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Non-Traditional Sources of Biomass Feedstocks

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In 2001, the U.S. consumed approximately 97 quadrillion btus (Quads) of primary energy. Petroleum was the single largest source (40%), followed by natural gas (24%), coal (23%), and nuclear energy (8%). Renewable energies provided 5.5 % of the total energy use with biomass energy the largest component (47%) followed by conventional hydroelectric energy (40%). Wind, solar, MSW incineration, and geothermal energies comprised the remainder (Figure 1) (DOE, 2003).

Research, development, and policy efforts are underway to substantially increase the use of renewable energy in the U.S. This paper will focus on biomass energy systems. Total biomass energy use in 2001 was 2.57 Quads and included the use of wood for residential heating (0.39 Quads), ethanol from grain (0.15 Quads), industrial power and heat (1.77 Quads mainly from black liquor and other pulp industry wastes), electricity from utilities (0.15 Quads), and other commercial uses (0.11 Quads)(DOE, 2003). As the biomass industry expands, existing sources of biomass feedstocks will continue to play a major role, but for a large scale expansion, additional biomass resources will be required, primarily in the form of cellulosic feedstocks.

The recent Energy Bill (Energy Policy Act of 2005) defines lignocellulosic or hemicellulosic matter as that which is available on a renewable or recurring basis including (1) dedicated energy crops and trees, (2) wood and wood residues, (3) plants, (4) grasses, (5) agricultural residues, (6) fibers, (7) animal wastes and other waste materials, and (8) municipal solid waste. Several studies have indicated that the principal sources of cellulosic feedstocks will be forest residues, primary mill residues, agricultural crop residues, dedicated energy crops, and urban wood wastes. This paper will summarize estimates of the current supplies of these five feedstock categories that includes consideration of the geographic distribution of each feedstock. A brief discussion of factors which will affect future supplies will be presented.

A. Forest Residues. Forest residues consist primarily of logging residues and other removals. Logging residues are defined as the unused portion of growing stock trees (commercial species with a diameter breast height of at least 5 inches, excluding cull trees) cut or killed by logging and left behind. Other removals are the unutilized wood volume from cut or otherwise killed growing stock, from cultural operations such as precommercial thinnings, or from timberland clearing (such as for urban development).

Few national level forest residue supply curves exist. Some analysts have constructed local and/or regional supply curves (see Kerstetter, 2001 for example), but the majority of the available studies involve constructing an inventory of quantities of residues generated with no economic analysis included. The Antares group estimated the availability of 72.2 million wet tons of forest residues in the U.S. and estimated a total quantity of 111 million wet tons of wood wastes (includes mill residues and urban wood wastes) available at prices of less than $4.00/million btu but did not separate the feedstock sources in their report (Antares, 1999). Oak

Ridge National Laboratory, using an somewhat updated version of a model developed by McQuillan (McQuillan,1988), estimated forest residue quantities of 23.7 million dry tons at <$30/dt delivered, 34.8 million dry tons at <$40/dt delivered, and 44.9 million dry tons at < $50/dt delivered (Walsh, 2000).

Walsh, relying on the use of the McQuillan model with additional updates and the U.S. Forest Service County Level Database of logging residues and other removals, estimated new forest residue supply curves. The McQuillan model uses forest inventory data along with information on logging and chipping costs, hauling distances and costs, stocking densities, wood types, and slope and equipment operability constraints to estimate regional supply schedules (for nine regions) for both softwood and hardwood chips for the base year of their study (1983) with projections for years 1990, 2010, and 2030. The model includes recoverability factors such as site accessibility (i.e., roads), and equipment limitations (e.g., collecting small pieces; assumed to be 50% in the model). For the analysis, the inventory was updated, although the structure and distribution remained the same as in the original model–thus the revised inventory totals were allocated proportionately across the same increments as by McQuillan. The analysis added a stumpage fee ($2.00/dry ton), factored out the transportation component, and updated prices to $2000. The estimated regional supply schedules for softwood and hardwood logging residues and other removals were then applied to the USDA Forest Service county level data (USDA-FS TPO) of the quantities of logging residues and other removals generated to construct the national forest residue supply curves contained in Table 1. The quantities of residues that can be removed and used for bioenergy are limited to 50 percent of those generated to allow for not only limits in equipment efficiency, but also to allow for covering of the ground to help control erosion. According to the Forest Service, the total quantities of residues produced in 2002 were 46.3 million dry tons of logging residues and 18.5 million dry tons of other removals. The estimated supplies should be viewed as preliminary at the time of this paper.

