forwarder (forwarding loose residue), FB-forwarder (forwarding bundles), SD-slash bundler, LD-loader, CP-chipper, GL-grinder (loose residue), GB-grinder (bundles), HV-hauling vehicle.

^b Assumptions adopted from Brinker et al. (2002). ^c Li et al. (2006). ^d Wang (2007).

Table 2.2. Cost calculations for the different handling machines.

Machine ^a	Hourly cost (\$ h ⁻¹)	Productivity (t h ⁻¹) ^b	Cost (\$ t ⁻¹) ^b
CD	81.34	6.34	12.83
GD	102.72	11.46	8.96
FL	124.35	12.71	9.78
FB	145.14	20.74 ^c	7.00
SD	205.51 ^d	13.00 ^e	15.81
LD	85.96	16.04	5.36
CP	185.62	30.00 ^f	6.19
GL	212.27	91.00 ^f	2.33
GB	237.05	120.00 ^f	1.98

^a CD-cable skidder, GD-grapple skidder, FL-forwarder (forwarding loose residue), FB-forwarder (forwarding bundles), SD-slash bundler, LD-loader, CP-chipper, GL-grinder (loose residue), GB-grinder (bundles).

^b Wet basis.

^c Kärhä and Vartiamaäki (2006).

^d Baling twine cost which was estimated at 5 \$ h⁻¹ given the productivity of 20 bundles h⁻¹ was included (Rummer et al. 2004).

^e Rummer et al. (2004).

^f Leinonen (2004).

2.4 Results

2.4.1 Base Case

The optimization of a biomass-based plant with a demand of 900 metric tons of dry woody biomass per day was summarized in terms of delivered cost, average hauling distance, and optimal plant location by the woody biomass handling systems (Table 2.3). The optimal biomass-based plant was located approximately at Addison (Forest District 3) in West Virginia. The grapple skidder-loose residue system (S3) was the most cost-effective with delivered cost of \$2.77 GJ⁻¹, while the forwarder-bundle system (S7) was the most expensive across the handling systems with delivered cost of \$3.01 GJ⁻¹. As the procurement distance increased, the average delivered cost of woody biomass increased. Equations (2.25) and (2.26) were used to compute the average hauling or procurement distance for logging residue and mill residue, respectively. Results showed that the average delivery distance for mill residue was farther than that of logging residue across the systems.

Table 2.3. Optimization summary of woody biomass handling by system in the base case.

System ^a	Average delivered cost ^b	Logging residue delivered cost ^b	Mill residue delivered cost ^b	Logging residue hauling distance ^c	Mill residue hauling distance ^c	Optimal plant location
S1	2.93	3.06	2.89	38.06	62.65	Forest District 3
S2	2.98	3.26	2.89	38.06	62.65	Forest District 3
S3	2.77	2.79	2.76	47.34	56.90	Forest District 3
S4	2.83	2.93	2.76	47.22	56.98	Forest District 3
S5	2.81	2.88	2.77	46.92	57.36	Forest District 3
S6	2.87	3.02	2.77	46.62	57.85	Forest District 3
S7	3.01	3.32	2.93	33.37	63.09	Forest District 3

^a S1-cable skidder-loose residue, S2-cable skidder-chips, S3-grapple skidder-loose residue, S4-grapple skidder-chips, S5-forwarder-loose residue, S6-forwarder-chips, and S7-forwarder-bundle.

^b Unit: \$ GJ⁻¹. Woody biomass: 1t = 17.48 GJ.

^c Unit: km.

$$distl = \frac{\sum_{i=1}^I \sum_{j=1}^J \sum_{h=1}^H \sum_{m=1}^M d_{ij} x t_{ijhm}}{\sum_{i=1}^I \sum_{j=1}^J \sum_{h=1}^H \sum_{m=1}^M x t_{ijhm}} \quad (2.25)$$

$$distm = \frac{\sum_{i=1}^I \sum_{j=1}^J \sum_{r=1}^R \sum_{m=1}^M d_{ij} x m_{ijrm}}{\sum_{i=1}^I \sum_{j=1}^J \sum_{r=1}^R \sum_{m=1}^M x m_{ijrm}} \quad (2.26)$$

The quantity of woody biomass delivered per year was examined for each woody biomass handling system (Figure 2.3). Logging residue accounted for 19 (S7) to 40 (S3, S4, S5, S6) percent of the total woody biomass delivered while the rest was mill residue. Systems 1, 2, and 7 were heavily dependent on mill residue, thus may face competition from current users and prospective utilization. The quantity of woody biomass delivered in each month can also be examined by the handling system. For the most cost effective grapple skidder-loose residue system (S3), the proportion of logging residue delivered changed from 41 percent to 39 percent from the period of January-April to May-August and then increased to 43 percent until

December. These changes could be attributed to the difference of monthly availability of logging residue, seasonal work days, precipitation, and other factors.

Figure 2.3. Woody biomass delivered per year by handling system (dry weight).

The delivered cost of logging residue included the costs associated with stumpage, bundling (if any), extraction, storage (if any), loading and hauling, and chipping/grinding. Extraction and transportation were the major cost components for systems S1-S6, accounting for an average of 39 percent and 22 percent of the total delivered cost, respectively, which were followed by chipping/grinding and loading (Figure 2.4). For the forwarder-bundle system (S7), bundling was the major cost component and accounted for 53 percent of the total delivered cost. It was followed by extraction (25 percent), transportation (13 percent), grinding (7 percent) and stumpage (3 percent). The comparisons among the handling systems for the base case indicated that delivering loose logging residue was much cheaper than shipping chips to the optimal plant. No storage cost was incurred in any of the systems. Since timber harvesting takes place all year round in West Virginia, logging residue is accordingly available and ready for collection for the whole year. Typically, there is no need to store logging residue at landings or roadside. Onsite

storage without cost incurs in system 7 because slash bundles extracted were assumed to be entered into storage for drying.

Figure 2.4. Delivered cost composition of logging residue by woody biomass handling system for the base case.

The delivered cost per unit of mill residue averaged $\$2.83 \text{ GJ}^{-1}$ and varied slightly among the different woody biomass handling systems. Purchase cost was the largest component and accounted for approximately 79 percent of the total mill residue delivered cost, followed by transportation cost (21 percent). In general, the delivered cost of woody biomass was higher than that of coal ($\$2.50 \text{ GJ}^{-1}$) (US EIA 2010) and switchgrass ($\$1.84\text{-}2.37 \text{ GJ}^{-1}$) (Kumar and Sokhansanj 2007).

2.4.2 Sensitivity Analyses

(1) Woody Biomass Availability

A decrease in logging residue availability would increase the delivered cost of woody biomass due primarily to longer hauling distances (Figure 2.5a). Compared to the base case with 65 percent of logging residue available, if the availability of logging residue was down to 30

percent, the delivered cost would increase 2 percent ($\$0.05 \text{ GJ}^{-1}$) for the cable skidder-loose residue system, 1 percent ($\$0.03 \text{ GJ}^{-1}$) for the cable skidder-chips system, 4 percent ($\$0.10 \text{ GJ}^{-1}$) for the grapple skidder-loose residue system, 3 percent ($\$0.07 \text{ GJ}^{-1}$) for the grapple skidder-chips system, 3 percent ($\$0.09 \text{ GJ}^{-1}$) for the forwarder-loose residue system, 2 percent ($\$0.06 \text{ GJ}^{-1}$) for the forwarder-chips system, and 1 percent ($\$0.03 \text{ GJ}^{-1}$) for the forwarder-bundle system. Efficient harvesting such as collecting logging residue during timber harvesting is critical to the future economic viability of logging residue utilization (Grushecky et al. 2007). However, the implications of increased harvest efficiency must be weighed against potential impacts on site productivity, especially for low-productivity sites (Scott and Dean 2006).

As a byproduct, mill residue is limited by production constraints in sawmills. The utilization of mill residue for biofuels will compete with other established uses such as pellet fuel, boiler fuel, and others in the central Appalachian region. If the mill residue availability changed from 40 percent (base case) to 20 percent, the delivered cost would increase 9 percent for the cable skidder systems (S1 and S2), 6 percent for the grapple skidder systems (S3 and S4) and the forwarder systems (S5 and S6), and 10 percent for the forwarder-bundle system (S7) (Figure 2.5b).

Figure 2.5. Sensitivity analyses of the woody biomass delivered cost by residue availability and purchase cost (1 gt=1 green metric ton).

(2) Woody Biomass Purchase Price

At current market price, the value of uncollected logging residue is very low. Therefore, a stumpage price of \$1 metric ton⁻¹ was assumed for logging residue in the base case. As the market for biomass develops, more biomass will be needed and forest land owners may expect a higher return for these raw materials. The delivered cost would increase \$0.01-\$0.04 GJ⁻¹ as a result of every one dollar per green ton increase in the stumpage cost of logging residue (Figure 2.5c). The purchase price of mill residue was based on current market pricing in the region. Mill residue has been traditionally used as pellet and boiler fuels in the region. The potential competition between current uses and prospective utilization for biofuels could raise the price of mill residue, especially when they are in high demand. Sensitivity analysis indicated how the

variation of mill residue purchase price affected the delivered cost of mill residue (Figure 2.5d). Increasing the purchase price of mill residue by 10 percent would cause an increase of delivered cost by 5 percent for the cable skidder systems (S1 and S2), 4 percent for the grapple skidder and forwarder systems (S3-S6), and 6 percent for the forwarder-bundle system (S7).

(3) Woody Biomass Supplied

The average delivered cost increased dramatically for all systems as the supply of woody biomass to the plant increased (Figure 2.6a). The grapple skidder-loose residue system (S3) presented the lowest procurement cost while the forwarder-bundle handling system (S7) was the most expensive system at different supply levels of woody biomass. The delivered cost of woody biomass would increase 3 percent, 6 percent, and 10 percent on average compared to the base case if the supply increased 200 dry metric tons day⁻¹, 400 dry metric tons day⁻¹, and 600 dry metric tons day⁻¹, respectively. The supply of biomass is constrained by the availability of known forest resources in the region. Considering the defined biomass resource constraints (65 percent of availability for logging residue and 40 percent for mill residue), slope constraints for extraction operations, and the current harvesting rate in West Virginia, the available wood residues could sustainably supply one woody biomass-based plant with capacity up to 2,400 dry metric tons per day. Other biomass resources such as roundwood or other non-forest biomass need to be utilized to meet demand above that level.

(4) Logging Residue Skidding Distance

The productivity of extraction machines (i.e., cable skidder, grapple skidder, and forwarder) generally decreased as the skidding distance increased, and the extraction cost would increase accordingly (Li et al. 2006). The delivered cost of woody biomass increased as the extraction distance increased (Figure 2.6b). The sensitivity analysis showed that the delivered

cost would increase \$0.002-\$0.100 GJ^{-1} for every 30 m (approximately 100 feet) skidding distance increase depending on the system used. The forwarder-bundle system (S7) resulted in the highest delivered cost, followed by the cable skidder systems (S1 and S2). Pan et al. (2008) suggested that shortening skidding distance and balancing other additional costs (i.e., hauling, building landings) should be factored in harvest planning.

(5) Fuel Price

Fuel (diesel) prices increased to historically high levels, increasing from \$0.66 l^{-1} (\$2.51 gallon^{-1}) in Feb. 2007 to \$1.23 l^{-1} (\$4.66 gallon^{-1}) in July 2008 (U.S. Energy Information Administration 2008). The woody biomass extraction machines (skidders and forwarders), loaders, slash bundlers, chipper/grinders, and transportation vehicles typically use diesel fuel. The delivered cost of woody biomass generally increased as the fuel price increased (Figure 2.6c). For every \$0.10 l^{-1} increase in diesel price, the delivered cost would increase \$0.041 GJ^{-1} for the cable skidder-loose residue system, \$0.042 GJ^{-1} for the cable skidder-chips system, \$0.046 GJ^{-1} for the grapple skidder-loose residue system, \$0.047 GJ^{-1} for the grapple skidder-chips system, \$0.044 GJ^{-1} for the forwarder-loose residue system, \$0.045 GJ^{-1} for the forwarder-chips system, and \$0.049 GJ^{-1} for the forwarder-bundle system.

Figure 2.6. Sensitivity analyses of the delivered cost by woody biomass demand, skidding distance, and fuel price (dry weight).

2.5 Conclusions and Discussion

The mixed integer programming model developed can be used to facilitate woody biomass handling cost analysis and to locate a potential woody biomass utilization plant under certain supply, demand, and other operational and market factors. For the base case scenario, the optimum biomass-based plant was located approximately at Addison (Forest District 3) in West Virginia, where abundant and inexpensive woody biomass could be provided. All the potential plant locations were initially assumed to be evenly distributed in six forest districts of West Virginia in the application. Other factors that could affect locating a woody biomass-based plant include the possibility of using existing facilities, accessibility to transportation networks and utilities, local community support, and target market for biofuels or bioproducts (CFDC and NEB 2006). All these factors should be considered in future research to obtain more precise, applicable plant locations and results.

The average delivered cost of woody biomass for the base case ranged from $\$2.77 \text{ GJ}^{-1}$ to $\$3.01 \text{ GJ}^{-1}$ using the different woody biomass handling systems. This estimation was within the range of $\$1.55$ - $\$5.09 \text{ GJ}^{-1}$ ($\$27$ to $\$89 \text{ dry metric ton}^{-1}$) estimated by Grushecky et al. (2007) for the same region. However, it was higher than the USDOE (US Department of Energy) target cost of $\$2.21 \text{ GJ}^{-1}$ ($\$38.58 \text{ dry metric ton}^{-1}$) in 2012 at which level the production cost of biofuels (ethanol) from woody biomass could be competitive with gasoline (Perlack et al. 2005). Several factors contribute to the higher delivered cost of woody biomass in the central Appalachian region, including the mountainous terrain, hardwood species, and fuel economy. Cable and grapple skidders are the most commonly used extraction machines partially due to the difficult terrain in the region. The fuel economy for hauling woody biomass in the region was estimated at 2.12 km l^{-1} ($5.0 \text{ miles gallon}^{-1}$) after consulting with local loggers; however, it could be up to

3.83 km l⁻¹ (9 miles gallon⁻¹) in other regions with gentle terrain (Jensen et al. 2002). More importantly, some of the cost estimate parameters were based on reasonable assumptions from literature and are subject to change. For instance, a large-scale woody biomass-based biofuels facility could increase demand competition for woody biomass and raise the price of raw materials. Fuel price can fluctuate with worldwide and regional supply and demand, seasonal demand, and other factors.

Sensitivity analyses demonstrated that woody biomass supplied level at the plant, purchase price of mill residue, and mill residue availability had greater impacts on the average delivered cost of woody biomass compared to the other factors. The skidding distance had the least impacts. The grapple skidder-loose residue system (S3) consistently presented the lowest delivered cost while the forwarder-bundle system (S7) was the most expensive system due to initial cost, production rate, payload size, and extraction distance of the system. The stabilization of feedstock supply is critical to success for a woody biomass-based biofuel plant. 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 net annual growth is greater than the annual removals of the growing stock. To secure the supply chain of woody biomass, it is essential to find niche supply markets for wood residues through long-term contracts, or collaborative relationships with landowners and major forest products companies. The average delivered cost of woody biomass varied significantly as demand at the plant changed. To determine a reasonable demand level, factors such as available funds, plant investment, land ownerships, and year-round feedstock supply stabilization also need to be addressed.

The model developed in this study targets one optimal biofuel plant location considering biomass availability and size of the potential application area. Our future work in terms of model improvement will include multiple optimal plant locations and multiple feedstocks (woody biomass, agricultural residues, and municipal waste) based on the needs of application regions. A computer-aided tool should be developed to facilitate data entry, perform economic analysis, and generate spatial output. A life cycle analysis could also be included to address the environmental aspects and potential impacts associated with the process of woody biomass utilization for biofuels.

This study provides a basis for the analysis of the economic feasibility of using woody biomass as feedstock for bioenergy in the central Appalachian region and will help facilitate rural economic development in the region. Our findings would also be useful for researchers to assess woody biomass utilization for bioenergy in other regions.

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Appendix 2.A. List of symbols

Table 2.A1. Data sets and descriptions.

Set	Description
I	Set of woody biomass supply counties, $i = \{\text{All counties in West Virginia}\}$.
J	Set of possible woody biomass-based plant locations, $j = \{\text{Grafton, Moorefield, Addison, Shady Spring, Alum Creek, Grantsville}\}$.
M	Set of months, $m = \{1, 2, 3, \dots, 12\}$.
H	Woody biomass handling systems, $h = \{\text{cable skidder-loose residue, cable skidder-chips, grapple skidder-loose residue, grapple skidder-chips, forwarder-loose residue, forwarder-chips, forwarder-bundle}\}$.
R	Mill residue types, $r = \{\text{bark, chips, sawdust}\}$.
S	Breakpoint indices, $s = \{0, 1, \dots, S\}$.

Table 2.A2. Parameters and descriptions.

Parameter	Description
a_s	Breakpoints over the quantity of annually delivered logging residue from supply county i ;
bc_h	Bundling cost of logging residue associated with handling system h (\$ metric ton ⁻¹).
biv_i	Volume of logging residue at supply county i (metric tons).
bp_i	Proportion of logging residue available for extraction at supply county i (%).
bvs_i	Volume of logging residue on sites with a slope of 35% or less at supply county i (metric tons).
cs_h	In-woods chipping cost associated with handling system h (\$ metric ton ⁻¹).
cp_h	Chipping cost at a plant associated with system h (\$ metric ton ⁻¹).
$capacity$	Woody biomass demand at plant (dry metric tons day ⁻¹).
d_{ij}	One way over-the-road distance between supply county i to plant j (km).
$distl$	Averaged hauling distance of logging residue (km).
$distm$	Averaged hauling distance of mill residue (km).
dwh	Driver's wages per hour including a fringe benefit rate at 40% (\$ h ⁻¹).
D_b	Logging residue spatial density (metric tons km ⁻²).
ext_m	Limitation of logging residue extracted in month m as a percentage of the whole year (%).
fc_s	Slope of the s^{th} line segment in the range (a_{s-1}, a_s) .
fpl	Fuel (diesel) price per liter (\$ l ⁻¹).
hc_h	Logging residue extraction cost associated with handling system h (\$ metric ton ⁻¹).
$iitr$	Interest, insurance, and taxes rate of trucks (%).
kpl	The distance a fully loaded vehicle can travel on one liter of fuel (km l ⁻¹).
kph	Average travel speed of a fully loaded vehicle (km h ⁻¹).
lc_h	Loading cost of woody biomass associated with system h (\$ metric ton ⁻¹).
$load_h$	Vehicle payload associated with handling system h (metric tons).
lmc	Average moisture content of logging residue (%).
mc_r	Purchase price for mill residue type r (\$ metric ton ⁻¹).
mt	Mill residue transportation cost rate (\$ metric ton ⁻¹ km ⁻¹).
miv_{ir}	Volume of mill residue r at supply county i (metric tons).
mmc_r	Moisture content of mill residue type r (%).
mp_{ir}	Proportion of mill residue r available at supply county i (%).
mr	Maintenance and repair rate, expressed as a percentage of depreciation (%).
$mnbin$	Minimum inventory at a plant (dry metric tons).

Table 2.A2. Parameters and descriptions (continued).

Parameter	Description
n	Vehicle economic life (yr).
nl_i	Number of loggers in supply county i .
nm_h	Average number of extraction machines that a logging crew owns.
p_h	Productivity of extraction machine associated with handling system h (metric tons h^{-1}).
rs_i	Half of the longest straight-line distance of supply county i (km).
sc	Logging residue storage cost in the field (\$ metric ton $^{-1}$).
sp	Stumpage price (purchase cost) of logging residue (\$ metric ton $^{-1}$).
smh	Scheduled trucking hours per year ($h\ yr^{-1}$).
τ_{ijh}	Round trip transportation cost from supply county i to plant j for system h (\$ metric ton $^{-1}$).
t_h	Off-highway transportation cost rate for system h (\$ metric ton $^{-1}\ km^{-1}$).
tp	Transportation vehicle purchase price (\$).
ts	Vehicle salvage value (\$), calculated as a percentage of vehicle purchase price.
t_{ij}	The total cost per vehicle load from supply location i to plant location j (\$).
ut	Average vehicle annual utilization rate (%).
λ	Monthly productive time per machine (h).
ρ	Scheduled working days of the plant per month (days).
δ	Loss rate of woody biomass due to transportation (%), $\delta = 2\%$.
θ_i	Usable proportion of stored logging residue at supply location i (%).
ϕ	Usable proportion of stored woody biomass at a plant (%).

Table 2.A3. Variables and descriptions.

Variable	Description
α_{ih}	A binary variable related to woody biomass handling system h at supply county i , $\alpha_{ih} = \{0, 1\}$.
β_j	A binary variable related to plant j , $\beta_j = \{0, 1\}$.
lct	Under-estimated transportation cost (\$).
sm_i	Average turnover for delivering biomass within supply county i (metric ton-km).
xh_{ihm}	Quantity of logging residue extracted in month m at supply county i using system h (metric tons).
xt_{ijhm}	Quantity of logging residue delivered from supply county i to plant j in month m associated with system h (metric tons).
xps_{ihm}	Quantity of logging residue entered into storage at supply county i in month m associated with system h (metric tons).
xm_{ijrm}	Quantity of mill residue r delivered from supply county i to plant j in month m (metric tons).
xs_{ihm}	Quantity of logging residue stored at supply county i in month m associated with system h (metric tons).
xsn_{ihm}	Quantity of logging residue removed from storage at supply county i in month m associated with system h (metric tons).
xss_{jm}	Quantity of woody biomass stored at plant j in month m (dry metric tons).
xpp_{jm}	Quantity of woody biomass processed at plant j in month m (dry metric tons).
xtl_{ijhs}	Increment of logging residue annually shipped out of supply county i to plant j associated with system h in the range (a_{s-1}, a_s) (metric tons).
z	Total annual delivered cost of woody biomass (\$).

CHAPTER 3: ECONOMIC FEASIBILITY OF A WOODY BIOMASS-BASED ETHANOL PLANT IN CENTRAL APPALACHIA, USA^{*}

^{*} Submitted to Journal of Agricultural and Resource Economics.

Abstract

A mixed integer programming model was developed to assist in siting a woody biomass-based ethanol facility based on the economic feasibility. The model is designed to maximize the net present value (NPV) of a facility over its economic life. Model inputs include biomass availability, biomass handling system type, plant investment and capacity, transportation logistics, feedstock and product pricing, project financing, and taxes. Four alternative woody biomass handling systems which include all the processes from forest to the plant are considered. The model was applied in the central Appalachian hardwood region. Eleven feasible plant locations were identified based on the requirements of site selection. Results showed that the optimal plant location was in Buckhannon, West Virginia. The NPV of the plant with a demand of 1,814 metric tons (2,000 dry tons) per day of woody biomass and plant life of 20 years varied from \$17.28 million to \$35.54 million among the systems. The average production cost of ethanol was approximately \$1.92-\$1.98 per gallon. It was found that the production cost was most impacted by biomass availability, mill residue purchase price, plant investment and capacity, ethanol yield, and financing. Findings suggest that a woody biomass-based ethanol facility in central Appalachia could be economically feasible under certain operational scenarios.

3.1 Introduction

Recently, the interest in using biomass as feedstock for biofuel production in the United States has been increasing due to the concerns about volatile oil prices, climate change, and the impact of diverting crops from food to fuel. Woody biomass is a potentially important feedstock for biofuels (Perlack et al. 2005). Wood-based biomass includes residues produced during timber harvesting, fuelwood extracted from forestlands, and residues generated at primary and secondary wood processing facilities (Wang et al. 2006). A variety of liquid fuels can be

produced from woody biomass, however, ethanol is one of the most promising (Tyner and Taheripour 2007). Most ethanol currently produced in the U.S. is from fermentation of corn, which has been blamed for driving up food prices (Taheripour and Tyner 2008). Cellulose ethanol, a type of biofuel produced from lignocellulose, has all the advantages of corn-based ethanol such as renewable and clean but can be made from a variety of non-food raw materials such as corn stover, switchgrass, and woody biomass. Laboratory testing has demonstrated the technical feasibility of converting woody biomass into ethanol (Zerbe 1991), however, the economic viability of a commercial scale woody biomass-based ethanol plant has not been fully addressed.

An economic feasibility study of a biomass-based facility considers investment, operating costs, time value of money, risk and uncertainty, quality of available data, and a sensitivity analysis to assess the robustness of the results. Some studies for estimating the economic feasibility of cellulosic ethanol have been conducted in the U.S. Kaylen et al. (2000) built a mathematical model to analyze the economic feasibility of producing ethanol from lignocellulosic feedstocks (crop residues and woody biomass). Four cost modules including capital cost, operating cost, feedstock cost, and transportation cost were considered in their model. The optimal size of an ethanol plant was determined by the trade-off between increasing transportation costs for feedstock versus decreasing average plant costs as the plant size increases. Kaylen et al. (2000) determined that the optimal plant used 3,964 dry metric tons of feedstock per day, primarily crop residues with some woody biomass. Tembo et al. (2003) developed a multi-region, multi-period, mixed integer mathematical programming model encompassing alternative feedstocks (corn stover, native perennial grasses, and switchgrass), feedstock production, delivery, and processing methods. The most economically efficient source

of lignocellulosic biomass, timing of harvest and storage, inventory management, and biorefinery size and location for a gasification-fermentation process can be determined in the model. Five large (100 million gallons per year) and one medium (50 million gallons per year) biorefineries were optimally located with an expected Net Present Value (NPV) of \$1,143 million over a 15-year plant life. Mapemba (2005) made some modifications to Tembo's model by adding harvesting systems and suitable harvest days. However, none of these studies considered the handling activities involved in using woody biomass. Kaylen et al. (2000) used purchase price as feedstock cost and estimated the transportation cost using a grid system, rather than actual distance. Tembo et al. (2003) and Mapemba (2005) focused on agricultural residues, which required different harvest systems from woody biomass. Other studies performed economic analysis of lignocellulosic biomass to ethanol plant using Geographic Information System (GIS). Graham et al. (2000) used GIS to estimate the cost and environmental implications of supplying specific amounts of energy crop feedstock to a biorefinery. Noon et al. (2002) identified candidate switchgrass-to-ethanol conversion plant locations using GIS-based analysis of marginal price (delivered cost) variation in Alabama. Results showed that Southern Alabama is the most promising area for switchgrass-to-ethanol plants. Even though the GIS models can provide direct-viewing, the results tend to be static and other site selection criteria such as availability of utilities and access to pre-existing infrastructure were not considered.

Located in central Appalachia, West Virginia is the third most forested state in the U.S., and the harvesting process annually yields approximately 2.19 million dry metric tons of wood residue (Wang et al. 2006). A small portion of logging residue is used for firewood or other purposes in West Virginia. However, there are no statistical data to indicate the amount of logging residue being used annually for these or other purposes (Wang et al. 2006). The

demand/supply ratio of mill residue in West Virginia averaged 68% in 2005 (Wang et al. 2006). There is a growing interest in more efficient utilization of wood residues and conversion of these underutilized materials to biofuels. Currently, there is no large-scale woody biomass-based biofuel facility operating in the state. Industries that could use woody biomass as a feedstock, such as biorefining, biochemicals and biopolymers, have limited start-up potential due to a lack of solid economic and business related information. Therefore, the objectives of this paper are to (1) develop an economic model to assess economic feasibility of an ethanol plant which incorporates woody biomass handling systems, biomass availability/accessibility, plant investment and capacity, transportation logistics, feedstock and product pricing, project financing, and taxes; and (2) conduct sensitivity analyses to assess the impacts of the above factors on the economic feasibility of a woody biomass-based ethanol plant in the central Appalachian region.

3.2 Methods and Materials

3.2.1. Model development

Objective function

Several types of investment appraisals can be used to assess whether an investment project is worthwhile or not, such as payback period, accounting rate of return (ARR), internal rate of return (IRR), profitability index, and net present value (NPV) (McMenamin 1999). The NPV is by far the most common project evaluation approach used by firms (Volker et al. 2009).

A mixed integer programming model would be more appropriate than a linear programming model for optimizing site location because a binary variable associated with site location could be an integer (0 or 1). Therefore, a mixed integer programming model is

developed in the paper to maximize the NPV of a woody biomass-based ethanol facility. The model is solved using General Algebraic Modeling System (GAMS)/CPLEX, a high-level modeling system for mathematical programming and optimization. All the notations for variables and symbols used in the model can be found in Appendix 3.A. The NPV is a function of annual revenue (R_n), annual feedstock cost (F_n), operating and maintenance cost (OM_n), income taxes (T_n), and plant investment (Ω). It is assumed that R_n , F_n , and OM_n are constant across years ($R_n = R$, $F_n = F$, $OM_n = OM$ for all n). The depreciation cost (C_n) and income taxes are the only things that change across years. Therefore, the objective of the model is expressed as:

$$\text{Max } NPV = \sum_{n=1}^N (R_n - F_n - OM_n - T_n) \cdot PVI_n - \Omega = \sum_{n=1}^N (R - F - OM - T_n) \cdot PVI_n - \Omega \quad (3.1)$$

The annual revenue R is the sum of the sale of each product g (ethanol or electricity) at plant location j throughout the year (Eq. (3.2)). Ethanol is the main product of the co-current dilute acid prehydrolysis and enzymatic hydrolysis (Wooley et al. 1999). The process produces excess steam that is used to generate electricity for use in the plant and for sale to the grid.

$$R = \sum_{j=1}^J \sum_{g=1}^G \sum_{m=1}^{12} P_g \cdot q_{jgm} \quad (3.2)$$

Logging and mill residues are assumed to be the primary feedstock for ethanol production in central Appalachia. Based on the two commonly used extraction machines (cable and grapple skidders) and biomass forms (loose residue and chips) delivered in the region, four woody biomass handling systems were considered in the model: cable skidder-loose residue (S1), cable skidder-chips (S2), grapple skidder-loose residue (S3), and grapple skidder-chips (S4).

The annual feedstock cost (F) includes the cost components associated with woody biomass purchase cost, extraction, storage, loading and hauling, chipping/grinding, and transportation, which is computed using Eq. (3.3) (Wu et al. 2008). The woody biomass supply locations were represented by counties in the study region and a town located near the geographic center of each county was used to represent the location for that county. LCT is the under-estimated transportation cost. The reason for calculating LCT is that $\sum TC_{ijh} \cdot xt_{ijhm}$ in Eq. (3.3) may underestimate the actual transportation cost if the supply and plant locations are in the same county or adjacent counties ($D_{ij} \leq RS_i$). A nonlinear transportation cost model developed by Dornburg and Faaij (2001) can be used to determine the under-estimated cost LCT . To make the MIP model solvable, the separable programming (Taha 2006) was used to convert the nonlinear model into a piecewise linear function.

$$\left\{ \begin{array}{l} F = \sum_{i=1}^I \sum_{h=1}^H \sum_{m=1}^{12} [(HC_h + SP) \cdot xh_{ihm} + SC \cdot xps_{ihm}] + \sum_{i=1}^I \sum_{j=1}^J \sum_{h=1}^H \sum_{m=1}^{12} (TC_{ijh} + LC_h + CS_h + CP_h) \cdot xt_{ijhm} \\ \quad + \sum_{i=1}^I \sum_{j=1}^J \sum_{m=1}^{12} (MC + MT \cdot D_{ij}) \cdot xm_{ijm} + LCT \\ LCT = \sum_{i=1}^I \sum_{j=1}^J \sum_{h=1}^H \sum_{s=1}^S T_h \cdot FC_s \cdot xtl_{ijhs}, \text{ where } D_{ij} \leq RS_i, 0 \leq xtl_{ijhs} \leq a_s - a_{s-1}. \\ \sum_{s=1}^S xtl_{ijhs} = \sum_{m=1}^{12} xt_{ijhm}, \forall i, j, h. \end{array} \right. \quad (3.3)$$

Total investment cost Ω in Eq. (3.4) is the sum of each individual investment cost TPC_j at each possible plant location. β_j is a binary variable related to investment decision, $\beta_j = \{0,1\}$. If $\beta_j=1$, a facility will be built at location j , 0 otherwise. The other associated costs such as warehouse, site development, and field expense are included in TPC_j . Construction cost of the plant can easily differ due to site characteristics and other factors. Here it is assumed to be

the same for all the possible plant locations. The order of magnitude estimation method was used to estimate the investment cost of a woody biomass-based ethanol plant in Eq. (3.5). This method uses the seven-tenth power law exponent to scale investment cost from known investment cost data (Ulrich 1984). The Marshall & Swift (M&S) all industry equipment cost index was used to adjust the cost from a historical year to the initial project year. It is also assumed that there is one ethanol plant to be built in the study region in Eq. (3.6).

$$\Omega = \sum_{j=1}^J \beta_j TPC_j \quad (3.4)$$

$$TPC_j = TPC_0 (CAPACITY / CAPACITY_0)^{0.7} (MS / MS_0) \quad (3.5)$$

$$\sum_{j=1}^J \beta_j = 1 \quad (3.6)$$

Operating and maintenance cost (OM) is estimated in terms of variable and fixed operating costs. Variable operating cost includes waste handling charges, water consumption, and chemical inputs and it is a linear function of the plant capacity (Kaylen et al. 2000). Fixed operating cost includes labor, overhead, maintenance, and insurance & property taxes. The fixed operating cost exhibits economies of scale, which is estimated using the order of magnitude method.

The income taxes T_n at the n^{th} year are calculated by Eq. (3.7). Since the taxable income ($R - F - OM - C_n$) is usually negative at the initial stages of the project (e.g., 1st year), zero tax is applied instead of negative tax. C_n is the capital depreciation at the n^{th} project year.

$$T_n = (R - F - OM - C_n) \cdot t, \forall n. \quad (3.7)$$

The IRS Modified Accelerated Cost Recovery System (MARCS) required by the United States income tax code was used to determine the capital depreciation cost (Short et al. 1995).

The General Depreciation System (GDS) within the MARCS allows both 200% and 150% declining balance (DB) of depreciation. Short et al. (1995) also reported that steam production plants should use a 20-year recovery period with 150% DB depreciation and other property unspecified should use a 7-year recovery period with 200% DB depreciation. In this study, the plant is segmented into a general plant and a steam plant using the methods by Wooley et al. (1999). The depreciation cost of the plant is computed using Eqs. (3.8) - (3.13). The sum of the unrecovered capital cost of the general and steam plant on the first year is equal to the plant investment cost in Eq. (3.8). The recovery period of each type of facility is: $NR_{general_plant} = 7$, $NR_{steam_plant} = 20$. Eqs. (3.9) - (3.12) are used to compute the depreciation cost of the general (or steam) plant each year. The total depreciation at the n^{th} year is the sum of the depreciation cost of the general and the steam plant (Eq. (3.13)).

$$TPC_j = \sum_{k=1}^K CR_{k1} \quad (3.8)$$

$$CFD_{kn} = \begin{cases} \frac{2 CR_{kn}}{NR_k}, & n \leq NR_k, \text{ where } k = 1. \\ \frac{1.5 CR_{kn}}{NR_k}, & n \leq NR_k, \text{ where } k = 2. \\ 0 & , \forall k, n > NR_k. \end{cases} \quad (3.9)$$

$$CFS_{kn} = \begin{cases} \frac{CR_{kn}}{NR_k - n + 1}, & \forall k, n \leq NR_k. \\ 0 & , \forall k, n > NR_k. \end{cases} \quad (3.10)$$

$$CF_{kn} = \max(CFD_{kn}, CFS_{kn}), \quad \forall k, n. \quad (3.11)$$

$$CR_{kn+1} = CR_{kn} - CF_{kn}, \quad \forall k, n = 1, 2, \dots, N-1. \quad (3.12)$$

$$C_n = \sum_{k=1}^K CF_{kn}, \quad n = 1, 2, \dots, N \quad (3.13)$$

The present value index PVI_n at the n^{th} year depends on the selection of the discount rate which can greatly affect the economics and the decision making, particularly in capital-intensive projects like ethanol facilities. The discount rate can be thought of as an opportunity cost.

