Appendix A - Conversions

Contents	Data Type	Updated
Lower and Higher Heating Values of Gas, Liquid and Solid Fuels	Table	09/30/2011
Heat Content Ranges for Various Biomass Fuels	Table	09/30/2011
Average Heat Content for Selected Waste Fuels	Table	09/30/2011
The Effect of Moisture on Heating Values	Table	09/30/2011
Forestry Volume Unit to Biomass Weight Considerations	Table	09/30/2011
Estimation of Biomass Weights from Forestry Volume Data	Table	09/30/2011
Forestry Volume Unit to Biomass Weight Examples	Table	09/30/2011
Stand Level Biomass Estimation	Table	09/30/2011
Number of Trees per Acre and Hectare by Tree Spacing Combination	Table	09/30/2011
Wood and Log Volume to Volume Conversion Factors	Table	09/30/2011
Estimating Tons of Wood Residues Per Thousand Board Feet of Lumber Produced by Sawmills	Table	09/30/2011
Estimating Tons of Wood Residue Per Thousand Board Feet of Wood Used for Selected Products	Table	09/30/2011
Area and Length Conversions	Table	09/30/2011
Mass Units and Mass per Unit Area Conversions	Table	09/30/2011
Distance and Velocity Conversions	Table	09/30/2011
Capacity, Volume and Specific Volume Conversions	Table	09/30/2011
Power Unit Conversions	Table	09/30/2011
Small and Large Energy Units and Energy per Unit Weight Conversions	Table	09/30/2011
Most Commonly Used Biomass Conversion Factors	Table	09/30/2011
Alternative Measures of Greenhouse Gases	Table	09/30/2011
Fuel Efficiency Conversions	Table	09/30/2011
SI Prefixes and Their Values	Table	09/30/2011
Metric Units and Abbreviations	Table	09/30/2011
Cost per Unit Conversions	Table	09/30/2011

Section: Appendix A
Lower and Higher Heating Values of Gas, Liquid and Solid Fuels

Fuels	Lower Heating Value (LHV) [1]			Higher Heating Value (HHV) [1]			Density
Gaseous Fuels @ 32 F and 1 atm	**Btu/ft3 [2]**	**Btu/lb [3]**	**MJ/kg [4]**	**Btu/ft3 [2]**	**Btu/lb [3]**	**MJ/kg [4]**	**grams/ft3**
Natural gas	983	20,267	47.141	1089	22,453	52.225	22.0
Hydrogen	290	51,682	120.21	343	61,127	142.18	2.55
Still gas (in refineries)	1458	20,163	46.898	1,584	21,905	50.951	32.8
Liquid Fuels	**Btu/gal [2]**	**Btu/lb [3]**	**MJ/kg [4]**	**Btu/gal [2]**	**Btu/lb [3]**	**MJ/kg [4]**	**grams/gal**
Crude oil	129,670	18,352	42.686	138,350	19,580	45.543	3,205
Conventional gasoline	116,090	18,679	43.448	124,340	20,007	46.536	2,819
Reformulated or low-sulfur gasoline	113,602	18,211	42.358	121,848	19,533	45.433	2,830
CA reformulated gasoline	113,927	18,272	42.500	122,174	19,595	45.577	2,828
U.S. conventional diesel	128,450	18,397	42.791	137,380	19,676	45.766	3,167
Low-sulfur diesel	129,488	18,320	42.612	138,490	19,594	45.575	3,206
Petroleum naphtha	116,920	19,320	44.938	125,080	20,669	48.075	2,745
NG-based FT naphtha	111,520	19,081	44.383	119,740	20,488	47.654	2,651
Residual oil	140,353	16,968	39.466	150,110	18,147	42.210	3,752
Methanol	57,250	8,639	20.094	65,200	9,838	22.884	3,006
Ethanol	76,330	11,587	26.952	84,530	12,832	29.847	2,988
Butanol	99,837	14,775	34.366	108,458	16,051	37.334	3,065
Acetone	83,127	12,721	29.589	89,511	13,698	31.862	2,964
E-Diesel Additives	116,090	18,679	43.448	124,340	20,007	46.536	2,819
Liquefied petroleum gas (LPG)	84,950	20,038	46.607	91,410	21,561	50.152	1,923
Liquefied natural gas (LNG)	74,720	20,908	48.632	84,820	23,734	55.206	1,621
Dimethyl ether (DME)	68,930	12,417	28.882	75,610	13,620	31.681	2,518
Dimethoxy methane (DMM)	72,200	10,061	23.402	79,197	11,036	25.670	3,255
Methyl ester (biodiesel, BD)	119,550	16,134	37.528	127,960	17,269	40.168	3,361
Fischer-Tropsch diesel (FTD)	123,670	18,593	43.247	130,030	19,549	45.471	3,017
Renewable Diesel I (SuperCetane)	117,059	18,729	43.563	125,294	20,047	46.628	2,835
Renewable Diesel II (UOP-HDO)	122,887	18,908	43.979	130,817	20,128	46.817	2,948
Renewable Gasoline	115,983	18,590	43.239	124,230	19,911	46.314	2,830
Liquid Hydrogen	30,500	51,621	120.07	36,020	60,964	141.80	268
Methyl tertiary butyl ether (MTBE)	93,540	15,094	35.108	101,130	16,319	37.957	2,811
Ethyl tertiary butyl ether (ETBE)	96,720	15,613	36.315	104,530	16,873	39.247	2,810
Tertiary amyl methyl ether (TAME)	100,480	15,646	36.392	108,570	16,906	39.322	2,913
Butane	94,970	19,466	45.277	103,220	21,157	49.210	2,213
Isobutane	90,060	19,287	44.862	98,560	21,108	49.096	2,118
Isobutylene	95,720	19,271	44.824	103,010	20,739	48.238	2,253
Propane	84,250	19,904	46.296	91,420	21,597	50.235	1,920
Solid Fuels	**Btu/ton [2]**	**Btu/lb [5]**	**MJ/kg [4]**	**Btu/ton [2]**	**Btu/lb [5]**	**MJ/kg [4]**	
Coal (wet basis) [6]	19,546,300	9,773	22.732	20,608,570	10,304	23.968	
Bituminous coal (wet basis) [7]	22,460,600	11,230	26.122	23,445,900	11,723	27.267	
Coking coal (wet basis)	24,600,497	12,300	28.610	25,679,670	12,840	29.865	
Farmed trees (dry basis)	16,811,000	8,406	19.551	17,703,170	8,852	20.589	
Herbaceous biomass (dry basis)	14,797,555	7,399	17.209	15,582,870	7,791	18.123	
Corn stover (dry basis)	14,075,990	7,038	16.370	14,974,460	7,487	17.415	
Forest residue (dry basis)	13,243,490	6,622	15.402	14,164,160	7,082	16.473	
Sugar cane bagasse	12,947,318	6,474	15.058	14,062,678	7,031	16.355	
Petroleum coke	25,370,000	12,685	29.505	26,920,000	13,460	31.308	

