INTEGRATED WASTE SERVICES ASSOCIATION

Fact Sheet

Waste-to-Energy and the Production Tax Credit:

A tax credit for new, waste-to-energy facilities or new generating units at existing facilities continues the federal government's policy to encourage clean, renewable electricity, and promotes energy diversity while helping cities meet the challenge of trash disposal. Here is why the tax credit deserves your support.

- Waste-to-energy facilities produce electricity "with less environmental impact than almost any other source of electricity," according to the U.S. Environmental Protection Agency. The "outstanding performance" of waste-to-energy enables America "to continue to rely on municipal solid waste as a clean, reliable, renewable source of energy."

- Waste-to-energy facilities generate electricity and steam using municipal solid waste (garbage) as fuel. The garbage burns in specially designed boilers to ensure complete combustion, and facilities employ the most modern pollution control equipment available to scrub emissions. The result is clean, renewable energy.

- Nationwide, 89 waste-to-energy plants supply about 2700 megawatts of electricity to the grid. Plants operate 365-days-a-year, 24-hours a day. Facilities average greater than 90% availability of installed capacity. Waste-to-energy plants generally operate in or near an urban area, easing transmission to the customer.

- Facility revenues come from fees paid to dispose of the garbage and the price paid for electricity generated by waste-to-energy plants. New facilities or new generating units built at existing facilities require significant capital investment. The capital, and the operation and maintenance (O&M) costs at a facility equal about $100 for each ton of garbage processed at a facility. On an energy revenue basis, about 20 cents per kWh would be required for capital and O&M. For example, a facility that processes 2000 tons of trash each day into 60 MW of electricity would require about $200,000 in revenues daily, coming from either disposal fees or electricity revenues, or both.

- Waste-to-energy power must be sold as "base load" electricity and cannot be operated to supply "peak load" power simply because there is a constant need for trash disposal by combustion that keeps power generation steady and reliable.

- Similar to other alternative energy sources, waste-to-energy plants are qualified facilities (QFs) eligible under PURPA for mandatory power purchase at avoided cost. Most existing facilities have been financed based, in part, on long-term PURPA contracts that run commensurate with the facility debt.

- The biomass content of waste-to-energy's fuel, municipal solid waste, is about 75% on a Btu-output basis.

- The market price and disposal fee will, on average, not be sufficient to cover the cost of a new waste-to-energy unit. A tax credit is needed to encourage this form of clean, renewable electricity.

WASTE-TO-ENERGY *More Than Ever Part of the Solution*

1331 H Street N.W., Suite 801 • Washington, DC 20005 • (202) 467-6240 • FAX: (202) 467-6225

Biomass Feedstock Availability in the United States: 1999 State Level Analysis

Marie E. Walsh[a], Robert L. Perlack[a], Anthony Turhollow[a], Daniel de la Torre Ugarte[b], Denny A. Becker[c], Robin L. Graham[a], Stephen E. Slinsky[b], and Daryll E. Ray[b]

[a]Oak Ridge National Laboratory, Oak Ridge, TN 37831-6205

[b]University of Tennessee, Knoxville, TN 37901-1071

[c]Science Applications International Corporation, Oak Ridge, TN 37830

April 30, 1999, Updated January, 2000

I. Introduction

Interest in using biomass feedstocks to produce power, liquid fuels, and chemicals in the U.S. is increasing. Central to determining the potential for these industries to develop is an understanding of the location, quantities, and prices of biomass resources. This paper describes the methodology used to estimate biomass quantities and prices for each state in the continental U.S. An Excel™ spreadsheet contains estimates of biomass quantities potentially available in five categories: mill wastes, urban wastes, forest residues, agricultural residues and energy crops. Availabilities are sorted by anticipated delivered price. A presentation that explains how this information was used to support the goal of increasing biobased products and bioenergy 3 times by 2010 expressed in Executive Order 13134 of August 12, 1999 is also available.

II. Biomass Feedstock Availability

For the purpose of this analysis, biomass feedstocks are classified into five general categories: forest residues, mill residues, agricultural residues, urban wood wastes, and dedicated energy crops. Forestry is a major industry in the United States encompassing nearly 559 million acres in publicly and privately held forest lands in the continental U.S. (USDA, 1997). Nearly 16 million cubic feet of roundwood are harvested and processed annually to produce sawlogs, paper, veneers, composites and other fiber products (USDA, 1998a). The extensive forest acreage and roundwood harvest generate logging residues and provide the potential to harvest non-merchantable wood for energy. Processing of the wood into fiber products creates substantial quantities of mill residues that could potentially be used for energy. Agriculture is another major industry in the United States. Approximately 337 million acres of cropland are currently in agricultural production (USDA, 1997). Following the harvest of many of the traditional agricultural crops, residues (crop stalks) are left in the field. A portion of these residues could potentially be collected and used for energy. Alternatively, crop acres could be used to grow dedicated energy crops. A final category of biomass feedstocks includes urban wood wastes. These wastes include yard trimmings and other wood materials that are generally disposed of in municipal solid waste (MSW) and construction/demolition (C/D) landfills. Following is a description of the potential availability of these biomass feedstocks in the United States.

A. Forest Residues

Forest wood residues can be grouped into the following categories--logging residues; rough, rotten, and salvable dead wood; excess saplings; and small pole trees [(1)]. The forest wood residue supplies that could potentially be available for energy use in the U.S. are estimated using an updated version of a model originally developed by McQuillan et al. (1984). The McQuillan model estimates the total quantities of forest wood residues that can be recovered by first classifying the total forest inventory by the above wood categories (for both softwood and hardwood), and by volume, haul distances, and equipment operability constraints. This total inventory is then revised downward to reflect the quantities that can be recovered in each class due to constraints on equipment retrieval efficiencies, road access to a site, and impact of site slope on harvest equipment choice [(2)].

The costs of obtaining the recoverable forest wood residues are estimated for each category. Prices include collection, harvesting, chipping, loading, hauling, and unloading costs, a stumpage fee, and a return for profit and risk. Prices are in 1995 dollars. For the purposes of this analysis, we have included only logging residues and rough, rotten, and salvable dead wood quantities. The potential annual forest waste residues available by state for three price scenarios are presented in Table 1. Quantities are cumulative quantities at each price (i.e., quantities at $50/dt include all quantities available at $40/dt plus quantities available between $40 and $50/dt).

Polewood, which represent the growing stock of merchantable trees, has not been included in the analysis due to the fact that it could potentially be left to grow and used for higher value fiber products. It is doubtful that these trees will be harvested for energy use. However, if harvested, they could add another 17 million dry tons at less than $30/dt delivered; 37.7 million dry tons at less than $40 delivered; and 65 million dry tons at less than $50/dt delivered. For a more detailed explanation of the methodology used to estimate the forest wood residue quantities and prices, see Walsh et al, 1998.