Investors will require a rate of return at least as great as the percentage return they can earn in the most nearly comparable investment opportunity. Since there remain uncertainties in determining the opportunity cost, the most widely accepted approach, weighted average cost of capital (WACC), was used as the discount rate for the project, which is expressed in Eq. (3.14).

The PVI_n is given by Eq. (3.15).

$$WACC = w_e r_e + (1 - w_e) \cdot r_d \cdot (1 - t) \quad (3.14)$$

$$PVI_n = \frac{1}{(1 + WACC)^n}, \quad \forall n. \quad (3.15)$$

Constraints

Several constraints are considered in relation to the logistic process of woody biomass handling from the forest to the plant gate. It is assumed that there is one woody biomass handling system used at each supply location and the model evaluates each woody biomass handling system separately (Eq. (3.16)). The index of handling system h ranges from 1 to 4. As stated by Eq. (3.16), the model will evaluate the cable skidder-loose residue system (S1). The parameter $ALFA_{ih}$ for other handling systems (S2-S4) will be equal to zero.

$$\begin{cases} \sum_{h=1}^H ALFA_{ih} = 1, \forall i, h = 1, 2, \dots, 4. \\ ALFA_{ih} = 1, \forall i, \text{ where } h = 1. \end{cases} \quad (3.16)$$

The quantity of logging residue annually extracted using system h at supply location i should be less than the available logging residue at that location (Eq.(3.17)). In terms of biomass accessibility, a terrain constraint is considered to further limit logging residue availability. All of the extraction machines are assumed to be able to operate on forest lands with a slope of 35% or less. The amount of logging residue extracted is also subject to the availability of logging residue for a specific time period (Eq. (3.18)) and extraction capacity of local loggers (Eq. (3.19)). Wet or other extreme weather can limit loggers' ability to operate their harvesting equipment due to site accessibility, safety and environmental concerns (Cusack 2008). There are certain times of the year when harvesting is limited due to wet or other extreme weather. An average rate of logging residue availability was evenly assigned for each month within a year. For instance, the logging residue extracted cannot be more than 1/12 of the total available amount if extracted in January. Then, this rate was adjusted based on historical production data and monthly precipitation in the study region. Local loggers' capability of extracting logging residue is defined by $\lambda PD_h NL_i NM_h$. Where, λ is monthly productive time per machine, PD_h is productivity of extraction machine associated with system h , NL_i is the number of loggers at supply location i , and NM_h is the number of extraction machines that a logging crew uses. The availability of mill residue is described by Eq. (3.20) (Wu et al. 2008).

$$\begin{cases} \sum_{m=1}^{12} xh_{ihm} - ALFA_{ih} \cdot BP_i \cdot BIV_i \leq 0, \forall i, h. \\ \sum_{m=1}^{12} xh_{ihm} - ALFA_{ih} \cdot BP_i \cdot BVS_i \leq 0, \forall i, h. \end{cases} \quad (3.17)$$

$$\sum_{h=1}^H xh_{ihm} - EXT_m \cdot BP_i \cdot BVS_i \leq 0, \forall i, m. \quad (3.18)$$

$$xh_{ihm} - \lambda \cdot PD_h \cdot NL_i \cdot NM_h \leq 0, \forall i, h, m. \quad (3.19)$$

$$\sum_{j=1}^J \sum_{m=1}^{12} xm_{ijm} - MP_i \cdot MIV_i \leq 0, \forall i. \quad (3.20)$$

The total logging residue shipped to plant locations plus the amount stored at landings should not exceed the total logging residue extracted at current month and the usable portion of logging residue stored (Eq. (3.21)) (Tembo et al. 2003). The storage balance of logging residue for one year is expressed as Eq. (3.22). The interrelationship among logging residue extracted, logging residue entered into storage and removed from storage, and logging residue transported to demand locations is described in Eq. (3.23).

$$xh_{ihm} + \theta_i xs_{ihm-1} - \sum_{j=1}^J xt_{ijkm} - xs_{ihm} \geq 0, \forall i, h, m. \quad (3.21)$$

$$\sum_{m=1}^{12} \sum_{h=1}^H xh_{ihm} - (1 - \theta_i) \sum_{m=1}^{12} \sum_{h=1}^H xs_{ihm} - \sum_{j=1}^J \sum_{h=1}^H \sum_{m=1}^{12} xt_{ijkm} = 0, \forall i. \quad (3.22)$$

$$\sum_{h=1}^H xh_{ihm} - \sum_{h=1}^H xps_{ihm} + \sum_{h=1}^H xsn_{ihm} - \sum_{h=1}^H \sum_{j=1}^J xt_{ijkm} = 0, \forall i, m. \quad (3.23)$$

The total woody biomass delivered to an ethanol plant j plus the usable biomass stored in the previous months at the plant (ϕxss_{jm-1}) should be equal to the amount of woody biomass stored (xss_{jm}) and being processed at current month (xpp_{jm}) (Eq. (3.24)).

$$\sum_{i=1}^I \sum_{h=1}^H (1 - \delta) xt_{ijkm} + \sum_{i=1}^I xm_{ijm} + \phi xss_{jm-1} - xss_{jm} - xpp_{jm} = 0, \forall j, m. \quad (3.24)$$

The amount of woody biomass processed (xpp_{jm}) in month m at plant location j is equal to the feedstock demand ($30CAPACITY$) at that location (Eq. (3.25)). σ is the moisture content of woody biomass. The plant is assumed to have 30 scheduled working days per month.

$$(1 - \sigma) \cdot xpp_{jm} - 30CAPACITY \cdot \beta_j = 0, \forall j, m. \quad (3.25)$$

The amount of product g produced at plant location j in month m (q_{jgm}) is less than the amount of dry woody biomass processed multiplying by the corresponding yield (η_g) from one dry metric ton of woody biomass.

$$q_{jgm} - (1 - \sigma) \cdot \eta_g \cdot xpp_{jm} \leq 0, \forall j, g, m. \quad (3.26)$$

The inventory of woody biomass at a plant (xss_{jm}) should be greater than the minimum inventory defined to ensure continuous production.

$$xss_{jm} - MNBIN \cdot \beta_j \geq 0, \forall j, m. \quad (3.27)$$

Finally, the following decision variables should be nonnegative:

$$xh, xt, xtl, xm, xs, xps, xsn, xss, xpp, q \geq 0 \quad (3.28)$$

Given base values for all the parameters, the above model which integrates multiple equations can be solved using GAMS/CPLEX solver and the optimal plant location, NPV, and quantity of woody biomass delivered by handling system can be determined. Note that if the income taxes in the first few years were negative, the NPV would be adjusted accordingly. The internal rate of return (IRR) of the optimal plant will then be derived from the model solution.

3.2.2 Model assumptions

Supply and plant locations

The model was applied in the central Appalachian hardwood region, U.S. Ninety-nine counties in West Virginia and part of Virginia, Kentucky, Ohio, and Pennsylvania were selected as potential woody biomass supply sources (Figure 3.1). A town near the geographic center of each county was used to represent the average location for the county. Many factors should be considered when choosing a woody biomass-based ethanol plant location, including feedstock availability, utilities (such as electricity, gas, and water) availability and cost, transportation

(such as highways or railroads), site size, product market, and community support (Blagojevich et al. 2006, Clean Fuels Development Coalition and Nebraska Ethanol Board, 2006). Proximity and availability of woody biomass as well as competition from other uses are the primary concerns about plant location, because a guaranteed supply of woody biomass at a competitive price within a reasonable radius of an ethanol plant is critical for the profitability and viability of the plant. An intermediate size (50 million gallons per year) ethanol plant may require 4-6 ha land depending on plant technology and configuration (Clean Fuels Development Coalition and Nebraska Ethanol Board 2006). In this study, feasible sites for woody biomass-based ethanol plants were selected from available industrial parks due to availability of utilities and easy access to pre-existing infrastructure. A total of 15 out of 110 industrial parks in West Virginia were selected based on city limits, attainability, non-attainment area (which is designated by the U.S. Environmental Protection Agency), utility (electricity and gas) availability, access to water and sewer, continuous land area greater than 4 ha, and within a distance of 16 km from interstate highways. The selected industrial parks were represented by towns where they are located. If two industrial parks were located in the same town, they were treated as one feasible plant location. As a result, eleven unique locations were identified as feasible plant locations (Figure 3.1). They were: Beaver (Raleigh), Belington (Barbour), Bluefield (Mercer), Buckhannon (Upshur), Holden (Logan), Kenna (Jackson), Millwood (Jackson), Morgantown (Monongalia), Oak Hill (Fayette), Point Pleasant (Mason), and Williamson (Mingo). The names in the brackets are the counties where the cities are located. Distances over-the-road between supply and plant locations were computed based on an online distance calculator (MyRatePlan.com 2008).

Figure 3.1. Pre-selected woody biomass-based potential ethanol plant locations and biomass supply counties.

Woody biomass availability and characteristics

The volume of logging residue by county was computed based on annual harvested area obtained from West Virginia Forestry Statistics (WVDOF 2006) and logging residue spatial density from a previous survey (Grushecky et al. 2006). Data from an annual report of wood byproducts by West Virginia University's Appalachian Hardwood Center (Bragonje et al. 2006) were used to estimate the annual production of mill residue in West Virginia. Wood residues in the neighboring states of West Virginia were based on the USDA Forestry Inventory and Analysis (FIA) - Timber Product Output (TPO) data (USDA-FS 2008). The recovery rate of logging residue in West Virginia was assumed to be 65 percent on harvested sites with a slope of 35 percent or less in consideration of operational accessibility and economic feasibility in the region. The percentage of forest lands in West Virginia that meet this requirement ranges from

24% to 92% by county. Forty percent of mill residue was assumed to be available for ethanol production (Wang et al. 2006). The average moisture content of woody biomass was assumed to be 43% (wet basis) (Wang et al. 2006). The assumptions related to feedstock logistics including hourly machine cost, machine productivity, and cost per ton of production during woody biomass handling process are presented in Table 3.1. Hourly machine cost was computed using machine rate method (Miyata 1980). The productivity of handling machines (skidders, loader, and chippers) were based on the existing models developed for the central Appalachian hardwood region and other literature (Wang et al. 2004, Kärhä and Vartiamäki 2006, Li et al. 2006). Transportation cost was assumed to be \$0.18 t⁻¹km⁻¹ for loose residue and \$0.12 t⁻¹km⁻¹ for wood chips, respectively (Kerstetter and Lyons 2001).

Table 3.1. Cost assumptions for woody biomass handling machines in central Appalachia.

	Hourly cost (\$ h ⁻¹)	Productivity (t h ⁻¹)	Unit cost (\$ t ⁻¹) ^a
Cable skidder	81.34	6.34	12.83
Grapple skidder	102.72	11.46	8.96
Loader	85.96	16.04	5.36
Chipper	185.62	30	6.19
Grinder	212.27	91	2.33

^a green ton basis.

Plant assumptions

The co-current dilute acid prehydrolysis and enzymatic hydrolysis was considered as the conversion method from woody biomass to ethanol as described by Wooley et al. (1999). Since yellow-poplar and oaks are the most common hardwood species in central Appalachia (USDA-FS 2008), it is appropriate to assume the yield of woody biomass-derived ethanol to be 290 l t⁻¹ (70 gallons dry short ton⁻¹) (Wooley et al. 1999). The weighted average cost of capital was

computed as 8.9 percent using Eq. (14). The minimum feedstock inventory stored at a plant per month was assumed to be 7 days (12,700 dry metric tons month⁻¹). The economic assumptions related to the base ethanol plant are summarized in Table 3.2. Mill residue purchase price was obtained by consulting with several sawmill owners in the region. The stumpage cost of logging residue was assumed to be \$1 t⁻¹ (wet basis) in the base case. All ethanol and electricity produced were assumed to be sold in West Virginia and the bordering states.

Table 3.2. Assumptions for a 1,814 t/day woody biomass-based ethanol plant.

Parameter	Assumption in the base case
Primary product	Fuel ethanol
Feedstock requirement (dry weight) (t day ⁻¹)	1,814
Plant life (yr)	20
Equity proportion (%)	40
Cost of Equity ^a (%)	15
Cost of debt ^a (%)	8
Federal tax (%)	39
General plant depreciation ^b (yr)	7
Steam plant depreciation ^b (yr)	20
Ethanol selling price (\$ l ⁻¹)	0.55
Electricity value (\$ kWh ⁻¹)	0.05
Ethanol yield ^c (l t ⁻¹)	290
Excess electricity generated ^c (kWh l ⁻¹ ethanol)	0.46
Capital cost ^c (\$ million)	265
Operation and maintenance cost ^c (\$ million yr ⁻¹)	27.7
Mill residue purchase price (\$ t ⁻¹)	22
Logging residue stumpage price (\$ t ⁻¹)	1.00
Storage cost at landings (\$ t ⁻¹)	0.00
Biomass inventory at plants (dry weight) (t month ⁻¹)	12,700
Usable proportion of logging residue at landings (%)	95
Usable proportion of woody biomass at plants (%)	95
Dry matter loss due to transportation (%)	2
Operating time (days yr ⁻¹)	360

Source: ^a Specca (2009), ^b Short et al. (1995), ^c Adapted from Wooley et al. (1999).

3.3 Results and Discussion

3.3.1 Base case

The optimization results of the model are summarized in terms of NPV, optimal plant location, internal rate of return (IRR), and quantity of woody biomass delivered by handling system (Table 3.3). Because the income taxes were negative in the first two years for the cable skidder handling systems (S1 and S2) and in the first year for the grapple skidder handling systems (S3 and S4), zero taxes were charged instead of the negative values. Thus, the NPV were adjusted based on the adjusted taxes accordingly. The adjusted NPV ranged from \$17.28 million for the cable skidder-chips system (S2) to \$35.54 million for the grapple skidder-chips system (S4) over the plant life of 20 years. IRR is the average annual return earned through the life of an investment. The IRR of the ethanol facility was computed based on a series of cash flows, which averaged 10.46 percent among the four woody biomass handling systems. The net cash flow of the project became positive by the end of 8th year for all systems. The town of Buckhannon, WV, was the optimal location for all systems due to the maximum NPV. Since the investment and operating and maintenance costs were the same for all the feasible sites, Buckhannon was the optimal site because the delivered cost of feedstock was the lowest. Annual ethanol production at the plant was 189 million liters (50 million gallons). Approximately 649 to 748 thousand tons of logging residue (wet basis) and 454 to 552 thousand tons of mill residue (wet basis) would be needed at this location with an average delivered cost of \$56.79 to \$61.12 per dry metric ton.

Table 3.3. Optimization of the woody biomass-based ethanol facility by biomass handling systems (base case).

Woody biomass handling system	NPV (\$ million)	Optimal plant location	IRR after tax (%)	Quantity of logging residue delivered ^a	Quantity of mill residue delivered ^a
S1	17.61	Buckhannon, WV	9.96	649	552
S2	17.28	Buckhannon, WV	9.94	654	547
S3	34.42	Buckhannon, WV	10.93	734	469
S4	35.54	Buckhannon, WV	10.99	748	454

^a 1,000 t yr⁻¹ (wet basis).

3.3.2 Ethanol production cost

Ethanol production cost includes the costs associated with capital recovery, operation and maintenance, raw materials (excluding woody biomass), and woody biomass delivered cost. The average production cost of woody biomass-derived ethanol varied from US¢ 53.17 to US¢ 54.70 l⁻¹ without consideration of electricity credit. Feedstock (woody biomass) and capital recovery were the two major cost components, accounting for about 39 percent and 33 percent of the total production cost, respectively. The complexity of producing ethanol from woody biomass compared to corn-based ethanol was attributable to the higher capital cost (Greer 2007). This conversion technology requires more costly equipment and more processing steps to produce ethanol (Bullis, 2006). In this study, the fixed operating costs (including labor/supervision, general and direct overhead, maintenance, and insurance/property taxes) and variable operating costs (including all the raw materials except woody biomass, water consumption, and waste disposal) accounted for 16.56 percent and 10.53 percent of the total cost, respectively. Wooley et al. (1999) estimated that 1.76 kWh electricity can be generated along with the production of

3.785 liter (1 gallon) of ethanol. Therefore, the production cost of ethanol would be in the range from US¢ 50.85 to US¢ 52.38 l⁻¹ after deducting the electricity credit of US¢ 2.32 l⁻¹ given the electricity price of US¢ 5 kWh⁻¹.

3.3.3 Sensitivity analyses

NPV and IRR vs. ethanol price

Ethanol price is critical to the evaluation of a cellulosic ethanol facility, and can have great impacts on NPV and IRR. The ethanol price is relatively volatile and subject to changes in the wholesale price of unleaded regular gasoline with additional volatility due to local, regional and national supply and demand for ethanol (BBI International 2002). Current relatively lower oil prices have reduced the demand for ethanol, and the spot prices of ethanol are trending down in line with the softness in energy markets. The NPV and IRR were estimated in terms of various ethanol prices by different woody biomass handling systems (Figure 3.2). The grapple skidder handling systems (S3 and S4) presented higher NPV and IRR than the cable skidder handling systems (S1 and S2). The magnitude of the NPV or IRR change was approximately proportional to the change of ethanol price for all systems. If ethanol price decreased US¢ 2.5 l⁻¹, the NPV of the base case plant (50 million gallons yr⁻¹) would decrease by \$27.60 million and the IRR would decrease 1.69 percent.

Figure 3.2. Net present value and internal rate of return vs. ethanol price.

Ethanol production cost vs. feedstock supply

The total feedstock was estimated to be 3.27 million dry metric tons per year in the state of West Virginia and some bordering counties of West Virginia's neighboring states (USDA-FS 2008). With the assumptions that 65 percent of logging residue on harvested sites with a slope of 35 percent or less and 40 percent of mill residue are available, the usable feedstock could be up to 1.70 million dry metric tons. Given the plant capacity of 1,814 dry metric tons per day in the base case, the feedstock needed annually is approximately 0.70 million dry tons, or 41 percent of the total available. The average production cost of ethanol decreased as the available residue increased (Figures 3.3a, 3.3b). There were significant differences among the woody biomass handling systems in terms of ethanol production cost. The grapple skidder systems (S3 and S4) tended to have lower production cost compared to the cable skidder systems. Logging residue

had greater impacts on ethanol production cost in contrast with mill residue because more logging residue could be delivered to the utilization facility. The production cost of ethanol increased as the stumpage cost of logging residue increased (Figure 3.3c). For every US\$1 t⁻¹ increase in the stumpage cost, the production cost would increase US¢ 0.34 l⁻¹ for the cable skidder-loose residue system (S1), US¢ 0.35 l⁻¹ for the cable skidder chips system (S2), US¢ 0.37 l⁻¹ for the grapple skidder-loose residue system (S3), and US¢ 0.40 l⁻¹ for the grapple skidder-chips system (S4). If the purchase price of mill residue increased from US\$22 t⁻¹ (base case) to US\$30 t⁻¹, the production cost would increase 2.9-4.0 percent accordingly from the base case depending on the biomass handling system used (Figure 3.3d). Note that the production cost increased at a decreasing rate as mill residue purchase price increased among the systems. Since both logging residue and mill residue were possible feedstock for the ethanol plant, increasing mill residue purchase price will lead to more utilization of logging residue. If mill residue purchase price were high enough, no mill residue would be used and all the feedstock entering into the plant would be logging residue.

Figure 3.3. Ethanol production cost vs. feedstock availability and cost by system (wet basis).

Ethanol production cost vs. capital cost

A cellulosic ethanol plant is a capital-intensive investment. To date, there are no commercial cellulosic ethanol plants in production in North America. Only a few small demonstration biorefineries are producing ethanol from cellulosic feedstock including Iogen Corporation (Canada), the world's first cellulosic ethanol producer, and Verenium (U.S.), the first cellulosic ethanol plant in the U.S. (Fehrenbacher 2008, Deutscher 2009). In this study, the total scale-adjusted investment estimation of \$265 million (US\$ 139 l⁻¹ of ethanol) using Eq. (5) for a first-of-a-kind cellulosic ethanol plant was based on a report published by the National Renewable Energy Laboratory (NREL) (Wooley et al. 1999) which was completed in

conjunction with a commercial ethanol plant developer. The production cost of ethanol increased proportionally as the total capital cost increased (Figure 3.4a). If the total capital cost increased 5 percent compared to the base case, the production cost of ethanol would increase 1.70-1.77 percent, depending on the biomass handling system used. If the total capital cost increased 10 percent, the ethanol production cost would increase 3.42-3.54 percent among the four handling systems.

Figure 3.4. Ethanol production cost vs. plant assumptions by system (dry weight).

Ethanol production cost vs. plant capacity

The average production cost of ethanol decreased as the use for woody biomass at plants increased (Figure 3.4b). As the plant scale increased, the average cost related to plant investment

decreased due to economy of scale. However, the marginal cost associated with transportation increased because the plant has to source feedstock from a greater distance. The production cost of ethanol reached the minimum when the use of woody biomass increased to 2,400 dry metric tons per day for S1 and S3, or 2,800 dry metric tons per day for S2 and S4. After that, the production costs went up again. At the demand level of 2,400 dry metric tons per day, the production cost in S1 and S3 decreased 0.59 percent compared to the base case. The production cost in S2 and S4 decreased 1.45 percent compared to the base case when the plant capacity approached 2,800 dry metric tons per day. The cable skidder handling systems (S1 and S2) always presented higher production cost compared to the grapple skidder handling systems (S3 and S4).

Ethanol production cost vs. ethanol yield

Technologies that convert wood to cellulosic ethanol are in varying stages of development and commercialization (Benjamin et al. 2009). The ethanol yield from one metric ton of dry woody biomass could vary from 208 to 500 liters depending on conversion technology and other operational conditions. The co-current dilute acid prehydrolysis and enzymatic hydrolysis developed by the NREL was considered as one of the available conversion methods and the ethanol yield could be 283 l from one dry metric ton of woody biomass (Wooley et al. 1999). The change of the average production cost of ethanol was assessed according to the ethanol yield (Figure 3.4c). For example, the average production cost would decrease US¢ 3.3 l⁻¹ for every 20 liter per ton increase in yield.

Ethanol production cost vs. project finance

Project financing and funding are considered by many to be a major obstacle to the development and commercialization of the ethanol industry (Solomon et al. 2007). The structure

of project financing can have a significant impact on the viability of a cellulosic ethanol project due largely to higher investment cost (Graf and Koehler 2000). Agribusiness lenders with Farm Credit Services of America suggest that the equity-to-asset ratio for an ethanol plant should be at least 40 percent (CFDC and NEB 2006), which means that investors should own no less than 40 percent of the total value of the plant and inventory. Several equity/debt ratios were analyzed in order to compare the ethanol production cost (Figure 3.4d). It was shown that the lower equity proportions resulted in lower production costs for all systems because of the lower discount rate (WACC) for the ethanol project and the capital cost per liter of ethanol. Compared to the base case financing assumption (40/60 equity/debt ratio), if this ratio was down to 30/70, the production cost of ethanol would decrease 3.10 percent on average for all systems. However, the risk associated with this plant would be higher because of more debt. If the equity/debt ratio increased to 50/50, the ethanol production cost would increase 3.25 percent.

3.3.4 Other implications

Security of feedstock supply

The stabilization of feedstock supply is critical to the success of a woody biomass-based facility. The increased regulations over forest practices, such as best management practices, and certifications, often increase woody biomass harvesting costs and limit resource availability in the short term (Benjamin et al. 2009). Logging residue has been considered as an under-utilized resource with limited value. As the biomass market develops for ethanol or other bioproducts, more biomass would be needed and a higher stumpage cost of logging residue would be inevitable. In considering the future availability of mill residue, several issues should be considered. Since mill residue is a by-product of lumber production, its availability depends on other markets, as demonstrated recently with the corresponding decline in production of mill

residue due to the housing slowdown (U.S. Census Bureau 2009). The supply of mill residue in the central Appalachian region remains more uncertain because of mill closures and long-term production constraints (Dye 2009). The utilization of woody biomass for biofuels will also confront competition from other uses such as pellet fuel and boiler fuel, which could increase the price of woody biomass. To secure the supply chain of woody biomass, it is essential to find niche supply markets for wood residues through long-term contracts, or collaborative relationships with landowners and major forest products companies.

Government policies

Government subsidies will initially be essential to the market success of woody biomass-based facilities. Without government subsidies, ethanol producers would have to sell their products at current market price. For example, in our case, the difference between the market price and the assumed value could be US¢ 5.4 l⁻¹. Government and other support mechanisms have been a consistent and essential part of the U.S. ethanol industry (Solomon et al. 2007). Various federal incentive programs have been designed to encourage the production and utilization of ethanol and other biofuels such as Excise Tax Incentives, Income Tax Credit for Alcohol Fuels, Ethanol Production Incentive, Income Tax Credit, Income Tax Credit for Small Ethanol Producers, and others. The most significant subsidy is the federal Volumetric Ethanol Excise Tax Credit (VEETC) (mainly for corn ethanol), which was established in 2004 as a US¢ 13 l⁻¹ payment to gasoline blenders which will end in 2010. The 2008 Farm Bill reduced the credit to US¢ 12 l⁻¹ and the credit for cellulosic ethanol was set at US¢ 27 l⁻¹ through 2012. At the current spot price of US¢ 49.6 l⁻¹ (DTN Ethanol Center, 2009), the cellulosic ethanol plant in central Appalachia would not be economically viable without the government subsidy.

Ethanol market

West Virginia is a moderate ethanol consumer with annual consumption of 542,620 barrels (22.79 million gallons) (U.S. Department of Energy 2009). The bordering states such as Ohio, Virginia, and Pennsylvania consumed approximately 11 million barrels of ethanol in 2005 (USDOE 2009). Most ethanol consumed in this region is from the Midwest corn-belt (Tyner, 2008). Due to the transport infrastructure bottleneck, ethanol availability is limited in the eastern states (Tyner 2008). A potential cellulose ethanol production of 50 million gallons in West Virginia could help meet the state's own needs as well as supply the markets in the neighboring states. The business will also stimulate economic development and create job opportunities in urban and rural communities in the region.

3.4 Conclusions

The economic model developed can be used to assess the location of a woody biomass-based ethanol facility in the central Appalachian region and to evaluate the economic viability under certain resource, capacity, and other constraints. This study differs from prior studies in several aspects. First, the delivered cost of woody biomass was computed based on a series of logistic constraints including supply and demand. This cost would change as the factors such as biomass availability, purchase price, and demand level at the ethanol plant changed. Second, the NPV was calculated in consideration of the income taxes, while most studies only considered revenue and fixed and variable operating costs. The NPV estimated using the mixed integer programming model provides a deep insight on the economic viability of the cellulose ethanol facility. Third, the model can deal with optimizing logistical decision-making when linked to feedstock requirements, collection, delivery, and production issues. Since this is a generalized model, it can also be applied to the other regions.

The application results of the base case showed that the optimal location for the woody biomass-based ethanol plant should be in Buckhannon, West Virginia, which is surrounded by abundant woody biomass resources. The NPV varied from \$17.28 million for the cable skidder-chips system (S2) to \$35.54 million for the grapple skidder-chips system (S4) with an after-tax discount rate of 8.9 percent over the plant life. The internal rate of return averaged 10.46 percent among the four woody biomass handling systems. The net cash flow of the plant became positive by the end of the 8th year. The primary revenue source of the facility came from the sale of ethanol and electricity, without considering the small ethanol producer tax credit. The production cost of ethanol varied from US¢ 50.85 l⁻¹ for the grapple skidder-chips system (S4) to US¢ 52.38 l⁻¹ for the cable skidder-chips system (S2). Silvers and Zacchi (1996) reviewed the economy of ethanol production from lignocellulosic material and found that the variation in the ethanol production cost is large, from US¢ 18 to US¢ 151 l⁻¹. The wide variation in ethanol production cost can be explained by different assumptions made in the technical and economic calculations, such as raw materials used, the type of process utilized, and the design of the process. Sensitivity analyses indicated that the production cost of ethanol in the facility in the central Appalachian hardwood region heavily depended upon biomass availability, plant investment and capacity, ethanol yield, and financial structure.

This study provides a solid base for further research in assessing the social and environmental issues of the woody biomass-based ethanol facility. More efforts are necessary to assess the detailed plant configuration including equipment, utilities, and labor availability. Necessary permits related to air emissions and water pollution controls required for the ethanol facility in the designated location should be considered as well.

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Appendix 3.A. Sets, parameters, and variables

Table 3.A1. Sets and descriptions.

Set	Description
G	Products; $g = \{\text{ethanol, electricity}\}$
H	Woody biomass handling systems; $h = \{\text{cableskidder_looseresidue, cableskidder_chips, grappleskidder_looseresidue, grappleskidder_chips}\}$
I	Woody biomass supply locations; $i = \{\text{All counties in West Virginia and some counties in the bordering states}\}$
J	Possible plant locations; $j = \{\text{Beaver, Belington, Bluefield, Buckhannon, Holden, Kenna, Millwood, Morgantown, Oak Hill, Point Pleasant, and Williamson}\}$
K	Facility type; $k = \{\text{general_plant, steam_plant}\}$
M	Months, $m = \{1, 2, \dots, 12\}$
N	Set of project year indices, $n = \{1, 2, \dots, N\}$
S	Set of breakpoints, $s = \{0, 1, \dots, 9\}$

Table 3.A2. Parameters and descriptions.

Parameter	Description
a_s	Breakpoints over the quantity of annually delivered logging residue from supply county i to plant j
$ALFA_{ih}$	A parameter associated with system h at supply location i , $ALFA_{ih} = \{0,1\}$
BP_i	Proportion of logging residue available for extraction at supply location i (%)
BIV_i	Volume of logging residue at supply location i (t)
BVS_i	Volume of logging residue on forest lands with a slope of 35% or less at supply location i (t)
C_n	Capital depreciations at the n^{th} year (\$)
CF_{kn}	Depreciation cost of facility type k at the n^{th} year (\$)
CFD_{kn}	Declining balance depreciation cost of facility type k at the n^{th} year (\$)
CFS_{kn}	Straight line depreciation cost of facility type k at the n^{th} year (\$)
CR_{kn}	Unrecovered capital cost of facility type k at the n^{th} year (\$)
CS_h	In-woods chipping cost associated with handling system h (\$ t ⁻¹)
CP_h	Chipping cost at a plant associated with system h (\$ t ⁻¹)
$CAPACITY$	Plant capacity in terms of woody biomass required (dry weight) (t day ⁻¹), $CAPACITY=1,814$ (base case).
$CAPACITY_0$	Production capacity of a known woody biomass-based plant (dry weight) (t day ⁻¹), $CAPACITY_0=2,000$.
D_{ij}	One-way over-the-road distance between supply location i to plant j (km)
EXT_m	Limitation of logging residue extracted in month m as a percentage of the whole year (%)
FC_s	The slope of the s^{th} line segment in the range (a_{s-1}, a_s)
HC_h	Logging residue extraction cost for handling system h (\$ t ⁻¹)
LC_h	Loading cost of woody biomass associated with system h (\$ t ⁻¹)
MC	Purchase price of mill residue (\$ t ⁻¹)
MT	Mill residue transportation cost rate (\$ t ⁻¹ km ⁻¹)
MIV_i	Volume of mill residue at supply location i (t)
MP_i	Mill residue availability at supply location i (%)
MS	Marshall & Swift index in the initial project year
MS_0	Marshall & Swift index in the historical year
$MNBIN$	Minimum biomass inventory at a plant (t), $MNBIN=12,700$ (base case).
NR_k	Recovery period of facility type k (yr)
NL_i	Number of loggers in supply location i
NM_h	Average number of extraction machines that a logging crew owns

Table 3.A2-Parameters and descriptions (continued).

Parameter	Description
OM_n	Annual operation and maintenance costs (\$), $OM_n = OM$ for all n
P_g	Whole sale price per unit of product g (\$ l ⁻¹ for ethanol and \$ kWh ⁻¹ for electricity)
PD_h	Productivity of extraction machine associated with system h (t h ⁻¹)
PVI_n	Present value of \$1 at the n^{th} year
r_e	Cost of equity (%)
r_d	Cost of debt (%)
RS_i	One half of the furthest straight-line distance (e.g., distance from the east to north) of supply county i (km)
SC	Logging residue storage cost at landings (\$ t ⁻¹)
SP	Stumpage price of logging residue (\$ t ⁻¹)
t	Federal tax rate applied to the ethanol facility (%)
TC_{ijh}	Round trip transportation cost from location i to plant j for system h (\$ t ⁻¹)
T_h	Off-highway transportation cost rate for system h (\$ t ⁻¹ km ⁻¹)
TPC_j	Plant investment cost at location j (\$)
TPC_0	Investment cost of a known woody biomass-based ethanol plant (\$)
w_e	Equity proportion of the project (%)
$WACC$	Weighted average cost of capital (%)
σ	Moisture content of woody biomass (%)
η_g	Conversion factor for product g from one dry metric ton of woody biomass
λ	Monthly productive time per machine (h)
δ	Dry matter loss due to woody biomass transportation (%)
θ_i	Usable proportion of woody biomass in the fields at location i (%)
ϕ	Usable proportion of woody biomass at a plant (%)

Table 3.A3. Variables and descriptions.

Variable	Description
β_j	A binary variable associated with plant j , $\beta_j = \{0,1\}$
q_{jgm}	Quantity of product g produced in month m at plant location j
F_n	Annual feedstock cost (\$), $F_n = F$ for all n
LCT	Under-estimated transportation cost (\$)
R_n	Annual revenue from the sale of products (\$), $R_n = R$ for all n
T_n	Income taxes at the n^{th} year (\$)
NPV	Net present value of the plant (\$)
Ω	Total investment cost at all feasible sites (\$)
xh_{ihm}	Quantity of logging residue extracted in month m at supply location i using system h (t)
xm_{ijm}	Quantity of mill residue delivered from supply location i to plant j in month m (t)
xpp_{jm}	Quantity of woody biomass processed at plant j in month m (t)
xps_{ihm}	Quantity of logging residue entered into storage at supply location i in month m associated with system h (t)
xs_{ihm}	Quantity of logging residue stored at location i in month m associated with system h (t)
xsn_{ihm}	Quantity of logging residue removed from storage at location i in month m associated with system h (t)
xss_{jm}	Quantity of woody biomass stored at plant j in month m (t)
xt_{ijhm}	Quantity of logging residue delivered from supply location i to plant j in month m associated with system h (t)
xtl_{ijhs}	The increment of logging residue annually shipped out of supply location i in the range (a_{s-1}, a_s) (t)

CHAPTER 4: ECONOMIC ASSESSMENT OF COAL AND BIOMASS TO LIQUID FUELS IN CENTRAL APPLACHIA, USA^{*}

^{*} To be submitted to Biomass and Bioenergy.