Table 1: Estimated Supply Curve for Forest Residues

	Preliminary Estimates of Forest Residue Supplies (thousand dry tons)						
	$20/dt	$25/dt	$30/dt	$35/dt	$40/dt	$45/dt	$50/dt
Logging Residues	0	4,366	12,482	20,592	23,148	23,148	23,148
Other Removals	611	3,327	6,492	7,739	8,184	8,590	8,988
TOTAL	611	7,693	18,974	28,331	31,332	31,738	32,136

The distribution of forest residues (at $40/dt) are presented in Figure 2. Residues are concentrated in the Southeast, Pacific Northwest, upper Lake States and New England, consistent with the existing forest industry.

A key limitation of the estimates is the ability to adequately update the original

McQuillan model and to change some structural assumptions. Complete model documentation is no longer available to permit these changes. Additionally, the model estimates costs at a regional level, precluding detailed differentiated cost estimates at a local level. Thus, while the existing estimates are a useful approximation of the supply of forest residues, the analysis would benefit from the development of a new forest residue model.

A potential additional source of forest industry feedstocks are those associated with the removal of excess biomass to reduce the risk of catastrophic fires and/or improve forest health. The USDA Forest Service is currently developing supply curves for fuel reduction biomass, but they are not yet available as of the writing of this paper. However, the quantities could be substantial. The Forest Service estimates that in the western U.S. (15 states), even if only 60 percent of the treatable timberland in fire regime condition class 3 was accessible for fuel treatment, this would require treatment (removal) of 346 million dry tons of biomass. However, much of the biomass involves small diameter trees which are expensive to harvest. Estimated harvest costs range from $35 to $62/dt depending on species, terrain, density, and diameter among other factors (Rummer, 2003).

B. Primary Mill Residues. Primary mills are those that convert roundwood products (i.e., logs) into other wood products and include sawmills that produce lumber, pulp mills, veneer mills, etc. In the process of converting trees into wood products, waste residues are generated consisting of bark, fine wood residues, and coarse wood residues. Bark is primarily used as a hog fuel. Fine wood residues include sawdust and shavings and are not suitable for chipping or use in fiber products because of the small particle size and the large proportion of fibers that are cut or broken. They are used mostly to produce particleboard, or for other uses such as bedding. Coarse residues include chunks, slabs, and larger pieces of wood that can be used in a variety of fiber uses including for pulp and oriented strandboard.

There are few examples of primary mill residue supply curves. Most of the analyses are quantity only and are based either on data from the USDA Forest Service Timber Product Output databasehttp://www.fia.fs.fed.us) or from surveys of local producers (e.g., Buehlmann, 2001). The Forest Service PTO provides county estimates of the quantities of bark, fines, and coarse wood produced at primary mills and their use by broad categories. According to the database, for 2002, 91.9 million tons of primary mill residues were produced, but only 1.86 million tons were not used either as fuel
(mostly in low efficiency boilers), for fiber uses, and for other uses. Given the extensive use of primary mill residues, most studies simply assume that the only quantities available for bioenergy are those not already used (i.e., less than 2 million tons). Walsh uses a different approach and assumes that residues currently used to produce products are still available for bioenergy uses, but that it will require a sufficiently high price to attract the feedstocks away from their existing uses to bioenergy uses.