Table 1: Estimated Annual Cumulative Forest Residues Quantities (dry tons), by Delivered Price and State			
	< $30/dry ton delivered	< $40/dry ton delivered	< $50/dry ton delivered
Alabama	1009000	1475000	1899000
Arizona	134000	200000	261400
Arkansas	928000	1352000	1737800
California	1231000	1819000	2364400
Colorado	373000	554000	720300
Connecticut	109000	159000	204100
Delaware	26000	37000	48400
Florida	515000	755000	9757000
Georgia	1041000	1525000	1967800
Idaho	605000	902000	1179500
Illinois	228000	330000	423300
Indiana	253000	367000	470100
Iowa	72000	105000	135000
Kansas	47000	68000	88100
Kentucky	475000	690000	883500
Louisiana	872000	1275000	1641800
Maine	806000	1182000	1529100
Maryland	189000	273000	351200
Massachusetts	196000	284000	366200
Michigan	710000	1034000	1327900
Minnesota	468000	682000	874900
Mississippi	946000	1380000	1774600
Missouri	505000	733000	938700

Montana	676000	1007000	1316700
Nebraska	19000	27000	34400
Nevada	8000	11000	14400
New Hampshire	299000	438000	564400
New Jersey	70000	102000	130700
New Mexico	125000	185000	241900
New York	933000	1360000	1746400
North Carolina	1068000	1557000	2004900
North Dakota	11000	17000	21700
Ohio	232000	335000	430100
Oklahoma	156000	228000	292200
Oregon	1299000	1928000	2515900
Pennsylvania	948000	1377000	1763000
Rhode Island	20000	27000	35900
South Carolina	613000	898000	1158400
South Dakota	33000	49000	64300
Tennessee	930000	1351000	1732600
Texas	557000	814000	1050700
Utah	90000	133000	173000
Vermont	265000	386000	497200
Virginia	959000	1397000	1793600
Washington	1230000	1825000	2379600
West Virginia	727000	1056000	1352500
Wisconsin	609000	886000	1138400
Wyoming	132000	196000	256100

U.S. Total	23747000	34771000	44871800

B. Primary Mill Residues

The quantities of mill residues generated at primary wood mills (i.e., mills producing lumber, pulp, veneers, other composite wood fiber materials) in the U.S. are obtained from the data compiled by the USDA Forest Service for the 1997 Resource Policy Act (RPA) Assessment (USDA, 1998a). Mill residues are classified by type and include bark; coarse residues (chunks and slabs); and fine residues (shavings and sawdust). Data is available for quantities of residues generated by residue type and on uses of residues by residue type and use category (i.e., not used, fuel, pulp, composite wood materials, etc.). Data is available at the county, state, subregion, and regional level. In cases where a county has fewer than three mills, data from multiple counties are combined to maintain the confidentiality of the data provided by individual mills. Data represent short run average quantities.

Because primary mill residues are clean, concentrated at one source, and relatively homogeneous, nearly 98 percent of all residues generated in the United States are currently used as fuel or to produce other fiber products. Of the 24.2 million dry tons of bark produced in the U.S., 2.2 percent is not used while 79.4 percent is used for fuel and 18 percent is used for such things as mulch, bedding, and charcoal. Only about 1.4 percent of the 38.7 million dry tons of coarse residues are not used. The remainder are used to produce pulp or composite wood products such as particle board, wafer board, and oriented strand board (78 percent) and about 13 percent are used for fuel. Of the 27.5 million dry tons of fine wood residues, approximately 55.6 percent are used for fuel, 23 percent are used to produce pulp or composite wood products, 18.7 percent are used for bedding, mulch and other such uses, and about 2.6 percent are unused.

The residues, while currently used, could potentially be available for energy use if utilities could pay a higher price for the residues than their value in their current uses. Data regarding the value of these residues in their current uses are difficult to obtain. Much of the residues used for fuel are used on site by the residue generator in low efficiency boiler systems to produce heat and steam. Conversations with those in the industry and other anecdotal evidence suggests that these residues could be purchased for $15-25/dry ton for use in higher efficiency fuel systems. Similar anecdotal evidence suggests that residues used to produce fiber products (pulp, composite wood materials) sell for about $30-40/dry ton. For the purposes of this analysis, we assume that the residues not currently used could potentially be available for energy uses at delivered prices of less than $20/dry ton (assuming transportation distances of less than 50 miles). For similar transportation distances, we assume that residues currently used for fuel could be available at less than $30/dry ton delivered and residues currently used for pulp, composite wood materials, mulch, bedding, and other such uses could potentially be available at delivered prices of less than $50/dry ton. Table 2 presents the cumulative annual quantities of mill residues by delivered price for each state.

Table 2: Estimated Annual Cumulative Mill Residue Quantities (dry tons), by Delivered Price and State			
	< $20/dry ton delivered	< $30/dry ton delivered	< $50/dry ton delivered
Alabama	17000	4581000	7802000
Arizona	0	75000	251000
Arkansas	2000	2497000	4705000
California	8000	2294000	4823000
Colorado	86000	121000	180000
Connecticut	0	40000	91000
Delaware	0	4000	16000
Florida	4000	1412000	2678000
Georgia	72000	3913000	7969000
Idaho	69000	1629000	4400000
Illinois	19000	117000	282000
Indiana	31000	213000	699000
Iowa	2000	46000	158000
Kansas	1000	9000	20000
Kentucky	109000	421000	1940000
Louisiana	64000	1943000	3245000
Maine	43000	209000	504000
Maryland	0	13000	166000
Massachusetts	0	44000	135000
Michigan	10000	932000	1564000
Minnesota	71000	916000	1121000
Mississippi	128000	3178000	6029000

Missouri	162000	315000	1196000
Montana	17000	659000	2173000
Nebraska	12000	21000	69000
Nevada	0	0	0
New Hampshire	23000	439000	1109000
New Jersey	0	8000	21000
New Mexico	25000	61000	125000
New York	28000	495000	1274000
North Carolina	33000	2060000	5028000
North Dakota	0	3000	4000
Ohio	0	0	0
Oklahoma	0	318000	698000
Oregon	10000	1738000	6834000
Pennsylvania	172000	591000	1628000
Rhode Island	0	11000	25000
South Carolina	4000	1706000	3382000
South Dakota	8000	46000	124000
Tennessee	202000	1325000	2018000
Texas	18000	1649000	4043000
Utah	20000	67000	102000
Vermont	0	59000	124000
Virginia	80000	1234000	2860000
Washington	5000	2262000	5689000
West Virginia	136000	459000	967000
Wisconsin	42000	1202000	192000
Wyoming	47000	124000	255000