Abstract

Liquid fuels from coal and biomass have the potential to reduce petroleum fuel use and CO₂ emission in the U.S. transportation sector. A multi-equation model was developed to assess the economics of a coal/biomass-to-liquids (CBTL) fuel plant in the central Appalachian region. Specifically, the objective was to minimize the total annual cost subject to a series of regional supply, demand, and other constraints. The model was developed and solved using General Algebraic Modeling System/Cplex solver. Model inputs include coal and biomass availability, biomass handling system type, plant investment, production capacity, transportation logistics, and project financing; while outputs include the optimal logistical decision-making together with feedstock requirement, collection, delivery, and liquid fuel production. The results indicated that the required selling price (RSP) of Fischer-Tropsch (FT) diesel for a 40,000 barrel-per-day CBTL plant with coal/biomass ratio of 85/15 varied between \$79.30 bbl⁻¹ and \$79.57 bbl⁻¹ using the different biomass handling systems. The RSP of FT diesel heavily depended upon plant capacity, capital cost, coal price, and liquid fuel yield. The crude-oil-equivalent price of FT fuels must be above \$62 bbl⁻¹ for a CBTL plant to be profitable in central Appalachia for the long run. These results can help investors/decision-makers evaluate future CBTL developments in the region.

4.1 Introduction

Concerns about tightening global supplies of oil, energy security, and climate change have caused a renewed interest in alternative sources of energy. The production of liquid fuels from coal provides an option of reducing the petroleum fuel use in the U.S. transportation sector and enhancing national and economic security by decreasing the nation's reliance on foreign oil (National Academy of Sciences 2009, Paul 2009). The technologies of coal-to-liquids (CTL) are

well established and have existed for more than 80 years (Bibber et al. 2007). Two basic approaches can be used to produce liquid fuels from coal: direct coal liquefaction (DCL) and indirect coal liquefaction (ICL). Today, the world's major CTL production is located in South Africa, based on locally available low cost coal. Coal liquefaction is also given high priority in China. The largest coal producer, Shenhua Group, has launched a DCL plant with a capacity of 24,000 barrels per day. The obvious drawback of CTL technologies is the high carbon footprint of the process (Gray et al. 2007, Bartis et al. 2008). The life-cycle greenhouse-gas (GHG) emissions are about twice those of petroleum-based fuels (Bartis et al. 2008). The ability to capture and store carbon dioxide released is very important to producing liquid fuels from coal. If carbon capture and storage technologies were employed, a reduction of 5-12% lifecycle GHG emissions could be achieved compared to the average emissions profile of petroleum-derived diesel (Tarka et al. 2009).

Biomass is the only carbon-bearing renewable energy resource, which makes it especially valuable for making carbon-bearing liquid transportation fuels. The introduction of biomass in a CTL process could further reduce GHG emissions (National Academy of Sciences 2009, Paul 2009, Gray et al. 2007, Tarka et al. 2009). The carbon contained in the biomass is not counted as a carbon input penalty because the biomass has removed this carbon from the atmosphere by photosynthesis (Gray et al. 2007). A recent study from the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL) reported that a mixture of 8% biomass and 92% coal (by weight) can produce fuels which have 20% lower life cycle GHG emissions than petroleum-derived diesel fuel (Tarka et al. 2009).

Located in the central Appalachian region, the state of West Virginia (WV) is advancing CTL projects as an alternative to imported petroleum. As the nation's second largest coal-

producing state, WV produced approximately 140 million metric tons of coal in 2007, about 13% of the U.S. total (West Virginia Coal Association 2007). It is also the third most heavily forested state and the harvesting process annually yields approximately 2.19 million dry metric tons of woody biomass which can be utilized as feedstock for liquid fuels (Wang et al. 2006). Other potential biomass feedstocks include agricultural residue and switchgrass. The abundant coal and biomass resources in WV provide a great opportunity for the production of liquid fuels using coal/biomass-to-liquid (CBTL) technologies. To date, there are no commercial CBTL facilities in WV. Industries that are interested in CBTL have very limited information about the availability of biomass and the impacts of factors such as biomass availability and feedstock cost on the production cost of liquid fuels. Work must be done to design a biomass harvesting and collection routine that enables such significant volume of biomass efficiently and economically to reach the CBTL plant gate on a daily basis.

The objective of this study was to develop a multi-equation economic model which incorporates several alternative biomass handling systems to assess the annual production cost of liquid fuels from coal and biomass in central Appalachia. Comparisons were made in terms of the required selling price (RSP) of liquid fuels among the systems in order to select the most suitable biomass handling system for the study region. The optimal logistical decision-makings linked to feedstock requirement, collection, delivery, and production were derived from the model results, which offered an opportunity to control the feedstock flow for the CBTL plant. Sensitivity analyses were carried out to examine the uncertainties of feedstock availability and cost, plant capacity, capital cost, and liquid fuel yield on the RSP. Some other issues relevant to the economics of the CBTL facility such as crude oil prices, government policies, etc. were also discussed.

4.2 Methodology

4.2.1 Description of the study area and feedstock availability

The study area was the central Appalachian region of the U.S. A 40,000 barrel-per-day (BPD) CBTL plant was assumed to be located at Boone County, WV, where abundant coal resources have been found. The coal required for the plant was sourced from WV. Woody biomass was obtained from WV and the adjacent states including Kentucky (KY), Ohio (OH), Virginia (VA), Maryland (MD), and Pennsylvania (PA). Woody biomass inventory in central Appalachia was approximately 16.23 million dry metric tons (2005-2006 data) (USDA Forest Service 2009) (Table 4.1). The geographic distribution of coal and woody biomass in WV by county was illustrated in Figure 4.1. Cities near the center of the coal/biomass supply counties were used to represent the average locations of the counties. Subject to operational accessibility, harvesting techniques, and economic and environmental constraints, the recovery rate of logging residue was assumed to be 65%. Only 40% of mill residue was assumed to be available for liquid fuels production due to the fact that mill residue at primary and secondary wood processing mills has been utilized as feedstock for agricultural/horticultural products, fiber and composites products, industrial fuel, and others. Therefore, the total woody biomass available could be up to 8.79 million metric tons per year.

Table 4.1. Woody biomass in the central Appalachian region^a.

States	Logging residue inventory (t yr ⁻¹)	Mill residue inventory (t yr ⁻¹)	Total woody biomass (t yr ⁻¹)
West Virginia	1,143,979	997,862	2,141,841
Kentucky	1,877,458	1,409,522	3,286,980
Maryland	365,576	202,279	567,855
Ohio	769,603	320,802	1,090,405
Pennsylvania	2,320,933	1,480,124	3,801,057
Virginia	2,711,508	2,634,514	5,346,022
Total	9,189,057	7,045,103	16,234,160

^a Data source: USDA Forest Service 2009. Moisture content: 43%.

Figure 4.1. The scope of the study area. The bars symbolize the annual coal and woody biomass production in West Virginia.

Switchgrass is another potential biomass feedstock for the CBTL plant. However, there is no switchgrass produced in WV or other states. The potential production was predicted by replacing some existing hay lands and reclaimed/un-reclaimed mines in WV with switchgrass. It was assumed that 10% of hay lands in WV, approximately 24,282 ha, could be used to produce switchgrass (USDA National Agricultural and Statistics Service 2008), which can result in 339,943 metric tons (Figure 4.2a). Ten percent of reclaimed and un-reclaimed coal mines in WV were assumed to be able to produce switchgrass with a potential yield of 6.74 t ha^{-1} (Figure 4.2b). Therefore, the total switchgrass production on hay lands and reclaimed mine areas in WV could be up to 0.48 million metric tons.

Figure 4.2. Predicted annual switchgrass production on (a) hay lands and (b) reclaimed mine fields in West Virginia assuming 10% of lands used.

4.2.2 Economic model description

The structure of the model was shown in Appendix 4.A. All the parameters and variables in the model are described in Appendix 4.B. The General Algebraic Modeling System (GAMS)

programming language was used and the model was solved using Cplex solver (Brooke et al. 1998).

A mixed-integer programming model has been developed by Wu et al. (2008) to estimate the delivered cost of woody biomass from forest to a plant. In this study, this model was expanded to incorporate annual plant investment, operating and maintenance costs, and coal and biomass (woody biomass and switchgrass) delivered cost. Four alternative biomass handling systems which include a series of process activities (i.e., extraction, storage, loading and hauling, and chipping/grinding) from forest to the CBTL plant were considered. Based on the extraction equipment used and the forms of biomass delivered, these systems were abbreviated as cable skidder-loose residue system (S1), cable skidder-chips system (S2), grapple skidder-loose residue system (S3), and grapple skidder-chips system (S4).

Hourly machine cost for each woody biomass handling activity was calculated using the machine rate method (Miyata 1980). The corresponding productivity was estimated based on the existing models developed for the study region (Li et al. 2006, Wang 2007). Therefore, the unit costs for extraction, loading, and chipping/grinding can be derived by dividing machine cost by the corresponding productivity. The costs associated with switchgrass handling activities include establishment, growth, harvest, storage, and transportation. The costs associated with coal include mining cost and transportation cost. Transportation cost was computed based on the delivery distance and the quantity delivered. Logging residue storage cost in the field was assumed to be zero. The storage cost of switchgrass was \$2.00 per metric ton (wet basis).

The new model has some special features that make it different from previous studies. First, various biomass handling systems were considered in the model, which allowed comparisons of the RSP and assisted to choose the most suitable biomass handling system for the

study region. Factors affecting the quantity of biomass delivered to the plant such as productivity, local infrastructure capability, and seasonal harvesting rate were also considered in the model. Second, most studies assumed the prices paid for “as-received” feedstocks as constant, while in this model the feedstock cost varied depending on the availability of feedstock and the delivery distance from the supply sources to the plant. Meanwhile, the modeling results linked to feedstock requirement, collection, delivery, and production offers an opportunity to monitor the feedstock flow for the CBTL plant. Third, the annual investment cost was computed in consideration of commodity inflation, construction period, production period, and interest rate (using weighted average cost of capital in this paper). The financing structure (i.e., equity/debt), which is directly related to the weighted average cost of capital for the CBTL plant, was allowed to change to get in-depth insight on the RSP of FT diesel.

4.2.3 Model assumptions

Plant assumptions

The assumptions associated with the CBTL plant were summarized in Table 4.2. All the liquid fuels were converted to FT diesel-equivalent fuels assuming that the other product, naphtha, could be sold at 75% of diesel price on a per barrel basis (Gray et al. 2007). The four biomass handling systems (S1-S4) were employed in the model separately. The mix ratio of coal and biomass was assumed to be 85/15 (by weight) for all biomass handling systems. Given the financing assumptions, the weighted average cost of capital was 8.93% per year and the levelized amortization factor was 16.55%.

Table 4.2. Summary of plant-related assumptions.

Parameters	Assumptions in the base case
Plant location	Boone County, WV
Plant capacity (barrel day ⁻¹)	40,000
Total investment cost (US\$ billion)	2.87 ^a
Operation and maintenance cost (US\$ million yr ⁻¹)	204 ^a
Conversion method	Indirect liquefaction
Primary liquid fuel products	Diesel, naphtha, power
Proportion of liquid fuels produced as a percentage of the total liquid fuels	Diesel: 68.18% ^a Naphtha: 31.82% ^a
Liquid fuels yield (barrel t ⁻¹)	Coal: 2.475 ^b Biomass: 1.452 ^c
Coal/biomass ratio (by weight)	85/15
Construction period (yr)	3
Plant life (yr)	30
Plant maintenance factor	1.04
Commodity inflation rate (%)	2
Equity proportion (%)	40
Cost of Equity (%)	15
Cost of debt (%)	8
Federal tax (%)	39
Minimum inventory at the plant (days)	7
Maximum inventory at the plant (days)	45
Operating time (days yr ⁻¹)	350

^a Adapted and updated from Gray et al. 2007. The costs of biomass and coal are not included in the operating and maintenance cost. All the costs are in 2007 US\$;

^b Adapted from Bellman 2007;

^c Adapted from Williams 2007.

Feedstock requirement

Total feedstock (coal and biomass) required for a CBTL facility is dependent on the plant scale and the mix ratio of coal and biomass. The 40,000 BPD CBTL plant will require approximately 0.9 million dry metric tons of biomass and 5.1 million metric tons of coal per year. Figure 4.3 illustrated the annual feedstock needed corresponding to different plant scales

and coal/biomass ratios. Considering the availability of the feedstock in the study region, it was sufficient to support the CBTL facility even if the plant capacity expanded to 80,000 barrels per day.

Figure 4.3. Annual feedstock requirement curve for each coal/biomass ratio.

Feedstock characterization and handling costs

The characterization of biomass in the study region was presented in Table 4.3. The assumptions of hourly machine cost, machine productivity, and unit production cost during biomass handling process were presented in Table 4.4. A stumpage cost $\$1 \text{ t}^{-1}$ (wet basis) was assumed for logging residue. The availability of logging residue by month was assumed to be (1-12, 8.3%, 8.3%, 8.3%, 8.3%, 7.5%, 7.5%, 7.5%, 7.5%, 9.2%, 9.2%, 9.2%, 9.2%) in consideration of the historical harvesting activities that occurred and the impact of monthly precipitation on the accessibility to forest lands in the region (USDS 2009). The potential yield of switchgrass by harvest month was assumed to be (1-12, 0, 0, 0, 0, 0, 0, 100%, 100%, 100%, 95%, 90%, 85%) (Mapemba 2005). Transportation cost rate was assumed to be $\$0.18 \text{ t}^{-1} \text{ km}^{-1}$ for loose logging residue, $\$0.12 \text{ t}^{-1} \text{ km}^{-1}$ for wood chips, and $\$0.14 \text{ t}^{-1} \text{ km}^{-1}$ for switchgrass bales, respectively.

Table 4.3. Biomass characterization.

	Logging residue	Mill residue	Switchgrass
Stumpage/purchase price (\$ t ⁻¹) ^a	1.00	22.00	50
Moisture content (%)	43	43	15
Availability (%)	65	40	10 ^b
Usable proportion in the field (%) ^c	95	95	95
Usable proportion at the plant (%) ^c	99	99	99
Onsite storage cost (\$ t ⁻¹)	0	0	2.00 ^c

^a Given as wet weight;^b Percentage of hay lands and reclaimed coal mines available for switchgrass production.^c Adapted from Mapemba 2005, given as wet weight.

Table 4.4. Summary of cost assumptions by woody biomass handling machines.

	Hourly cost (\$ h ⁻¹)	Productivity (t h ⁻¹) ^a	Cost (\$ t ⁻¹) ^a
Cable skidder	81.34	6.34	12.83
Grapple skidder	102.72	11.46	8.96
Loader	85.96	16.04	5.36
Chipper	185.62	30 ^b	6.19
Grinder	212.27	91 ^b	2.33

^a Given as wet weight^b Adapted from Kärhä and Vartiamäki 2006.

The coal-fired power plants were assumed to be the primary coal consumers due primarily to the fact that approximately 99% of electricity in WV is generated by coal produced in the state. The value for steam coal from U.S. Department of Energy's Annual Energy Outlook 2009 (USDOE 2009) was used to estimate the mine-mouth coal price (not including transportation cost). Adjusted for the base year of 2007, the value applied was \$1.84 MMBTU⁻¹

or $\$50.60 \text{ t}^{-1}$ for central Appalachian coal. The transportation rate of coal was assumed to be $\$0.10 \text{ t}^{-1}\text{km}^{-1}$. Thus, hauling one metric ton of coal 50 km (one way) would cost \$10.00.

4.3 Results

4.3.1 Required selling price of FT diesel

With the assumptions above the highest RSP of FT diesel ($\$79.57 \text{ bbl}^{-1}$, $\$13.82 \text{ GJ}^{-1}$) occurred with the cable skidder-chips system (S2), followed by the cable skidder-loose residue system ($\$79.55 \text{ bbl}^{-1}$, $\$13.81 \text{ GJ}^{-1}$) (S1), the grapple skidder-loose residue system ($\$79.33 \text{ bbl}^{-1}$, $\$13.77 \text{ GJ}^{-1}$) (S3), and the grapple skidder-chips system ($\$79.30 \text{ bbl}^{-1}$, $\$13.77 \text{ GJ}^{-1}$) (S4). Since a lower RSP may lead to a higher profit, the grapple skidder-chips system would be the most suitable handling system for the CBTL plant. Table 4.5 presented the optimal biomass mix for the four biomass handling systems. Logging residue was the primary biomass feedstock delivered to the plant, followed by mill residue. The least quantity of switchgrass was delivered to the CBTL plant using the grapple skidder-chips system (S4). The following analysis will focus on the grapple skidder-chips system (S4).

Table 4.5. Biomass delivered to the CBTL plant by system (40,000 bbl/day).

Systems	Logging residue ^a	Mill residue ^a	Switchgrass ^a	Total biomass ^b
S1	575,006	558,874	321,403	919,504
S2	660,194	493,150	308,350	919,504
S3	829,034	493,150	195,128	919,504
S4	1,047,257	319,085	165,517	919,504

^a Given as t yr⁻¹ (wet weight).

^b Given as t yr⁻¹ (dry weight).

The RSP of FT diesel on a barrel basis can be partitioned into capital cost, operating and maintenance (OM) cost, coal cost, and biomass cost (Figure 4.4). Comparisons in terms of RSP were made among five mixture ratios of coal/biomass including 100/0 (coal only), 85/15 (base case), 80/20, 75/25, and 70/30 using the most efficient system S4. The RSP increased gradually as more biomass was mixed with coal. The difference of RSP between the scenarios of coal only and coal/biomass ratio of 70/30 was as much as \$7.97 bbl⁻¹, increasing by almost 10.50%. Since the use of biomass can reduce the life cycle greenhouse gas emissions (GHG), this increase can be treated as credit for greenhouse gas emissions offset. The cost of coal in a barrel of FT diesel-equivalent liquid fuel decreased from 32% to 23% as the proportion of coal decreased from 100% to 70%. Meanwhile, the cost of biomass increased from 0% to 12%. Capital cost and operation and maintenance cost increased slightly as the percentage of biomass increase in that additional equipment will be needed for biomass handling at the CBTL plant.

Figure 4.4. Cost components of one barrel of FT diesel-equivalent liquid fuel by coal/biomass ratio.

4.3.2 Logistics optimization

Figure 4.5 illustrated the optimal quantity of fuel delivered to the CBTL plant by month and by state using the grapple skidder-chips system. Approximately 66% of the logging residue delivered was from WV, followed by Kentucky (20%), Virginia (9%), and Ohio (5%). The quantities of logging residue obtained from WV during May to August were lower than those in the other months, because the accessibility of logging residue was limited due to the higher average monthly precipitation during this period. For mill residue, 55% were from WV, 20% from Ohio, 18% from Kentucky, and the rest were from Virginia. The delivery of mill residue was concentrated from January to June. The annual demand of approximately 5.10 million metric tons of coal could be met via Boone County, WV. The peak value of the quantity of coal delivered presented in January due to the requirement of inventory at the plant. Switchgrass was delivered to the plant from July to December because of the seasonal difference of growing yield.

Figure 4.5. Feedstock delivered to the CBTL plant by month and by state.

4.3.3 Sensitivity analyses

Biomass availability and cost

Woody biomass was the primary biomass feedstock for the CBTL plant, accounting for approximately 70-85% of the total biomass (dry weight) delivered among the different coal/biomass ratios using the grapple skidder-chips system. Therefore, the variation of woody biomass availability is likely to have considerable impact on the RSP. Figure 4.6a displayed that the RSP of FT diesel decreased as the availability of woody biomass increased. If the availability of woody biomass decreased to 10%, the RSP would increase 1.11-3.78% compared to the base case depending upon the percentage of biomass co-fed with coal. Increases in harvest efficiency

are important to the future economic viability of forest residues, however, the implications must be weighted against potential impacts on site productivity, especially for low-productivity sites (Grushecky et al. 2007, Scott and Dean 2006). The availability of hay lands and reclaimed coal mines that could be switched to switchgrass production had minor impact on the average RSP (Figure 4.6b) due to the high production cost and the scattered distribution of the lands used for switchgrass production.

As more mill residue is utilized, the intense competition on this feedstock will force the purchase price to increase. Figure 4.6c illustrated that the RSP of FT diesel increased as the purchase price of mill residue at mill gates increased. If the purchase price decreased 55% to \$10 t^{-1} , the RSP would decrease 0.94-1.36% compared to the base case. A 36% increase of mill residue purchase price (from \$22 t^{-1} to \$30 t^{-1}) would cause the RSP to increase 0.18-0.46%. Similar to the effects of increasing mill residue purchase price, increasing the production cost of switchgrass would increase the RSP especially with lower coal/biomass ratios (Figure 4.6d). If the production cost increased 30%, the RSP would increase 0.03-0.35% compared to the base case among the different coal/biomass ratios. By contrast, a 30% decrease of switchgrass production cost would cause a decrease of 0.49-1.11% in RSP.

Figure 4.6. Effects of feedstock availability and costs on the RSP.

Plant capacity

The plant capacity was found to have significant impact on the RSP of FT diesel among the four mix levels of coal and biomass (Figure 4.7a). The RSP for a large-scale CBTL plant was smaller due to the economy of scale. As the plant capacity increased, the average production cost of FT diesel associated with the plant investment decreased. Meanwhile, the economy of scale was partially offset by increased transport costs associated with hauling feedstock (coal and biomass) or more expensive nearby feedstock such as switchgrass. As shown earlier, the RSP was higher when the mix ratio of coal and biomass was lower. If the plant capacity was decreased from 40,000 barrels to 10,000 barrels per day, the RSP would be around \$101.05-

104.86 bbl⁻¹, increasing by 25–27% among the different coal/biomass ratios. If the capacity approached 80,000 barrels per day, the RSP would decrease 8.3-9.7% compared to the base case.

Figure 4.7. Effects of plant-related assumptions on the RSP.

Capital cost

Limited data is available for the actual capital cost of a CBTL plant in the U.S., since no commercial CBTL plants have been built in the nation. In the base case, the capital cost was adapted from a NETL report (Gray et al. 2007). A typical scale factor 0.7 and Marshall & Swift equipment cost index was applied to adjust the capital cost to the 40,000 BPD production level at the initial project year. The total plant cost was estimated as \$₂₀₀₇2.87 billion. The high estimates are due to the significant risks related to building a first-of-a-kind plant, including uncertainties

about technical performance, capital and production costs, and environmental performance (Paul 2009). As multiple plants are built, this cost is likely to decrease through design advancements and process improvements. Figure 4.7b illustrated the impact of the variation of capital cost on the RSP. It is important to note that a change in capital cost by 5% would change the RSP by 2.24-2.34%, and a 10% change would result in a change of 4.48-4.68% in RSP.

Mine-mouth price of coal

The average mine-mouth price of Appalachian coal is generally higher than that in the Western and Interior regions in the U.S. The average spot prices of central Appalachian coal commodity have presented wide variation within the past two years with the peak value of \$154 t^{-1} during mid-2008 and the lowest value of \$45 t^{-1} in early 2007 (USDOE 2009). Since the delivered cost of coal accounted for approximately 23-32% of the RSP for one barrel FT liquid fuel, the variation of mine-mouth price of central Appalachia coal is likely to have considerable impact on the RSP. Figure 4.7c showed that the RSP increased linearly with the mine-mouth price of coal holding the other system assumptions constant. For every \$10 t^{-1} increase in coal price, the RSP would increase \$4.14 bbl^{-1} for the coal/biomass ratio of 85/15, \$3.98 bbl^{-1} for the ratio of 80/20, \$3.82 bbl^{-1} for the ratio of 75/25, and \$3.65 bbl^{-1} for the ratio of 70/30. If the mine-mouth price of coal increased to 80 \$ t^{-1} , the RSP would increase 13-15% among the different coal/biomass ratios compared to the base case.

Liquid fuel yield

The liquid fuel yield is also an important factor affecting the economics of CBTL plants. In the study, 2.475 barrels of liquid fuels from one metric ton of coal and 1.452 barrels of liquid

fuels from one dry metric ton of biomass were assumed as the base case. The changes of the RSP were approximately proportional to the change of FT liquid fuel yield holding other parameters in the model constant (Figure 4.7d). If the liquid fuel yield increased by 5%, the RSP would decrease 4.70% for all the mix levels of coal and biomass. An increase in liquid fuel yield by 10% changed the RSP by 9.24%.

4.3.4 Diesel replacement and greenhouse gas emissions

The annual production capacity of the CBTL plant is 14 million barrels per year, which includes about 9.55 million barrels of FT diesel and 4.45 million barrels of Naphtha. Since the energy content of FT diesel is about 93% of diesel fuel, 8.93 million barrels of diesel fuel consumption could be replaced with FT diesel in the central Appalachian region.

The greenhouse gas emissions (GHG) from CBTL can be significantly lower than that of petroleum-derived diesel fuel (Tarka et al. 2009). The “Well-to-Wheels” (WTW) life cycle GHG emissions from petroleum-derived diesel are 95 kg CO₂ equivalent/MMBtu (Tarka et al. 2009). If 15% biomass (by weight) was mixed with coal, the GHG emissions could be 63.4 kg CO₂ equivalent/MMBtu, decreasing by 33% compared to petroleum-derived diesel. For the base plant (40,000 BPD), approximate 3.31 million metric tons of CO₂ equivalent GHG would be emitted per year. If the same amount of energy were produced from petroleum-derived diesel fuel, the GHG emissions would be 4.95 metric tons per year.

4.4 Conclusions and discussion

This study developed an economic model to estimate the total annual cost and RSP of liquid fuels from coal and biomass subject to regional supply, demand, and other constraints. The

central Appalachian region in the U.S. was used as a case study. Results showed that the RSP of FT liquid fuels for a 40,000 BPD plant in the study region varied between \$79.30 bbl⁻¹ (\$13.77 GJ⁻¹) and \$79.57 bbl⁻¹ (\$13.82 GJ⁻¹) among four biomass handling systems with coal/biomass ratio of 85/15, or between \$79.30 bbl⁻¹ (\$13.77 GJ⁻¹) and \$83.87 bbl⁻¹ (\$14.56 GJ⁻¹) among the different coal/biomass ratios using the most efficient handling system (S4), which was significantly lower than the energy cost of cellulosic ethanol (\$24.27-25.03 GJ⁻¹) (Wu et al. 2009). All the coal required for the plant was from Boone County, WV. Woody biomass was the major biomass feedstock for the plant, accounting for approximately 70-85% of the total biomass delivered among the different coal/biomass ratios. A limited amount of switchgrass was in demand especially when the coal/biomass ratio is higher.

The RSP of FT liquid fuels were shown to heavily depend upon plant capacity, capital cost, mine-mouth coal price, and liquid fuel yield. A large-scale plant required a lower RSP to recover the production cost by taking advantage of economies of scale. However, potential technical and financial risks are also higher along with a larger plant. An increase in plant scale will cause the demand of feedstock, especially coal, to increase accordingly. The competition for coal used for power generation and coal exports could potentially drive up the price of coal for the CBTL plant to the point of it not being economically viable. Reliable operation is also important to assure that the cost of project development and construction can be recovered (Bibber et al. 2007). Biomass availability and costs have showed moderate impacts on the RSP. Meanwhile, the security of biomass supply chain was an important factor to be considered. The CBTL system could include many key market players such as forest industries, mine industries, and farms or landowners. A cooperative program is necessary among these players to assure the raw materials supply for the CBTL commercial development.

Other external factors that could affect the economics of the CBTL plant in the central Appalachian region include crude oil prices, project financing, and government policies. During the past four years, crude oil prices have changed between \$30.28 and \$145.31 per barrel in the U.S. (Figure 4.8). It is generally agreed that CTL/CBTL plants can be profitable at very low gas prices and relatively sustained high oil prices. If a factor of 1.3 was used to convert the RSP to crude oil equivalent (COE) price based on an average price ratio of low sulfur No.2 diesel to West Texas intermediate crude oil (Gray et al. 2007), the COE of FT fuels would vary between \$61.00 and \$61.21 per barrel among the four biomass handling systems. Notice that the cost for carbon dioxide transportation, sequestering, and monitoring (TS&M) was not included. Gray et al. (2007) assumed that a cost of \$4.60 t⁻¹ can be added for CO₂ TS&M, which increased the RSP of the FT fuels by about 1.8%. Therefore, the COE price of FT fuels must be above \$62 bbl⁻¹ for the CBTL plant (coal/biomass=85/15) with CCS to make long-term economic sense.

Figure 4.8. Crude oil price projections (USDOE 2009) and COE of FT diesel products.

Project financing is the biggest challenge to the CBTL plant. Even though the clean coal technology is proven, the high construction cost associated with building a commercial plant is still a major hurdle. Some technical risks that would be considered by process developers and

industry partners could be reduced substantially as soon as several first-mover plants become operational. However, current low prices in the crude oil market, continued uncertainty on regulatory rules, and the financial crisis are making the financing of CBTL plants difficult. In this study, the project was financed with 40% equity and 60% debt. A 10% increase in owner's equity may increase the RSP by about 2.30% holding other financing assumptions constant.

Government support in terms of tax incentives, guarantee loans, and grants are important to maintain commercial viability for the CBTL plant. Due to the potential risk and high construction cost, current FT projects often involve a complex mix of industry partners and government subsidies. The relevant federal subsidy for liquid fuels from coal is the \$21 bbl⁻¹ (50 cents gallon⁻¹) incentive included in the 2005 Federal Transportation Bill, which will end in 2009 (Bibber 2007). Loan guarantees and price floors can ensure that liquid fuels from CBTL process can compete with conventional petroleum-derived fuels even in the event that oil prices drop in the future.

Future research will be needed to enhance the insight in the environmental impacts of the CBTL plant and the sustainability of biomass supply in the central Appalachian region. The life cycle assessment of GHG emissions, potential risk to water quality, and land use competitions will be conducted.

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Appendix 4.A. Economic analysis model specification

The model is designed to produce the required amount of liquid fuels from coal and biomass using the indirect coal liquefaction technology at a minimum cost subject to a series of regional supply, demand, and logistical constraints.