The overall approach is to approximate the price that can be paid for mill residues to produce other products such as softwood and hardwood pulp, oriented strandboard, medium density fiberboard, particleboard, clean fuel chips, and other uses such as mulch and bedding. The analysis includes some additional processing costs (for example, size reduction of coarse wood chunks), and accounts for disposal costs of waste materials (i.e., tipping fees). Utilizing the TPO database of mill residues uses by type, along with supplemental state studies that further delineate residue uses, supply curves can be constructed (Table 2). The analysis is rough, includes a number of simplifying assumptions due to the lack of data, and is conducted in a static rather than dynamic framework, but indicates that at an appropriate price, some mill residues currently used in other uses (particularly lower valued uses such as on site heat generation, bedding, and mulch) could potentially become available for commercial bioenergy applications. Prices are in $2000 and are preliminary estimates.

Table 2: Estimated Supply Curve for Primary Mill Residues

Preliminary Estimates of Primary Mill Residue Supplies(thousand dry tons)							
$15/dt	$20/dt	$25/dt	$30/dt	$35/dt	$40/dt	$45/dt	$50/dt
1,655	33,305	36,342	36,342	41,538	47,648	47,648	53,669

Figure 3 presents the distribution of mill residues available for bioenergy uses at $40/dt. The distribution of mill residues is similar to those for forest residues.

C. Urban Wood Wastes. Urban wood wastes is a catchall term for wood contained in municipal solid waste such as packaging (containers, crates, pallets), durables (furniture) and yard trimmings; residential and non-residential construction wastes; residential and non-residential demolition wastes; and renovation and remodeling wastes. Some analysts also include wood wastes from the maintenance of municipal parks, utility line and right-of-way maintenance, urban land clearing, residues from commercial nurseries and landscapers, etc. Urban residues produced as a result of storm events are sometimes also included in the description. Most studies, however, limit the analysis to municipal solid waste (MSW) including yard trimmings, and construction, renovation, and demolition (C&D) wastes.

The majority of studies estimate the quantities available either locally (usually by survey) or nationally. Examples of local studies include the Triangle J study in North Carolina (Buehlmann, 2001). National assessments include the MSW and C&D Characterization studies conducted by Franklin and Associates for the Environmental Protection Agency (EPA, 2000; Franklin and Associates, 1998). Additional studies that provide national estimates are the landfill surveys from Virginia Polytech University (Araman, 1997; Bush, 1997) and *BioCycle* magazine's annual State of the Garbage Survey.

A national study by McKeever (2003) estimates a total of 65.3 million tons of MSW, yard trim and C&D wastes were generated in 2001 (18.9 million tons of MSW/yard trim; 9 million tons of construction/renovation wastes; and 27.4 million tons of demolition wastes). Of these quantities, he estimates that 6.2 million tons of MSW/yard trim, 6.9 million tons of construction/renovation wood wastes, and 11.2 million tons of demolition wastes are available for bioenergy use. McKeever does not provide estimates of the price that would need to be paid for the wood wastes and follows the convention of limiting the quantities of urban wood wastes available only to those that are not currently recovered and recycled into other products.

As noted above, the Antares Group includes urban wood waste quantities in their estimated national supply curve but do not sort out the different feedstock sources by price. They do however, report a total of 10.1 million wet tons of yard trim, 6.2 million wet tons of construction wood waste, 7.9 million wet tons of demolition wood wastes, and 6.8 million wet tons of other MSW wood wastes are available annually. Wiltsee (1998) surveyed the wood wastes generated in 30 metropolitan areas in the U.S. and extrapolated the data to the remainder of the US. He reports up to 60 million tons of wood wastes could be available at prices of less than $0/ton based on tipping fees.