U.S. Total	1780000	41459000	90418000

C. Agricultural Residues

Agriculture is a major activity in the United States. Among the most important crops in terms of average total acres planted from 1995 to 1997 are corn (77 million acres), wheat (72 million acres), soybeans (65 million acres), hay (60.5 million acres), cotton (15 million acres), grain sorghum (10 million acres), barley (7 million acres), oats (5 million acres), rice (3 million acres), and rye (1.5 million acres) (USDA, 1998b). After harvest, a portion of the stalks could potentially be collected for energy use. The analysis in this paper is limited to corn stover and wheat straw. Large acreage is dedicated to soybean production, but in general, residue production is relatively small and tends to deteriorate rapidly in the field, limiting the usefulness of soybean as an energy feedstock. However, additional residue quantities could be available from this source that have not been included in this analysis. Similarly, additional residue quantities could be available if barley, oats, rice, and rye production were included. Production of some of these crops (rice in particular) tends to be concentrated in a relatively small geographic area, and thus these crops could be an important local source of resources. Another potential source in the southern U.S. is cotton. A recent study (NEOS, 1998) suggests that approximately 500,000 dry tons of cotton gin trash is currently produced in the United States and this material is generally given away to farmers for use as a soil amendment. Another 171,000 dry tons of textile mill residues are produced, but much of this material is used to make other textiles and sells for prices in excess of $100/dry ton. These quantities are not included in this analysis.

The quantities of corn stover and wheat straw residues that can be available in each state are estimated by first calculating the total quantities of residues produced and then calculating the total quantities that can be collected after taking into consideration quantities that must be left to maintain soil quality (i.e., maintain organic matter and prevent erosion). Residue quantities generated are estimated using grain yields, total grain production, and a ratio of residue quantity to grain yield,[(3)]

The net quantities of residue per acre that are available for collection are estimated by subtracting from the total residue quantity generated, the quantities of residues that must remain to maintain quality (Lightle, 1997). Quantities that must remain differ by crop type, soil type, typical weather conditions, and the tillage system used. A state average was used for this analysis. In general, about 30 to 40 percent of the residues can be collected.

The estimated prices of corn stover and wheat straw include the cost of collecting the residues, the premium paid to farmers to encourage participation, and transportation costs.

The cost of collecting the agricultural residues are estimated using an engineering approach. For each harvest operation, an equipment complement is defined. Using typical engineering specifications, the time per acre required to complete each operation and the cost per hour of using each piece of equipment is calculated (ASAE, 1995; NADA, 1995; USDA, 1996; Doanes, 1995). For corn stover, the analysis assumes 1x mow, 1x rake, 1x bale with a large round baler, and pickup, transport, and unloading of the bales at the side of the field where they are stored until transport to the user facility. The same operations are assumed for wheat straw minus the mowing. The operations assumed are conservative--mowing is often eliminated and the raking operation is also eliminated in some circumstances. The method used to estimate collection costs is consistent with that used by USDA to estimate the costs of producing agricultural crops (USDA, 1996).

An additional cost of $20/dry ton is added to account for the premium paid to farmers and the transportation cost from the site of production to the user facility. Currently, several companies purchase corn stover and/or wheat straw to produce bedding, insulating materials, particle board, paper, and chemicals (Gogerty, 1996). These firms typically pay $10 to $15/dry ton to farmers to compensate for any lost nutrient or environmental benefits that result from harvesting residues. The premium paid to farmers depends, in part, on transportation distance with farmers whose fields are at greater distances from the user facility receiving lower premiums. Studies have estimated that the cost of transporting giant round bales of switchgrass are $5 to $10 per dry ton for haul distances of less than 50 miles (Bhat et al, 1992; Graham et al, 1996; Noon et al, 1996). Agricultural residue bales are of similar size, weight, and density as switchgrass bales, and a similar transportation cost is assumed. This cost is similar to the reported transportation costs of facilities that utilize agricultural residues (Schechinger, 1997). Prices are in 1995$. For a more detailed explanation of the methodology used to estimate agricultural residue quantities and prices, see Walsh et al, 1998. The estimated annual cumulated agricultural residues quantities, by delivered price and state are contained in Table 3. Table 3 also contains by state, the percent of the total available residues that are corn stover.

Table 3: Estimated Annual Cumulative Agricultural Residue Quantities (dry tons), by Delivered Price and State

	< $30/dry ton delivered		< $40/dry ton delivered		< $50/dry ton delivered	
	Quantity	% Corn	Quantity	% Corn	Quantity	% Corn
Alabama	0	0	0	0	19267	0
Arizona	0	0	221864	24	221864	24
Arkansas	0	0	859361	0	984495	13

California	0	0	1478283	40	1478283	40
Colorado	0	0	2523820	90	2523820	90
Connecticut	0	0	0	0	0	0
Delaware	0	0	88077	0	300736	0
Florida	0	0	14824	0	14824	0
Georgia	0	0	344423	0	779871	56
Idaho	0	0	1248120	10	1248120	10
Illinois	0	0	24270757	94	24270757	94
Indiana	0	0	11883845	94	11883845	94
Iowa	0	0	23911214	99	23911214	99
Kansas	0	0	8570003	48	8570003	48
Kentucky	0	0	471819	0	2280603	49
Louisiana	0	0	80930	0	380557	79
Maine	0	0	0	0	0	0
Maryland	0	0	272468	0	802298	66
Massachusetts	0	0	0	0	0	6
Michigan	0	0	680783	0	4265671	84
Minnesota	0	0	11935896	88	11935896	88
Mississippi	0	0	0	0	37877	0
Missouri	0	0	1204353	0	4081358	70
Montana	0	0	406592	9	406592	9
Nebraska	0	0	16326915	98	16326915	98
Nevada	0	0	15350	0	15350	0
New Hampshire	0	0	0	0	0	0
New Jersey	0	0	32723	0	32723	0

New Mexico	0	0	476529	55	476529	55
New York	0	0	129515	0	129515	0
North Carolina	0	0	473229	0	1130744	58
North Dakota	0	0	14015	0	3715404	0
Ohio	0	0	7634476	82	7634476	82
Oklahoma	3214403	0	3440745	7	3440745	7
Oregon	0	0	155855	40	155855	40
Pennsylvania	0	0	197689	0	1031195	0
Rhode Island	0	0	0	0	0	0
South Carolina	0	0	239680	0	239680	0
South Dakota	0	0	3686246	71	2852740	71
Tennessee	0	0	300849	0	1004781	70
Texas	0	0	4497784	66	4497784	66
Utah	0	0	216546	29	216546	29
Vermont	0	0	0	0	0	0
Virginia	0	0	297986	0	585717	21
Washington	0	0	1364254	30	1364254	30
West Virginia	0	0	12008	0	51295	77
Wisconsin	0	0	5179618	97	5179618	97
Wyoming	0	0	171585	51	171585	51
U.S. Total	3214403	0	135331029	81	150651402	80