Objective:

$$\text{Min } OBJ = F + OM + \zeta \times TPC \quad (\text{A.1})$$

Where,

$$\zeta = \psi \times \left[\frac{q^{N+p} - 1}{(q-1) \times q^{N+p}} - \frac{q^p - 1}{(q-1) \times q^p} \right]^{-1} \quad (\text{A.2})$$

$$q = (1 + WACC) \times (1 + r) \quad (\text{A.3})$$

$$WACC = w_e \times R_e + (1 - w_e) \times R_d \times (1 - ft) \quad (\text{A.4})$$

Subject to:

Eq. (A.5) describes the annual feedstock cost F , which is composed of the costs associated with all the handling activities of woody biomass, switchgrass, and coal from supply locations to the plant location.

$$\begin{aligned} F = & \sum_{i=1}^I \sum_{h=1}^H \sum_{m=1}^{12} [(HC_h + SP) \times xh_{ihm} + SC \times xps_{ihm}] + \sum_{i=1}^I \sum_{j=1}^J \sum_{h=1}^H \sum_{m=1}^{12} (TC_{ijh} + LC_h + CS_h + CP_h) \times xt_{ijhm} \\ & + \sum_{i=1}^I \sum_{j=1}^J \sum_{m=1}^{12} (MC + MT \times D_{ij}) \times xm_{ijm} + \sum_{w=1}^W \sum_{m=1}^{12} (SWC \times xsw_{wm} + SWS \times xpw_{wm}) \\ & + \sum_{w=1}^W \sum_{j=1}^J \sum_{m=1}^{12} (SWT_{wj} + SCP) \times xtw_{wjm} + \sum_{w=1}^W \sum_{j=1}^J \sum_{m=1}^{12} (CT + PC) \times xco_{wjm} + LCT_1 + LCT_2 \end{aligned} \quad (\text{A.5})$$

Eq. (A.6) is used to compute the under-estimated transportation cost for woody biomass and switchgrass when the supply and demand locations are in the same county or adjacent counties (Wu et al. 2008).

$$\begin{cases}
LCT_1 = \sum_{i=1}^I \sum_{j=1}^J \sum_{h=1}^H \sum_{s=1}^S T_h \times FC_s \times xtl_{ijhs}, \text{ where } D_{ij} \leq RS_i, 0 \leq xtl_{ijhs} \leq a_s - a_{s-1} \\
LCT_2 = \sum_{w=1}^W \sum_{j=1}^J \sum_{s=1}^S TSW \times FC'_s \times xtwl_{wjs}, \text{ where } D_{wj} \leq RS_w, 0 \leq xtwl_{wjs} \leq b_s - b_{s-1} \\
\sum_{s=1}^S xtl_{ijhs} = \sum_{m=1}^{12} xtl_{ijhm}, \forall i, j, h. \\
\sum_{s=1}^S xtwl_{wjs} = \sum_{m=1}^{12} xtwl_{wjm}, \forall w, j.
\end{cases} \quad (A.6)$$

Eq. (A.7) describes the number of CBTL plants being built in the study region.

$$\sum_{j=1}^J \beta_j = 1 \quad (A.7)$$

Eq. (A.8) defines the number of biomass handling systems used in the study region. The model will evaluate each handling system separately, depending on the value Eq. (A.8) is set to. As stated by Eq. (A.8), the cable skidder-loose residue system will be applied in all the biomass supply locations.

$$\begin{cases}
\sum_{h=1}^H ALFA_{ih} = 1, \forall i, h = 1, \dots, 4. \\
ALFA_{ih} = 1, \quad \forall i, \text{ where } h = 1.
\end{cases} \quad (A.8)$$

Eqs. (A.9) - (A.12) are the constraints for the availability of logging residue and mill residue. The amount of logging residue extracted is subject to the available logging residue left in the study region in Eq. (A.9).

$$\sum_{m=1}^{12} xh_{ihm} - ALFA_{ih} \times BP_i \times BIV_i \leq 0, \forall i, h. \quad (A.9)$$

The availability of logging residue during a certain time period (e.g. a month) is also considered in Eq. (A.10). Seasonal difference of wood harvesting caused by weather condition

and other factors is contributable to the variation of the proportion of logging residue available during a certain time period.

$$\sum_{h=1}^H xh_{ihm} - EXT_m \times BP_i \times BIV_i \leq 0, \forall i, m. \quad (A.10)$$

Eq. (A.11) is the constraint for local loggers' capability of extracting logging residue, which is affected by the number of loggers in the study region, the number of machines owned, and the productivity of extraction machines.

$$xh_{ihm} - \lambda \times PD_h \times NL_i \times NM_h \leq 0, \forall i, h, m. \quad (A.11)$$

Eq. (A.12) requires that the quantity of mill residue shipped out of a supply county is limited by the available mill residue at that location.

$$\sum_{j=1}^J \sum_{m=1}^{12} xm_{ijm} - MP_i \times MIV_i \leq 0, \forall i. \quad (A.12)$$

Eqs. (A.13) – (A.15) are the constraints for the storage balance of logging residue at landings. The logging residue shipped to plant locations together with the amount stored at landings should not exceed the total logging residue extracted and the usable storage for any supply location at any time in Eq. (A.13). The biomass shipped out plus the biomass lost in-field should be balanced with the total biomass extracted in the year in Eq. (A.14). Eq. (A.15) describes the interrelationship among logging residue extracted, entered into storage, removed from storage, and transported to plant locations (Wu et al. 2008).

$$xh_{ihm} + \theta_i \times xs_{ihm-1} - \sum_{j=1}^J xt_{ijhm} - xs_{ihm} \geq 0, \forall i, h, m. \quad (A.13)$$

$$\sum_{m=1}^{12} \sum_{h=1}^H xh_{ihm} - (1 - \theta_i) \times \sum_{m=1}^{12} \sum_{h=1}^H xs_{ihm} - \sum_{j=1}^J \sum_{h=1}^H \sum_{m=1}^{12} xt_{ijhm} = 0, \forall i. \quad (A.14)$$

$$\sum_{h=1}^H xh_{ihm} - \sum_{h=1}^H xps_{ihm} + \sum_{h=1}^H xsn_{ihm} - \sum_{h=1}^H \sum_{j=1}^J xt_{ijhm} = 0, \forall i, m. \quad (A.15)$$

Eq. (A.16) imposes the constraint that the quantity of switchgrass produced is subject to the availability of different land types that can be used to produce switchgrass, the potential yield of switchgrass on these lands, and the seasonal difference of switchgrass yield.

$$xsw_{wm} - \sum_{l=1}^L SMP_m \times SLP_l \times SWP_l \times AS_{wl} \leq 0, \forall w, m. \quad (A.16)$$

Eqs. (A.17) - (A.19) are the constraints for switchgrass storage balance in the field, which are similar to the principles of logging residue storage at landings.

$$xsw_{wm} + \theta'_w \times xw_{wm-1} - \sum_{j=1}^J xtw_{wjm} - xw_{wm} \geq 0, \forall w, m. \quad (A.17)$$

$$\sum_{m=1}^{12} xsw_{wm} - (1 - \theta'_w) \times \sum_{m=1}^{12} xw_{wm} - \sum_{j=1}^J \sum_{m=1}^{12} xtw_{wjm} = 0, \forall w. \quad (A.18)$$

$$xsw_{wm} - xpw_{wm} + xwn_{wm} - \sum_{j=1}^J xtw_{wjm} = 0, \forall w, m. \quad (A.19)$$

Eq. (A.20) restricts that the quantity of coal delivered to plants at any month is limited to the amount of coal after deducting the consumption of primary users (e.g. coal fired power plants) in the study region.

$$\sum_{j=1}^J xco_{wjm} - 1000(QCP_{wm} - QCU_{wm}) \leq 0, \forall w, m. \quad (A.20)$$

Eq. (A.21) describes the total amount of feedstock (coal and biomass) delivered to plant j in month m ($xf d_{cjm}$) in terms of coal and biomass.

$$x\text{fd}_{cjm} = \begin{cases} \left[\sum_{i=1}^I \sum_{h=1}^H (1-\delta) \times x\text{t}_{ijhm} + \sum_{i=1}^I x\text{m}_{ijm} \right] \times (1-\sigma) + \sum_{w=1}^W (1-\kappa) \times x\text{tw}_{wjm}, \forall j, m, \text{ where } c = \text{biomass} \\ \sum_{w=1}^W x\text{co}_{wjm}, \forall j, m, \text{ where } c = \text{coal} \end{cases} \quad (\text{A.21})$$

Eq. (A.22) insures that the total amount of feedstock processed and stored at each plant should be balanced with the sum of all the feedstock delivered to the plant and the undeteriorated portion of the feedstock stored onsite from the previous month (Tembo et al. 2003).

$$x\text{fd}_{cjm} + \mu_c \times x\text{ss}_{cjm-1} - x\text{pp}_{cjm} - x\text{ss}_{cjm} = 0, \forall c, j, m. \quad (\text{A.22})$$

Eq. (A.23) and Eq. (A.24) defines the minimum and maximum inventory at each plant, respectively, to ensure smooth production of the CBTL facility.

$$x\text{ss}_{cjm} - \text{MNBIN}_c \times \beta_j \geq 0, \forall c, j, m. \quad (\text{A.23})$$

$$x\text{ss}_{cjm} - \text{MXBIN}_c \times \beta_j \leq 0, \forall c, j, m. \quad (\text{A.24})$$

Eq. (A.25) insures that the amount of feedstock processed ($x\text{pp}_{cjm}$) in month m at plant location j is no less than the monthly feedstock demand ($\rho \times FN_c$) at that location.

$$x\text{pp}_{cjm} - \rho \times FN_c \geq 0, \forall c, j, m. \quad (\text{A.25})$$

Eq. (A.26) states that the amount of liquid fuel t produced at plant location j in month m (q_{tjm}) is equal to the total amount of liquid fuels produced ($\sum_{c=1}^C \eta_c \times x\text{pp}_{cjm}$) times the corresponding fuel proportion (γ_t).

$$q_{tjm} - \gamma_t \times \sum_{c=1}^C \eta_c \times x\text{pp}_{cjm} = 0, \forall t, j, m. \quad (\text{A.26})$$

Eq. (A.27) contains the non-negativity conditions for the decision variables.

$$xh, xt, xtl, xs, xps, xsn, xm, xsw, xpw, xw, xtw, xtwl, xwn, xco, xss, xpp, xfd, q \geq 0 \quad (\text{A.27})$$

Appendix 4.B. Nomenclatures

Table 4.B1. Data sets and descriptions.

Set	Description
C	Set of feedstock, $c = \{\text{biomass, coal}\}$.
H	Set of woody biomass handling systems, $h = \{\text{cable skidder-loose residue, cable skidder-chips, grapple skidder-loose residue, grapple skidder-chips}\}$.
I	Set of woody biomass supply counties, $i = \{\text{All the counties within West Virginia, Pennsylvania, Ohio, Virginia, Kentucky, and Maryland}\}$.
J	Set of plant locations, $j = \{\text{Boone}\}$.
L	Set of lands, $l = \{\text{hayland, coalrelaimed}\}$.
M	Set of months, $m = \{1, 2, 3, \dots, 12\}$.
S	Set of breakpoints, $s = \{0, 1, \dots, 9\}$.
T	Set of FT liquid fuels, $t = \{\text{diesel, naphtha}\}$.
W	Set of switchgrass and coal supply counties, $w = \{\text{All the counties in WV}\}$.

Table 4.B2. Parameters and descriptions.

Parameter	Description
a_s	A breakpoint over the quantity of annually delivered logging residue from each supply county.
AS_{wl}	Area of land type l at county w (km^2).
BIV_i	Quantity of logging residue left after harvesting at supply location i (t).
BP_i	Proportion of logging residue available for extraction at supply location i (%).
b_s	A breakpoint over the quantity of annually delivered switchgrass from each supply county.
CT	Unit transportation cost of coal ($\$ \text{t}^{-1}$).
CP_h	Grinding cost at a plant associated with system h ($\$ \text{t}^{-1}$).
CS_h	In-wood chipping cost associated with system h ($\$ \text{t}^{-1}$).
D_{ij}	Distance between supply location i and plant j (km).
D_{wj}	Distance between supply location w and plant j (km).
EXT_m	Percentage of logging residue extracted in month m (%).
ft	Federal tax rate applied to the CBTL facility.
FN_c	Quantity of feedstock c needed per day (dry weight) (t day^{-1}).
FC_s	Slope of the s^{th} line segment in the range (a_{s-1}, a_s) .
FC'_s	Slope of the s^{th} line segment in the range (b_{s-1}, b_1) .
HC_h	Extraction cost of logging residue using system h ($\$ \text{t}^{-1}$).
LC_h	Loading cost of logging residue associated with system h ($\$ \text{t}^{-1}$).
MC	Purchase price of mill residue ($\$ \text{t}^{-1}$).
MT	Round trip transportation cost rate of mill residue ($\$ \text{t}^{-1} \text{km}^{-1}$).
MIV_i	Quantity of mill residue produced at supply location i (t).
MP_i	Proportion of mill residue available at supply location i (%).
$MNBIN_c$	Minimum inventory of feedstock c at a plant (dry weight) (t).
$MXBIN_c$	Maximum inventory of feedstock c at a plant (dry weight) (t).
N	Plant life (yr).
NL_i	Number of loggers in supply location i .
NM_h	Average number of extraction machines that a logging crew owns.
OM	Annual operating and maintenance cost ($\$ \text{yr}^{-1}$).
p	Construction period.
PC	Unit mining cost of coal ($\$ \text{t}^{-1}$).
PD_h	Productivity of extraction machine associated with system h (t h^{-1}).
QCP_{wm}	Quantity of coal produced monthly at location w (1,000 t).

Table 4.B2. Parameters and descriptions (continued).

Parameter	Description
QCU_{wm}	Quantity of coal consumed monthly at location w (1,000 t).
r	Rate of inflation ($r=1.13\%$ in this paper).
R_e	Cost of equity.
R_d	Cost of debt.
RS_i	One half of the furthest straight-line distance (e.g., from the east to west) of supply county i (km).
RS_w	One half of the furthest straight-line distance of supply county w (km).
SC	Storage cost of logging residue in the field ($\$ \text{ t}^{-1}$).
SP	Stumpage cost of logging residue ($\$ \text{ t}^{-1}$).
SCP	Grinding cost of switchgrass at a plant ($\$ \text{ t}^{-1}$).
SWC	The cost of switchgrass associated with establishment, growth, and harvest activities ($\$ \text{ t}^{-1}$).
SWS	Unit storage cost of switchgrass in the field ($\$ \text{ t}^{-1}$).
SWT_{wj}	Round trip transportation cost of switchgrass from supply location w to plant j ($\$ \text{ t}^{-1}$).
SMP_m	Proportion of potential yield of switchgrass by harvest month (%).
SLP_l	Proportion of land type l that can be used to produce switchgrass (%).
SWP_l	Potential yield of switchgrass on land type l (t km^{-2}).
TC_{ijh}	Round trip transportation cost from supply location i to plant j for system h ($\$ \text{ t}^{-1}$).
T_h	Off-highway transportation cost rate of woody biomass for system h ($\$ \text{ t}^{-1} \text{ km}^{-1}$).
TSW	Off-highway transportation cost rate of switchgrass ($\$ \text{ t}^{-1} \text{ km}^{-1}$).
TPC	Total investment cost of a coal/biomass-to-liquids plant (\$).
w_e	Percentage of financing that is equity (%).
$WACC$	Weighted average cost of capital.
λ	Monthly productive time per machine (h).
σ	Moisture content of woody biomass (%).
η_c	Potential yield of liquid fuels produced from one tonne of feedstock c (bbl t^{-1}).
γ_t	Liquid fuel product t as a percentage of the total fuels (%).
ρ	Scheduled working days of the plant per month (days).
δ	Rate of matter loss due to transportation (%).
κ	Moisture content of switchgrass (%).
θ_i	Usable proportion of logging residue stored at supply location i (%).
θ'_w	Usable proportion of switchgrass stored at supply location w (%).
μ_c	Usable proportion of feedstock c at the plant (%).
ψ	Plant maintenance factor.
ζ	Amortization factor.

Table 4.B3. Variables and descriptions.

Variable	Description
$ALFA_{ih}$	A binary variable related to biomass handling system h at supply location i , $ALFA_{ih} = \{0, 1\}$.
β_j	A binary variable related to plant j , $\beta_j = \{0, 1\}$.
F	Annual feedstock cost (\$ yr ⁻¹).
LCT_1	Under-estimated transportation cost of logging residue(\$ yr ⁻¹).
LCT_2	Under-estimated transportation cost of switchgrass (\$ yr ⁻¹).
OBJ	Annual production cost of liquid fuels (\$ yr ⁻¹).
q_{tjm}	Quantity of liquid fuel products produced at plant j in month m (bbl).
xfd_{cjm}	Quantity of feedstock c delivered to plant j in month m (dry weight) (t).
xh_{ihm}	Quantity of logging residue extracted at supply location i using system h in month m (t).
xt_{ijhm}	Quantity of logging residue extracted using system h and delivered from supply location i to plant j in month m (t).
xps_{ihm}	Quantity of logging residue extracted using system h and entered into storage at supply location i in month m (t).
xs_{ihm}	Quantity of logging residue extracted using system h and stored at supply location i in month m (t).
xsn_{ihm}	Quantity of logging residue extracted using system h and removed from storage at supply location i in month m (t).
xm_{ijm}	Quantity of mill residue delivered from supply location i to plant j in month m (t).
xsw_{wm}	Quantity of switchgrass harvested in supply location w in month m (t).
xpw_{wm}	Quantity of switchgrass entered into storage at supply location w in month m (t).
xw_{wm}	Quantity of switchgrass stored at supply location w in month m (t).
xwn_{wm}	Quantity of switchgrass removed from supply location w in month m (t).
xco_{wjm}	Quantity of coal delivered from supply location w to plant j in month m (t).
xtl_{ijhs}	Increment of logging residue annually shipped out of supply county i in the range (a_{s-1}, a_s) .
$xtwl_{wjs}$	Increment of switchgrass annually shipped out of supply county w in the range (b_{s-1}, b_s) .
xpp_{cjm}	Quantity of feedstock c processed at plant location j in month m (dry weight) (t).
xss_{cjm}	Quantity of feedstock c stored at plant location j in month m (dry weight) (t).

CHAPTER 5: SUMMARY

Three mixed integer programming models were developed to assess the economics of woody biomass to biofuels and applied in the central Appalachian region. Based on the modeling processes, case scenarios, and sensitivity analyses, the following conclusions can be drawn:

(1) The average delivered cost of woody biomass for a base case plant with daily demand of 900 metric tons (990 short tons) of dry woody biomass in central Appalachia ranged from \$2.77- \$3.01 per GJ (\$44.07 to \$47.77 per short ton) using the different woody biomass handling systems. Factors such as woody biomass demand level at the plant, purchase price of mill residue, and mill residue availability had greater impacts on the average delivered cost of woody biomass, while skidding distance had the least impact. These findings could be useful to help researchers assess woody biomass utilization for bioenergy in other regions.

(2) Considering site selection criteria for a woody biomass-based ethanol plant including feedstock availability, utilities (such as electricity, gas, and water) availability and cost, transportation, site size, product market, community support, and other optimized results, the optimal biomass plant location should be in Buckhannon, West Virginia. With the assumptions of 1,814 dry metric tons/day of woody biomass requirement, a 20 year plant life, and equity/debt ratio of 40/60, the net present value (NPV) of the plant would vary from \$17.28 million for the cable skidder-chips system to \$35.54 million for the grapple skidder-chips system. The production cost of ethanol varied from US¢ 50.85/liter (\$1.92 per gallon or \$24.27/GJ) for the grapple skidder-chips system to US¢ 52.38/liter (\$1.98 per gallon or \$25.03/GJ) for the cable skidder-chips system. Ethanol production cost can be significantly affected by biomass availability, plant investment and capacity, ethanol yield, and financial structure. Our study

indicated that a woody biomass-based ethanol facility in central Appalachia could be economically feasible under certain operational scenarios.

(3) The production of liquid fuels from coal and biomass is another way of utilizing biomass resources, which provides an option of reducing the U.S. dependence on foreign oil and enhancing national and economic security. Our study suggested that the required selling price (RSP) of Fischer-Tropsch (FT) liquid fuels for a 40,000 barrel per day (BPD) plant in central Appalachia varied between \$79.30/bbl (\$13.77/GJ) and \$79.57/bbl (\$13.82/GJ) among four biomass handling systems with coal/biomass ratio of 85/15, or between \$79.30/bbl (\$13.77/GJ) and \$83.87/bbl (\$14.56/GJ) among different coal/biomass ratios (85/15, 80/20, 75/25, 70/30) using the grapple skidder-chips system. The RSP was heavily dependent on plant capacity, capital cost, mine-mouth price of coal, and liquid fuel yield from coal and biomass. The liquid fuels from coal and biomass would be cost-competitive with oil priced at \$62/bbl. These results can help decision-makers evaluate future CBTL developments in central Appalachia.

Recently, much attention has been given to the production of biofuels. Based on results from this study, the following suggestions for future research are proposed:

(1) Environmental impacts of biofuel production

Fossil fuel energy used in the whole biofuel production chain should be determined and used to calculate the net energy benefit associated with the biofuel. The life cycle assessment (LCA), also known as a cradle-to-grave analysis, can be used to investigate and estimate greenhouse gas emissions of the biofuel production chain. Other environmental factors that need to be considered include soil health and quality, water use and quality, waste water and solid waste streams.

(2) Sustainability of biomass supply

Accurately estimating long-term supply of biomass for a biomass-based plant presents challenges. Changes in current and future conditions will significantly impact the availability of biomass at any given price range. Factors such as the price of fuel, technological advancements, competition for limited biomass supply, and efficiencies of biomass conversion to energy should be considered. Sustainable woody biomass removal rates need to be determined and should be considered part of the best management practices.

APPENDIX I: WOODY BIOMASS DELIVERED COST MODEL

I.1 Introduction to GAMS

The General Algebraic Modeling System (GAMS) is a high-level modeling system for mathematical programming and optimization. It consists of a **language compiler** and a stable of integrated high-performance **solvers**.

I.2 System requirement

To run the delivered cost model, the following requirements must be met:

- The GAMS system must be installed in a computer. For more detailed instruction, please go to <http://www.gams.com/default.htm>.
- A GAMS/Cplex license file must be presented.

I.3 Source code

\$ontext

This program is used to determine the delivered cost of woody biomass at the utilization plant given the daily feedstock requirement. The objective function is to minimize the total cost, which includes extracting, storage, transportation, and chipping/grinding cost.

Programmed by Jinzhuo Wu

Division of Forestry and Natural Resources

West Virginia University

Oct 28, 2008

\$offtext

\$OFFSYMLIST OFFSYMREF

OPTION LIMCOL = 0;

OPTION LIMROW = 0;

OPTION SOLSLACK = 1;

Sets

I Logging residue supply locations in West Virginia

/Barbour, Boone, Braxton, Cabell, Calhoun, Clay, Doddridge, Fayette, Gilmer, Grant, Greenbrier, Hampshire, Hardy, Harrison, Jackson, Kanawha, Lewis, Lincoln, Logan, McDowell, Marion, Marshall, Mason, Mercer, Mineral, Mingo, Monongalia, Monroe, Nicholas, Pendleton, Pleasants, Pocahontas, Preston, Putnam, Raleigh, Randolph, Ritchie, Roane, Summers, Taylor, Tucker, Tyler, Upshur, Wayne, Webster, Wetzel, Wirt, Wood, Wyoming/

J Potential locations for the woody biomass processing plant in WV

/Grafton, Moorefield, Addison, Mabscott, Alum_creek, Grantsville/

M Months of the production year

/Jan, Feb, Mar, Apr, May, Jun, Jul, Aug, Sep, Oct, Nov, Dec/

H Logging residue handling systems

/Cable-skidder, Cableskidder-chip, Grapple-skidder, Grappleskidder-chip, Forwarder-loose, Forwarder-chip, Forwarder-bundle/

R Mill residue types
/Bark, Chips, Sawdust, planer-shavings, slabs, others/

LogStat Logging residues related statistics for each county
/Quantities, SlopeLess35, IntraDistance/

SI Separated line segment index for nonlinear programming
/1*9/;

* Hourly machine cost is calculated by using the Machine Rate method *

Scalar BundlerCost Hourly cost of slash bundler in US dollars /205.51/;

Parameter MC(H) Hourly cost of extraction machine (\$ per PMH)

/Cable-skidder	81.34
Cableskidder-chip	81.34
Grapple-skidder	102.72
Grappleskidder-chip	102.72
Forwarder-loose	124.35
Forwarder-chip	124.35
Forwarder-bundle	145.14 /;

Parameter AED(H) Average extraction distance (feet);

AED(H)=984;

*The average payload sizes for a cable skidder, a grapple skidder, and a forwarder are from *
*Shawn et al. 2007. Influence of site characteristics and cost of extraction and trucking on *
*logging residue utilization in southern West Virginia. Payload size of bundles for forwarder is *
*assumed to be 4 bone dry ton per cycle. *

Parameter PL(H) Average payload size (cubic foot)

/Cable-skidder	106
Cableskidder-chip	106
Grapple-skidder	107.87
Grappleskidder-chip	107.87
Forwarder-loose	300
Forwarder-chip	300
Forwarder-bundle	420 /;

Scalar PB Slash bundler productivity in green tons per hour /13/;

Scalar BZ Bunch size (cubic foot) /54/;

*The following equations are from: Li, Y., Wang, J., Miller, G., and McNeel, J. 2006. Production *
*economics of harvesting small-diameter hardwood stands in central Appalachia. Forest *
*Products Journal 56(3), 81-86. *

Parameter PD(H) Productivity of extraction machine (cubic foot per hour);
 $PD(H) \$ (ORD(H) LE 2) = 144.22 - 0.00001 * AED(H) ** 2 + 1.60 * PL(H) - 1087.54 / PL(H) - 0.0003 * PL(H) ** 2;$
 $PD(H) \$ (ORD(H) EQ 3 \text{ or } ORD(H) EQ 4) = 505.88 - 0.00004 * AED(H) ** 2 + 0.005 * PL(H) ** 2;$
 $PD(H) \$ (ORD(H) EQ 5 \text{ or } ORD(H) EQ 6) = 831.29 - 0.00005 * AED(H) * AED(H) - 5.2 * PL(H) + 0.009 * PL(H) * PL(H) + 15.04 * BZ - 0.09 * BZ * BZ;$
 $PD(H) \$ (ORD(H) EQ 7) = 703;$

 *The extraction costs are converted to the unit of \$ per green ton *

Parameter EC(H) Extraction cost for each system (\$ per green ton) ;
 $EC(H) \$ (ORD(H) LE 6) = MC(H) / (PD(H) / 35.3 * 0.77);$
 $EC(H) \$ (ORD(H) EQ 7) = 4.672 + 0.0092 * AED(H) / 3.28;$

Parameters BC(H) Bundling cost for each system (\$ per green ton);
 $BC(H) \$ (ORD(H) LE 6) = 0;$
 $BC(H) \$ (ORD(H) EQ 7) = \text{BundlerCost} / PB;$

Scalar Loader_Cost Hourly cost of loader (\$ per hour) /85.96/;

Scalar Bundle_D Small end diameter of a slash bundle (inch) /22/;

Scalar Logres_D Small end diameter of slash /5/;

Scalar NL Number of small logs or slash grappled per turn /5/;

Parameter LC(H) Average loading cost corresponding to harvesting system (\$ per ton);
 $LC(H) \$ (ORD(H) LE 6) = \text{Loader_cost} / ((-10.14 + 1.23 * \text{Logres_D} + 1.7058 * NL) * 162 / 35.3 * 0.77);$
 $LC(H) \$ (ORD(H) EQ 7) = 0;$

Parameter Cost_Chipper(H) Hourly chipping or grinding cost (\$)

/Cable-skidder	212.27
Cableskidder-chip	185.62
Grapple-skidder	212.27
Grappleskidder-chip	185.62
Forwarder-loose	212.27
Forwarder-chip	185.62
Forwarder-bundle	237.05 /;

Parameter Productivity_Chipper(H) Hourly chipping or grinding productivity (green tons)

/Cable-skidder	91
Cableskidder-chip	30
Grapple-skidder	91
Grappleskidder-chip	30
Forwarder-loose	91
Forwarder-chip	30
Forwarder-bundle	120 /;

Parameter ChippingSite(H) Chipping cost on forest landings (\$ per ton);
 ChippingSite(H)\$ (ORD(H) EQ 1 OR ORD(H) EQ 3 OR ORD(H) EQ 5 OR ORD(H) EQ 7) = 0;
 ChippingSite(H)\$ (ORD(H) EQ 2 OR ORD(H) EQ 4 OR ORD(H) EQ 6)
 =Cost_Chipper(H) / Productivity_Chipper(H);

Parameter ChippingPlant(H) Chipping cost at the plant (\$ per green ton);
 ChippingPlant(H)\$ (ORD(H) EQ 2 OR ORD(H) EQ 4 OR ORD(H) EQ 6)=0;
 ChippingPlant(H)\$ (ORD(H) EQ 1 OR ORD(H) EQ 3 OR ORD(H) EQ 5 OR ORD(H) EQ 7)
 =Cost_Chipper(H)/Productivity_Chipper(H);

Table LoggingResidue(I,LogStat) Logging residues statistics by county(quantities in green tons)

	Quantities	SlopeLess35	IntraDistance
Barbour	23885	0.79	13
Boone	52539	0.37	16
Braxton	85558	0.67	15
Cabell	19352	0.89	12
Calhoun	38323	0.63	13
Clay	61457	0.66	11
Doddridge	49434	0.65	12
Fayette	108269	0.63	18
Gilmer	41961	0.71	15
Grant	25182	0.74	15
Greenbrier	70650	0.76	20
Hampshire	29328	0.92	15
Hardy	19834	0.71	15
Harrison	43089	0.76	13
Jackson	26038	0.87	15
Kanawha	158324	0.63	24
Lewis	40551	0.60	14
Lincoln	18459	0.72	17
Logan	16380	0.24	16
McDowell	70707	0.40	17
Marion	42215	0.90	14
Marshall	31743	0.66	10
Mason	18170	0.87	17
Mercer	44234	0.69	14
Mineral	12671	0.64	14
Mingo	69417	0.31	17
Monongalia	28661	0.82	16
Monroe	42422	0.92	19
Nicholas	87436	0.74	21
Pendleton	28134	0.53	18
Pleasants	23575	0.71	8
Pocahontas	29431	0.71	26
Preston	90343	0.85	15
Putnam	23471	0.80	15
Raleigh	80051	0.58	17
Randolph	113787	0.68	25
Ritchie	63995	0.85	13
Roane	44518	0.76	15

Summers	12775	0.59	12
Taylor	23885	1.00	9
Tucker	36716	0.77	15
Tyler	23575	0.86	10
Upshur	65941	0.84	14
Wayne	22491	0.73	19
Webster	88773	0.53	16
Wetzel	47065	0.61	13
Wirt	39527	0.90	9
Wood	30324	1.00	14
Wyoming	30324	0.43	15

;

Scalar BP Proportion of woody biomass that can be economically harvested /0.65/;

Parameter Loggingavai(I) Logging residues in tons for each supply location;

Loggingavai(I)=LoggingResidue(I,"Quantities")*BP ;

Parameter LoggingSlope(I) Logging residues at sites with less than 35 percent slope;

loggingSlope(I)=Loggingavai(I)*LoggingResidue(I,"SlopeLess35");

Scalar Logres_mc Logging residue moisture content /0.43/;

Parameter ExtProp(M) Extracted proportion as a percentage of the whole year

/Jan	0.083
Feb	0.083
Mar	0.083
Apr	0.083
May	0.075
Jun	0.075
Jul	0.075
Aug	0.075
Sep	0.092
Oct	0.092
Nov	0.092
Dec	0.092 /;

Parameter Ext_amt(I,M) Extraction limit per month by county in green tons;

Ext_amt(I,M)=loggingSlope(I)* ExtProp(M);

* Proportion of available woody biomass on site *

Scalar UPS Usable proportion of logging residues at supply locations /0.95/;

Scalar Stumpage Stumpage cost of logging residues in dollar per ton /0.91/;

Scalar SC Storage cost for logging residues in dollar per ton /0.00/;

Table MillResidue(I, R) Amounts of mill residues per week by county in green tons

	Bark	Chips	Sawdust	Planer-shavings	Slabs	Others
Barbour	150	200	200	0	0	0
Boone	0	0	0	0	0	0

Braxton	388	440	380	30	0	81
Cabell	0	0	0	0	0	0
Calhoun	0	0	0	0	0	0
Clay	120	268	140	0	0	0
Doddridge	130	125	140	0	40	0
Fayette	135	215	160	0	0	0
Gilmer	0	0	1	0	25	5
Grant	0	0	72	0	0	0
Greenbrier	1375	480	887	0	0	0
Hampshire	0	0	0	0	0	0
Hardy	45	25	31	0	2	0
Harrison	0	0	0	0.5	0	0
Jackson	0	0	60	0	0	0
Kanawha	280	565	340	0	0	0
Lewis	0	0	12	0	40	0
Lincoln	0	0	0	0	0	0
Logan	0	0	0	0	0	0
McDowell	0	0	0	0	0	0
Marion	0	0	0	0	0	0
Marshall	0	0	0	0	0	0
Mason	0	0	0	0	0	0
Mercer	0	0	20	0	0	40
Mineral	0	0	100	0	20	0
Mingo	300	763	445.1	0	15	0
Monongalia	0	0	1	0	0.5	0
Monroe	80	110	60	0	0	0
Nicholas	932	2595	598	6	0	8
Pendleton	85	300	100	0	0	0
Pleasants	0	0	0	0	0	0
Pocahontas	865	863	735	50	0	0
Preston	652	1252	858	0	11	0
Putnam	0	0	0	0	0	0
Raleigh	250	500	350	10	0	0
Randolph	767.67	1170	3269.66	0	2	61
Ritchie	15.63	41.67	20.83	0	0	0
Roane	0	0	10	0	0	130
Summers	100	100	100	0	0	0
Taylor	0	5	10	0	0	0
Tucker	0	0	0	0	0	0
Tyler	0	0	0	0	0	0
Upshur	0	600	550	0.125	24	20
Wayne	0	0	0	0	0	0
Webster	147	150	147	0	8	0
Wetzel	364.5	110	50	0	0	0
Wirt	0	0	0	0	0	0
Wood	0	0	3.02	0	8.25	1
Wyoming	0	0.2	0.1	0.05	0	0

;

Parameter MillProp(I) Proportion of mill residues available in each county;
MillProp(I)=0.4;

Table DIS(I,J) Distance from supply source i to demand location j

	Grafton	Moorefield	Addison	Mabscott	Alum_creek
Barbour	13.000	58.000	51.000	115.000	113.000
Boone	131.000	169.000	81.000	38.000	14.000
Braxton	61.000	100.000	21.000	68.000	62.000
Cabell	130.000	177.000	94.000	68.000	19.000
Calhoun	65.000	115.000	48.000	80.000	60.000
Clay	83.000	121.000	36.000	48.000	43.000
Doddridge	41.000	98.000	60.000	108.000	90.000
Fayette	107.000	134.000	48.000	20.000	43.000
Gilmer	52.000	100.000	39.000	83.000	71.000
Grant	53.000	9.000	78.000	141.000	155.000
Greenbrier	102.000	120.000	38.000	32.000	67.000
Hampshire	68.000	23.000	107.000	172.000	182.000
Hardy	60.000	0.000	87.000	151.000	162.000
Harrison	18.000	75.000	55.000	115.000	105.000
Jackson	98.000	148.000	74.000	77.000	39.000
Kanawha	108.000	147.000	61.000	41.000	18.000
Lewis	32.000	80.000	39.000	97.000	90.000
Lincoln	134.000	177.000	93.000	60.000	17.000
Logan	148.000	183.000	96.000	43.000	29.000
McDowell	157.000	181.000	96.000	31.000	60.000
Marion	17.000	75.000	72.000	131.000	120.000
Marshall	45.000	100.000	93.000	146.000	127.000
Mason	112.000	162.000	86.000	79.000	35.000
Mercer	148.000	164.000	85.000	28.000	72.000
Mineral	46.000	24.000	92.000	158.000	164.000
Mingo	163.000	197.000	110.000	53.000	46.000
Monongalia	21.000	72.000	82.000	146.000	132.000
Monroe	124.000	133.000	62.000	36.000	85.000
Nicholas	85.000	115.000	27.000	41.000	54.000
Pendleton	61.000	38.000	59.000	119.000	133.000
Pleasants	63.000	122.000	77.000	113.000	85.000
Pocahontas	77.000	83.000	25.000	69.000	92.000
Preston	23.000	48.000	81.000	146.000	141.000
Putnam	116.000	161.000	80.000	64.000	17.000
Raleigh	126.000	151.000	64.000	0.000	49.000
Randolph	35.000	50.000	38.000	104.000	113.000
Ritchie	56.000	112.000	61.000	100.000	77.000
Roane	81.000	129.000	56.000	72.000	44.000
Summers	125.000	141.000	62.000	19.000	64.000
Taylor	0.000	60.000	63.000	126.000	121.000
Tucker	29.000	34.000	59.000	124.000	130.000
Tyler	49.000	108.000	75.000	120.000	98.000
Upshur	27.000	67.000	36.000	100.000	98.000
Wayne	152.000	196.000	112.000	74.000	36.000
Webster	63.000	87.000	0.000	66.000	76.000
Wetzel	39.000	97.000	76.000	127.000	109.000
Wirt	77.000	130.000	67.000	90.000	59.000
Wood	81.000	135.000	77.000	99.000	65.000

Wyoming	146.000	173.000	87.000	22.000	51.000
+	Grantsville				
Barbour	59.000				
Boone	71.000				
Braxton	27.000				
Cabell	66.000				
Calhoun	0.000				
Clay	32.000				
Doddridge	31.000				
Fayette	60.000				
Gilmer	14.000				
Grant	106.000				
Greenbrier	69.000				
Hampshire	129.000				
Hardy	115.000				
Harrison	48.000				
Jackson	34.000				
Kanawha	48.000				
Lewis	35.000				
Lincoln	70.000				
Logan	88.000				
McDowell	106.000				
Marion	61.000				
Marshall	68.000				
Mason	48.000				
Mercer	107.000				
Mineral	109.000				
Mingo	103.000				
Monongalia	79.000				
Monroe	96.000				
Nicholas	46.000				
Pendleton	97.000				
Pleasants	34.000				
Pocahontas	73.000				
Preston	88.000				
Putnam	51.000				
Raleigh	80.000				
Randolph	66.000				
Ritchie	20.000				
Roane	16.000				
Summers	87.000				
Taylor	65.000				
Tucker	79.000				
Tyler	41.000				
Upshur	47.000				
Wayne	88.000				
Webster	48.000				
Wetzel	51.000				
Wirt	19.000				
Wood	29.000				

Wyoming 95.000

;

*Assumptions about transportation cost *

Scalar TP Truck purchased cost in dollars /140000/;
Scalar TSP Truck salvage value as a percentage of purchased cost /0.20/ ;
Scalar MPG_1 Truck miles per gallon on highways /5/;
Scalar MPG_2 Truck miles per gallon on local roads /5/;
Scalar MPH_1 Miles per hour on highways /35/;
Scalar MPH_2 Miles per hour on local roads /25/;
Scalar FPG Fuel price per gallon /3.55/;
Scalar DWH Driver's wage per hour including benefits /14/;
Scalar N Economic life of trucks /8/;
Scalar SMH Scheduled machine hours per year /2000/;
Scalar ITR Interest insurance and tax rate /0.20/;
Scalar MR Mainenance and repair rate as a percentage of depreciation /0.90/;
Scalar UT Utilization rate of trucks /0.90/;