Walsh has estimated county level supply curves for MSW (packaging, crates), MSW yard trim, construction wastes (residential and non-residential), demolition wastes (residential and non-residential) and renovation wastes (residential). MSW and yard trim quantities are estimated using the State of the Garbage surveys as a starting point and adjusting for regional wood quantities using data from Franklin and Associates and Araman. These sources were also used to identify quantities of wood wastes that are recycled into other products (such as mulch, compost, bedding, fuel, etc.). Residential construction waste quantities are estimated for single family and multi-family housing using total housing starts and the distribution of size (square feet) within each category. Average waste wood generated per square foot factors were applied to calculate total wood wastes generated. For non-residential construction, total expenditures and average cost/square foot factors were used to estimate total square foot. Application of waste/square foot factors allowed for the estimate of wood wastes generated as a result of non-residential construction. A similar methodology is used to estimate renovation wastes using expenditures for major renovation categories (such as kitchen and bath remodels, adding a deck, etc.). Demolition wastes are estimated using data on total C&D wastes landfilled and regional estimates of the composition of the wastes. Walsh estimates total urban wood quantities generated of 94.5 million dry tons/year with MSW/yard trim accounting for 26.1 million dry tons, construction and renovation wastes accounting for 18.6 million dry tons, and demolition wastes accounting for 18.5 million dry tons.

The price that must be paid is estimated as a function of sorting costs (mixed and source separated by waste stream type), net tipping fees (fee received minus that which must be paid for contaminated wood that must be disposed of after sorting), and the value of other products resulting from sorting (i.e., metal, glass, plastic). Similar to the approach for primary mill residues, it is assumed that wood wastes used to produce other products (mulch, compost, bedding, etc.) can be available for bioenergy use if the price is sufficiently high and rough approximations of the profits from these products is included in the estimate. Table 3 summarizes the estimated supply curves for urban wood wastes. The estimates are preliminary and are in $2000.

Table 3: Estimated Supply Curve for Urban Wood Wastes

	Preliminary Estimate of Urban Wood Waste Supplies (million dry tons)

	$15/dt	$20/dt	$25/dt	$30/dt	$35/dt	$40/dt	$45/dt	$50/dt
MSW/Yard Trim	5.9	6.9	7.6	8.0	5.3	8.8	9.6	10.0
Construction & Renovation	1.5	3.1	4.1	5.5	7.5	9.6	12.1	13.4
Demolition	0.3	0.4	0.8	4.0	9.4	12.2	15.0	15.4
TOTAL	7.7	10.4	12.5	17.5	22.2	30.6	36.7	38.8

Figure 4 shows the distribution of urban wood wastes available at $40/dt. Not surprisingly, the greatest concentrations occur near large cities and highly populated areas.

D. Agricultural Crop Residues. Agricultural crop residues are complementary products to the production of grain and oilseed crops, and thus the same factors that drive the production of agricultural crops will also drive the overall quantities of crop residues produced. However, the quantities of crop residues that can be potentially available for bioenergy uses must also account for the quantities that must be left on the field to maintain soil characteristics (i.e., control erosion, soil organic matter, soil moisture, etc.) taking into consideration tillage practices, crop rotations, field topography, and soil type. The costs and efficiency of collecting the residues, the costs of replacing lost nutrients from residue removal, and a return to farmers will be the principal determinants of agricultural crop residue prices.

All of the major grain and oilseed crops can be potential suppliers of agricultural residues, but most of the analyses focus on corn stover and wheat straw because these two feedstocks represent the largest potential quantities of agricultural crop residues and are the most widely distributed across the United States. However, some studies examine other agricultural crop residue supplies that are important at a local level (see for example Fife, 1999 for rice straw in California). Most studies estimate quantities only (no economic analysis) and do so using relatively simple assumptions regarding the quantities of residues that must remain to maintain soil quality. Gallagher (2003) estimated 98.9 million tons of corn stover available for bioenergy uses in the eleven largest corn producing states. Estimated corn stover harvest costs (including fertilizer replacement costs) were approximately $12.50/dt.