D. Dedicated Energy Crops

Dedicated energy crops include short rotation woody crops (SRWC) such as hybrid poplar and hybrid willow, and herbaceous crops such as switchgrass (SG). Currently, dedicated energy crops are not produced in the United States, but could be if they could be sold at a price that ensures the producer a profit at least as high as could be earned using the land for alternative uses such as producing traditional agricultural crops. The POLYSYS model is used to estimate the quantities of energy crops that could potentially be produced at various energy crop prices. POLYSYS is an agricultural sector model that includes all major agricultural crops (wheat, corn, soybeans, cotton, rice, grain sorghum, barley, oats, alfalfa, other hay crops); a livestock sector; and food, feed, industrial, and export demand functions. POLYSYS was developed and is maintained by the Agricultural Policy Analysis Center at the University of Tennessee and is used by the USDA Economic Research Service to conduct economic and policy analysis. Under a joint project between USDA and DOE, POLYSYS is being modified to include dedicated energy crops. A workshop consisting of USDA and DOE experts was held in November, 1997 to review the energy crop data being incorporated into the POLYSYS model.

The analysis includes cropland acres that are presently planted to traditional crops, idled, in pasture, or are in the Conservation Reserve Program. Energy crop production is limited to areas climatically suited for their production--states in the Rocky Mountain region and the Western Plains region are excluded. Because the CRP is an environmental program, two management scenarios have been evaluated--one to optimize for biomass yield and one to provide for high wildlife divesity. Energy crop yields vary within and between states, and are based on field trial data and expert opinion. Energy crop production costs are estimated using the same approach that is used by USDA to estimate the cost of producing conventional crops (USDA, 1996). Recommended management practices (planting density, fertilizer and chemical applications, rotation lengths) are assumed. Additionally, switchgrass stands are assumed to remain in production for 10 years before replanting, are harvested annually, and are delivered as large round bales. Hybrid poplars are planted at a 8 x 10 foot spacing (545 trees/acre) and are harvested in the 10th year of production in the northern U.S., after 8 years of production in the southern U.S., and after 6 years of production in the Pacific Northwest. Poplar harvest is by custom operation and the product is delivered as whole tree wood chips. Hybrid willow varieties are suitable for production in the northern U.S. The analysis assumes 6200 trees/acre, with first harvest in year 4 and subsequent harvests every three years for a total of 7 harvests before replanting is necessary. Willow is delivered as whole tree chips.

The estimated quantities of energy crops are those that could potentially be produced at a profit at least as great as could be earned producing traditional crops on the same acres, given the assumed energy crop yield and production costs, and the 1999 USDA baseline production costs, yields, and traditional crop prices (USDA, 1999b). In the U.S., switchgrass production dominates hybrid poplar and willow production at the equivalent (on an MBTU basis) market prices. The POLYSYS model estimates the farmgate price; an average transportation cost of $8/dt is added to determine the delivered price. Prices are in $1997. Table 4 presents the estimated annual cumulative quantities of energy crops by state by delivered price. For a more detailed explanation of the methodology used to estimate dedicated energy crop prices and quantities, see Walsh et al, 1998 and de la Torre Ugarte et al, 1999.

Table 4: Estimated Annual Cumulative Energy Crop Quantities (dry tons), by Delivered Price and State			
	< $30/dry ton delivered	< $40/dry ton delivered	< $50/dry ton delivered
Alabama	0	3283747	6588812
Arizona	0	0	0
Arkansas	0	1709915	5509780
California	0	0	0
Colorado	0	0	0
Connecticut	0	0	199646
Delaware	0	0	31454
Florida	0	0	1268290
Georgia	0	1321438	3958181
Idaho	0	0	0
Illinois	0	1427349	7689694
Indiana	0	418042	5026234
Iowa	0	234292	8295486
Kansas	0	2859261	11438271
Kentucky	0	3598827	5128780
Louisiana	0	3923954	5813200
Maine	0	0	0
Maryland	0	0	298653
Massachusetts	0	0	235908
Michigan	0	1154228	4179308
Minnesota	0	427467	5783002
Mississippi	0	5330671	9304782
Missouri	0	5251442	12780923

Montana	0	0	2778386
Nebraska	0	1922058	5172860
Nevada	0	0	0
New Hampshire	0	0	158757
New Jersey	0	0	142902
New Mexico	0	0	0
New York	0	0	3388035
North Carolina	0	639228	1632077
North Dakota	0	1928463	16757889
Ohio	0	3808089	9657080
Oklahoma	0	3644173	8083722
Oregon	0	0	0
Pennsylvania	0	0	2338243
Rhode Island	0	0	4943
South Carolina	0	1338745	2438152
South Dakota	0	5613863	12757734
Tennessee	0	6616717	9350856
Texas	0	4549899	9139885
Utah	0	0	0
Vermont	0	0	333465
Virginia	0	1260668	2609867
Washington	0	0	0
West Virginia	0	269250	1190299
Wisconsin	0	3595636	6114270
Wyoming	0	0	487361

U.S. Total	0	66127422	188067187

E. Urban Wood Wastes

Urban wood wastes include yard trimmings, site clearing wastes, pallets, wood packaging, and other miscellaneous commercial and household wood wastes that are generally disposed of at municipal solid waste (MSW) landfills and demolition and construction wastes that are generally disposed of in construction/demolition (C/D) landfills. Data regarding quantities of these wood wastes is difficult to find and price information is even rarer. Additionally, definitions differ by states. Some states collect data on total wastes deposited at each MSW and C/D landfill in their states, and in some states, the quantities are further categorized by type (i.e., wood, paper and cardboard, plastics, etc.). However, not all states collect this data. Therefore, the quantities presented are crude estimates based on survey data (Glenn, 1998; Bush et al, 1997; Araman et al, 1997).

For municipal solid wastes (MSW) a survey by Glenn, 1998 is used to estimate total MSW generated by state. These quantities are adjusted slightly to correspond to regional MSW quantities that are land-filled as estimated by a survey conducted by Araman et al, 1997. Using the Araman survey, the total amount of wood contained in land-filled MSW is estimated. According to this survey, about 6 percent of municipal solid waste in the Midwest is wood, with 8 percent of the MSW being wood in the South, 6.6 percent being wood in the Northeast and 7.3 percent being wood in the West. Estimated quantities were in wet tons; they were corrected to dry tons by assuming a 15 percent moisture content by weight.