Parameter TC(I,J) Transportation cost from location i to location j;
$$TC(I,J)=2*DIS(I,J)*(FPG/MPG_1+DWH/MPH_1+((TP-TP*TSP)*(1+MR)+ITR*((TP-TP*TSP)*(N+1)/2+N*TP*TSP))/N/SMH/UT/MPH_1);$$

Parameter TL(H) Truck load for handling system H in tons

/Cable-skidder	14
Cableskidder-chip	21
Grapple-skidder	14
Grappleskidder-chip	21
Forwarder-loose	14
Forwarder-chip	21
Forwarder-bundle	20 /;

Parameter TLT(I,J,h) Trucking cost in dollar per ton ;

$TLT(I,J,h)= TC(I,J)/TL(h);$

Parameter LTC(H) Transportation cost off highway within counties (\$ per ton.mile);

$$LTC(H)=2*(FPG/MPG_2+DWH/MPH_2+((TP-TP*TSP)*(1+MR)+ITR*((TP-TP*TSP)*(N+1)/2+N*TP*TSP))/N/SMH/UT/MPH_2)/TL(h);$$

Parameter Millcost(R) Cost of mill residue (\$ per green ton)

/Bark	22.73
chips	22.73
sawdust	27.27
Planer-shavings	18.18
slabs	18.18
others	9.09 /;

Parameter Mill_mc(R) Moisture content of mill residue

/Bark	0.50
chips	0.30
sawdust	0.30

planer-shavings	0.20
slabs	0.50
others	0.50 /;

Scalar Mill_load Load of mill residue in green tons /21/;

Parameter Milltrancost Cost of delivering mill residue (\$ per ton per mile);

$$\text{Milltrancost} = 2 * (\text{FPG} / \text{MPG}_1 + \text{DWH} / \text{MPH}_1 + ((\text{TP} - \text{TP} * \text{TSP}) * (1 + \text{MR}) + \text{IITR} * ((\text{TP} - \text{TP} * \text{TSP}) * (\text{N} + 1) / 2 + \text{N} * \text{TP} * \text{TSP})) / \text{N} / \text{SMH} / \text{UT} / \text{MPH}_1) / \text{Mill_load};$$

Scalar TLoss Dry matter loss due to transportation /0.03/;

 * Woody biomass-based processing plant assumption *

Scalar Capacity Plant capacity in terms of daily feedstock requirement in tons /990/;

Parameter FC(SI) Coefficients of linearized local transportation turnover function

/1	1.583
2	3.322
3	4.738
4	6.474
5	9.156
6	11.856
7	14.040
8	15.925
9	18.377/;

Parameter B(SI) Right hand side of the constraints for separated variables in linearized function

/1	1000
2	2000
3	2000
4	5000
5	10000
6	10000
7	10000
8	10000
9	25000/;

Scalar UUP Proportion of woody biomass usable at plant /0.99/;

Parameter MINBV Minimum inventory at plant ;

$$\text{MINBV} = 0 * \text{Capacity};$$

Variables

OBF	Objective
xh(I,H,M)	Amounts of logging residues extracted by H at source I in month M
xt(I,J,H,M)	Amounts of logging residues extracted by H transported from I to J in month M
xtl(I,J,H,SI)	Annual separated delivered logging residues from I to J extracted by H

xm(I,J,R,M) Amounts of mill residue R delivered from source I to plant J in month M
 xs(I,H,M) Logging residue extracted by H stored at source I in month M
 xps(I,H,M) Logging residue extracted by H going into storage at source I in month M
 xsn(I,H,M) Logging residue extracted by H removed from storage at source I in month M
 xss(J,M) Woody biomass stored at plant J in month M
 xpp(J,M) Woody biomass processed at plant J in month M
 Beta(J) Binary variable for plant location J
 Alfa(I,H) Binary variable for extracting method H at source I
 ;
 Positive variables xh, xt, xm, xs, xps, xsn, xss, xpp, xt1;
 Binary variables Beta, Alfa;

Equations

Obj Objective function
 HSlope35(I,H) Logging residues availability
 Ext_limit_1(I,M) Extraction limit of logging residues at source I in month M
 Ext_limit_2(I,H,M) Extraction limit by cable skidder at source I in month M
 Ext_limit_3(I,H,M) Extraction limit by grapple skidder at source I in month M
 Ext_limit_4(I,H,M) Extraction limit by forwarder at source I in month M
 Trans(I,J,H) Sum of annual delivered logging residues from I to J by H at different section
 Tran_con1(I,J,H,SI) Annual delivered logging residues at different section from I to J by H
 Storage1(I,H,M) Woody biomass supply balance using system H at source I in month M
 Storage2(I) Woody biomass supply balance at source I
 Storage3(I,H,M) Woody biomass storage system at source I in month M
 Storage4(I,H,M) In-woods chipping system
 Storage5(I,H,M) Loose residue system
 Bundlestorage(I,H,M) Amounts of residues that are bundled entering storage
 Milltrant(I,R,M) Mill residues purchased at source I in month M
 CP(J,M) Plant storage balance
 CP_2(J,M) Plant capacity constraint
 Inven(J,M) Minimum inventory at a plant
 MXplant Maximum of one plant selected
 MXHarvest(I) Maximum of one harvesting system used
 One(I) Assign one handling system
 ;
 Obj..
 OBF =E= SUM(M,SUM((I,H), (BC(H)+EC(H)+Stumpage)* xh(I,H,m))+SUM((I,H),SC * xps(I,H,m))
 +SUM((I,J,H),(ChippingSite(H)+LC(H) +TLT(I,J,H)+ ChippingPlant(H))*xt(I,J,H,M))
 +SUM((I,J,R),Millcost(R)*xm(I,J,R,M))+ SUM((I,J,R),Milltrancost*DIS(I,J)*xm(I,J,R,M)))
 +SUM((I,J,H,SI)\$ (Dis(I,J) LE LoggingResidue(I,"Intradistance")),LTC(H)*FC(SI)
 *xt1(I,J,H,SI));

 HSlope35(I,H)..
 SUM(M ,xh(I,H,M))-Alfa(I,H)*LoggingSlope(I)=L=0;

 Ext_limit_1(I,M)..
 SUM(H,xh(I,H,M))-Ext_amt(I,M) =L=0;

 Ext_limit_2(I,H,M)\$(ORD(H) LE 2)..

$xh(I,H,M)-20*120*1.5*PD(H)/35.3*0.77 =L=0;$
Ext_limt_3(I,H,M)\$ (ORD(H) EQ 3 OR ORD(H) EQ 4)..
 $xh(I,H,M)-20*120*1.6*PD(H)/35.3*0.77 =L=0;$
Ext_limt_4(I,H,M)\$ (ORD(H) GE 5)..
 $xh(I,H,M)-20*120*1*PD(H)/35.3*0.77 =L=0;$
Trans(I,J,H)..
 $SUM(SI,xt1(I,J,H,SI))-SUM((M),xt(I,J,H,M))=E=0;$
Tran_con1(I,J,H,SI)..
 $xt1(I,J,H,SI)=L=B(SI);$
Storage1(I,H,M)..
 $xh(I,H,M)+ UPS*xs(I,H,M-1)-SUM(J,xt(I,J,H,M))-xs(I,H,M) =G=0;$
Storage2(I)..
 $SUM((H,M),xh(I,H,M))-SUM((J,H,M),xt(I,J,H,M))-(1-UPS)*SUM((H,M),xs(I,H,M)) =E=0;$
Storage3(I,H,M)..
 $xh(I,H,M)-xps(I,H,M)+xsn(I,H,M)-SUM((J),xt(I,J,H,M)) =E=0;$
Storage4(I,H,M)\$ (ORD(H) EQ 2 or ORD(H) EQ 4 or ORD(H) EQ 6)..
 $xps(I,H,M)=E=0;$
Storage5(I,H,M)\$ (ORD(H) EQ 1 or ORD(H) EQ 3 or ORD(H) EQ 5)..
 $xps(I,H,M)-xh(I,H,M) =L=0;$
Bundlestorage(I,H,M) \$ (ORD(H) EQ 7)..
 $xps(I,H,M)-xh(I,H,M) =E=0;$
Milltrant(I,R,M)..
 $SUM(J,xm(I,J,R,M))-MillProp(I)*4*MillResidue(I,R)=L=0;$
CP(J,M)..
 $SUM((I,R),(1-Mill_mc(R))*xm(I,J,R,M))+SUM((I,H),(1-Logres_mc)*(1-TLoss)*xt(I,J,H,M))$
 $+UUP*xss(J,M-1)-xss(J,M)-xpp(J,M) =E=0;$
CP_2(J,M)..
 $xpp(J,M)-30*Capacity*Beta(J) =E=0;$
Inven(J,M)..
 $xss(J,M)-MINBV*Beta(J)=G=0;$
MXplant..
 $SUM(J, Beta(J))=E=1;$
MXHarvest(I)..
 $SUM(H,Alfa(I,H)) =E=1;$

```
One(I)..
  Alfa(I,"Cable-skidder")=E=1;
```

```
*****
```

Model Bioplant /all/;

```
Solve Bioplant minimizing OBF using MIP;
Option solprint=off;
```

```
*****
```

```
*Results *
```

```
*****
```

```
*Unit delivered cost of woody biomass (logging residue and mill residue jointly) *
```

```
*****
```

```
Parameter unitcost_dryton, unitcost_metric;
```

```
unitcost_dryton=OBF./((SUM((I,J,R,m),(1-Mill_mc(R))*xm.l(I,J,R,M))+SUM((I,J,H,m),(1-
logres_mc)*xt.l(I,J,H,M))));
```

```
unitcost_metric=1.1*OBF./((SUM((I,J,R,m),(1-Mill_mc(R))*xm.l(I,J,R,M))+SUM((I,J,H,m),(1-
logres_mc)*xt.l(I,J,H,M))));
```

```
Display unitcost_dryton, unitcost_metric;
```

```
*****
```

```
*Unit delivered cost of logging residue/mill residue *
```

```
*****
```

```
Parameter log_cost, mill_cost, log_cost_metric, mill_cost_metric;
```

```
log_cost=(sum((I,H,m), (BC(H)+EC(H)+stumpage)* xh.l(I,H,m))+sum((I,H,m),SC *xps.l(I,H,m))
+sum((I,J,H,m),(LC(H) +TLT(I,J,H))*xt.l(I,J,H,M))+sum((I,J,H,SI)$(Dis(I,J) LE
LoggingResidue(I,"Intradistance")),LTC(H)*FC(SI)*xt1.l(I,J,H,SI))
+sum((I,J,H,m),(ChippingSite(H)+ChippingPlant(H))* xt.l(I,J,H,M)))
/SUM((I,J,H,m),(1-logres_mc)*xt.l(I,J,H,M));
```

```
mill_cost=(sum((I,J,R,m),Milltrancost*Dis(I,J)*xm.l(I,J,R,M))+sum((I,J,R,m),Millcost(R)
*xm.l(I,J,R,M)))/SUM((I,J,R,m),(1-Mill_mc(R))*xm.l(I,J,R,M));
```

```
log_cost_metric=log_cost*1.10;
```

```
mill_cost_metric=mill_cost*1.10;
```

```
Display log_cost, mill_cost,log_cost_metric, mill_cost_metric;
```

```
*****
```

```
*Average hauling distance for logging residue and mill residue *
```

```
*****
```

```
Parameters avg_dis_log, avg_dis_mill;
```

```
avg_dis_log=sum((I,J,H,m),Dis(I,J)* xt.l(I,J,H,M))/sum((I,J,H,m),xt.l(I,J,H,M));
```

```
avg_dis_mill=sum((I,J),Dis(I,J)*sum((R,m),xm.l(I,J,R,M)))/sum((I,J,R,m),xm.l(I,J,R,M));
```

```
Display avg_dis_log, avg_dis_mill;
```

```

*****
*Decomposition of logging/mill residue delivered cost *
*Logging residue: bundling, extraction, storage, transportation, loading, and chipping/grinding. *
*Mill residue: purchase cost and transportation cost. *
*****
Parameters log_c1_metric, log_c2_metric, log_c3_metric, log_c4_metric, log_c5_metric, log_c6_metric,
log_c7_metric, mill_c1_metric, mill_c2_metric;

log_c1_metric=1.10*sum((I,H,m), BC(H)* xh.l(I,H,m))/SUM((I,J,H,m),(1-logres_mc) *xt.l(I,J,H,M));

log_c2_metric=1.10*sum((I,H,m), EC(H)* xh.l(I,H,m))/SUM((I,J,H,m),(1-logres_mc)* xt.l(I,J,H,M));

log_c3_metric=1.10*sum((I,H,m),SC * xps.l(I,H,m))/SUM((I,J,H,m),(1-logres_mc)* xt.l(I,J,H,M));

log_c4_metric=1.10*(sum((I,J,H,m),TLT(I,J,H)*xt.l(I,J,H,M))+SUM((I,J,H,SI)$ (Dis(I,J) LE
LoggingResidue(I,"Intradistance")),LTC(H)*FC(SI)*xt1.l(I,J,H,SI)))
/SUM((I,J,H,m),(1-logres_mc)* xt.l(I,J,H,M));

log_c5_metric=1.10*sum((I,J,H,m),LC(H)*xt.l(I,J,H,M))/SUM((I,J,H,m),(1-logres_mc)* xt.l(I,J,H,M));

log_c6_metric=1.10*sum((I,J,H,m),(ChippingSite(H)+ChippingPlant(H))* xt.l(I,J,H,M))
/SUM((I,J,H,m),(1-logres_mc)*xt.l(I,J,H,M));

log_c7_metric=1.10*sum((I,H,m),(stumpage)* xh.l(I,H,M))/SUM((I,J,H,m),(1-logres_mc)
* xt.l(I,J,H,M));

mill_c1_metric=1.10*sum((I,J,R,m),Millcost(R)*xm.l(I,J,R,M))/SUM((I,J,R,m),(1-Mill_mc(R))
*xm.l(I,J,R,M));

mill_c2_metric=1.10* sum((I,J,R,m),Milltrancost*Dis(I,J)*xm.l(I,J,R,M))
/SUM((I,J,R,m),(1-Mill_mc(R)) *xm.l(I,J,R,M));

Display log_c1_metric, log_c2_metric, log_c3_metric, log_c4_metric, log_c5_metric, log_c6_metric,
log_c7_metric, mill_c1_metric, mill_c2_metric;

```

APPENDIX II: ECONOMIC ANALYSIS MODEL FOR A WOOD BIOMASS PLANT

II.1 System requirement

To run the economic analysis model, the following requirements must be met:

- The GAMS system must be installed in a computer. For more detailed instruction, please go to <http://www.gams.com/default.htm>.
- A GAMS/Cplex license file must be presented.

II.2 Source code

\$ontext

This program is used to determine the best location for a woody-biomass based ethanol facility given the feedstock requirement per day. The objective function is to maximize the Net Present Value of the facility.

Programmed by Jinzhuo Wu

Division of Forestry

West Virginia University

June 26, 2009

\$offtext

\$OFFSYMLIST OFFSYMXREF

OPTION LIMCOL = 0;

OPTION LIMROW = 0;

OPTION SOLSLACK = 1;

OPTION ITERLIM=5000000;

OPTION RESLIM=1000000;

Sets

I Woody biomass supply locations

/Barbour,Boone, Braxton, Cabell, Calhoun, Clay, Doddridge, Fayette, Gilmer, Grant, Greenbrier, Hampshire, Hardy, Harrison, Jackson, Kanawha, Lewis, Lincoln, Logan, Marion, Marshall, McDowell, Mason, Mercer, Mineral, Mingo, Monongalia, Monroe, Nicholas, Pleasants, Pendleton, Pocahontas, Preston, Putnam, Raleigh, Randolph, Ritchie, Roane, Summers, Taylor, Tucker, Tyler, Upshur, Wayne, Webster, Wetzel, Wirt, Wood, Wyoming, V_Alleghany, V_Buchanan, V_Bath, V_Bland, V_Craig, V_Dickenson, V_Giles, V_Highland, V_Russell, V_Smyth, V_Tazewell, V_Wise, K_Boyd, K_Carter, K_Elliott, K_Floyd, K_Greenup, K_Johnson, K_Lawrence, K_Martin, K_Magoffin, K_Morgan, K_Pike, O_Athens, O_Belmont, O_Gallia, O_Jackson, O_Lawrence, O_Meigs, O_Monroe, O_Morgan, O_Noble, O_Scioto, O_Vinton, O_Washington, P_Allegheny, P_Beaver, P_Fayette, P_Greene, P_Somerset, P_Washington, P_Westmoreland, M_Garrett, M_Allegany/

J Potential locations for the woody biomass-based ethanol plant

/Beaver_Raleigh, Belington, Bluefield, Buckhannon, Holden, Kenna, Millwood, Morgantown, Oak_Hill_Fayette, Point_Pleasant, Williamson/

M Months of the production year

/Jan, Feb, Mar, Apr, May, Jun, Jul, Aug, Sep, Oct, Nov, Dec/

H Logging residue handling systems

/Cable-skidder, Cableskidder-chip, Grapple-skidder, Grappleskidder-chip/

LogStat Logging residues related statistics for each county
/Quantities, SlopeLess35, IntraDistance/

G Products
/Ethanol, Electricity/

Process_area Woody biomass to ethanol process area
/Feed_handling, Pretreatment, SSCF, Cellulase_production, Distillation, WWT, Storage,
Boiler_turbogen, Utilities/

Project_year Index of the project year
/1*20/

SI Separated line segment index for nonlinear programming
/1*9/;

Parameter MC(H) Hourly cost of extraction machine (\$ per PMH)
/Cable-skidder 81.34
Cableskidder-chip 81.34
Grapple-skidder 102.72
Grappleskidder-chip 102.72 /;

Parameter AED(H) Average extraction distance (feet);
AED(H)=984;

Parameter PL(H) Average payload size (cubic foot)
/Cable-skidder 106
Cableskidder-chip 106
Grapple-skidder 107.87
Grappleskidder-chip 107.87 /;

Scalar BZ Bunch size (cubic foot) /54/;

Parameter PD(H) Productivity of extraction machine (cubic foot per hour);
PD(H) \$ (ORD(H) LE 2)=144.22-0.00001*AED(H)**2+1.60*PL(H)-1087.54/PL(H)
-0.0003*PL(H)**2+0.14*BZ+7.35/BZ-0.0008*BZ*BZ;
PD(H) \$ (ORD(H) EQ 3 or ORD(H) EQ 4)=505.88-0.00004*AED(H)**2+
0.005*PL(H)**2;

Parameter EC(H) Extraction cost for each system (\$ per green ton) ;
EC(H) =MC(H)/(PD(H)/35.3*0.77);

Scalar Loader_cost Hourly cost of loader (\$ per hour) /85.96/;

Scalar Logres_D Small end diameter of slash /5/;

Scalar NL Number of small logs or slash grappled per turn /5/;

Parameter LC(H) Average loading cost corresponding to harvesting system (\$ per ton);

$$LC(H)=\text{Loader_cost}/((-10.14+1.23*\text{Logres_D}+1.7058*NL)*162/35.3*0.77);$$

Parameter Cost_chipper(H) Hourly chipping cost (\$)

/Cable-skidder 212.27
 Cableskidder-chip 185.62
 Grapple-skidder 212.27
 Grappleskidder-chip 185.62 /;

Parameter Productivity_chipper(H) Hourly chipping productivity (green tons)

/Cable-skidder 91
 Cableskidder-chip 30
 Grapple-skidder 91
 Grappleskidder-chip 30 /;

Parameter ChippingSite(H) Chipping cost on forest landings (\$ per ton);

ChippingSite(H)\$ (ORD(H) EQ 1 OR ORD(H) EQ 3)=0;

ChippingSite(H)\$ (ORD(H) EQ 2 OR ORD(H) EQ 4)

=Cost_chipper(H)/Productivity_chipper(H);

Parameter ChippingPlant(H) Chipping cost at the plant (\$ per green ton);

ChippingPlant(H)\$ (ORD(H) EQ 2 OR ORD(H) EQ 4)=0;

ChippingPlant(H)\$ (ORD(H) EQ 1 OR ORD(H) EQ 3)

=Cost_chipper(H)/Productivity_chipper(H);

*In the following table, the value “1.00” indicates “no data” for the selected counties. *

Table LoggingResidue(I,LogStat) Logging residues statistics by county(quantities in green tons)

	Quantities	SlopeLess35	IntraDistance
Barbour	23885	0.79	13
Boone	52539	0.37	16
Braxton	85558	0.67	15
Cabell	19352	0.89	12
Calhoun	38323	0.63	13
Clay	61457	0.66	11
Doddridge	49434	0.65	12
Fayette	108269	0.63	18
Gilmer	41961	0.71	15
Grant	25182	0.74	15
Greenbrier	70650	0.76	20
Hampshire	29328	0.92	15
Hardy	19834	0.71	15
Harrison	43089	0.76	13
Jackson	26038	0.87	15
Kanawha	158324	0.63	24
Lincoln	18459	0.72	17
Logan	16380	0.24	16
Lewis	40551	0.60	14
Marion	42215	0.90	14
Marshall	31743	0.66	10
McDowell	70707	0.40	17

Mason	18170	0.87	17
Mercer	44234	0.69	14
Mineral	12671	0.64	14
Mingo	69417	0.31	17
Monongalia	28661	0.82	16
Monroe	42422	0.92	19
Nicholas	87436	0.74	21
Pendleton	28134	0.53	18
Pleasants	23575	0.71	8
Pocahontas	29431	0.71	26
Preston	90343	0.85	15
Putnam	23471	0.80	15
Raleigh	80051	0.58	17
Randolph	113787	0.68	25
Ritchie	63995	0.85	13
Roane	44518	0.76	15
Summers	12775	0.59	12
Taylor	23885	1.00	9
Tucker	36716	0.77	15
Tyler	23575	0.86	10
Upshur	65941	0.84	14
Wayne	22491	0.73	19
Webster	88773	0.53	16
Wetzel	47065	0.61	13
Wirt	39527	0.90	9
Wood	30324	1.00	14
Wyoming	30324	0.43	15
V_Alleghany	35539	1.00	12
V_Buchanan	6620	1.00	16
V_Bath	22848	1.00	12
V_Bland	16778	1.00	12
V_Craig	6620	1.00	14
V_Dickenson	96078	1.00	12
V_Giles	23087	1.00	14
V_Highland	28967	1.00	11
V_Russell	10564	1.00	17
V_Smyth	17758	1.00	16
V_Tazewell	8150	1.00	18
V_Wise	19502	1.00	15
K_Boyd	6716	1.00	8
K_Carter	34177	1.00	14
K_Elliott	13097	1.00	10
K_Floyd	21391	1.00	16
K_Greenup	26123	1.00	12
K_Johnson	12524	1.00	12
K_Lawrence	9010	1.00	13
K_Martin	16419	1.00	10
K_Magoffin	8939	1.00	14
K_Morgan	31118	1.00	14
K_Pike	64602	1.00	19
O_Athens	25694	1.00	15

O_Belmont	10355	1.00	17
O_Gallia	12893	1.00	16
O_Jackson	93231	1.00	14
O_Lawrence	6858	1.00	15
O_Meigs	37114	1.00	15
O_Monroe	0	1.00	14
O_Morgan	25021	1.00	14
O_Noble	7565	1.00	15
O_Scioto	82788	1.00	17
O_Vinton	95245	1.00	15
O_Washington	16779	1.00	22
P_Allegheny	10226	1.00	16
P_Beaver	2051	1.00	15
P_Fayette	54443	1.00	18
P_Greene	23573	1.00	18
P_Somerset	92975	1.00	24
P_Washington	15454	1.00	22
P_Westmoreland	43896	1.00	24
M_Allegany	63394	1.00	16
M_Garrett	110094	1.00	21

;

Scalar BP Proportion of woody biomass that can be economically harvested /0.65/;

Parameter Loggingavai(I) Logging residue in tons for each supply location;

Loggingavai(I)=LoggingResidue(I,"Quantities")*BP ;

Parameter LoggingSlope(I) Logging residue at sites with less than 35 percent slope;

*WV counties

LoggingSlope(I)\$ (ORD(I) LE 49)=Loggingavai(I)*LoggingResidue(I,"SlopeLess35");

*Non WV counties

LoggingSlope(I)\$ (ORD(I) GE 50)=0.65*LoggingResidue(I,"Quantities");

Scalar WC Moisture content /0.43/;

Parameter ExtProp(M) Extracted proportion as a percentage of the whole year

/Jan 0.083

Feb 0.083

Mar 0.083

Apr 0.083

May 0.075

Jun 0.075

Jul 0.075

Aug 0.075

Sep 0.092

Oct 0.092

Nov 0.092

Dec 0.092 /;

Parameter Ext_amt(I,H,M) Extraction limit per month by county in green tons;

Ext_amt(I,H,M)=LoggingSlope(I)* ExtProp(M);

 * Proportion of available woody biomass on site *

Scalar UPS Usable proportion of logging residues at supply locations /0.95/;

Scalar Stumpage Stumpage cost of logging residues in dollar per ton /0.91/;

Scalar SC Storage cost for logging residues in the field in dollar per ton /0.00/;

Parameter MillResidue(I) Amounts of mill residues by county in green tons

/Barbour	19200
Boone	0
Braxton	39360
Cabell	0
Calhoun	0
Clay	19584
Doddridge	12720
Fayette	18000
Gilmer	48
Grant	3456
Greenbrier	65616
Hampshire	0
Hardy	2688
Harrison	0
Jackson	2880
Kanawha	43440
Lewis	576
Lincoln	0
Logan	0
Marion	0
Marshall	0
Mcdowell	0
Mason	0
Mercer	960
Mineral	4800
Mingo	57989
Monongalia	48
Monroe	8160
Nicholas	153264
Pleasants	0
Pendleton	19200
Pocahontas	76704
Preston	101280
Putnam	0
Raleigh	40800
Randolph	213104
Ritchie	3000
Roane	480
Summers	9600
Taylor	720
Tucker	0

Tyler	0
Upshur	55200
Wayne	0
Webster	14256
Wetzel	7680
Wirt	0
Wood	145
Wyoming	14
V_Alleghany	48757
V_Buchanan	21102
V_Bath	0
V_Bland	0
V_Craig	0
V_Dickenson	0
V_Giles	0
V_Highland	0
V_Russell	0
V_Smyth	0
V_Tazewell	0
V_Wise	0
K_Boyd	0
K_Carter	49167
K_Elliott	0
K_Floyd	27924
K_Greenup	4131
K_Johnson	0
K_Lawrence	0
K_Martin	0
K_Magoffin	293
K_Morgan	65488
K_Pike	177548
O_Athens	11514
O_Belmont	87840
O_Gallia	23363
O_Jackson	41977
O_Lawrence	0
O_Meigs	66733
O_Monroe	0
O_Morgan	0
O_Noble	0
O_Scioto	44388
O_Vinton	286279
O_Washington	125023
P_Allegheny	8567
P_Beaver	0
P_Fayette	104890
P_Greene	3900
P_Somerset	67440
P_Washington	1348
P_Westmoreland	55750
M_Garrett	0

M_Allegany 353183 /;

Parameter MillProp(I) Proportion of mill residues available in each county;
MillProp(I)=0.4;

*Get the distance between any supply location and potential plant location from computer *

\$CALL GDXXRW.EXE C:\GAMS_Dis\distance.xls par=dis rng=D4:O97

Parameter dis(i,j);
\$GDXXIN distance.gdx
\$Load dis
\$GDXXIN
Display dis;

*Assumptions about transportation cost *

Scalar TP Truck purchased cost in dollars /140000/;
Scalar TSP Truck salvage value as a percentage of purchased cost /0.20/ ;
Scalar MPG_1 Truck miles per gallon on highways /5/;
Scalar MPG_2 Truck miles per gallon on local roads /5/;
Scalar MPH_1 Miles per hour on highways /35/;
Scalar MPH_2 Miles per hour on local roads /25/;
Scalar FPG Fuel price per gallon /3.55/;
Scalar DWH Driver's wage per hour including benefits /14/;
Scalar N Economic life of trucks /8/;
Scalar SMH Scheduled machine hours per year /2000/;
Scalar IITR Interest insurance and tax rate /0.20/;
Scalar MR Maintenance and repair rate as a percentage of depreciation /0.90/;
Scalar UT Utilization rate of trucks /0.90/;

Parameter TC(I,J) Transportation rate from location i to location j;
$$TC(I,J)=2*Dis(I,J)*(FPG/MPG_1+DWH/MPH_1+((TP-TP*TSP)*(1+MR)+IITR*((TP-TP*TSP)* (N+1)/2+N*TP*TSP))/N/SMH/UT/MPH_1) ;$$

*Truck and trailer loads for loose slash and chips *

Parameter TL(H) Truck load for harvesting system H in tons
/Cable-skidder 14
Cableskidder-chip 21
Grapple-skidder 14
Grappleskidder-chip 21 /;

Parameter TLT(I,J,h) Trucking cost in dollar per ton ;
TLT(I,J,h)= TC(I,J)/TL(h);

*Transportation distance within each county is assumed to be off-highway. *
*The transportation cost rate was calculated using Jesen's WTRANS program. *

Parameter LTC(H) Transportation cost off highway within counties (\$ per ton.mile);

$$LTC(H)=2*(FPG/MPG_2+DWH/MPH_2+((TP-TP*TSP)*(1+MR)+IITR*((TP-TP*TSP)* (N+1)/2+N*TP*TSP))/N/SMH/UT/MPH_2)/TL(h) ;$$

Parameter FC(SI) Coefficients of linearized local transportation turnover function

/1	1.583
2	3.322
3	4.738
4	6.474
5	9.156
6	11.856
7	14.040
8	15.925
9	18.377/;

Parameter B(SI) Right hand side of the constraints for separated variables in linearized function

/1	1000
2	2000
3	2000
4	5000
5	10000
6	10000
7	10000
8	10000
9	25000/;

Scalar Millcost Cost of mill residues (\$ per green ton) /20/;

Scalar Mill_load Load of mill residues in green tons /21/;

Parameter Milltrancost Cost of delivering mill residues (\$ per ton per mile);

$$Milltrancost=2*(FPG/MPG_1+DWH/MPH_1+((TP-TP*TSP)*(1+MR)+IITR*((TP-TP*TSP)* (N+1)/2+N*TP*TSP))/N/SMH/UT/MPH_1)/Mill_load;$$

Scalar TLoss Dry matter loss due to transportation /0.02/;

* Woody biomass-based biorefinery plant assumptions *

Scalar Capacity Plant capacity in terms of feedstock (dry tons) per day /2000/;

Parameter N Plant life;

$$N=CARD(project_year);$$

Scalar FT Federal tax applied to ethanol facility /0.39/;

Scalar Equity_prop Proportion of equity in the total investment /0.4/;

Scalar Re Cost of equity /0.15/;

Scalar Rd Cost of debt /0.08/;

Parameter WACC Weighted average cost of capital;

$$WACC = \text{Equity_prop} * Re + (1 - \text{Equity_prop}) * Rd * (1 - FT);$$

Parameter PVI(Project_year) Present value index at each project year;

$$PVI(\text{Project_year}) = 1 / \text{Power}((1 + WACC), \text{ORD}(\text{Project_year}));$$

Scalar M_S_97 Marshall & Swift all industry equipment cost index in 1997 /1056.8/;

Scalar M_S_07 Marshall & Swift all industry equipment cost index in 2007 /1373.3/;

Scalar GPD_97 Gross national product deflator index in 1997 /95.851/;

Scalar GPD_07 Gross national product deflator index in 2007 /120.737/;

Scalar Exponent Exponent indicator /0.7/;

Scalar R_cap Plant capacity in the reference in metric tons /2000/;

Parameter PEC_ref(Process_area) Plant equipment cost in the reference (\$)

/Feed_handling	4903353
Pretreatment	26320534
SSCF	13398435
Cellulase_production	15540831
Distillation	12974545
WWT	10381196
Storage	1820753
Boiler_turbogen	44465109
Utilities	5220291 /;

Parameter PEC(process_area) Plant equipment cost corresponding to demand level (\$);

$$PEC(\text{process_area}) = PEC_ref(\text{Process_area}) * M_S_07 / M_S_97 * ((\text{Capacity} / R_cap / 1.1) ** \text{Exponent});$$

Parameter TEC Total equipment cost (\$);

$$TEC = \text{Sum}(\text{process_area}, PEC(\text{process_area}));$$

Parameter WH Warehouse cost (\$);

$$WH = 0.015 * TEC;$$

Parameter SD Site development (\$);

$$SD = 0.09 * (PEC("Feed_handling") + PEC("Pretreatment") + PEC("SSCF") + PEC("Cellulase_production") + PEC("Distillation"));$$

Parameter TIC Total installed cost (\$);

$$TIC = TEC + WH + SD;$$

Parameter Field_expense Field expenses (\$);

$$\text{Field_expense} = 0.1 * TIC;$$

Parameter Homeoffice_construction Home office and construction fee (\$);

$$\text{Homeoffice_construction} = 0.25 * TIC;$$

Parameter Project_contingency Project contingency (\$);
 $\text{Project_contingency} = 0.03 * \text{TIC};$

Parameter Total_capital Total capital investment (\$);
 $\text{Total_capital} = \text{TIC} + \text{Field_expense} + \text{Homeoffice_construction} + \text{Project_contingency};$

Parameter Other_costs Other costs (\$);
 $\text{Other_costs} = 0.1 * \text{Total_capital};$

Parameter TPC Total project investment (\$);
 $\text{TPC} = (\text{Total_capital} + \text{other_costs});$

Parameter TPCC(J);
 $\text{TPCC(J)} = \text{TPC};$

Scalar R_Non_feedstock Non-feedstock raw material cost (1997\$) in the reference /8350000/;

Scalar R_water Water cost (1997\$) in the reference /450000/;

Scalar R_Waste_disposal Waste disposal cost in the reference (1997\$) /610000/;

Parameter Non_feedstock Non-feedstock raw material cost (2007\$);
 $\text{Non_feedstock} = \text{R_Non_feedstock} * (\text{GPD_07}/\text{GPD_97}) * (\text{Capacity}/\text{R_cap}/1.1);$

Parameter Waste_disposal Waste disposal cost (2007\$);
 $\text{Waste_disposal} = \text{R_Waste_disposal} * (\text{GPD_07}/\text{GPD_97}) * (\text{Capacity}/\text{R_cap}/1.1);$

Parameter Water Water cost (2007\$);
 $\text{Water} = \text{R_Water} * (\text{GPD_07}/\text{GPD_97}) * (\text{Capacity}/\text{R_cap}/1.1);$

Scalar R_Salary Total salaries in the reference (1997\$) /1532000/;

Parameter T_salary Total salary (2007\$);
 $\text{T_salary} = \text{R_salary} * \text{GPD_07}/\text{GPD_97} * ((\text{Capacity}/\text{R_cap}/1.1)^{\text{Exponent}});$

Parameter Direct_Overhead Direct Overhead (\$);
 $\text{Direct_Overhead} = 0.6 * \text{T_salary};$

Parameter Maintenance Maintenance (\$);
 $\text{Maintenance} = 0.03 * \text{TEC};$

Parameter Insurance Insurance and taxes (\$);
 $\text{Insurance} = 0.015 * \text{TIC};$

Parameter T_fixed_oper Total fixed operating costs (\$);
 $\text{T_fixed_oper} = \text{T_salary} + \text{Direct_Overhead} + \text{Maintenance} + \text{Insurance};$