Nelson (2003) estimated the quantities of corn stover and wheat straw that can be removed by soil type, topography, tillage practice (conventional, reduced till, and no-till) and crop rotation while controlling for wind and rain erosion at or below the tolerable soil loss level, T (T is the maximum rate of soil erosion that will not lead to prolonged soil deterioration and/or loss of productivity as defined by the U.S. Department of Agriculture-Natural Resource Conservation Service). The quantities of agricultural crops residues that must remain to control for erosion are estimated using RUSLE (Revised Universal Soil Loss Equation) for water erosion and the Wind Erosion Equation (WEQ) for wind erosion. RUSLE estimates long-term average annual soil loss (tons/acre/year) from water erosion as a function of soil types, slopes, cropping rotations, and cropping management practices. WEQ is a function of a wind erodibility index (a measure of soil susceptibility to detach and be transported by wind), a soil ridge-roughness factor that describes the condition of the field surface at a particular time, a climate factor that represents the amount of erosive wind energy present at a particular location, wind direction and the unsheltered median travel distance across a field, and a vegetative factor.

The supply analysis assumes that agricultural crop residues are in the form of large round bales and collection costs include the cost of mowing, raking, and baling the residue, moving the bales to the edge of the field (staging), and stacking them at field's edge for storage. Different collection practices (combinations of windrowing, mowing, raking and baling operations) and equipment configurations (use of a crop processor or not) are assumed depending on removable quantity level. Fertilizer replacement costs are included, but not a return to the farmer. Table 4 presents the estimated supplies of corn stover and wheat straw under different tillage and crop rotation assumptions. Prices are in $2002.

Table 4: Estimated Supply Curves for Agricultural Crop Residues

Crop, Rotation, Tillage Combinations	Estimated Supplies of Agricultural Crop Residues (million dry tons)					
	$25/dt	$30/dt	$35/dt	$40/dt	$45/dt	$50/dt
Corn Stover, Corn-Soybean, Current Tillage Mix	0	25.6	40.5	42.3	43.8	44.4
Corn Stover, Corn-Soybean, All No-Till	0	95.4	123.7	126.8	129.5	130.2
Corn Stover, Continuous Corn, Current Tillage Mix	0	2.3	81.9	101.6	106.4	110.1
Corn Stover, Continuous Corn, All No-Till	0	34.3	160.9	181.9	187.7	192.6
Wheat Straw, Continuous Wheat, Current Tillage Mix	0.02	7.1	15.6	18.8	20.4	21.0
Wheat Straw, Continuous Wheat, All No-Till	0.03	14.7	41.5	54.6	60.1	62.1

Figures 5 and 6 present the distribution of corn stover and wheat straw at $40/dt assuming a continuous cropping system and all acres in no-till production–the maximum quantities available. Figure 7 presents the distribution of corn stover in the ten largest corn producing states under a corn-soybean rotation and assuming the current mix of tillage practices. This figure is most representative of the current situation.

E. Dedicated Energy Crops. Dedicated energy crops will compete for agricultural land with existing agricultural uses. The profitability of energy crops relative to the alternative uses for land will be a prime determinant of the quantities of these feedstocks that can potentially be available for bioenergy uses. To examine the potential for energy crop production in the United States, de la Torre Ugarte (2000), modified the POLYSYS model to include switchgrass, hybrid poplar, and willow. POLYSYS is a model of the agricultural sector and includes food, feed, industrial, and export demand; carry-over stocks; supply functions for the major crops (corn, grain sorghum, oats, barley, wheat, soybeans, cotton, rice, alfalfa, and other hay); supply functions for the major livestock sectors (beef, pork, lamb and mutton, broilers, turkeys, eggs, and milk); and edible oils and meals sectors. POLYSYS includes the major cropland categories (cropped, idle, pasture, and Conservation Reserve Program) and is comprised of 305 geographic regions. The model is tied to the USDA baseline projections.