To estimate construction and demolition wastes (C/D), the Glenn study and the Bush et al, 1997 survey were used. The Glenn study provided the number of C/D landfills by state, and the Bush et al survey provided the average quantity of waste received per C/D landfill by region as well as the regional percent of the waste that was wood. According to the Bush et al survey, C/D landfills in the Midwest receive an average 25,700 tons of waste per year with 46 percent of that quantity being wood. In the South, C/D landfills receive an average 36,500 tons of waste/yr with 39 percent being wood. Northeastern C/D landfills receive an average 13,700 tons of waste/yr with 21 percent being wood and Western C/D landfills receive an average 28,800 tons of waste/yr with 18 percent being wood. Estimated quantities were in wet tons; they were corrected to dry tons by assuming a 15 percent moisture content by weight.

Yard trimmings taken directly to a compost facility rather than land-filled, were estimated from the Glenn study. This estimate was made by multiplying the number of compost facilities in each state by the national average tons of material received by site (2750 tons). The total compost material was then corrected for the percent that is yard trimmings (assumed to be 80 percent) and for the quantity that is wood (assumed to be 90 percent). Quantities were corrected to dry tons by assuming a 40 percent moisture by weight.

In an effort to reduce the quantities of waste materials that are land-filled, most states actively encourage the recycling of wastes. Quantities and prices of recycled wood wastes are not readily available. However, the Araman and Bush surveys report limited data on the recycling of wood wastes at MSW and C/D sites. They report that in the South, approximately 36 percent of C/D landfills and 50 percent of MSW landfills operate a wood/yard waste recycling facility and that about 34 percent of the wood at C/D landfills and 39 percent of the wood at MSW landfills is recycled. In the Midwest, about 31 percent of the MSW and 25 percent of the C/D landfills operate wood recycling facilities with 16 percent of the MSW wood and 1 percent of the C/D wood is recycled. In the West, 27 percent of the MSW and C/D landfills operate wood recycling facilities and recycle 25 percent each of their wood. In the Northeast, 39 percent of the MSW and 28 percent of the C/D landfills operate wood recycling facilities and recycle 39 percent of the MSW wood and 28 percent of the C/D wastes.

The surveys do not report the use of total recycled wood, but do report the uses of recycled pallets which represent about 7 percent of the total wood and 4 percent of the recycled wood at C/D landfills and about 24 percent of the total wood and about 13 percent of the recycled wood at MSW landfills. At C/D landfills, about 14 percent of the recycled pallets are re-used as pallets, about 39 percent are used as fuel, and the remainder is used for other purposes such as mulch and composting. About 69 percent of the recyclers reported that they gave away the pallet material. Of those selling the material, the mean sale price was $11.01/ton and the median sale price was $10.50/ton. At MSW landfills, about 3 percent of the recycled pallets are re-used as pallets, about 41 percent are used as fuel, and the remainder is used for other purposes such as mulch and composting. About 58 percent of the C/D recyclers reported that they gave away the pallet material. Of those selling the material, the mean sale price was $13.17/ton and the median sale price was $10.67/ton. Transportation costs must still be added to the sale price. Given the lack of information regarding prices, we assumed that of the total quantity available, 60 percent could be available at less than $20/dry ton and that the remaining quantities could be available at less than $30/dry ton. Table 5 presents the estimated annual cumulative quantities of urban wood wastes by state and price.

Table 5: Estimated Annual Cumulative Urban Wood Waste Quantities (dry tons), by Delivered Price and State

	< $20/dry ton	< $30/dry ton	< $40/dry ton	< $50/dry ton
Alabama	823566	1372610	1372610	1372610
Arizona	219736	366227	366227	366227
Arkansas	400364	667273	667273	667273
California	1579813	2633022	2633022	2633022
Colorado	94661	157769	157769	157769

Connecticut	246938	411563	411563	411563
Delaware	38959	64931	64931	64931
Florida	2757950	4596584	4596584	4596584
Georgia	862094	1436823	1436823	1436823
Idaho	135265	338162	338162	338162
Illinois	416047	693411	693411	693411
Indiana	316610	527684	527684	527684
Iowa	171802	286337	286337	286337
Kansas	736289	1227148	1227148	1227148
Kentucky	345699	576165	576165	576165
Louisiana	452322	753870	753870	753870
Maine	108358	180597	180597	180597
Maryland	204643	341071	341071	341071
Massachusetts	419272	698787	698787	698787
Michigan	495734	826224	826224	826224
Minnesota	919517	1532529	1532529	1532529
Mississippi	470831	784719	784719	784719
Missouri	315547	525911	525911	525911
Montana	52060	86766	86766	86766
Nebraska	102073	170121	170121	170121
Nevada	184112	306853	306853	306853
New Hampshire	110579	184298	184298	184298
New Jersey	389089	648481	648481	648481
New Mexico	142896	238160	238160	238160
New York	1140080	1900133	1900133	1900133
North Carolina	636035	1060056	1060056	1060056
North Dakota	326510	544184	544184	544184
Ohio	744518	1240864	1240864	1240864
Oklahoma	111173	185289	185289	185289
Oregon	182532	304220	304220	304220
Pennsylvania	399963	666605	666605	666605
Rhode Island	29803	49671	49671	49671

South Carolina	1289900	2149833	2149833	2149833
South Dakota	123982	206637	206637	206637
Tennessee	676029	1126715	1126715	1126715
Texas	1209449	2015749	2015749	2015749
Utah	138765	231275	231275	231275
Vermont	40802	68004	68004	68004
Virginia	519454	865757	865757	865757
Washington	292432	487387	487387	487387
West Virginia	105236	175393	175393	175393
Wisconsin	383466	639110	639110	639110
Wyoming	177383	295638	295638	295638
U.S. Total	22040338	36846616	36846616	36846616

III. Summary

Table 6 summarizes the estimated total annual cumulative quantities of biomass resources available by state and delivered price. It is estimated that substantial quantities of biomass (510 million dry tons) could be available annually at prices of less that $50/dt delivered. However, several caveats should be noted. There is a great deal of uncertainty surrounding some of the estimates. For example, while there is substantial confidence in the estimated quantities of mill residues available by state, there is a great deal of uncertainty about the estimated prices of these residues. The value of these feedstocks in their current uses is speculative and based solely on anecdotal discussions. Given that the feedstock is already being used--much of it under contract or in-house by the generator of the waste--energy facilities may need to pay a higher price than assumed to obtain the feedstock. Additionally, both the quantity and price of urban wastes are highly speculative. The analysis is based solely on one national study and regional averages taken from two additional surveys. There is no indication of the quality of the material present (i.e., whether the wood is contaminated with chemicals, etc.). Because of the ways in which the surveys were conducted, there may be double counting of some quantities (i.e., MSW may contain yard trimmings and C/D wastes as well). Additionally, the analysis assumes that the majority of this urban wood is available for a minimal fee, with much of the cost resulting from transportation. Other industries have discovered that once a market is established, these "waste materials" become more valuable and are no longer available at minimal price. This situation could also happen with urban wastes used for energy if a steady customer becomes available. It should also be noted however, that some studies indicate that greater quantities of urban wastes are available, and are available at lower prices, than are assumed in this analysis (Wiltsee, 1998). Given the high level of uncertainty surrounding the quantity and price estimates of urban wastes and mill residues, and the fact that these wastes are estimated to be the least cost feedstocks available, they should be viewed with caution until a more detailed analysis is completed.