Source:

GREET, The Greenhouse Gases, Regulated Emissions, and Energy Use In Transportation Model, GREET 1.8d.1, developed by Argonne National Laboratory, Argonne, IL, released August 26, 2010.
http://greet.es.anl.gov/

Notes:

[1] The **lower heating value** (also known as net calorific value) of a fuel is defined as the amount of heat released by combusting a specified quantity (initially at 25°C) and returning the temperature of the combustion products to 150°C, which assumes the latent heat of vaporization of water in the reaction products is not recovered. The LHV are the useful calorific values in boiler combustion plants and are frequently used in Europe.

The **higher heating value** (also known as gross calorific value or gross energy) of a fuel is defined as the amount of heat released by a specified quantity (initially at 25°C) once it is combusted and the products have returned to a temperature of 25°C, which takes into account the latent heat of vaporization of water in the combustion products. The HHV are derived only under laboratory conditions, and are frequently used in the US for solid fuels.

[2] Btu = British thermal unit.

[3] The heating values for gaseous fuels in units of Btu/lb are calculated based on the heating values in units of Btu/ft3 and the corresponding

[4] The heating values in units of MJ/kg, are converted from the heating values in units of Btu/lb.

[5] For solid fuels, the heating values in units of Btu/lb are converted from the heating values in units of Btu/ton.

[6] Coal characteristics assumed by GREET for electric power production.

[7] Coal characteristics assumed by GREET for hydrogen and Fischer-Tropsch diesel production.