Parameter OM Annual operating and maintenance cost without general overhead (\$);
 $\text{OM} = \text{T_fixed_oper} + \text{Non_feedstock} + \text{water} + \text{Waste_disposal};$

```

*****
*Calculate depreciation cost in terms of general plant and steam plant
*****
Parameter General_plant  General plant cost;
    General_plant=(1-PEC("Boiler_turbogen")/TEC)*TPC;

Parameter Steam_plant  Electricity steam plant cost;
    Steam_plant=TPC-General_plant;

Parameter C_general_remain;
    C_general_remain=General_plant;

Parameter N_general;
    N_general=7;

Parameter C_steam_remain ;
    C_steam_remain=Steam_plant;

Parameter N_steam;
    N_steam=20;

Parameter CG(Project_year)  Depreciation cost of general plant ;

Parameter C_general1(Project_year)  Depreciation cost of general plant using DDB;

Parameter C_general2(Project_year)  Depreciation cost of general plant using SL;

LOOP(Project_year,
    C_general1(Project_year)$(ORD(Project_year)LE N_general)=C_general_remain * 2 /N_general;
    C_general1(Project_year)$(ORD(Project_year)GT N_general)=0;
    C_general2(Project_year)$(ORD(Project_year)LE N_general)
        =C_general_remain/(N_general + 1 -ORD(Project_year));
    C_general2(Project_year)$(ORD(Project_year)GT N_general)=0;

    CG(Project_year)$(C_general1(Project_year)GT C_general2(Project_year))
        =C_general1(Project_year) ;
    CG(Project_year)$(C_general1(Project_year)LE C_general2(Project_year))
        =C_general2(Project_year) ;
    C_general_remain=C_general_remain-CG(Project_year);
);

Parameter CS(Project_year)  Depreciation cost of steam plant ;

Parameter C_steam1(Project_year)  Depreciation cost of steam plant using DDB;

Parameter C_steam2(Project_year)  Depreciation cost of steam plant using SL;

LOOP(Project_year,
    C_steam1(Project_year)=C_steam_remain * 1.5 / N_steam;
    C_steam2(Project_year)=C_steam_remain/(N_steam + 1-ORD(Project_year));
    CS(Project_year)$(C_steam1(Project_year)GT C_steam2(Project_year))

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```

=C_steam1(Project_year) ;
CS(Project_year)$(C_steam1(Project_year)LE C_steam2(Project_year))
=C_steam2(Project_year) ;
C_steam_remain=C_steam_remain-CS(Project_year);
);

Display CG, CS;
*****
*Capital recovery factor*
*****
Parameter rr;
rr=1/(1+WACC);

Scalar y0 the year of operation /3/;

Scalar ym the midpoint of the construction period /1/;

Parameter CRF Capital recovery factor;
CRF= (1-rr)/(1-power(rr,N))/power(rr,(y0-ym+1));

Display CRF;
*****
*Ethanol price is referred to the average ethanol price as of Feb 21, 2008 from Ethanol Market*
*Weekly News and Market Report*
*****
Parameter P(G) Price of products
/Ethanol 2.08
Electricity 0.05/;

Parameter Lambda(G) Conversion factors ;
Lambda("Ethanol")= 69.65;
Lambda("Electricity")= 1.76 * Lambda("ethanol");

Parameter Min Minimum storage at the plant;
Min= 7*capacity*2;

*****
Variables
OBF Objective
R Revenue
F Feedstock cost
T(Project_year) Federal tax at each project year
xh(I,H,m) Amounts of logging residues harvested at source i using harvest method h
in month m
xt(I,J,H,M) Amounts of logging residues transported from i to j in month m
xtl(I,J,H,SI) Annual separated delivered logging residues from I to J extracted by H
xm(I,J,M) Amounts of mill residues delivered from source i to plant j
xs(I,H,m) Logging residue stored at source i in month m
xps(I,H,m) Logging residue going into storage at source i in month m
xsn(I,H,m) Logging residue removed from storage at source i in month m
Beta(J) Binary variable for plant at location j

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Alfa(I,H)	Binary variable for harvesting method
Q(J,G,M)	Production of product G at location j in month m
SS(J,M)	Woody biomass stored at plant j in month m
SP(J,M)	Woody biomass processed at plant j in month m

;
Positive Variables xh, xt, xt1, xm, xs, xps, xsn, Q, SS, SP;
Binary Variables Beta, Alfa;

Equations

Obj	Objective function
Revenue	Annual revenue
Feedstock	Feedstock function
Tax(Project_year)	Federal Tax at each project year
Tax1(Project_year)	The situation of zero tax
Logresidue(I,H)	Logging residues available at source i
HSlope35(I,H)	Harvesting slope constraint
Ext_limit_1(I,H,M)	Extraction limit of logging residues at source i in month m
Ext_limit_2(I,H,M)	Extraction limit by cable skidder
Ext_limit_3(I,H,M)	Extraction limit by grapple skidder
Ext_limit_4(I,H,M)	Extraction limit by forwarder
Trans(I,J,H)	Sum of annual delivered logging residues from I to J by H at different section
Tran_con1(I,J,H,SI)	Annual delivered logging residues at different section from I to J by system H
Storage1(I,H,M)	Woody biomass supply balance using system h at source i in month m
Storage2(I)	Woody biomass supply balance at source i
Storage3(I,M)	Woody biomass storage system at source i in month m
Milltrant(I)	Amounts of Mill residues purchased at source i
MXplant	Maximum of one plant
MXHarvest(I)	Maximum of harvesting system
One(I)	Assign one harvesting system
P1(J,M)	Plant storage balance
P2(J,M)	Plant inventory requirement
P3(J,M)	Feedstock requirement at plant j in month m
Conversion(J,G,M)	Product conversion

Obj..

$$OBF = E = \text{sum}(\text{Project_year}, (R - F - OM - 0.06 * R - T(\text{Project_year})) * PVI(\text{Project_year})) - \text{sum}(J, \text{Beta}(J) * TPCC(J));$$

Revenue..

$$R - \text{sum}((J, G, M), P(G) * Q(J, G, M)) = E = 0;$$

Feedstock..

$$F - (\text{sum}((I, H, M), (EC(H) + \text{stumpage}) * xh(I, H, M)) + \text{sum}((I, H, M), SC * xps(I, H, m)) + \text{sum}((I, J, H, M), (\text{ChippingSite}(H) + LC(H) + TLT(I, J, H) + \text{ChippingPlant}(H)) * xt(I, J, H, M)) + \text{sum}((I, J, H, SI), (\text{Dis}(I, J) * LE \text{ LoggingResidue}(I, "Intradistance"), LTC(H) * FC(SI) * xt1(I, J, H, SI)) + \text{Millcost} * \text{sum}((I, J, M), xm(I, J, M)) + \text{sum}((I, J, M), \text{Milltrancost} * \text{Dis}(I, J) * xm(I, J, M))) = E = 0 ;$$

Tax(Project_year)\$(ORD(Project_year) GT 1)..

$$T(\text{Project_year}) - (R - F - OM - 0.06 * R - CG(\text{Project_year}) - CS(\text{Project_year})) * ft = E = 0;$$

Tax1(Project_year)\$ (ORD(Project_year) EQ 1)..
T(Project_year) =E=0;

Logresidue(I,H)..
sum(M,xh(I,H,M))-Alfa(I,H)*loggingavai(I) =L=0;

HSlope35(I,H)..
sum(M,xh(I,H,M))-Alfa(I,H)*loggingSlope(I)=L=0;

Ext_limt_1(I,H,M)..
xh(I,H,M)-Ext_amt(I,H,M) =L=0;

Ext_limt_2(I,H,M)\$ (ord(H) LE 2)..
xh(I,H,M)-20*80*1.5*PD(H)/35.3*0.77 =L=0;

Ext_limt_3(I,H,M)\$ (ord(H) EQ 3 or ord(H) EQ 4)..
xh(I,H,M)-20*80*1.6*PD(H)/35.3*0.77 =L=0;

Ext_limt_4(I,H,M)\$ (ord(H) GE 5)..
xh(I,H,M)-20*80*1*PD(H)/35.3*0.77 =L=0;

Trans(I,J,H)..
sum(SI,xt1(I,J,H,SI))-sum(M,xt(I,J,H,M))=E=0;

Tran_con1(I,J,H,SI)..
xt1(I,J,H,SI)=L=B(SI);

Storage1(I,H,M)..
xh(I,H,M)+ UPS*xs(I,H,M-1)-sum(J,xt(I,J,H,M))-xs(I,H,M) =G=0;

Storage2(I)..
sum((H,M),xh(I,H,M))-sum((J,H,M),xt(I,J,H,M))-(1-UPS)*sum((H,M),xs(I,H,M)) =E=0;

Storage3(I,M)..
sum(H,xh(I,H,M))-sum(H,xps(I,H,M))+sum(H,xsn(I,H,M))-sum((J,H),xt(I,J,H,M)) =E=0;

Milltrant(I)..
sum((J,M),xm(I,J,M))-MillProp(I)*MillResidue(I)=L=0;

MXplant..
sum(J, Beta(J)) =E=1;

MXHarvest(I)..
sum(H, Alfa(I,H)) =E=1;

One(I)..
Alfa(I, "Cable-skidder")=E=1;

P1(J,M)..
sum(I,xm(I,J,M))+sum((I,H),xt(I,J,H,M))*(1-TLoss)+UPS*SS(J,M-1)-SP(J,M)-SS(J,M)=E=0;

P2(J,M)..
SS(J,M)-MIN*Beta(J) =G=0;

P3(J,M)..
 $(1-WC)*SP(J,M)-30*Capacity*Beta(J)=E=0;$

Conversion(J,G,M)..
 $Q(J,G,M)-(1-WC)*Lambda(G)*SP(J,M)=L=0;$

 *Solve the model *

 Model Bioplant /all/;

Solve Bioplant maximizing OBF using MIP;

Option solprint=off;

 *Results *

Parameter Adj_tax(project_year) Adjusted tax for each project year;
 $Adj_tax(project_year)\$((R.l-F.l-(OM+0.06*R.l)-CG(Project_year)-CS(Project_year)) \leq 0) = 0;$
 $Adj_tax(project_year)\$((R.l-F.l-(OM+0.06*R.l)-CG(Project_year)-CS(Project_year)) > 0)$
 $= (R.l-F.l-(OM+0.06*R.l)-CG(Project_year)-CS(Project_year))*FT;$

Display Adj_tax;

Parameter T_OM Total operation and maintenance cost;
 $T_OM = OM + 0.06*R.l;$
 Display T_OM;

Parameter Adj_obj Adjusted net present value;
 $Adj_obj = SUM(Project_year, ((R.l-F.l-OM-0.06*R.l-Adj_tax(project_year))*PVI(Project_year)))$
 $-sum(J, TPCC(J)*beta.l(J));$
 Display Adj_obj;

 *Ethanol production cost per gallon *
 *c1-capital cost; c2-feedstock cost (biomass); c3-non-feedstock cost; c4-water cost; *
 *c5-waste disposal; c6-salary; c7-maintenance cost; c8-direct overhead; c9-sales related overhead *
 *c10-insurance; c11-electricity credit *

Parameter c1,c2,c3,c4,c5,c6,c7,c8,c9,c10,c11, c12 unit cost by category and total cost per gallon;
 $c1 = sum(J, Beta.l(J)*TPCC(J))*CRF/sum((J,G,M)\$(ord(G) EQ 1), Q.L(J,G,M));$

$c2 = F.L/sum((J,G,M)\$(ord(G) EQ 1), Q.L(J,G,M));$

$c3 = Non_feedstock/sum((J,G,M)\$(ord(G) EQ 1), Q.L(J,G,M));$

$c4 = Water/sum((J,G,M)\$(ord(G) EQ 1), Q.L(J,G,M));$

$c5 = Waste_disposal/sum((J,G,M)\$(ord(G) EQ 1), Q.L(J,G,M));$

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c6=T_salary/sum((J,G,M)$ (ord(G) EQ 1),Q.L(J,G,M));

c7=Maintenance/sum((J,G,M)$ (ord(G) EQ 1),Q.L(J,G,M));

c8=Direct_overhead/sum((J,G,M)$ (ord(G) EQ 1),Q.L(J,G,M));

c9=0.06*R.l/sum((J,G,M)$ (ord(G) EQ 1),Q.L(J,G,M));

c10=Insurance/sum((J,G,M)$ (ord(G) EQ 1),Q.L(J,G,M));

c11=1.76*P("Electricity");

c12=c1+c2+c3+c4+c5+c6+c7+c8+c9+c10 - c11;

Display c1,c2,c3,c4,c5,c6,c7,c8,c9,c10,c11,c12;

*****
*Woody biomass delivered per year*
*****
Parameter Trans_log, Trans_mill;
      Trans_log=sum((I,J,H,M),xt.l(I,J,H,M));

      Trans_mill=sum((I,J,M),xm.l(I,J,M));
Display Trans_log, Trans_mill;

*****
*End of code*
*Note: Some data are stored in the Excel spreadsheets and not visible in the GAMS code. The*
*followings are the detailed data.*
*****

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PARAMETER dis

	Beaver_Raleigh	Belington	Bluefield	Buckhannon	Holden
Barbour	114.000	11.000	145.000	15.000	143.000
Boone	42.000	121.000	64.000	107.000	20.000
Braxton	67.000	51.000	100.000	33.000	94.000
Cabell	72.000	126.000	95.000	110.000	43.000
Calhoun	81.000	63.000	115.000	47.000	91.000
Clay	50.000	73.000	83.000	57.000	69.000
Doddridge	109.000	49.000	142.000	37.000	122.000
Fayette	22.000	92.000	55.000	80.000	53.000
Gilmer	84.000	49.000	118.000	33.000	101.000
Grant	140.000	44.000	165.000	59.000	177.000
Greenbrier	47.000	75.000	69.000	69.000	94.000
Hampshire	171.000	67.000	196.000	82.000	206.000
Hardy	150.000	52.000	175.000	67.000	187.000
Harrison	115.000	28.000	147.000	21.000	136.000
Jackson	80.000	96.000	111.000	81.000	70.000

Kanawha	45.000	98.000	75.000	84.000	46.000
Lewis	97.000	29.000	129.000	14.000	119.000
Lincoln	64.000	128.000	85.000	113.000	32.000
Logan	46.000	137.000	59.000	124.000	5.000
Marion	34.000	38.000	19.000	133.000	42.000
Mcdowell	147.000	144.000	180.000	70.000	161.000
Mason	82.000	110.000	110.000	95.000	63.000
Mercer	26.000	130.000	10.000	121.000	61.000
Mineral	157.000	49.000	185.000	64.000	191.000
Mingo	54.000	152.000	57.000	135.000	9.000
Monongalia	146.000	42.000	178.000	47.000	170.000
Monroe	35.000	104.000	44.000	98.000	85.000
Nicholas	41.000	71.000	74.000	59.000	72.000
Pleasants	115.000	72.000	148.000	59.000	119.000
Pendleton	117.000	42.000	140.000	52.000	154.000
Pocahontas	67.000	56.000	91.000	53.000	110.000
Preston	143.000	34.000	174.000	45.000	171.000
Putnam	67.000	110.000	95.000	95.000	47.000
Raleigh	4.000	109.000	36.000	99.000	46.000
Randolph	103.000	13.000	131.000	21.000	137.000
Ritchie	102.000	61.000	135.000	47.000	109.000
Roane	74.000	78.000	107.000	62.000	77.000
Summers	16.000	107.000	33.000	98.000	66.000
Taylor	126.000	22.000	158.000	27.000	153.000
Tucker	124.000	17.000	152.000	33.000	158.000
Tyler	122.000	61.000	155.000	51.000	132.000
Upshur	100.000	16.000	131.000	0.000	127.000
Wayne	78.000	146.000	94.000	131.000	35.000
Webster	65.000	45.000	95.000	36.000	99.000
Wetzel	128.000	55.000	162.000	46.000	142.000
Wirt	92.000	79.000	125.000	63.000	93.000
Wood	101.000	85.000	133.000	70.000	99.000
Wyoming	24.000	132.000	28.000	121.000	34.000
V_Alleghany	58.000	86.000	71.000	83.000	108.000
V_Buchanan	62.000	170.000	48.000	158.000	40.000
V_Bath	88.000	64.000	106.000	68.000	135.000
V_Bland	44.000	147.000	12.000	139.000	72.000
V_Craig	53.000	112.000	54.000	108.000	103.000
V_Dickenson	80.000	188.000	65.000	175.000	52.000
V_Giles	40.000	123.000	32.000	117.000	86.000
V_Highland	97.000	46.000	120.000	53.000	142.000
V_Russell	72.000	181.000	50.000	170.000	57.000
V_Smyth	61.000	170.000	31.000	161.000	68.000
V_Tazewell	47.000	157.000	19.000	147.000	56.000
V_Wise	95.000	202.000	78.000	189.000	64.000
K_Boyd	94.000	156.000	110.000	141.000	50.000
K_Carter	106.000	169.000	120.000	154.000	60.000
K_Elliott	115.000	185.000	125.000	170.000	66.000
K_Floyd	89.000	183.000	87.000	169.000	42.000
K_Greenup	108.000	159.000	126.000	143.000	67.000
K_Johnson	98.000	183.000	102.000	168.000	48.000

K_Lawrence	88.000	164.000	98.000	149.000	39.000
K_Martin	78.000	166.000	84.000	152.000	28.000
K_Magoffin	105.000	191.000	107.000	176.000	55.000
K_Morgan	116.000	196.000	121.000	181.000	66.000
K_Pike	77.000	176.000	73.000	162.000	34.000
O_Athens	121.000	118.000	150.000	103.000	104.000
O_Belmont	158.000	87.000	191.000	81.000	164.000
O_Gallia	99.000	128.000	125.000	112.000	73.000
O_Jackson	121.000	145.000	145.000	129.000	90.000
O_Lawrence	94.000	139.000	116.000	123.000	60.000
O_Meigs	108.000	112.000	137.000	97.000	92.000
O_Monroe	137.000	77.000	170.000	68.000	143.000
O_Morgan	137.000	111.000	169.000	98.000	127.000
O_Noble	138.000	93.000	170.000	81.000	136.000
O_Scioto	127.000	165.000	148.000	149.000	89.000
O_Vinton	128.000	137.000	155.000	122.000	104.000
O_Washington	119.000	87.000	152.000	73.000	118.000
P_Allegheny	197.000	98.000	229.000	101.000	213.000
P_Beaver	204.000	111.000	237.000	112.000	216.000
P_Fayette	171.000	65.000	203.000	72.000	196.000
P_Greene	149.000	54.000	182.000	55.000	168.000
P_Somerset	198.000	88.000	228.000	100.000	228.000
P_Washington	175.000	81.000	208.000	82.000	190.000
P_Westmoreland	195.000	88.000	227.000	96.000	219.000
M_Garrett	159.000	49.000	188.000	61.000	190.000
M_Allegany	245.000	173.000	260.000	188.000	293.000

+	Kenna	Millwood	Morgantown	Oak_Hill_Fayette	Point_Pleasant
Barbour	93.000	100.000	34.000	100.000	114.000
Boone	43.000	57.000	148.000	36.000	58.000
Braxton	48.000	65.000	80.000	53.000	79.000
Cabell	31.000	34.000	144.000	62.000	29.000
Calhoun	35.000	41.000	79.000	65.000	56.000
Clay	35.000	53.000	101.000	33.000	65.000
Doddridge	64.000	65.000	50.000	93.000	79.000
Fayette	53.000	70.000	126.000	5.000	79.000
Gilmer	48.000	55.000	68.000	68.000	70.000
Grant	138.000	147.000	62.000	130.000	162.000
Greenbrier	85.000	102.000	115.000	25.000	113.000
Hampshire	163.000	169.000	67.000	160.000	184.000
Hardy	148.000	156.000	66.000	140.000	170.000
Harrison	83.000	86.000	32.000	100.000	100.000
Jackson	10.000	9.000	110.000	65.000	23.000
Kanawha	26.000	43.000	124.000	31.000	50.000
Lewis	69.000	76.000	50.000	82.000	90.000
Lincoln	36.000	44.000	149.000	56.000	40.000
Logan	60.000	72.000	165.000	47.000	70.000
Marion	91.000	106.000	179.000	116.000	108.000
Mcdowell	99.000	94.000	36.000	45.000	104.000
Mason	17.000	11.000	124.000	69.000	12.000

Mercer	95.000	112.000	168.000	42.000	117.000
Mineral	143.000	150.000	46.000	145.000	164.000
Mingo	75.000	81.000	181.000	60.000	79.000
Monongalia	113.000	115.000	0.000	131.000	129.000
Monroe	96.000	114.000	145.000	43.000	123.000
Nicholas	52.000	69.000	105.000	27.000	80.000
Pleasants	56.000	51.000	68.000	98.000	63.000
Pendleton	126.000	135.000	76.000	109.000	149.000
Pocahontas	91.000	106.000	98.000	60.000	119.000
Preston	120.000	124.000	18.000	132.000	138.000
Putnam	16.000	27.000	129.000	55.000	28.000
Raleigh	67.000	85.000	144.000	15.000	91.000
Randolph	97.000	107.000	55.000	91.000	122.000
Ritchie	49.000	49.000	66.000	85.000	63.000
Roane	19.000	28.000	95.000	58.000	42.000
Summers	82.000	100.000	145.000	26.000	107.000
Taylor	100.000	104.000	21.000	112.000	118.000
Tucker	113.000	121.000	42.000	112.000	136.000
Tyler	69.000	66.000	52.000	105.000	79.000
Upshur	80.000	88.000	47.000	86.000	103.000
Wayne	53.000	55.000	166.000	72.000	47.000
Webster	69.000	83.000	84.000	53.000	97.000
Wetzel	81.000	80.000	39.000	112.000	93.000
Wirt	30.000	28.000	87.000	76.000	42.000
Wood	36.000	28.000	89.000	85.000	40.000
Wyoming	76.000	94.000	165.000	35.000	96.000
V_Alleghany	105.000	122.000	128.000	59.000	132.000
V_Buchanan	102.000	115.000	202.000	73.000	112.000
V_Bath	117.000	132.000	106.000	84.000	145.000
V_Bland	113.000	129.000	186.000	61.000	133.000
V_Craig	115.000	133.000	154.000	62.000	142.000
V_Dickenson	115.000	126.000	219.000	91.000	122.000
V_Giles	109.000	127.000	164.000	53.000	133.000
V_Highland	114.000	128.000	87.000	90.000	141.000
V_Russell	118.000	131.000	215.000	84.000	128.000
V_Smyth	121.000	136.000	207.000	77.000	137.000
V_Tazewell	107.000	123.000	193.000	63.000	124.000
V_Wise	128.000	137.000	232.000	105.000	132.000
K_Boyd	61.000	59.000	173.000	88.000	47.000
K_Carter	73.000	69.000	184.000	100.000	57.000
K_Elliott	90.000	86.000	201.000	112.000	74.000
K_Floyd	98.000	103.000	209.000	93.000	96.000
K_Greenup	64.000	56.000	171.000	100.000	42.000
K_Johnson	92.000	94.000	205.000	99.000	84.000
K_Lawrence	71.000	73.000	184.000	85.000	63.000
K_Martin	79.000	84.000	191.000	79.000	77.000
K_Magoffin	100.000	102.000	213.000	106.000	92.000
K_Morgan	102.000	101.000	215.000	116.000	89.000
K_Pike	95.000	103.000	204.000	83.000	97.000
O_Athens	50.000	33.000	117.000	106.000	32.000
O_Belmont	101.000	93.000	59.000	141.000	103.000

O_Gallia	37.000	24.000	137.000	87.000	9.000
O_Jackson	58.000	43.000	149.000	109.000	30.000
O_Lawrence	43.000	37.000	152.000	84.000	24.000
O_Meigs	38.000	20.000	116.000	93.000	21.000
O_Monroe	79.000	72.000	60.000	120.000	83.000
O_Morgan	68.000	53.000	101.000	121.000	57.000
O_Noble	73.000	63.000	78.000	121.000	71.000
O_Scioto	73.000	61.000	171.000	118.000	47.000
O_Vinton	60.000	43.000	137.000	115.000	35.000
O_Washington	55.000	45.000	82.000	103.000	55.000
P_Allegheny	151.000	147.000	55.000	181.000	159.000
P_Beaver	153.000	147.000	70.000	188.000	157.000
P_Fayette	138.000	139.000	26.000	157.000	152.000
P_Greene	109.000	108.000	17.000	134.000	121.000
P_Somerset	174.000	176.000	61.000	185.000	190.000
P_Washington	128.000	124.000	40.000	159.000	136.000
P_Westmoreland	160.000	159.000	49.000	180.000	172.000
M_Garrett	138.000	142.000	32.000	146.000	157.000
M_Allegany	264.000	275.000	185.000	241.000	290.000

+ Williamson

Barbour	158.000
Boone	37.000
Braxton	110.000
Cabell	53.000
Calhoun	107.000
Clay	86.000
Doddridge	138.000
Fayette	69.000
Gilmer	117.000
Grant	194.000
Greenbrier	107.000
Hampshire	223.000
Hardy	203.000
Harrison	152.000
Jackson	85.000
Kanawha	60.000
Lewis	136.000
Lincoln	43.000
Logan	20.000
Marion	45.000
Mcdowell	176.000
Mason	76.000
Mercer	68.000
Mineral	206.000
Mingo	9.000
Monongalia	185.000
Monroe	95.000
Nicholas	89.000
Pleasants	133.000

Pendleton	170.000
Pocahontas	125.000
Preston	187.000
Putnam	61.000
Raleigh	59.000
Randolph	154.000
Ritchie	125.000
Roane	92.000
Summers	76.000
Taylor	168.000
Tucker	173.000
Tyler	146.000
Upshur	143.000
Wayne	39.000
Webster	116.000
Wetzel	158.000
Wirt	107.000
Wood	112.000
Wyoming	42.000
V_Alleghany	119.000
V_Buchanan	32.000
V_Bath	148.000
V_Bland	75.000
V_Craig	112.000
V_Dickenson	40.000
V_Giles	93.000
V_Highland	155.000
V_Russell	48.000
V_Smyth	65.000
V_Tazewell	56.000
V_Wise	51.000
K_Boyd	52.000
K_Carter	58.000
K_Elliott	61.000
K_Floyd	28.000
K_Greenup	69.000
K_Johnson	38.000
K_Lawrence	35.000
K_Martin	19.000
K_Magoffin	44.000
K_Morgan	57.000
K_Pike	19.000
O_Athens	114.000
O_Belmont	177.000
O_Gallia	81.000
O_Jackson	97.000
O_Lawrence	66.000
O_Meigs	102.000
O_Monroe	156.000
O_Morgan	139.000
O_Noble	149.000

O_Scioto	92.000
O_Vinton	111.000
O_Washington	130.000
P_Allegheny	227.000
P_Beaver	230.000
P_Fayette	210.000
P_Greene	183.000
P_Somerset	243.000
P_Washington	204.000
P_Westmoreland	233.000
M_Garrett	205.000
M_Allegany	306.000

APPENDIX III: ECONOMIC ANALYSIS MODEL FOR A CBTL PLANT

III.1 System requirement

To run the economic analysis model, the following requirements must be met:

- The GAMS system must be installed in a computer. For more detailed instruction, please go to <http://www.gams.com/default.htm>.
- A GAMS/Cplex license file must be presented.

III.2 Source code

\$ontext

This program is used to determine the economics of a coal/biomass to liquid fuels facility within the central Appalachian region.

Programmed by Jinzhuo Wu

Division of Forestry

West Virginia University

July 25, 2009

\$offtext

\$OFFSYMLIST OFFSYMREF

OPTION LIMCOL = 0;

OPTION LIMROW = 0;

OPTION SOLSLACK = 1;

OPTION ITERLIM=5000000;

OPTION RESLIM=1000000;

Sets

I Woody biomass supply locations

/KY_Adair, KY_Allen, KY_Anderson, KY_Ballard, KY_Barren, KY_Bath, KY_Bell,
KY_Boone, KY_Bourbon, KY_Boyd, KY_Boyle, KY_Bracken, KY_Breathitt,
KY_Breckinridge, KY_Bullitt, KY_Butler, KY_Caldwell, KY_Calloway,
KY_Campbell, KY_Carlisle, KY_Carroll, KY_Carter, KY_Casey, KY_Christian,
KY_Clark, KY_Clay, KY_Clinton, KY_Crittenden, KY_Cumberland, KY_Daviess,
KY_Edmonson, KY_Elliott, KY_Estill, KY_Fayette, KY_Fleming, KY_Floyd,
KY_Franklin, KY_Fulton, KY_Gallatin, KY_Garrard, KY_Grant, KY_Graves,
KY_Grayson, KY_Green, KY_Greenup, KY_Hancock, KY_Hardin, KY_Harlan,
KY_Harrison, KY_Hart, KY_Henderson, KY_Henry, KY_Hickman, KY_Hopkins,
KY_Jackson, KY_Jefferson, KY_Jessamine, KY_Johnson, KY_Kenton, KY_Knott,
KY_Knox, KY_Larue, KY_Laurel, KY_Lawrence, KY_Lee, KY_Leslie, KY_Letcher,
KY_Lewis, KY_Lincoln, KY_Livingston, KY_Logan, KY_Lyon, KY_McCracken,
KY_McCreary, KY_McLean, KY_Madison, KY_Magoffin, KY_Marion,
KY_Marshall, KY_Martin, KY_Mason, KY_Meade, KY_Menifee, KY_Mercer,
KY_Metcalf, KY_Monroe, KY_Montgomery, KY_Morgan, KY_Muhlenberg,
KY_Nelson, KY_Nicholas, KY_Ohio, KY_Oldham, KY_Owen, KY_Owsley,
KY_Pendleton, KY_Perry, KY_Pike, KY_Powell, KY_Pulaski, KY_Robertson,
KY_Rockcastle, KY_Rowan, KY_Russell, KY_Scott, KY_Shelby, KY_Simpson,
KY_Spencer, KY_Taylor, KY_Todd, KY_Trigg, KY_Trimble, KY_Union, KY_Warren,
KY_Washington, KY_Wayne, KY_Webster, KY_Whitley, KY_Wolfe, KY_Woodford,
VA_Accomack, VA_Albemarle, VA_Alleghany, VA_Amelia, VA_Amherst,
VA_Appomattox, VA_Arlington, VA_Augusta, VA_Bath, VA_Bedford, VA_Bland,

VA_Botetourt, VA_Brunswick, VA_Buchanan, VA_Campbell, VA_Caroline,
 VA_Carroll, VA_Charles_City, VA_Charlotte, VA_Chesterfield, VA_Clarke,
 VA_Craig, VA_Culpeper, VA_Cumberland, VA_Dickenson, VA_Essex, VA_Fairfax,
 VA_Fauquier, VA_Floyd, VA_Fluvanna, VA_Franklin, VA_Frederick,
 VA_Giles, VA_Gloucester, VA_Goochland, VA_Grayson, VA_Greene, VA_Greensville,
 VA_Halifax, VA_Hanover, VA_Henrico, VA_Henry, VA_Highland,
 VA_Isle_of_Wight, VA_James_City, VA_King_and_Queen, VA_King_George,
 VA_King_William, VA_Lancaster, VA_Lee, VA_Loudoun, VA_Louisa, VA_Madison,
 VA_Mathews, VA_Mecklenburg, VA_Middlesex, VA_Montgomery, VA_Nelson,
 VA_New_Kent, VA_Northampton, VA_Northumberland, VA_Nottoway, VA_Orange,
 VA_Page, VA_Patrick, VA_Pittsylvania, VA_Powhatan, VA_Prince_Edward,
 VA_Prince_George, VA_Prince_William, VA_Pulaski, VA_Rappahannock,
 VA_Richmond, VA_Roanoke, VA_Rockbridge, VA_Rockingham, VA_Russell,
 VA_Scott, VA_Shenandoah, VA_Smyth, VA_Southampton, VA_Spotsylvania,
 VA_Stafford, VA_Surry, VA_Sussex, VA_Tazewell, VA_Warren,
 VA_Westmoreland, VA_Wise, VA_Wythe, VA_York, PA_Adams, PA_Allegheny,
 PA_Armstrong, PA_Beaver, PA_Bedford, PA_Berks, PA_Blair, PA_Bradford,
 PA_Bucks, PA_Butler, PA_Cambria, PA_Cameron, PA_Carbon, PA_Centre,
 PA_Chester, PA_Clarion, PA_Clearfield, PA_Clinton, PA_Columbia, PA_Crawford,
 PA_Cumberland, PA_Dauphin, PA_Delaware, PA_Elk, PA_Erie, PA_Fayette,
 PA_Forest, PA_Franklin, PA_Fulton, PA_Greene, PA_Huntingdon, PA_Indiana,
 PA_Jefferson, PA_Juniata, PA_Lackawanna, PA_Lancaster, PA_Lawrence,
 PA_Lebanon, PA_Lehigh, PA_Luzerne, PA_Lycoming, PA_McKean, PA_Mercer,
 PA_Mifflin, PA_Monroe, PA_Montgomery, PA_Montour, PA_Northampton,
 PA_Northumberland, PA_Perry, PA_Philadelphia, PA_Pike, PA_Potter, PA_Schuylkill,
 PA_Snyder, PA_Somerset, PA_Sullivan, PA_Susquehanna, PA_Tioga, PA_Union,
 PA_Venango, PA_Warren, PA_Washington, PA_Wayne, PA_Westmoreland,
 PA_Wyoming, PA_York, MD_Allegany, MD_Anne_Arundel, MD_Baltimore,
 MD_Baltimore_City, MD_Calvert, MD_Caroline, MD_Carroll, MD_Cecil,
 MD_Charles, MD_Dorchester, MD_Frederick, MD_Garrett, MD_Harford, MD_Howard,
 MD_Kent, MD_Montgomery, MD_Prince_Georges, MD_Queen_Annes,
 MD_Saint_Marys, MD_Somerset, MD_Talbot, MD_Washington, MD_Wicomico,
 MD_Worcester, OH_Adams, OH_Allen, OH_Ashland, OH_Ashtabula, OH_Athens,
 OH_Auglaize, OH_Belmont, OH_Brown, OH_Butler, OH_Carroll, OH_Champaign,
 OH_Clark, OH_Clermont, OH_Clinton, OH_Columbiana, OH_Coshocton,
 OH_Crawford, OH_Cuyahoga, OH_Darke, OH_Defiance, OH_Delaware, OH_Erie,
 OH_Fairfield, OH_Fayette, OH_Franklin, OH_Fulton, OH_Gallia, OH_Gauga,
 OH_Greene, OH_Guernsey, OH_Hamilton, OH_Hancock, OH_Hardin, OH_Harrison,
 OH_Henry, OH_Highland, OH_Hocking, OH_Holmes, OH_Huron, OH_Jackson,
 OH_Jefferson, OH_Knox, OH_Lake, OH_Lawrence, OH_Licking, OH_Logan,
 OH_Lorain, OH_Lucas, OH_Madison, OH_Mahoning, OH_Marion, OH_Medina,
 OH_Meigs, OH_Mercer, OH_Miami, OH_Monroe, OH_Montgomery,
 OH_Morgan, OH_Morrow, OH_Muskingum, OH_Noble, OH_Ottawa, OH_Paulding,
 OH_Perry, OH_Pickaway, OH_Pike, OH_Portage, OH_Prebble, OH_Putnam,
 OH_Richland, OH_Ross, OH_Sandusky, OH_Scioto, OH_Seneca, OH_Shelby,
 OH_Stark, OH_Summit, OH_Trumbull, OH_Tuscarawas, OH_Union, OH_Van_Wert,
 OH_Vinton, OH_Warren, OH_Washington, OH_Wayne, OH_Williams, OH_Wood,
 OH_Wyandot, WV_Barbours, WV_Boone, WV_Braxton, WV_Cabell, WV_Calhoun,
 WV_Clay, WV_Doddridge, WV_Fayette, WV_Gilmer, WV_Grant, WV_Greenbrier,
 WV_Hampshire, WV_Hardy, WV_Harrison, WV_Jackson, WV_Kanawha,
 WV_Lincoln, WV_Logan, WV_Lewis, WV_Marion, WV_Marshall,

WV_McDowell, WV_Mason, WV_Mercer, WV_Mineral, WV_Mingo,
WV_Monongalia, WV_Monroe, WV_Nicholas, WV_Pendleton, WV_Pleasants,
WV_Pocahontas, WV_Preston, WV_Putnam, WV_Raleigh, WV_Randolph,
WV_Ritchie, WV_Roane, WV_Summers, WV_Taylor, WV_Tucker, WV_Tyler,
WV_Upshur, WV_Wayne, WV_Webster, WV_Wetzel, WV_Wirt, WV_Wood,
WV_Wyoming /

J Potential location for the CBTL plant
/WV_Boone/

W(I) Switchgrass and coal supply locations
/WV_Barbours, WV_Boone, WV_Braxton, WV_Cabell, WV_Calhoun, WV_Clay,
WV_Doddridge, WV_Fayette, WV_Gilmer, WV_Grant, WV_Greenbrier,
WV_Hampshire, WV_Hardy, WV_Harrison, WV_Jackson, WV_Kanawha,
WV_Lincoln, WV_Logan, WV_Lewis, WV_Marion, WV_Marshall,
WV_McDowell, WV_Mason, WV_Mercer, WV_Mineral, WV_Mingo,
WV_Monongalia, WV_Monroe, WV_Nicholas, WV_Pendleton, WV_Pleasants,
WV_Pocahontas, WV_Preston, WV_Putnam, WV_Raleigh, WV_Randolph,
WV_Ritchie, WV_Roane, WV_Summers, WV_Taylor, WV_Tucker, WV_Tyler,
WV_Upshur, WV_Wayne, WV_Webster, WV_Wetzel, WV_Wirt, WV_Wood,
WV_Wyoming /

Feedstock Feedstock used in CBTL
/Coal, Biomass/

Wood_residue Wood residue categories
/Log_wet, Mill_dry/

Avail_land Other available land for switchgrass production
/Hay_land, Coal_claimed_acre/

Coal_cate Coal production and use
/Coal_prod, Coal_use/

M Months of the production year
/Jan, Feb, Mar, Apr, May, Jun, Jul, Aug, Sep, Oct, Nov, Dec/

H Logging residue handling systems
/Cable-skidder, Cableskidder-chip, Grapple-skidder, Grappleskidder-chip/

G Products
/Diesel, Naphtha, Power/

Project_year Index of the project year
/1*30/

SI Separated line segment index for nonlinear programming
/1*9/

Product Final products
/Diesel, Naphtha/

SPA Activities associated with switchgrass production
/Establishment, Growth, Harvest/

;

Parameter MC(H) Hourly cost of extraction machine (\$ per PMH)

/Cable-skidder	81.34
Cableskidder-chip	81.34
Grapple-skidder	102.72
Grappleskidder-chip	102.72 /;

Parameter AED(H) Average extraction distance (feet);

AED(H)=984;

Parameter PL(H) Average payload size (cubic foot)

/Cable-skidder	106
Cableskidder-chip	106
Grapple-skidder	107.87
Grappleskidder-chip	107.87/;

*Productivities of extraction machines are from Li et al. 2006. Production economics of
*harvesting small-diameter hardwood stands in central Appalachia. *

Scalar BZ Bunch size (cubic foot) /54/;

Parameter PD(H) Productivity of extraction machine (cubic foot per hour);

PD(H) \$ (ORD(H) LE 2)=144.22-0.00001*AED(H)**2+1.60*PL(H)-1087.54/PL(H)
-0.0003*PL(H)**2+0.14*BZ+7.35/BZ-0.0008*BZ*BZ;

PD(H) \$ (ORD(H) EQ 3 or ORD(H) EQ 4)=505.88-0.00004*AED(H)**2+
0.005*PL(H)**2;

Parameter EC(H) Extraction cost for each system (\$ per green ton) ;

EC(H) =MC(H)/(PD(H)/35.3*0.77);

*Loading cost is derived by machine rate method. Loading productivity is calculated
*using Wang's model (2007). Hardwood log bucking and loading efficiency in West Virginia. *
*1MBF=1.62 cunit, 1 cunit=4.012 green tons. *

Scalar Loader_cost Hourly cost of loader (\$ per hour) /85.96/;

Scalar Logres_D Small end diameter of slash /5/;

Scalar NL Number of small logs or slash grappled per turn /5/;

Parameter LC(H) Average loading cost corresponding to harvesting system (\$ per ton);

LC(H)=Loader_cost/((-10.14+1.23*Logres_D+1.7058*NL)*162/35.3*0.77);

*Hourly chipping/grinding costs and productivity *

Parameter Cost_chipper(H) Hourly chipping cost (\$)

/Cable-skidder	212.27
Cableskidder-chip	185.62
Grapple-skidder	212.27
Grappleskidder-chip	185.62 /;

Parameter Productivity_chipper(H) Hourly chipping productivity (green tons)

/Cable-skidder	91
Cableskidder-chip	30
Grapple-skidder	91
Grappleskidder-chip	30 /;

Parameter ChippingSite(H) Chipping cost on forest landings (\$ per ton);

ChippingSite(H)\$ (ORD(H) EQ 1 OR ORD(H) EQ 3)=0;

ChippingSite(H)\$ (ORD(H) EQ 2 OR ORD(H) EQ 4)= Cost_chipper(H)/Productivity_chipper(H);

Parameter ChippingPlant(H) Chipping cost at the plant (\$ per green ton);

ChippingPlant(H)\$ (ORD(H) EQ 2 OR ORD(H) EQ 4)=0;

ChippingPlant(H)\$ (ORD(H) EQ 1 OR ORD(H) EQ 3)= Cost_chipper(H)/Productivity_chipper(H);

* Wood residues availability *

* Categories: logging residue-wet tons, mill residue-dry tons; *

\$call GDXXRW.EXE C:\GAMS_Dis\coalbiomassdata.xls PAR=Q_residue RNG= B1:D440

PARAMETER Q_residue(I,Wood_residue)

\$GDXIN coalbiomassdata.GDX

\$LOAD Q_residue

\$GDXIN

DISPLAY Q_residue;

Scalar BP Proportion of woody biomass that can be economically harvested /0.65/;

Parameter Loggingavai(I) Logging residues in tons for each supply location;

Loggingavai(I)=Q_residue(I,"log_weton") *BP ;

Scalar WC Woody biomass moisture content /0.43/;

Parameter ExtProp(M) Extracted proportion as a percentage of the whole year

/Jan	0.083
Feb	0.083
Mar	0.083
Apr	0.083
May	0.075
Jun	0.075
Jul	0.075
Aug	0.075
Sep	0.092
Oct	0.092
Nov	0.092

Dec 0.092 /;

Parameter Ext_amt(I,H,M) Extraction limit per month by county in green tons;
Ext_amt(I,H,M)=loggingavai(I)* ExtProp(M);

* Proportion of available woody biomass on site *

Scalar UPS Usable proportion of logging residues at supply locations /0.95/;

Scalar UPP Usable proportion of logging residues at plants /0.99/;

Scalar Stumpage Stumpage cost of logging residues in dollar per ton /0.91/;

Scalar SC Storage cost for logging residues in the field in dollar per ton /0.00/;

*Proportion of mill residue available *

Parameter MillProp(I) Proportion of mill residues available in each county;
MillProp(I)=0.4;

*The distance between any supply location and potential plant location *

* Distance between any woody biomass supply location and the plant location

\$call GDXXRW.EXE C:\GAMS_Dis\coalbiomassdata.xls PAR=dis RNG= H1:I440

PARAMETER dis(I,J)

\$GDXIN coalbiomassdata.GDX

\$ LOAD dis

\$GDXIN

DISPLAY dis;

* Distance between any switchgrass supply location and the plant location

\$call GDXXRW.EXE C:\GAMS_Dis\coalbiomassdata.xls PAR=ddis RNG= K391:L440

PARAMETER ddis(W,J)

\$GDXIN coalbiomassdata.GDX

\$ LOAD ddis

\$GDXIN

DISPLAY ddis;

* Hay lands and coal reclaimed area are used to produce switchgrass *

\$call GDXXRW.EXE C:\GAMS_Dis\coalbiomassdata.xls PAR=Acre RNG= M391:O440

PARAMETER Acre(W,Avai_land)

\$GDXIN coalbiomassdata.GDX

\$ LOAD Acre

\$GDXIN

DISPLAY Acre;

Parameter Switch_prod(Avai_land) Potential switchgrass production dry tons per acre
 /hay_land 6.23
 coal_claimed_acre 3.0 /;

Parameter Switch_landprop(Avai_land) Proportion of lands used in switchgrass production
 /hay_land 0.1
 coal_claimed_acre 0.1 /;

Parameter Switch_monthprop(M) Monthly production of switchgrass
 /Jan 0
 Feb 0
 Mar 0
 Apr 0
 May 0
 Jun 0
 Jul 1.00
 Aug 1.00
 Sep 1.00
 Oct 0.95
 Nov 0.90
 Dec 0.85 /;

 * Coal production and use in WV. Category: coal_prod, coal_use *
 *Coal production source: West Virginia Geological and Economic Survey *
 *http://www.wvgs.wvnet.edu/www/datastat/coalsummary/coal_summary.asp *
 * West Virginia coal statistics. <http://www.wvminesafety.org/STATS.HTM> *
 *The use of coal was mainly from electricity generation. The capability of large *
 *coal-fired power plants in WV were considered. *
 *1 ton coal can produce 2500 kWh electricity. *

\$call GDXXRW.EXE C:\GAMS_Dis\coalbiomassdata.xls PAR=Q_coal RNG= R391:T440
 PARAMETER Q_coal(W,coal_cate)
 \$GDXIN coalbiomassdata.GDX
 \$ LOAD Q_coal
 \$GDXIN
 DISPLAY Q_coal;

Parameter Coal_month(M) Monthly production of coal in 1000 tons
 /Jan 14160
 Feb 12771
 Mar 14899
 Apr 13363
 May 14228
 Jun 13274
 Jul 11507
 Aug 14459
 Sep 13370
 Oct 15061
 Nov 12037
 Dec 12116 /;

 *The transportation cost assumptions after consulting with local loggers in West Virginia. *

Scalar TP Truck purchased cost in dollars /140000/;
 Scalar TSP Truck salvage value as a percentage of purchased cost /0.20/;
 Scalar MPG_1 Truck miles per gallon on highways /5/;
 Scalar MPG_2 Truck miles per gallon on local roads /5/;
 Scalar MPH_1 Miles per hour on highways /35/;
 Scalar MPH_2 Miles per hour on local roads /25/;
 Scalar FPG Fuel price per gallon /3.55/;
 Scalar DWH Driver's wage per hour including benefits /14/;
 Scalar N Economic life of trucks /8/;
 Scalar SMH Scheduled machine hours per year /2000/;
 Scalar ITR Interest insurance and tax rate /0.20/;
 Scalar MR Maintenance and repair rate as a percentage of depreciation /0.90/;
 Scalar UT Utilization rate of trucks /0.90/;

Parameter TC(I,J) Transportation rate from location i to location j;

$$TC(I,J) = 2 * Dis(I,J) * (FPG/MPG_1 + DWH/MPH_1 + ((TP - TP * TSP) * (1 + MR) + ITR * ((TP - TP * TSP) * (N + 1) / 2 + N * TP * TSP)) / N / SMH / UT / MPH_1) ;$$

 *Truck and trailer loads for loose slash and chips were referred to "recovering logging residue: *
 *experiences from the Italian Eastern Alps". Since the load limit was 25 tons, therefore all the *
 *loads were adjusted accordingly. *

Parameter TL(H) Truck load for harvesting system H in tons
 /Cable-skidder 14
 Cableskidder-chip 21
 Grapple-skidder 14
 Grappleskidder-chip 21 /;

Parameter TLT(I,J,h) Trucking cost in dollar per ton ;

$$TLT(I,J,h) = TC(I,J) / TL(H);$$

Scalar Load_swch Truck load of switchgrass in green tons /18/;

Scalar Mois_swch Switchgrass moisture content /0.15/;

Scalar Storage_swch Switchgrass storage cost in the field /2.00/;

Parameter TS(W,J) Trucking cost of switchgrass in dollar per ton;

$$TS(W,J) = 2 * Dis(W,J) * (FPG/MPG_1 + DWH/MPH_1 + ((TP - TP * TSP) * (1 + MR) + ITR * ((TP - TP * TSP) * (N + 1) / 2 + N * TP * TSP)) / N / SMH / UT / MPH_1) / Load_swch;$$

Scalar Switch_purcost Purchase cost of switchgrass per short ton /45.45/;

Scalar Switch_grinding Grinding cost of switchgrass \$ per green ton /1.98/;

*Coal transport cost rate Data source: Energy Information Administration, Coal Transportation *
 *Rate Database, April 2004. *
 *Coal purchase cost source: Energy Information Administration, Coal News and Markets *
 * Dec. 12, 2008. According to EIA average open market sales price of coal by state and *

Scalar Coal_tranrate Transportation cost rate per ton mile /0.15/;

Scalar Coal_purcost Average mine-mouth price of coal per short ton /46/;

 *Transportation distance within each county is assumed to be off highway. *
 *The transportation cost rate was calculated using Jesen's WTRANS program. *

Parameter LTC(H) Transportation cost off highway within counties (\$ per ton.mile);

$$LTC(H)=2*(FPG/MPG_2+DWH/MPH_2+((TP-TP*TSP)*(1+MR)+IITR* \\ ((TP-TP*TSP)*(N+1)/2+N*TP*TSP))/N/SMH/UT/MPH_2)/TL(h) ;$$

Parameter Swch_ltc Switchgrass off highway transportation cost rate;

$$Swch_ltc=2*(FPG/MPG_2+DWH/MPH_2+((TP-TP*TSP)*(1+MR)+IITR* \\ ((TP-TP*TSP)*(N+1)/2+N*TP*TSP))/N/SMH/UT/MPH_2)/Load_swch ;$$

Parameter FC(SI) Coefficients of linearized local transportation turnover function (Woody biomass)

/1	1.583
2	3.322
3	4.738
4	6.474
5	9.156
6	11.856
7	14.04
8	15.925
9	18.377 /;

Parameter Swch_FC(SI) Coefficients of linearized local transportation turnover function (Switchgrass)

/1	2.11
2	4.43
3	6.32
4	8.64
5	12.22
6	15.82
7	18.73
8	21.25
9	25.01 /;

Parameter B(SI) Right hand side of the constraints for separated variable in linearized function

/ 1	1000
2	2000
3	2000
4	5000
5	10000
6	10000
7	10000

8 10000
9 25000 /;

Scalar Millcost Cost of mill residue (\$ per green ton) /20/;

Scalar Mill_load Load of mill residue in green tons /21/;

Parameter Milltrancost Cost of delivering mill residues (\$ per ton mile);

$$\text{Milltrancost} = 2 * (\text{FPG}/\text{MPG}_1 + \text{DWH}/\text{MPH}_1 + ((\text{TP} - \text{TP} * \text{TSP}) * (1 + \text{MR}) + \text{IITR} * ((\text{TP} - \text{TP} * \text{TSP}) * (\text{N} + 1) / 2 + \text{N} * \text{TP} * \text{TSP})) / \text{N} / \text{SMH} / \text{UT} / \text{MPH}_1) / \text{Mill_load};$$

Scalar TLoss Dry matter loss due to transportation /0.02/;

 * Coal/biomass to liquid fuels plant assumption *

Parameter Feedstock_needed_ref(Feedstock) Feedstock needed per day in the reference
 /Coal 4589
 Biomass 510/;

Scalar Day Working days per month /29/;

Parameter N Plant life ;
 N=CARD(project_year);

Scalar FT Federal tax applied to ethanol facility /0.39/;

Scalar Equity_prop Proportion of equity in the total investment /0.4/;

Scalar Re Cost of equity /0.15/;

Scalar Rd Cost of debt /0.08/;

Parameter WACC Weighted average cost of capital;

$$\text{WACC} = \text{Equity_prop} * \text{Re} + (1 - \text{Equity_prop}) * \text{Rd} * (1 - \text{FT});$$

* Compute amortization factor

Scalar r Inflation rate /0.02/;

Scalar p Construction period (years) /3/;

Scalar mf Maintenance factor /1.04/;

Parameter qq;

$$\text{qq} = (1 + \text{WACC}) * (1 + \text{r});$$

Parameter PVI Amortization factor;

$$\text{PVI} = 1 / (((\text{qq} ** (\text{N} + \text{p}) - 1) / ((\text{qq} - 1) * \text{qq} ** (\text{N} + \text{p})) - (\text{qq} ** \text{p} - 1) / ((\text{qq} - 1) * \text{qq} ** \text{p})) * \text{mf};$$

 Display PVI;

Scalar TPC_ref Total project investment in the reference 2005 dollar (\$) /1051000000/;

Scalar Fixed_OM_ref Annual operating and maintenance cost 2005 dollar (\$) /270000000/;

Scalar Var_OM_ref Variable operation and maintenance cost (\$) /35000000/;

Parameter Yield1(Product) Proportion of products produced based on total liquid fuels
/Diesel 0.6818
Naphtha 0.3182 /;

Parameter Yield3(Product) Proportion of products produced based on FT diesel equivalent
/Diesel 0.75
Naphtha 0.35 /;

Parameter Yield2(Feedstock) Liquid fuels from feedstock (bbls per ton of feedstock)
/Coal 2.25
Biomass 1.32/;

Parameter Daily_prod_ref Daily production in the reference barrels per day;
Daily_prod_ref=Sum(Feedstock,Yield2(Feedstock)*Feedstock_needed_ref(Feedstock));

* Plant capacity *

Parameter Feedstock_needed(Feedstock) Feedstock needed per day
/Coal 16110
Biomass 2843 /;

Parameter Daily_prod Daily production (barrels);
Daily_prod=Sum(Feedstock,Yield2(Feedstock)*Feedstock_needed(Feedstock));

Scalar M_S_05 Marshall & Swift all industry equipment cost index in 2005 /1244.5/;

Scalar M_S_07 Marshall & Swift all industry equipment cost index in 2007 /1373.3/;

Scalar GPD_05 Gross national product deflator index in 2005 /114.523/;

Scalar GPD_07 Gross national product deflator index in 2007 /120.737/;

Scalar Exponent Exponent indicator /0.7/;

*Extra capital and OM cost were based on: Gray et al. 2007. Increasing security and reducing *
*carbon emission of the U.S. transportation sector: A transformational role for coal with *
*biomass. US Department of Energy, National Energy Technology Laboratory. *

Parameter Extra_TPC Extra capital cost due to different coal biomass ratio;
Extra_TPC=4000000*(Feedstock_needed("Biomass")/Sum(Feedstock,
Feedstock_needed(Feedstock))-0.10)/0.05;

Parameter Extra_OM Extra operation and maintenance cost due to different coal biomass ratio;
Extra_OM=1000000*(Feedstock_needed("Biomass")/Sum(Feedstock,
Feedstock_needed(Feedstock))-0.10)/0.05;

Parameter TPC Total capital cost;
 $TPC = (TPC_ref + extra_TPC) * (M_S_07 / M_S_05) * (Daily_prod / Daily_prod_ref) ** 0.7;$

Parameter OM Operation and maintenance cost (\$);
 $OM = (Fixed_OM_ref * (Daily_prod / Daily_prod_ref) ** 0.65 + (Var_OM_ref + extra_OM) * Daily_prod / Daily_prod_ref) * (GPD_07 / GPD_05);$

Display Extra_TPC, Extra_OM, TPC, OM;

 *Calculate depreciation cost in terms of general plant and steam plant *

Parameter C_general_remain;
 $C_general_remain = TPC;$

Parameter N_general;
 $N_general = 16;$

Parameter CG(Project_year) Depreciation cost of general plant ;

LOOP(Project_year,
 $CG(Project_year)$(ORD(Project_year)LE N_general) = C_general_remain * 2 / N_general;$
 $CG(Project_year)$(ORD(Project_year)GT N_general) = 0;$
 $C_general_remain = C_general_remain - CG(Project_year);$
);
 Display CG;

Parameter Min_inventory(Feedstock) Minimum storage at the plant;
 $Min_inventory(Feedstock) = 7 * Feedstock_needed(Feedstock);$

Parameter Max_inventory(Feedstock) Maximum storage at the plant;
 $Max_inventory(Feedstock) = 45 * Feedstock_needed(Feedstock);$

Variables

OBF	Objective
F	Feedstock cost
xh(I,H,m)	Amounts of logging residues harvested at source i using harvest method h in month m
xt(I,J,H,M)	Amounts of logging residues transported from i to j in month m
xt1(I,J,H,SI)	Annual separated delivered logging residues from i to j extracted using h
xs(I,H,m)	Logging residue stored at source i in month m
xps(I,H,m)	Logging residue going into storage at source i in month m
xsn(I,H,m)	Logging residue removed from storage at source i in month m
xm(I,J,M)	Amounts of mill residues delivered from source i to plant j
xh_swch(W,M)	Switchgrass harvested at source w in month m
xt_swch(W,J,M)	Switchgrass transported from W to J at month m
swch_xt1(W,J,SI)	Annual separated delivered switchgrass from w to j
xs_swch(W,M)	Switchgrass stored in source w in month m
xsp_swch(W,M)	Switchgrass entered into storage in source w in month m
xsn_swch(W,M)	Switchgrass removed from storage in source w in month m

xt_co(w,J,M)	Coal delivered from location w to plant j in month m
Beta(J)	Binary variable for plant at location j
Alfa(I,H)	Binary variable for harvesting method
Q(J,Product,M)	Quantity of liquid fuels produced at plant j in month m
SS(J,Feedstock,M)	Quantity of feedstock stored at plant j in month m
SP(J,Feedstock,M)	Quantity of feedstock processed at plant j in month m
Delivered_feedstock(J,Feedstock,M)	Quantity of feedstock delivered to plant j in month m ;
Positive Variables	xh, xt, xt1, xs, xps, xsn, xm, Q, SS, SP, xh_swch, xt_swch, xs_swch, xsp_swch, xsn_swch, swch_xt1, xt_co, Delivered_feedstock;
Binary Variables	Beta, Alfa;

Equations

Obj	Objective function
Feedstock_func	Feedstock function
Logresidue(I,H)	Logging residues available at source i
Ext_limt_1(I,H,M)	Extraction limit of logging residues at source i in month m
Ext_limt_2(I,H,M)	Extraction limit by cable skidder
Ext_limt_3(I,H,M)	Extraction limit by grapple skidder
Ext_limt_4(I,H,M)	Extraction limit by forwarder
Trans(I,J,H)	Constraint 1 for woody biomass within county transportation
Tran_con1(I,J,H,SI)	Constraint 2 for woody biomass within county transportation
Storage1(I,H,M)	Woody biomass supply balance using system h at source i in month m
Storage2(I)	Woody biomass supply balance at source i
Storage3(I,M)	Woody biomass storage system at source i in month m
Milltrant(I)	Amounts of Mill residues purchased at source i
Swch_Trans(W,J)	Constraint 1 for switchgrass within county transportation
Swch_Trans_con1(W,J,SI)	Constraint 2 for switchgrass within county transportation
Switchgrass(W,M)	Switchgrass available at source w in month m
Switchgrass_st1(W,M)	Constraint 1 for switchgrass storage balance at source w in month m
Switchgrass_st2(W)	Constraint 2 for switchgrass storage balance at source w
Switchgrass_st3(W,M)	Constraint 3 for switchgrass storage balance at source w in month m
Coal_tran1(W,M)	Constraint for coal transportation 1
MXplant	Maximum of one plant
MXHarvest(I)	Maximum of harvesting system
One(I)	Assign one harvesting system
T1(J,M)	Biomass delivered
T2(J,M)	Coal delivered
P1(J,Feedstock,M)	Constraint 1 for plant processing
P2(J,Feedstock,M)	Constraint 2 for plant processing
P3(J,Feedstock,M)	Constraint 3 for plant processing
P4(J,Feedstock,M)	Constraint 4 for plant processing
Conversion(J,Product,M)	Coal to liquid conversion

Obj.. OBF =E=F+OM+TPC*PVI;

Feedstock_func.. F-(sum((I,H,M),(EC(H)+stumpage)* xh(I,H,M))+
sum((I,H,M),SC * xps(I,H,m))+sum((I,J,H,M),(ChippingSite(H)+
LC(H)+TLT(I,J,H)+ChippingPlant(H))* xt(I,J,H,M))+

$$\begin{aligned}
& \text{Millcost} * \text{sum}((I,J,M), \text{xm}(I,J,M)) + \\
& \text{sum}((I,J,M), \text{Milltrancost} * \text{Dis}(I,J) * \text{xm}(I,J,M)) + \\
& \text{sum}((I,J,H,SI) \$ (\text{Dis}(I,J) \text{ LE } 16), \text{LTC}(H) * \text{FC}(SI) * \text{xt1}(I,J,H,SI)) + \\
& \text{sum}((W,J,SI) \$ (\text{Dis}(W,J) \text{ LE } 16), \text{Swch_ltc} * \text{Swch_FC}(SI) * \text{swch_xt1}(W,J,SI)) + \\
& \text{sum}((W,M), \text{Switch_purcost} * \text{xh_swch}(W,M)) + \\
& \text{sum}((W,M), \text{storage_swch} * \text{xsp_swch}(W,M)) + \\
& \text{sum}((W,J,M), (\text{TS}(W,J) + \text{Switch_grinding}) * \text{xt_swch}(W,J,M)) + \\
& \text{sum}((W,J,M), \text{Coal_purcost} * \text{xt_co}(W,J,M)) + \\
& \text{sum}((W,J,M), \text{Coal_tranrate} * \text{ddis}(W,J) * \text{xt_co}(W,J,M))) \\
& = E = 0 ;
\end{aligned}$$

$$\begin{aligned}
& \text{Logresidue}(I,H).. \\
& \text{sum}(M, \text{xh}(I,H,M)) - \text{Alfa}(I,H) * \text{Loggingavai}(I) = L = 0;
\end{aligned}$$

$$\begin{aligned}
& \text{Ext_limt_1}(I,H,M).. \\
& \text{xh}(I,H,M) - \text{Ext_amt}(I,H,M) = L = 0;
\end{aligned}$$

$$\begin{aligned}
& \text{Ext_limt_2}(I,H,M) \$ (\text{ord}(H) \text{ LE } 2).. \\
& \text{xh}(I,H,M) - 20 * 180 * \text{PD}(H) * 0.02 = L = 0;
\end{aligned}$$

$$\begin{aligned}
& \text{Ext_limt_3}(I,H,M) \$ (\text{ord}(H) \text{ EQ } 3 \text{ or } \text{ord}(H) \text{ EQ } 4).. \\
& \text{xh}(I,H,M) - 20 * 192 * \text{PD}(H) * 0.02 = L = 0;
\end{aligned}$$

$$\begin{aligned}
& \text{Ext_limt_4}(I,H,M) \$ (\text{ord}(H) \text{ GE } 5).. \\
& \text{xh}(I,H,M) - 20 * 120 * \text{PD}(H) * 0.02 = L = 0;
\end{aligned}$$

$$\begin{aligned}
& \text{Trans}(I,J,H).. \\
& \text{Sum}(SI, \text{xt1}(I,J,H,SI)) - \text{sum}(M, \text{xt}(I,J,H,M)) = E = 0;
\end{aligned}$$

$$\begin{aligned}
& \text{Tran_con1}(I,J,H,SI).. \\
& \text{xt1}(I,J,H,SI) = L = B(SI);
\end{aligned}$$

$$\begin{aligned}
& \text{Storage1}(I,H,M).. \\
& \text{xh}(I,H,M) + \text{UPS} * \text{xs}(I,H,M-1) - \text{sum}(J, \text{xt}(I,J,H,M)) - \text{xs}(I,H,M) = E = 0;
\end{aligned}$$

$$\begin{aligned}
& \text{Storage2}(I).. \\
& \text{sum}((H,M), \text{xh}(I,H,M)) - \text{sum}((J,H,M), \text{xt}(I,J,H,M)) - (1 - \text{UPS}) * \text{sum}((H,M), \text{xs}(I,H,M)) = E = 0;
\end{aligned}$$

$$\begin{aligned}
& \text{Storage3}(I,M).. \\
& \text{sum}(H, \text{xh}(I,H,M)) - \text{sum}(H, \text{xps}(I,H,M)) + \text{sum}(H, \text{xsn}(I,H,M)) - \text{sum}((J,H), \text{xt}(I,J,H,M)) = E = 0;
\end{aligned}$$

$$\begin{aligned}
& \text{Swch_Trans}(W,J).. \\
& \text{Sum}(SI, \text{swch_xt1}(W,J,SI)) - \text{sum}(M, \text{xt_swch}(W,J,M)) = E = 0;
\end{aligned}$$

$$\begin{aligned}
& \text{Swch_Tran_con1}(W,J,SI).. \\
& \text{swch_xt1}(W,J,SI) = L = B(SI);
\end{aligned}$$

$$\begin{aligned}
& \text{Switchgrass}(W,M).. \\
& \text{xh_swch}(W,M) - \text{sum}(\text{Avai_land}, \text{Switch_monthprop}(M) * \text{Switch_prod}(\text{Avai_land}) \\
& / (1 - \text{Mois_swch}) * \text{Switch_landprop}(\text{Avai_land}) * \text{Acre}(W, \text{Avai_land})) = L = 0;
\end{aligned}$$