The analysis has assumed that substantial quantities of dead forest wood could be harvested. The harvest of deadwood is a particularly dangerous activity and not one relished by most foresters. Additionally, large polewood trees represent the growing stock of trees, that if left for sufficient time, could be harvested for higher value uses. These opportunity costs have not been considered. And, the sustainability of removing these forest resources has not been thoroughly analyzed.

We estimate the price of agricultural residues to be high largely because of the small quantities that can be sustainably removed on a per acre basis. Improvements in the collection/transport technologies and the ability to sustainably collect larger quantities (due to a shift in no-till site preparation practices for example) could increase quantities and decrease prices over time. Also, the inclusion of some of the minor grain crops (i.e., barley, oats, rye, rice) and soybeans could increase the total quantities of agricultural residues available by state. However, further elucidation of quantities that can sustainably be removed might lower available quantities.

Dedicated energy crops (i.e., switchgrass and short rotation wood crops) are not currently produced--the analysis is based on our best estimates of yield, production costs, and profitability of alternative crops that could be produced on the same land. Improving yields and decreasing production costs through improved harvest and transport technologies could increase available quantities at lower costs.

We have assumed a transportation cost of $8/dry ton for most feedstocks. This cost is based on a typical cost of transporting materials (i.e., switchgrass bales and wood chips) for less than 50 miles (Graham et al, 1996; Bhat et al, 1992; Noon et al, 1996). Finally, the analysis is conducted at a state level and the distribution of biomass resources within the state is not specifically considered. We have simply assumed that the feedstock is available within 50 miles of a user facility. This may not be the case which would result either in the cost of the feedstock being higher to a user facility due to increased transportation costs, or the quantities of available feedstock being lower to a user facility if the material is simply too far away from the end-user site to be practical to obtain. Biomass resource assessments are needed at a lower aggregation level than the state. Any facility considering using the analysis need to conduct its own local analysis to verify feedstock quantity and prices.

Table 6: Estimated Cumulative Biomass Quantities (dry ton/yr), by Delivered Price and State

	< $20/dry ton	< $30/dry ton	< $40/dry ton	< $50/dry ton
Alabama	840566	6962610	10712357	17681689
Arizona	219736	575227	863091	1100491
Arkansas	402364	4092273	7085549	13604348
California	1587813	6158022	8224305	11298705
Colorado	180661	651769	3356589	3581889
Connecticut	246938	560563	610563	906309
Delaware	38959	94931	194008	461521
Florida	2761950	6753122	6778408	9533398
Georgia	934094	6390823	8540684	16111675
Idaho	204265	2572162	4117282	7165782
Illinois	435047	1038411	26838517	33359162
Indiana	347610	993684	13409571	18606863
Iowa	173802	404337	24582843	32786037
Kansas	737289	1283148	12733412	21343522
Kentucky	454699	1472165	5757811	10809048
Louisiana	516322	3568870	7976754	11834427
Maine	151358	1195597	1571597	2213697
Maryland	204643	543071	899539	1959222
Massachusetts	419272	938787	1026787	1435895
Michigan	505734	2468224	4627235	12163103
Minnesota	990517	2916529	15493892	21247327
Mississippi	598831	4908719	10673390	17930978
Missouri	477547	1345911	8029706	19522892
Montana	69060	1421766	2159358	6761444

Nebraska	114073	210121	18467094	21773296
Nevada	184112	314853	333203	336603
New Hampshire	133579	922298	1061298	2016455
New Jersey	389089	726481	791204	975806
New Mexico	167896	424160	960689	1081589
New York	1168080	3328133	3884648	8438083
North Carolina	669035	4188056	5789513	10855777
North Dakota	326510	558184	2506662	21043177
Ohio	744518	1472864	13018429	18962520
Oklahoma	111173	3873692	7816207	12699956
Oregon	192532	3341220	4126075	9809975
Pennsylvania	571963	2205605	2832294	7427043
Rhode Island	29803	80671	87671	115514
South Carolina	1293900	4468833	6332258	9368065
South Dakota	131982	285637	9601746	16005411
Tennessee	878029	3381715	10720281	15232952
Texas	1227449	4221749	13526432	20747118
Utah	158765	388275	647821	722821
Vermont	40802	392004	513004	1022669
Virginia	599454	3058757	5055411	8714941
Washington	297432	3979387	5938641	9920241
West Virginia	241236	1361393	1971651	3736487
Wisconsin	425466	2450110	11502364	14963398
Wyoming	224383	551638	787223	1465684
U.S. Total	23820338	105496557	314535067	510855005