Switchgrass is planted for a 10 year production rotation and harvested as large round bales. Varieties appropriate to each region are assumed. Fertilizer (both quantity and type) vary by region. Hybrid poplar is planted for 6-10 year rotations (depending on geographic region) and harvested as whole tree chips. As with switchgrass, fertilizer applications vary by region. Willows are planted in 22 year rotations, harvested every third year with coppice regrowth, and delivered as whole tree chips. Fertilizer is applied in the year following harvest. Herbicide applications for all crops are limited to the first two years of the production rotation. Yields vary by region and cropland type. All management practices assumed are based on research results, demonstration or commercial field experience where available, and expert opinion. For the analysis, dedicated energy crop production is limited to geographic regions where they can be produced under rainfed conditions and where sufficient research has been conducted to provide yield and management data for which experts have reasonable confidence. Bioenergy crops can be grown in other regions of the U.S. than used in this analysis, but data regarding appropriate varieties, management practices, and expected yields are lacking. These restrictions result in 149 million hectares (368 million acres) of cropland suitable for the production of at least one of the bioenergy crops. Energy crops compete not only with existing agricultural uses for land, but with each other.

Because switchgrass has higher productivity and lower production costs that the short rotation woody crops, at the same energy prices ($/btu), switchgrass dominates and most of the acres that are converted to energy crop production are for switchgrass production. Table 5 presents the estimated supply curves for dedicated energy crops on non-CRP acres. Figure 8 presents the geographic distribution of switchgrass production at $40/dt. Prices are in $1998. It should be noted that the analysis is currently being updated, but results were not yet available at the time this paper was written. The energy crop analysis also examined the potential to use the Conservation Reserve Program as a source of biomass feedstocks. The study identified 16.9 million acres (out of an enrolled 29.8 million acres) that could be suitable for energy crop production and estimated that at $40/dt, approximately 47.6 million dry tons of energy crops could be produced under a management scenario designed to provide high wildlife habitat and 55.3 million dry tons available under a management scenario designed to provide high biomass yield. The analysis was used by Congress to permit the production and harvest of dedicated energy crops on CRP acres, however, the original analysis assumed harvest every two years, and USDA subsequently revised the policy to permit harvest only every three years.

Table 5: Estimated Supply Curves for Dedicated Energy Crops

	Estimated Supplies of Dedicated Energy Crops (million dry tons)

	$25/dt	$30/dt	$35/dt	$40/dt	$45/dt	$50/dt
Switchgrass	4.3	57.9	96.4	131.1	165.7	193.3
Hybrid Poplar	0	0	0	0.04	0.06	0.4
Willow	0	0	0	0	0	0.02
Total	4.3	57.9	96.4	131.14	165.8	193.7

F. Total Quantities–Current Status. Figure 9 summarizes the potential supplies of the major cellulosic feedstocks given current technology and market conditions as discussed above, and includes the estimated potential quantities of dedicated energy crops that could be produced. The estimated quantities represent upper bounds in that they assume a 100 percent participation rate by potential suppliers (i.e., for corn stover, it assumes collection from every acre in corn production), do not fully account for all of the environmental constraints (i.e., soil carbon and moisture in addition to erosion), and likely underestimate the price that suppliers will actually demand for the product. It should also be noted that these prices are farm-gate prices and do not include transportation costs from the site of production to end use or centralized storage facilities.

G. Future Quantities. Forest and mill residues are complementary products to timber harvest to meet primarily housing and paper/pulp needs. Thus the quantities of forest and mill residues generated will be driven by the same economic and demographic factors as drive the housing and paper/paperboard markets. According to the recent USDA Forest Service RPA assessment (Haynes, 2003), domestic timber harvest is expected to increase 24 percent between 1997 and 2050. Municipal sold wastes are primarily a function of population and will increase at a similar rate. Agricultural crop residues are a complementary product to grain and oilseed crop production and quantities generated will move in tandem with increases in crop yields assuming that the residue to grain ratio remains unchanged as grain yields increase. Accounting for other environmental factors in addition to erosion will result in lower available quantities while a shift to increased use of no-till practices will increase available quantities. All of this presumes that grain yields will remain unchanged with residue removal relative to no removal, which in fact may not be the case, particularly on soils low in organic matter or where soil moisture is an issue. Dedicated energy crops offer substantial potential to be a source of biomass feedstocks, but research funding to develop these crops is relatively small, limiting the potential. Improvements in yields, establishment rates, and harvesting technologies will substantially improve their potential.

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