Section: Appendix A

Heat Content Ranges for Various Biomass Fuels (dry weight basis[a]) with English and Metric Units

Fuel type & source	English			Metric[b]			
		Higher Heating Value		Higher Heating Value		Lower Heating Value	
	Btu/lb[c]	Btu/lb	MBtu/ton	kJ/kg	MJ/kg	kJ/kg	MJ/kg
Agricultural Residues							
Corn stalks/stover (1,2,6)	7,487	7,587 - 7,967	15.2 - 15.9	*17,636 - 18,519*	*17.6 - 18.5*	16,849 - 17,690	16.8 - 18.1
Sugarcane bagasse (1,2,6)	7,031	7,450 - 8,349	14.9 - 16.7	*17,317 - 19,407*	*17.3 - 19.4*	17,713 - 17,860	17.7 - 17.9
Wheat straw (1,2,6)		*6,964 - 8,148*	13.9 - 16.3	16,188 - 18,940	16.1 - 18.9	15,082 - 17,659	15.1 - 17.7
Hulls, shells, prunings (2,3)		6,811 - 8,838	13.6 - 17.7	*15,831 - 20,543*	*15.8 - 20.5*		
Fruit pits (2-3)		8,950 - 10,000	17.9 - 20.0				
Herbaceous Crops	7,791						
Miscanthus (6)				18,100 - 19,580	18.1 - 19.6	17,818 - 18,097	17.8 - 18.1
switchgrass (1,3,6)		7,754 - 8,233	15.5 - 16.5	*18,024 - 19,137*	*18.0 - 19.1*	16,767 - 17,294	16.8 - 18.6
Other grasses (6)				18,185 - 18,570	18.2 - 18.6	16,909 - 17,348	16.9 - 17.3
Bamboo (6)				19,000 - 19,750	19.0 - 19.8		
Woody Crops	8,852						
Black locust (1,6)		8,409 - 8,582	16.8 - 17.2	*19,546 - 19,948*	*19.5 - 19.9*	18,464	18.5
Eucalyptus (1,2,6)		*8,174* - 8,432	16.3 - 16.9	19,000 - *19,599*	*19.0 - 19.6*	17,963	18.0
Hybrid poplar (1,3,6)		*8,183* - 8,491	*16.4* - 17.0	19,022 - *19,737*	*19.0 - 19.7*	17,700	17.7
Willow (2,3,6)		7,983 - 8,497	16.0 - 17.0	18,556 - 19,750	18.6 - 19.7	16,734 - 18,419	16.7 - 18.4
Forest Residues	7,082						
Hardwood wood (2,6)		8,017 - 8,920	16.0 - 17.5	*18,635 - 20,734*	*18.6 - 20.7*		
Softwood wood (1,2,3,4,5,6)		8,000 - 9,120	16.0 - 18.24	*18,595 - 21,119*	*18.6 - 21.1*	17,514 - 20,768	17.5 - 20.8
Urban Residues							
MSW (2,6)		5,644 - 8,542	11.2 - 17.0	*13,119 - 19,855*	*13.1 - 19.9*	11,990 - 18,561	12.0 - 18.6
RDF (2,6)		*6,683 - 8,563*	*13.4 - 17.1*	15,535 - 19,904	15.5 - 19.9	14,274 - 18,609	14.3 - 18.6
Newspaper (2,6)		8,477 - 9,550	17 - 19.1	*19,704 - 22,199*	19.7 - 22.2	18,389 - 20,702	18.4 - 20.7
Corrugated paper (2,6)		7,428 -7,939	14.9 - 15.9	17,265 - 18,453	17.3 - 18.5	17,012	
Waxed cartons (2)		11,727 - 11,736	23.5 - 23.5	*27,258 - 27,280*	*27.3*	25,261	

Sources:

1 http://www1.eere.energy.gov/biomass/feedstock_databases.html

2 Jenkins, B., *Properties of Biomass*, Appendix to *Biomass Energy Fundamentals*, EPRI Report TR-102107, January, 1993.

3 Jenkins, B., Baxter, L., Miles, T. Jr., and Miles, T., *Combustion Properties of Biomass*, Fuel Processing Technology 54, pg. 17-46, 1998.

4 Tillman, David, *Wood as an Energy Resource*, Academic Press, New York, 1978

5 Bushnell, D., *Biomass Fuel Characterization: Testing and Evaluating the Combustion Characteristics of Selected Biomass Fuels*, BPA report, 1989

6 http://www.ecn.nl/phyllis

Original references are provided in the Phyllis database for biomass and waste of the Energy Research Centre of the Netherlands.

[a] This table attempts to capture the variation in reported heat content values (on a dry weight basis) in the US and European literature based on values in the Phyllis database, the US DOE/EERE feedstock database, and selected literature sources. Table A.3 of this document provides information on heat contents of materials "as received" with varying moisture contents.

[b] Metric values include both HHV and LHV since Europeans normally report the LHV (or net calorific values) of biomass fuels.