REFERENCES

1. American Society of Agricultural Engineers, *Standards 1995-Standards, Engineering Practices, and Data*, 1995.
2. P.A. Araman, R.J. Bush, and V.S. Reddy, Municipal Solid Waste Landfills and Wood Pallets--What's Happening in the U.S., *Pallet Enterprise*, March 1997, pp. 50-56.
3. M.B. Bhat, B.C. English, and M. Ojo, Regional Costs of Transporting Biomass Feedstocks, *Liquid Fuels From Renewable Resources*, John S. Cundiff (ed.), American Society of Agricultural Engineers, St. Joseph, MI, December 1992.
4. R.J. Bush, V.S. Reddy, and P.A. Araman, Construction and Demolition Landfills and Wood Pallets--What's Happening in the U.S., *Pallet Enterprise*, March 1997, pp. 27-31.
5. D.G. de la Torre Ugarte, S.P. Slinsky, and D.E. Ray, The Economic Impacts of Biomass Crop Production on the U.S. Agriculture Sector, University of Tennessee Agricultural Policy Analysis Center, Knoxville, TN, July 1999, Draft Document.
6. Doane's Agricultural Report, *Estimated Machinery Operating Costs, 1995*, Vol. 58, No. 15-5, April 14, 1995.
7. J. Glenn, The State of Garbage, *BioCycle*, April 1998, pp. 32-43.
8. R. Gogerty, Crop Leftovers: More Uses, More Value, *Resource: Engineering and Technology for a Sustainable World*, Vol. 3, No. 7, July 1996.
9. R.L. Graham, W. Liu, H.I. Jager, B.C. English, C.E. Noon, and M.J. Daly, A Regional-Scale GIS-Based Modeling System for Evaluating the Potential Costs and Supplies of Biomass From Biomass Crops, in *Proceedings of Bioenergy '96 - The Seventh National Bioenergy Conference*, Nashville, TN, September 15-20, 1996, Southeastern Regional Biomass Energy Program, pp. 444-450, 1996.
10. W.G. Heid, Jr., *Turning Great Plains Crop Residues and Other Products into Energy*, U.S. Department of Agriculture, Economic Research Service, Agricultural Economic Report No. 523, Washington, DC, November 1984.
11. D.T. Lightle, *A Soil Conditioning Index for Cropland Management Systems* (Draft), U.S. Department of Agriculture, Natural Resources Conservation Service, National Soil Survey Center, April 1997.
12. A. McQuillan, K. Skog, T. Nagle, and R. Loveless, *Marginal Cost Supply Curves for Utilizing Forest Waste Wood in the United States*, Unpublished Manuscript, University of Montana, Missoula, February 1984.
13. NEOS Corporation, *Non-synthetic Cellulosic Textile Feedstock Resource Assessment*, Southeastern Regional Biomass Energy Program, Muscle Shoals, AL, July 1998.
14. C.E. Noon, M.J. Daly, R.L. Graham, and F.B. Zahn, Transportation and Site Location Analysis for Regional Integrated Biomass Assessment (RIBA), in *Proceedings of Bioenergy '96 - The Seventh National Bioenergy Conference*, Nashville, TN, September 15-20, 1996, Southeastern Regional Biomass Energy Program, pp. 487-493, 1996.
15. North American Dealers Association, *Official Guide--Tractors and Farm Equipment*, 1995.
16. T. Schechinger, Great Lakes Chemical Corporation, personal communication, 1997.

17. U.S. Department of Agricultural, National Agricultural Statistics Service, World Agricultural Outlook Board, *USDA Agricultural Baseline Projections to 2009*, WAOB-99-1, Washington, DC, February 1999.
18. U.S. Department of Agriculture, Forest Service, *Forest Inventory and Analysis Timber Product Output Database Retrieval System*, (http://srsfia.usfs.msstate.edu/rpa/tpo), 1998a.
19. U.S. Department of Agriculture, National Agricultural Statistical Service, *Crop Production Summary*, Washington, DC, January 1998b.
20. U.S. Department of Agriculture, Economic Research Service, *Agricultural Resources and Environmental Indicators, 1996-1997*, Agricultural Handbook No. 712, Washington, DC, July 1997.
21. U.S. Department of Agriculture, Economic Research Service, *Economic Indicators of the Farm Sector: Costs of Production--Major Field Crops, 1995*, Washington, DC, 1996.
22. M.E. Walsh, R.L. Perlack, D.A. Becker, A. Turhollow, and R.L. Graham, *Evolution of the Fuel Ethanol Industry: Feedstock Availability and Price*, Oak Ridge National Laboratory, Oak Ridge, TN, April 21, 1998, Draft Document.
23. G. Wiltsee, *Urban Wood Waste Resources in 30 US Metropolitan Areas*, Appel Consultants, Inc., Valencia, CA, 1998.

1. Logging residues are the unused portion of the growing of stock trees (i.e., commercial species with a diameter breast height (dbh) greater than 5 inches, excluding cull trees) that are cut or killed by logging and left behind. Rough trees are those that do not contain a sawlog (i.e., 50 percent or more of live cull volume) or are not a currently merchantable species. Rotten trees are trees that do not contain a sawlog because of rot (i.e., 50 percent or more of the live cull volume). Salvable dead wood includes downed or standing trees that are considered currently or potentially merchantable. Excess saplings are live trees having a dbh of between 1.0 and 4.9 inches. Small pole trees are trees with a dbh greater than 5 inches, but smaller than saw timber trees. (back to report)

2. Retrieval efficiency accounts for the quantity of the inventory that can actually be recovered due to technology or equipment (assumed to be 40 percent). It is assumed that 50 percent of the resource is accessible without having to construct roads, except for logging residues for which 100 percent of the inventory is assumed accessible. Finally, inventory that lies on slopes greater than 20 percent or where conventional equipment cannot be used are eliminated for cost and environmental reasons. (back to report)

3. The assumed residue factors are--1 ton of corn stover for every 1 ton of corn grain produced; 1.7 tons of wheat straw for every 1 ton of winter wheat grain; and 1.3 ton of wheat straw for every 1 ton of spring and duram wheat grain (Heid, 1984). We assume a grain weight of 56 and 60 lb/bu for corn and wheat grain respectively. Grain moisture factors are assumed to be 1 for corn and .87 for wheat. (back to report)

This is a quick-reference list of conversion factors used by the Bioenergy Feedstock Development Programs at ORNL. It was compiled from a wide range of sources, and is designed to be concise and convenient rather than all-inclusive. Most conversion factors and data are given to only 3 significant figures. Users are encouraged to consult other original sources for independent verification of these numbers. The following are links to Web sites we have found useful (many universities worldwide maintain good guides and conversion calculator pages):

- U.S. National Institute of Standards and Technology (NIST)
- Centre for Innovation in Mathematics Teaching, University of Exeter, U.K.
- Department of Geological Sciences, University of Michigan
- Convertit.com Measurement Converter

Energy contents are expressed here as Lower Heating Value (LHV) unless otherwise stated (this is closest to the actual energy yield in most cases). Higher Heating Value (HHV, including condensation of combustion products) is greater by between 5% (in the case of coal) and 10% (for natural gas), depending mainly on the hydrogen content of the fuel. For most biomass feedstocks this difference appears to be 6-7%. The appropriateness of using LHV or HHV when comparing fuels, calculating thermal efficiencies, etc. really depends upon the application. For stationary combustion where exhaust gases are cooled before discharging (e.g. power stations), HHV is more appropriate. Where no attempt is made to extract useful work from hot exhaust gases (e.g. motor vehicles), the LHV is more suitable. In practice, many European publications report LHV, whereas North American publications use HHV.