```

Switchgrass_st1(W,M)..
    xh_swch(W,M)+ UPS*xs_swch(W,M-1)-sum(J,xt_swch(W,J,M))-xs_swch(W,M) =E=0;

Switchgrass_st2(W)..
    sum(M,xh_swch(W,M))-sum((J,M),xt_swch(W,J,M))-(1-UPS)* sum(M,xs_swch(W,M)) =E=0;

Switchgrass_st3(W,M)..
    xh_swch(W,M)-xsp_swch(W,M)+xsn_swch(W,M)-sum(J,xt_swch(W,J,M)) =E=0;

Milltrant(I)..
    sum((J,M),xm(I,J,M))-MillProp(I)*Q_residue(I,"mill_dryton")/(1-WC)=L=0;

Coal_tran1(W,M)..
    sum((J),xt_co(w,J,M))-1000*(Q_coal(W,"coal_prod")-Q_coal(W,"coal_use"))/12 =L=0;

MXplant..
    sum(J, Beta(J)) =E=1;
MXHarvest(I)..
    sum(H, Alfa(I,H)) =E=1;
One(I)..
    Alfa(I, "Cable-skidder")=E=1;
T1(J,M)..
    (sum((I,H),xt(I,J,H,M))*(1-Tloss)+sum(I,xm(I,J,M)))*(1-WC) + sum(W,xt_swch(W,J,M))
    *(1-Mois_swch)-Delivered_feedstock(J,"Biomass",M) =E=0;

T2(J,M)..
    sum(W,xt_co(w,J,M))-Delivered_feedstock(J,"Coal",M) =E=0;

P1(J,Feedstock,M)..
    Delivered_feedstock(J,Feedstock,M)+UPP*SS(J,Feedstock, M-1)-SP(J,Feedstock,M)
    -SS(J,Feedstock,M)=E=0;

P2(J,Feedstock,M)..
    SS(J,Feedstock,M)-MIN_inventory(Feedstock)*Beta(J) =G=0;

P3(J,Feedstock,M)..
    SP(J,Feedstock,M)- Day*Feedstock_needed(Feedstock) =G=0;

P4(J,Feedstock,M)..
    SS(J,Feedstock,M)-MAX_inventory(Feedstock)*Beta(J) =L=0;

Conversion(J,Product,M)..
    Q(J,product,M)-Yield1(Product) * Sum(Feedstock, Yield2(Feedstock) * SP(J,Feedstock,M))
    =E=0;

```

Model Bioplant /all/;

Solve Bioplant min OBF using MIP;

Option solprint=off;

```

*****
*Results*
*****
Parameter RSP   Required selling price of F-T diesel (dollar per barrel);
      RSP=OBF.l/sum((J,M),(Q.l(J,"Diesel",M)+ 0.75 * Q.l(J,"Naphtha",M)));
Display RSP;

Parameter Switchgrass_harvest   Switchgrass harvested (metric tons);
      Switchgrass_harvest=sum((W,J,M),xt_swch.l(W,J,M))/1.1;
Display switchgrass_harvest;

Parameter Woody_harvest, Mill_resi   Woody biomass delivered (metric tons);
      Woody_harvest=sum((I,J,H,M),xt.l(I,J,H,M))/1.1;
      Mill_resi=sum((I,J,M),xm.l(I,J,M))/1.1;
Display Woody_harvest, Mill_resi;

Parameter FCM   Fuel consumption during transportation of biomass (gallons);
      FCM=(Sum((I,J,H,M),2*Dis(I,J)*xt.L(I,J,H,M)/TL(H))+Sum((I,J,M),2*Dis(I,J)*xm.L(I,J,M)
      /Mill_load)+ Sum((W,J,M),2*Dis(W,J)*xt_swch.L(W,J,M)/Load_swch))/MPG_1;
Display FCM;

Parameter Coalcost, Biomasscost, Annutpc, Omm   F-T diesel cost by category;
      Coalcost=sum((w,J,M),(Coal_tranrate * ddis(W,J)+ Coal_purcost)*xt_co.l(w,J,M))
      /sum((J,M),(Q.l(J,"Diesel",M)+ 0.75 * Q.l(J,"Naphtha",M)));

      Biomasscost=(F.l-sum((w,J,M),(Coal_tranrate * ddis(W,J)+Coal_purcost)*xt_co.l(w,J,M))
      /sum((J,M),(Q.l(J,"Diesel",M)+ 0.75 * Q.l(J,"Naphtha",M)));

      Annutpc=TPC*PVI/sum((J,M),(Q.l(J,"Diesel",M)+ 0.75 * Q.l(J,"Naphtha",M)));

      Omm=OM/sum((J,M),(Q.l(J,"Diesel",M)+ 0.75 * Q.l(J,"Naphtha",M)));

Display Coalcost, Biomasscost, Omm, Annutpc;

*****
*Biomass supply by county*
*****
Parameter County_log(I,M), County_mill(I,M), County_swt(W,M)   Biomass delivered by county by
month (metric tons);

      County_log(I,M)=sum((J,H),xt.l(I,J,H,M))/1.1;

      County_mill(I,M)=sum((J),xm.l(I,J,M))/1.1;

      County_swt(W,M)=sum((J),xt_swch.l(W,J,M))/1.1;

Display County_log, County_mill, County_swt;

*****
*This part is used to export the delivered feedstock to excel files*

```

```
Execute_unload "results1.gdx" xt.l
Execute 'gdxxrw.exe results1.gdx o=results1.xls var=xt.l'
```

```
Execute_unload "results2.gdx" xm.l
Execute 'gdxxrw.exe results2.gdx o=results2.xls var=xm.l'
```

```
Execute_unload "results3.gdx" xt_co.l
Execute 'gdxxrw.exe results3.gdx o=results3.xls var=xt_co'
```

```
Execute_unload "results4.gdx" xt_swch.l
Execute 'gdxxrw.exe results4.gdx o=results4.xls var=xt_swch'
```

*End of code *

*Note: Some data are stored in the Excel spreadsheets and not visible in the GAMS code. The *

*followings are the detailed data. The data with value zero are not shown. *

Q_residue

	Log_weton	Mill_dryton
KY_Adair	53720.000	49749.000
KY_Allen	67720.000	18492.000
KY_Anderson	3400.000	
KY_Ballard	28760.000	61075.000
KY_Barren	62080.000	43844.000
KY_Bath	28040.000	
KY_Bell	35520.000	
KY_Boone	2560.000	
KY_Bourbon	3360.000	
KY_Boyd	11240.000	
KY_Boyle	15920.000	26862.000
KY_Bracken	5640.000	
KY_Breathitt	90920.000	
KY_Breckinridge	76320.000	77757.000
KY_Bullitt	14160.000	
KY_Butler	43800.000	
KY_Caldwell	41640.000	20660.000
KY_Calloway	31800.000	
KY_Campbell	560.000	
KY_Carlisle	36120.000	12457.000
KY_Carroll	4440.000	
KY_Carter	57200.000	25766.000
KY_Casey	93960.000	50035.000
KY_Christian	54840.000	6788.000
KY_Clark	3640.000	
KY_Clay	74640.000	
KY_Clinton	59920.000	18077.000
KY_Crittenden	63960.000	17637.000

KY_Cumberland	59720.000	31012.000
KY_Daviess	19000.000	
KY_Edmonson	14680.000	4761.000
KY_Elliott	21920.000	
KY_Estill	46680.000	49318.000
KY_Fayette	1760.000	
KY_Fleming	22760.000	15359.000
KY_Floyd	35800.000	14030.000
KY_Franklin	480.000	
KY_Fulton	12200.000	
KY_Gallatin	1360.000	
KY_Garrard	3200.000	
KY_Grant	7000.000	
KY_Graves	46800.000	14000.000
KY_Grayson	39840.000	4841.000
KY_Green	29400.000	12694.000
KY_Greenup	43720.000	2076.000
KY_Hancock	21880.000	
KY_Hardin	47640.000	10676.000
KY_Harlan	141320.000	61955.000
KY_Harrison	2240.000	1408.000
KY_Hart	58800.000	22590.000
KY_Henderson	11720.000	
KY_Henry	9480.000	7670.000
KY_Hickman	8720.000	
KY_Hopkins	51240.000	19375.000
KY_Jackson	20960.000	
KY_Jefferson	5360.000	
KY_Jessamine	1800.000	
KY_Johnson	20960.000	
KY_Kenton	1320.000	
KY_Knott	27040.000	
KY_Knox	132520.000	54583.000
KY_Larue	30520.000	
KY_Laurel	199960.000	60641.000
KY_Lawrence	15080.000	
KY_Lee	60280.000	13911.000
KY_Leslie	67600.000	
KY_Letcher	35960.000	
KY_Lewis	133960.000	45523.000
KY_Lincoln	28440.000	
KY_Livingston	48400.000	23005.000
KY_Logan	31160.000	20419.000
KY_Lyon	33560.000	
KY_McCracken	5000.000	
KY_McCreary	85440.000	35167.000
KY_McLean	29880.000	
KY_Madison	5760.000	17849.000
KY_Magoffin	14960.000	123.000
KY_Marion	47800.000	13954.000
KY_Marshall	27800.000	11459.000

KY_Martin	27480.000	
KY_Mason	13480.000	
KY_Meade	26160.000	
KY_Meniffee	29600.000	13725.000
KY_Mercer	2520.000	
KY_Metcalf	65880.000	26283.000
KY_Monroe	59680.000	55792.000
KY_Montgomery	3720.000	
KY_Morgan	52080.000	33623.000
KY_Muhlenberg	41280.000	57487.000
KY_Nelson	16840.000	5302.000
KY_Nicholas	480.000	
KY_Ohio	142120.000	33892.000
KY_Oldham	2920.000	
KY_Owen	7000.000	
KY_Owsley	24320.000	
KY_Pendleton	2360.000	
KY_Perry	51680.000	39866.000
KY_Pike	108120.000	15938.000
KY_Powell	36320.000	18624.000
KY_Pulaski	107240.000	71385.000
KY_Robertson	720.000	
KY_Rockcastle	41520.000	11207.000
KY_Rowan	35680.000	59543.000
KY_Russell	36200.000	
KY_Scott	3080.000	
KY_Shelby	5240.000	975.000
KY_Simpson	6280.000	
KY_Spencer	1800.000	
KY_Taylor	60240.000	15275.000
KY_Todd	24000.000	14077.000
KY_Trigg	59080.000	33357.000
KY_Trimble	4200.000	
KY_Union	6800.000	
KY_Warren	20760.000	
KY_Washington	14600.000	
KY_Wayne	85680.000	40210.000
KY_Webster	23520.000	
KY_Whitley	61160.000	
KY_Wolfe	45520.000	6317.000
VA_Accomack	13120.000	
VA_Albemarle	79120.000	56572.000
VA_Alleghany	59480.000	121996.000
VA_Amelia	126760.000	67270.000
VA_Amherst	66160.000	50525.000
VA_Appomattox	82600.440	
VA_Augusta	42400.000	85897.000
VA_Bath	38240.000	
VA_Bedford	94960.000	53107.000
VA_Bland	28080.000	
VA_Botetourt	50360.000	

VA_Brunswick	287520.000	60890.000
VA_Buchanan	11080.000	10603.000
VA_Campbell	134360.000	94607.000
VA_Caroline	127360.000	74974.000
VA_Carroll	123960.000	49831.000
VA_Charles_City	34800.000	
VA_Charlotte	195160.000	116491.000
VA_Chesterfield	34080.000	
VA_Clarke	11240.000	
VA_Craig	11080.000	
VA_Culpeper	41960.000	15843.000
VA_Cumberland	80960.000	
VA_Dickenson	160800.000	
VA_Essex	38000.000	
VA_Fairfax	10920.000	
VA_Fauquier	18280.000	
VA_Floyd	42000.000	
VA_Fluvanna	28240.000	
VA_Franklin	123120.000	55954.000
VA_Frederick	42640.000	16421.000
VA_Giles	38640.000	
VA_Gloucester	57720.000	30366.000
VA_Goochland	22960.000	
VA_Grayson	69880.000	83065.000
VA_Greene	13400.000	
VA_Greensville	114280.000	218601.000
VA_Halifax	226840.000	80514.000
VA_Hanover	34920.000	161587.000
VA_Henrico	9720.000	
VA_Henry	124360.000	75025.000
VA_Highland	48480.000	
VA_Isle_of_Wight	72800.000	267439.000
VA_James_City	19400.000	
VA_King_and_Queen	97280.000	27687.000
VA_King_George	28320.000	
VA_King_William	39920.000	
VA_Lancaster	21800.000	
VA_Lee	62040.000	23767.000
VA_Loudoun	35280.000	16033.000
VA_Louisa	97920.000	70482.000
VA_Madison	22640.000	12199.000
VA_Mathews	1920.000	
VA_Mecklenburg	151040.000	
VA_Middlesex	22000.000	
VA_Montgomery	21840.000	44057.000
VA_Nelson	73080.000	
VA_New_Kent	49560.000	
VA_Northampton	9880.000	
VA_Northumberland	18680.000	
VA_Nottoway	70480.000	218171.000
VA_Orange	37080.000	

VA_Page	3000.000	
VA_Patrick	104880.000	69580.000
VA_Pittsylvania	246480.000	76054.000
VA_Powhatan	54200.000	
VA_Prince_Edward	69920.000	
VA_Prince_George	67120.000	78040.000
VA_Prince_William	20880.000	
VA_Pulaski	4120.000	
VA_Rappahannock	9560.000	
VA_Richmond	40120.000	40167.000
VA_Roanoke	9640.000	
VA_Rockbridge	68000.000	116550.000
VA_Rockingham	21360.000	
VA_Russell	17680.000	
VA_Scott	61280.000	99738.000
VA_Shenandoah	25760.000	1940.000
VA_Smyth	29720.000	
VA_Southampton	263600.000	
VA_Spotsylvania	41360.000	23664.000
VA_Stafford	24800.000	
VA_Surry	101000.000	
VA_Sussex	158120.000	
VA_Tazewell	13640.000	
VA_Warren	12840.000	
VA_Westmoreland	34720.000	
VA_Wise	32640.000	
VA_Wythe	78160.000	20059.000
VA_York	3600.000	
PA_Adams	161784.760	10290.000
PA_Allegheny	17113.840	4358.000
PA_Armstrong	78595.600	19484.000
PA_Beaver	3432.080	
PA_Bedford	145168.000	61313.000
PA_Berks	31963.680	6011.000
PA_Blair	41914.360	
PA_Bradford	99689.560	23643.000
PA_Bucks	5060.040	6556.000
PA_Butler	48171.800	13020.000
PA_Cambria	117037.080	39831.000
PA_Cameron	47291.320	22523.000
PA_Carbon	9362.400	157.000
PA_Centre	123939.960	16996.000
PA_Chester	38937.280	724.000
PA_Clarion	86717.240	49051.000
PA_Clearfield	244030.240	60530.000
PA_Clinton	81785.400	11383.000
PA_Columbia	79352.400	11768.000
PA_Crawford	79921.920	45456.000
PA_Cumberland	33769.280	1821.000
PA_Dauphin	43869.000	22407.000
PA_Delaware	1442.800	

PA_Elk	188453.480	47704.000
PA_Erie	26250.680	12135.000
PA_Fayette	91118.720	53298.000
PA_Forest	101200.840	
PA_Franklin	154585.960	68747.000
PA_Fulton	103865.560	15257.000
PA_Greene	39453.120	1958.000
PA_Huntingdon	175498.720	53667.000
PA_Indiana	104658.880	31588.000
PA_Jefferson	140959.240	81295.000
PA_Juniata	119690.320	68954.000
PA_Lackawanna	22904.320	22100.000
PA_Lancaster	46490.120	26032.000
PA_Lawrence	37260.440	3991.000
PA_Lebanon	28439.320	55144.000
PA_Lehigh	6437.160	594.000
PA_Luzerne	52769.120	2667.000
PA_Lycoming	165341.240	66079.000
PA_McKean	110846.840	44710.000
PA_Mercer	83215.120	25061.000
PA_Mifflin	77379.160	19369.000
PA_Monroe	18786.960	2045.000
PA_Montgomery	9368.040	765.000
PA_Montour	1712.680	
PA_Northampton	2190.640	877.000
PA_Northumberland	30765.040	
PA_Perry	109840.400	22224.000
PA_Philadelphia	796.360	
PA_Pike	27731.440	
PA_Potter	321324.400	192813.000
PA_Schuylkill	106854.800	17204.000
PA_Snyder	62929.400	25728.000
PA_Somerset	155606.440	34286.000
PA_Sullivan	128881.240	5239.000
PA_Susquehanna	79256.000	12184.000
PA_Tioga	132425.520	18297.000
PA_Union	26210.240	21195.000
PA_Venango	131210.680	29324.000
PA_Warren	189551.160	37086.000
PA_Washington	25863.600	676.000
PA_Wayne	56661.600	20512.000
PA_Westmoreland	73465.920	28302.000
PA_Wyoming	55606.960	13217.000
PA_York	64229.800	18491.000
MD_Allegany	106098.160	222507.000
MD_Anne_Arundel	1.400	
MD_Baltimore	12951.520	
MD_Calvert	5006.680	
MD_Carroll	1719.680	
MD_Cecil	42134.480	
MD_Charles	32675.920	

MD_Dorchester	47163.880	
MD_Frederick	3813.600	
MD_Garrett	184257.680	
MD_Harford	19157.680	
MD_Howard	3698.960	
MD_Kent	2952.800	
MD_Montgomery	2874.320	
MD_Prince_Georges	19339.400	
MD_Saint_Marys	23875.040	
MD_Somerset	86168.080	
MD_Talbot	12861.640	
MD_Washington	19271.360	
MD_Wicomico	117654.680	
MD_Worcester	92468.120	
OH_Adams	55429.400	9518.960
OH_Allen	3916.640	6678.120
OH_Ashland	17564.760	
OH_Ashtabula	13145.720	
OH_Athens	43002.080	
OH_Auglaize	8580.840	
OH_Belmont	17330.920	50947.200
OH_Brown	9202.000	5603.380
OH_Butler	4311.800	
OH_Carroll	20634.920	
OH_Champaign	528.080	
OH_Clark	1235.080	
OH_Clermont	13131.440	
OH_Clinton	477.360	7360.200
OH_Columbiana	16914.280	
OH_Coshocton	46848.800	9108.900
OH_Crawford	972.400	
OH_Cuyahoga	1162.640	
OH_Darke	725.600	
OH_Defiance	828.160	
OH_Delaware	1339.800	3644.720
OH_Erie	141.800	
OH_Fairfield	9308.880	8001.680
OH_Fayette	787.680	
OH_Franklin	1836.680	
OH_Fulton	154.120	
OH_Gallia	21577.480	13550.540
OH_Gauga	22926.800	
OH_Greene	1988.560	
OH_Guernsey	30919.840	
OH_Hamilton	11050.600	
OH_Hancock	1288.920	
OH_Hardin	2710.920	
OH_Harrison	34708.600	
OH_Highland	21122.440	
OH_Hocking	100675.000	
OH_Holmes	33293.720	

OH_Huron	1.440	
OH_Jackson	156035.440	24346.660
OH_Jefferson	18256.640	
OH_Knox	28692.600	7001.180
OH_Lake	2660.200	
OH_Lawrence	11477.000	
OH_Licking	17832.400	
OH_Logan	4359.880	
OH_Lorain	30.520	
OH_Lucas	9.360	
OH_Mahoning	13900.120	
OH_Marion	1270.320	
OH_Medina	6619.040	
OH_Meigs	62115.760	38705.140
OH_Mercer	3528.480	
OH_Miami	716.080	
OH_Montgomery	1741.080	
OH_Morgan	41876.120	
OH_Morrow	823.000	
OH_Muskingum	30057.760	
OH_Noble	12660.560	
OH_Ottawa	14.080	
OH_Paulding	1123.080	
OH_Perry	31440.200	
OH_Pickaway	3890.640	
OH_Pike	144788.440	46843.120
OH_Portage	11487.640	
OH_Preble	4373.880	
OH_Putnam	3185.360	
OH_Richland	6234.200	
OH_Ross	102619.280	7572.480
OH_Sandusky	23.440	
OH_Scioto	138557.320	25745.040
OH_Seneca	23.440	
OH_Shelby	3600.560	
OH_Stark	22046.960	
OH_Summit	3174.560	
OH_Trumbull	19256.880	
OH_Tuscarawas	64747.880	27043.080
OH_Union	2318.200	
OH_Van_Wert	1104.480	
OH_Vinton	159405.600	166041.800
OH_Warren	477.360	
OH_Washington	28081.440	72513.340
OH_Wayne	21387.000	
OH_Wood	23.440	
OH_Wyandot	411.480	
WV_Barbour	23885.000	11136.000
WV_Boone	52539.000	
WV_Braxton	85558.000	22828.800
WV_Cabell	19352.000	

WV_Calhoun	38323.000	
WV_Clay	61457.000	11358.720
WV_Doddridge	49434.000	7377.600
WV_Fayette	108269.000	10440.000
WV_Gilmer	41961.000	27.840
WV_Grant	25182.000	2004.480
WV_Greenbrier	70650.000	38057.280
WV_Hampshire	29328.000	
WV_Hardy	19834.000	1559.040
WV_Harrison	43089.000	
WV_Jackson	26038.000	1670.400
WV_Kanawha	158324.000	25195.200
WV_Lincoln	18459.000	334.080
WV_Logan	16380.000	
WV_Lewis	40551.000	
WV_Marion	42215.000	
WV_Marshall	31743.000	
WV_McDowell	70707.000	
WV_Mason	18170.000	
WV_Mercer	44234.000	556.800
WV_Mineral	12671.000	2784.000
WV_Mingo	69417.000	33633.500
WV_Monongalia	28661.000	27.840
WV_Monroe	42422.000	4732.800
WV_Nicholas	87436.000	88893.120
WV_Pendleton	28134.000	
WV_Pleasants	23575.000	11136.000
WV_Pocahontas	29431.000	44488.320
WV_Preston	90343.000	58742.400
WV_Putnam	23471.000	
WV_Raleigh	80051.000	23664.000
WV_Randolph	113787.000	123600.100
WV_Ritchie	63995.000	1740.000
WV_Roane	44518.000	278.400
WV_Summers	12775.000	5568.000
WV_Taylor	23885.000	417.600
WV_Tucker	36716.000	
WV_Tyler	23575.000	
WV_Upshur	65941.000	32016.000
WV_Wayne	22491.000	
WV_Webster	88773.000	8268.480
WV_Wetzel	47065.000	4454.400
WV_Wirt	39527.000	
WV_Wood	30324.000	84.077
WV_Wyoming	30324.000	8.352

dis

WV_Boone

KY_Adair 204.000

KY_Allen	258.000
KY_Anderson	169.000
KY_Ballard	407.000
KY_Barren	238.000
KY_Bath	107.000
KY_Bell	138.000
KY_Boone	172.000
KY_Bourbon	134.000
KY_Boyd	50.000
KY_Boyle	165.000
KY_Bracken	130.000
KY_Breathitt	93.000
KY_Breckinridge	255.000
KY_Bullitt	213.000
KY_Butler	275.000
KY_Caldwell	340.000
KY_Calloway	372.000
KY_Campbell	153.000
KY_Carlisle	405.000
KY_Carroll	188.000
KY_Carter	65.000
KY_Casey	179.000
KY_Christian	324.000
KY_Clark	130.000
KY_Clay	125.000
KY_Clinton	206.000
KY_Crittenden	348.000
KY_Cumberland	215.000
KY_Daviess	291.000
KY_Edmonson	252.000
KY_Elliott	72.000
KY_Estill	121.000
KY_Fayette	146.000
KY_Fleming	108.000
KY_Floyd	59.000
KY_Franklin	167.000
KY_Fulton	420.000
KY_Gallatin	175.000
KY_Garrard	155.000
KY_Grant	155.000
KY_Graves	387.000
KY_Grayson	249.000
KY_Green	210.000
KY_Greenup	66.000
KY_Hancock	271.000
KY_Hardin	224.000
KY_Harlan	118.000
KY_Harrison	138.000
KY_Hart	231.000
KY_Henderson	316.000
KY_Henry	185.000

KY_Hickman	407.000
KY_Hopkins	317.000
KY_Jackson	127.000
KY_Jefferson	215.000
KY_Jessamine	152.000
KY_Johnson	57.000
KY_Kenton	162.000
KY_Knott	82.000
KY_Knox	141.000
KY_Larue	218.000
KY_Laurel	141.000
KY_Lawrence	44.000
KY_Lee	109.000
KY_Leslie	106.000
KY_Letcher	86.000
KY_Lewis	90.000
KY_Lincoln	161.000
KY_Livingston	368.000
KY_Logan	292.000
KY_Lyon	351.000
KY_McCracken	381.000
KY_McCreary	174.000
KY_McLean	301.000
KY_Madison	138.000
KY_Magoffin	72.000
KY_Marion	192.000
KY_Marshall	370.000
KY_Martin	42.000
KY_Mason	114.000
KY_Meade	239.000
KY_Menifee	100.000
KY_Mercer	168.000
KY_Metcalf	223.000
KY_Monroe	234.000
KY_Montgomery	117.000
KY_Morgan	81.000
KY_Muhlenberg	301.000
KY_Nelson	201.000
KY_Nicholas	123.000
KY_Ohio	282.000
KY_Oldham	196.000
KY_Owen	168.000
KY_Owsley	110.000
KY_Pendleton	144.000
KY_Perry	95.000
KY_Pike	56.000
KY_Powell	113.000
KY_Pulaski	168.000
KY_Robertson	126.000
KY_Rockcastle	147.000
KY_Rowan	90.000

KY_Russell	194.000
KY_Scott	150.000
KY_Shelby	187.000
KY_Simpson	278.000
KY_Spencer	193.000
KY_Taylor	201.000
KY_Todd	307.000
KY_Trigg	341.000
KY_Trimble	195.000
KY_Union	335.000
KY_Warren	266.000
KY_Washington	189.000
KY_Wayne	187.000
KY_Webster	324.000
KY_Whitley	159.000
KY_Wolfe	98.000
KY_Woodford	160.000
VA_Accomack	336.000
VA_Albemarle	181.000
VA_Alleghany	142.000
VA_Amelia	215.000
VA_Amherst	154.000
VA_Appomattox	170.000
VA_Arlington	261.000
VA_Augusta	149.000
VA_Bath	110.000
VA_Bedford	134.000
VA_Bland	76.000
VA_Botetourt	112.000
VA_Brunswick	235.000
VA_Buchanan	56.000
VA_Campbell	158.000
VA_Caroline	243.000
VA_Carroll	107.000
VA_Charles_City	264.000
VA_Charlotte	187.000
VA_Chesterfield	240.000
VA_Clarke	220.000
VA_Craig	100.000
VA_Culpeper	209.000
VA_Cumberland	198.000
VA_Dickenson	72.000
VA_Essex	269.000
VA_Fairfax	250.000
VA_Fauquier	222.000
VA_Floyd	114.000
VA_Fluvanna	194.000
VA_Franklin	128.000
VA_Frederick	211.000
VA_Giles	78.000
VA_Gloucester	292.000

VA_Goochland	216.000
VA_Grayson	105.000
VA_Greene	184.000
VA_Greensville	253.000
VA_Halifax	181.000
VA_Hanover	243.000
VA_Henrico	240.000
VA_Henry	143.000
VA_Highland	123.000
VA_Isle_of_Wight	291.000
VA_James_City	284.000
VA_King_and_Queen	270.000
VA_King_George	252.000
VA_King_William	263.000
VA_Lancaster	292.000
VA_Lee	119.000
VA_Loudoun	241.000
VA_Louisa	207.000
VA_Madison	194.000
VA_Mathews	303.000
VA_Mecklenburg	211.000
VA_Middlesex	286.000
VA_Montgomery	99.000
VA_Nelson	161.000
VA_New_Kent	267.000
VA_Northampton	325.000
VA_Northumberland	291.000
VA_Nottoway	300.000
VA_Orange	201.000
VA_Page	186.000
VA_Patrick	129.000
VA_Pittsylvania	157.000
VA_Powhatan	215.000
VA_Prince_Edward	194.000
VA_Prince_George	254.000
VA_Prince_William	239.000
VA_Pulaski	90.000
VA_Rappahannock	203.000
VA_Richmond	275.000
VA_Roanoke	114.000
VA_Rockbridge	130.000
VA_Rockingham	161.000
VA_Russell	81.000
VA_Scott	107.000
VA_Shenandoah	187.000
VA_Smyth	86.000
VA_Southampton	277.000
VA_Spotsylvania	230.000
VA_Stafford	240.000
VA_Surry	280.000
VA_Sussex	261.000

VA_Tazewell	66.000
VA_Warren	205.000
VA_Westmoreland	271.000
VA_Wise	86.000
VA_Wythe	86.000
VA_York	296.000
PA_Adams	275.000
PA_Allegheny	191.000
PA_Armstrong	226.000
PA_Beaver	198.000
PA_Bedford	223.000
PA_Berks	352.000
PA_Blair	245.000
PA_Bradford	383.000
PA_Bucks	390.000
PA_Butler	218.000
PA_Cambria	235.000
PA_Cameron	304.000
PA_Carbon	378.000
PA_Centre	292.000
PA_Chester	358.000
PA_Clarion	253.000
PA_Clearfield	272.000
PA_Clinton	314.000
PA_Columbia	350.000
PA_Crawford	263.000
PA_Cumberland	288.000
PA_Dauphin	305.000
PA_Delaware	368.000
PA_Elk	284.000
PA_Erie	295.000
PA_Fayette	169.000
PA_Forest	268.000
PA_Franklin	258.000
PA_Fulton	242.000
PA_Greene	154.000
PA_Huntingdon	264.000
PA_Indiana	227.000
PA_Jefferson	259.000
PA_Juniata	293.000
PA_Lackawanna	400.000
PA_Lancaster	326.000
PA_Lawrence	217.000
PA_Lebanon	329.000
PA_Lehigh	381.000
PA_Luzerne	385.000
PA_Lycoming	336.000
PA_McKean	314.000
PA_Mercer	234.000
PA_Mifflin	286.000
PA_Monroe	406.000

PA_Montgomery	375.000
PA_Montour	342.000
PA_Northampton	396.000
PA_Northumberland	330.000
PA_Perry	296.000
PA_Philadelphia	383.000
PA_Pike	436.000
PA_Potter	326.000
PA_Schuylkill	350.000
PA_Snyder	316.000
PA_Somerset	199.000
PA_Sullivan	365.000
PA_Susquehanna	408.000
PA_Tioga	349.000
PA_Union	330.000
PA_Venango	253.000
PA_Warren	297.000
PA_Washington	168.000
PA_Wayne	424.000
PA_Westmoreland	197.000
PA_Wyoming	393.000
PA_York	303.000
MD_Allegany	197.000
MD_Anne_Arundel	294.000
MD_Baltimore	295.000
MD_Baltimore_City	393.000
MD_Calvert	285.000
MD_Caroline	329.000
MD_Carroll	279.000
MD_Cecil	340.000
MD_Charles	265.000
MD_Dorchester	313.000
MD_Frederick	255.000
MD_Garrett	160.000
MD_Harford	311.000
MD_Howard	281.000
MD_Kent	320.000
MD_Montgomery	261.000
MD_Prince_Georges	279.000
MD_Queen_Annes	318.000
MD_Saint_Marys	281.000
MD_Somerset	333.000
MD_Talbot	315.000
MD_Washington	246.000
MD_Wicomico	339.000
MD_Worcester	349.000
OH_Adams	107.000
OH_Allen	223.000
OH_Ashland	196.000
OH_Ashtabula	260.000
OH_Athens	89.000

OH_Auglaize	215.000
OH_Belmont	147.000
OH_Brown	127.000
OH_Butler	175.000
OH_Carroll	178.000
OH_Champaign	176.000
OH_Clark	168.000
OH_Clermont	147.000
OH_Clinton	145.000
OH_Columbiana	195.000
OH_Coshocton	152.000
OH_Crawford	199.000
OH_Cuyahoga	236.000
OH_Darke	207.000
OH_Defiance	261.000
OH_Delaware	169.000
OH_Erie	239.000
OH_Fairfield	123.000
OH_Fayette	135.000
OH_Franklin	148.000
OH_Fulton	271.000
OH_Gallia	57.000
OH_Gauga	245.000
OH_Greene	161.000
OH_Guernsey	136.000
OH_Hamilton	164.000
OH_Hancock	228.000
OH_Hardin	203.000
OH_Harrison	158.000
OH_Henry	261.000
OH_Highland	126.000
OH_Hocking	107.000
OH_Holmes	172.000
OH_Huron	224.000
OH_Jackson	82.000
OH_Jefferson	171.000
OH_Knox	165.000
OH_Lake	255.000
OH_Lawrence	58.000
OH_Licking	143.000
OH_Logan	190.000
OH_Lorain	230.000
OH_Lucas	266.000
OH_Madison	154.000
OH_Mahoning	219.000
OH_Marion	188.000
OH_Medina	212.000
OH_Meigs	68.000
OH_Mercer	227.000
OH_Miami	189.000
OH_Monroe	123.000

OH_Montgomery	175.000
OH_Morgan	110.000
OH_Morrow	181.000
OH_Muskingum	131.000
OH_Noble	117.000
OH_Ottawa	246.000
OH_Paulding	259.000
OH_Perry	116.000
OH_Pickaway	123.000
OH_Pike	97.000
OH_Portage	216.000
OH_Preble	192.000
OH_Putnam	237.000
OH_Richland	191.000
OH_Ross	109.000
OH_Sandusky	238.000
OH_Scioto	79.000
OH_Seneca	223.000
OH_Shelby	199.000
OH_Stark	191.000
OH_Summit	209.000
OH_Trumbull	225.000
OH_Tuscarawas	169.000
OH_Union	172.000
OH_Van_Wert	244.000
OH_Vinton	90.000
OH_Warren	161.000
OH_Washington	96.000
OH_Wayne	190.000
OH_Williams	277.000
OH_Wood	249.000
OH_Wyandot	207.000
WV_Barbour	121.000
WV_Braxton	73.000
WV_Cabell	32.000
WV_Calhoun	71.000
WV_Clay	48.000
WV_Doddridge	102.000
WV_Fayette	38.000
WV_Gilmer	80.000
WV_Grant	159.000
WV_Greenbrier	61.000
WV_Hampshire	187.000
WV_Hardy	168.000
WV_Harrison	116.000
WV_Jackson	53.000
WV_Kanawha	23.000
WV_Lincoln	22.000
WV_Logan	21.000
WV_Lewis	99.000
WV_Marion	130.000

WV_Marshall	139.000
WV_McDowell	45.000
WV_Mason	48.000
WV_Mercer	61.000
WV_Mineral	170.000
WV_Mingo	32.000
WV_Monongalia	148.000
WV_Monroe	76.000
WV_Nicholas	54.000
WV_Pendleton	140.000
WV_Pleasants	98.000
WV_Pocahontas	94.000
WV_Preston	153.000
WV_Putnam	32.000
WV_Raleigh	38.000
WV_Randolph	118.000
WV_Ritchie	89.000
WV_Roane	57.000
WV_Summers	57.000
WV_Taylor	131.000
WV_Tucker	137.000
WV_Tyler	110.000
WV_Upshur	107.000
WV_Wayne	37.000
WV_Webster	81.000
WV_Wetzel	120.000
WV_Wirt	73.000
WV_Wood	79.000
WV_Wyoming	36.000

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WV_Boone

WV_Barbour	121.000
WV_Boone	20.000
WV_Braxton	73.000
WV_Cabell	32.000
WV_Calhoun	71.000
WV_Clay	48.000
WV_Doddridge	102.000
WV_Fayette	38.000
WV_Gilmer	80.000
WV_Grant	159.000
WV_Greenbrier	61.000
WV_Hampshire	187.000
WV_Hardy	168.000
WV_Harrison	116.000
WV_Jackson	53.000
WV_Kanawha	23.000

WV_Lincoln	22.000
WV_Logan	21.000
WV_Lewis	99.000
WV_Marion	130.000
WV_Marshall	139.000
WV_McDowell	45.000
WV_Mason	48.000
WV_Mercer	61.000
WV_Mineral	170.000
WV_Mingo	32.000
WV_Monongalia	148.000
WV_Monroe	76.000
WV_Nicholas	54.000
WV_Pendleton	140.000
WV_Pleasants	98.000
WV_Pocahontas	94.000
WV_Preston	153.000
WV_Putnam	32.000
WV_Raleigh	38.000
WV_Randolph	118.000
WV_Ritchie	89.000
WV_Roane	57.000
WV_Summers	57.000
WV_Taylor	131.000
WV_Tucker	137.000
WV_Tyler	110.000
WV_Upshur	107.000
WV_Wayne	37.000
WV_Webster	81.000
WV_Wetzel	120.000
WV_Wirt	73.000
WV_Wood	79.000
WV_Wyoming	36.000

Acre

	Hay_land	Coal_claimed_acre
WV_Barbour	15300.000	9566.000
WV_Boone	24543.000	
WV_Braxton	9600.000	739.000
WV_Cabell	7700.000	2.700
WV_Calhoun	7700.000	
WV_Clay	2400.000	5256.000
WV_Doddridge	11300.000	228.000
WV_Fayette	5300.000	21950.000
WV_Gilmer	8200.000	2616.000
WV_Grant	15000.000	889.000
WV_Greenbrier	24700.000	4016.000
WV_Hampshire	21600.000	

WV_Hardy	17200.000	
WV_Harrison	19900.000	88374.000
WV_Jackson	21700.000	24.000
WV_Kanawha	3300.000	17060.000
WV_Lincoln	3900.000	1326.000
WV_Logan	54149.000	
WV_Lewis	12400.000	21100.000
WV_Marion	10900.000	12515.000
WV_Marshall	20500.000	168.000
WV_McDowell	50150.000	
WV_Mason	22100.000	1709.000
WV_Mercer	10000.000	4423.000
WV_Mineral	14700.000	8824.000
WV_Mingo	43844.000	
WV_Monongalia	12800.000	18788.000
WV_Monroe	20300.000	
WV_Nicholas	10300.000	8697.000
WV_Pendleton	16800.000	
WV_Pleasants	4100.000	48.000
WV_Pocahontas	16000.000	508.000
WV_Preston	31200.000	35733.000
WV_Putnam	10700.000	5082.000
WV_Raleigh	8200.000	6566.000
WV_Randolph	14500.000	8235.000
WV_Ritchie	13500.000	
WV_Roane	17700.000	
WV_Summers	8700.000	17.000
WV_Taylor	9900.000	2985.000
WV_Tucker	5000.000	6423.000
WV_Tyler	9100.000	
WV_Upshur	11900.000	3605.000
WV_Wayne	4200.000	2823.000
WV_Webster	1700.000	921.000
WV_Wetzel	7000.000	36.000
WV_Wirt	6500.000	
WV_Wood	17100.000	
WV_Wyoming	18112.000	

Q_coal

	Coal_prod	Coal_use
WV_Barbour	2171.000	2171.000
WV_Boone	33628.000	7723.000
WV_Braxton	335.000	
WV_Clay	3743.000	
WV_Fayette	3956.000	507.000
WV_Grant	122.000	122.000
WV_Greenbrier	667.000	
WV_Harrison	360.000	360.000

WV_Kanawha	12342.000	12048.000
WV_Lincoln	737.000	
WV_Logan	14655.000	
WV_Marion	13285.000	13285.000
WV_Marshall	9745.000	9469.000
WV_McDowell	6190.000	
WV_Mason	590.000	590.000
WV_Mineral	55.000	
WV_Mingo	12205.000	
WV_Monongalia	10673.000	4219.000
WV_Nicholas	4425.000	
WV_Preston	1479.000	961.000
WV_Raleigh	9132.000	
WV_Randolph	1121.000	1121.000
WV_Tucker	2761.000	2761.000
WV_Upshur	2036.000	139.000
WV_Wayne	4719.000	3872.000
WV_Webster	5110.000	
WV_Wyoming	4598.000	