Energy units

Quantities

- 1.0 joule (J) = one Newton applied over a distance of one meter (= 1 kg m^2/s^2).
- 1.0 joule = 0.239 calories (cal)
- 1.0 calorie = 4.187 J
- 1.0 gigajoule (GJ) = 10^9 joules = 0.948 million Btu = 239 million calories = 278 kWh
- 1.0 British thermal unit (Btu) = 1055 joules (1.055 kJ)
- 1.0 Quad = One quadrillion Btu (10^{15} Btu) = 1.055 exajoules (EJ), or approximately 172 million barrels of oil equivalent (boe)
- 1000 Btu/lb = 2.33 gigajoules per tonne (GJ/t)
- 1000 Btu/US gallon = 0.279 megajoules per liter (MJ/l)

Power

- 1.0 watt = 1.0 joule/second = 3.413 Btu/hr
- 1.0 kilowatt (kW) = 3413 Btu/hr = 1.341 horsepower
- 1.0 kilowatt-hour (kWh) = 3.6 MJ = 3413 Btu
- 1.0 horsepower (hp) = 550 foot-pounds per second = 2545 Btu per hour = 745.7 watts =

0.746 kW

Energy Costs

- $1.00 per million Btu = $0.948/GJ
- $1.00/GJ = $1.055 per million Btu

Some common units of measure

- 1.0 U.S. ton (short ton) = 2000 pounds
- 1.0 imperial ton (long ton or shipping ton) = 2240 pounds
- 1.0 metric tonne (tonne) = 1000 kilograms = 2205 pounds
- 1.0 US gallon = 3.79 liter = 0.833 Imperial gallon
- 1.0 imperial gallon = 4.55 liter = 1.20 US gallon
- 1.0 liter = 0.264 US gallon = 0.220 imperial gallon
- 1.0 US bushel = 0.0352 m^3 = 0.97 UK bushel = 56 lb, 25 kg (corn or sorghum) = 60 lb, 27 kg (wheat or soybeans) = 40 lb, 18 kg (barley)

Areas and crop yields

- 1.0 hectare = 10,000 m^2 (an area 100 m x 100 m, or 328 x 328 ft) = 2.47 acres
- 1.0 km^2 = 100 hectares = 247 acres
- 1.0 acre = 0.405 hectares
- 1.0 US ton/acre = 2.24 t/ha
- 1 metric tonne/hectare = 0.446 ton/acre
- 100 g/m^2 = 1.0 tonne/hectare = 892 lb/acre
  - for example, a "target" bioenergy crop yield might be: 5.0 US tons/acre (10,000 lb/acre) = 11.2 tonnes/hectare (1120 g/m^2)

Biomass energy

- **Cord:** a stack of wood comprising 128 cubic feet (3.62 m^3); standard dimensions are 4 x 4 x 8 feet, including air space and bark. One cord contains approx. 1.2 U.S. tons (oven-dry) = 2400 pounds = 1089 kg
  - 1.0 metric tonne **wood** = 1.4 cubic meters (solid wood, not stacked)
  - Energy content of **wood fuel** (HHV, bone dry) = 18-22 GJ/t (7,600-9,600 Btu/lb)
  - Energy content of **wood fuel** (air dry, 20% moisture) = about 15 GJ/t (6,400 Btu/lb)
- Energy content of **agricultural residues** (range due to moisture content) = 10-17 GJ/t (4,300-7,300 Btu/lb)
- Metric tonne **charcoal** = 30 GJ (= 12,800 Btu/lb) (but usually derived from 6-12 t air-dry wood, i.e. 90-180 GJ original energy content)
- Metric tonne **ethanol** = 7.94 petroleum barrels = 1262 liters
  - ethanol energy content (LHV) = 11,500 Btu/lb = 75,700 Btu/gallon = 26.7 GJ/t = 21.1 MJ/liter. HHV for ethanol = 84,000 Btu/gallon = 89 MJ/gallon = 23.4 MJ/liter
  - ethanol density (average) = 0.79 g/ml (= metric tonnes/m^3)
- Metric tonne **biodiesel** = 37.8 GJ (33.3 - 35.7 MJ/liter)
  - biodiesel density (average) = 0.88 g/ml (= metric tonnes/m^3)

Fossil fuels

- **Barrel of oil** equivalent (boe) = approx. 6.1 GJ (5.8 million Btu), equivalent to 1,700 kWh. "Petroleum barrel" is a liquid measure equal to 42 U.S. gallons (35 Imperial gallons or 159 liters); about 7.2 barrels oil are equivalent to one tonne of oil (metric) = 42-45 GJ.
- **Gasoline:** US gallon = 115,000 Btu = 121 MJ = 32 MJ/liter (LHV). HHV = 125,000 Btu/gallon = 132 MJ/gallon = 35 MJ/liter
  - Metric tonne gasoline = 8.53 barrels = 1356 liter = 43.5 GJ/t (LHV); 47.3 GJ/t (HHV)
  - gasoline density (average) = 0.73 g/ml (= metric tonnes/m^3)
- **Petro-diesel** = 130,500 Btu/gallon (36.4 MJ/liter or 42.8 GJ/t)
  - petro-diesel density (average) = 0.84 g/ml (= metric tonnes/m^3)
- Note that the energy content (heating value) of petroleum products per unit mass is fairly constant, but their density differs significantly – hence the energy content of a liter, gallon, etc. varies between gasoline, diesel, kerosene.
- Metric tonne **coal** = 27-30 GJ (bituminous/anthracite); 15-19 GJ (lignite/sub-bituminous) (the above ranges are equivalent to 11,500-13,000 Btu/lb and 6,500-8,200 Btu/lb).
  - Note that the energy content (heating value) per unit mass varies greatly between different "ranks" of coal. "Typical" coal (rank not specified) usually means bituminous coal, the most common fuel for power plants (27 GJ/t).
- **Natural gas:** HHV = 1027 Btu/ft3 = 38.3 MJ/m^3; LHV = 930 Btu/ft3 = 34.6 MJ/m^3
  - Therm (used for natural gas, methane) = 100,000 Btu (= 105.5 MJ)

Carbon content of fossil fuels and bioenergy feedstocks

- **coal** (average) = 25.4 metric tonnes carbon per terajoule (TJ)
    - 1.0 metric tonne **coal** = 746 kg carbon
- **oil** (average) = 19.9 metric tonnes carbon / TJ
- 1.0 US gallon **gasoline** (0.833 Imperial gallon, 3.79 liter) = 2.42 kg carbon
- 1.0 US gallon **diesel/fuel oil** (0.833 Imperial gallon, 3.79 liter) = 2.77 kg carbon
- **natural gas (methane)** = 14.4 metric tonnes carbon / TJ
- 1.0 cubic meter **natural gas (methane)** = 0.49 kg carbon
- carbon content of **bioenergy feedstocks:** approx. 50% for woody crops or wood waste; approx. 45% for graminaceous (grass) crops or agricultural residues

---