[c] HHV assumed by GREET model given in Table A.1 of this document

Section: Appendix A
Average Heat Content of Selected Waste Fuels

Fuel Type	Heat Content[a]	Units
Agricultural Byproducts	8.248	Million Btu/Short Ton
Black Liquor	11.758	Million Btu/Short Ton
Digester Gas	0.619	Million Btu/Thousand Cubic Feet
Landfill Gas	0.490	Million Btu/Thousand Cubic Feet
MSW Biogenic	9.696	Million Btu/Short Ton
Methane	0.841	Million Btu/Thousand Cubic Feet
Paper Pellets	13.029	Million Btu/Short Ton
Peat	8.000	Million Btu/Short Ton
Railroad Ties	12.618	Million Btu/Short Ton
Sludge Waste	7.512	Million Btu/Short Ton
Sludge Wood	10.071	Million Btu/Short Ton
Solid Byproducts	25.830	Million Btu/Short Ton
Spent Sulfite Liquor	12.720	Million Btu/Short Ton
Utility Poles	12.500	Million Btu/Short Ton
Waste Alcohol	3.800	Million Btu/Barrel

Source:

U.S. Energy Information Administration, Renewable Energy Trends in Consumption and Electricity, 2008 Edition, Table 1.10, Average Heat Content of Selected Biomass Fuels. August 2010.
http://www.eia.doe.gov/cneaf/solar.renewables/page/trends/rentrends.html

[a] Higher heating value
MSW = Municipal Solid Waste

The Effect of Moisture on Heating Values

Definitions for heating value of a biomass

The heating value of any fuel is the energy released per unit mass or per unit volume of the fuel when the fuel is completely burned (ANSI/ASABE S593.1 2011). The term calorific value is synonymous to the heating value. Typical units for expressing calorific or heating value are MJ/kg in SI units or Btu/lb in English units. The heating value of a fuel depends on the assumption made on the condition of water molecules in the final combustion products. The higher heating value (*HHV*) refers to a condition in which the water is condensed out of the combustion products. Because of this condensation all of the heating value of the fuel including sensible heat and latent heat are accounted for. The lower heating value (*LHV*), on the other hand refers to the condition in which water in the final combustion products remains as vapor (or steam); i.e. the steam is not condensed into liquid water and thus the latent heat is not accounted for. The term net heating value (*NHV*) refers to *LHV* (ANSI/ASABE S593.1 2011). The term gross heating value (*GHV*) refers to *HHV*.

Determination of heating value of a biomass

Heating value of a biomass is measured experimentally in terms of the high heating value (HHV). The standard method uses a device called bomb calorimeter. The device burns a small mass of biomass in the presence of oxygen inside a sealed container (or bomb). The heat released from combustion is transferred to a mass of fluid (air or water) that surrounds the container. The heating value is calculated from the product of mass of fluid x specific heat of fluid x net temperature increase. The calculated heating value must be corrected for heat losses to the mass of container, heat conduction through the container wall, and heat losses to the surrounding of the device. In modern calorimeters the corrections are made automatically using sensors and controllers. The resulting measured heating value is considered gross heating value (high heating value) at constant volume because the biomass combustion in the container has taken place inside the fixed volume of the container. The resulting gross heating value can be expressed based on dry mass content of the sample biomass,

$$HHV_d = \frac{HHV}{1-M} \qquad 1$$

where HHV_d is the gross heating value of the biomass in MJ/kg of bone dry biomass, *HHV* is the gross heating value determined by the calorimeter. *M* is the moisture content of the biomass in decimal wet mass fraction.

The high heating value can be estimated from the composition of the fuel (Gaur and Reed 1995),

$$HHV_d = 0.35X_C + 1.18X_H + 0.10X_S - 0.02X_N - 0.10X_O - 0.02X_{ash} \qquad 2$$

where *X* is the mass fractions (percent mass dry basis) for Carbon C, Hydrogen (H), Sulfur (S), Nitrogen (N), Oxygen (O), and ash content (ash). The unit of *HHV* in Equation 2 is in MJ/kg dry mass. Equation 2 shows that the elements Carbon, Hydrogen, Sulfur increase the heating value whereas the elements Nitrogen, Oxygen, and ash suppress the heating value.

Net heating value of biomass

The *HHV* or *GHV* for woody biomass (including bark) that is determined experimentally is around 20 MJ/kg (8600 Btu/ lb) dry mass basis and for herbaceous biomass it is around 18.8 MJ/kg (8080 Btu/ lb) dry mass basis (Oberberger and Thek 2010). For a moist fuel, the heating value decreases because a portion of the combustion heat is used up to evaporate moisture in the biomass and this evaporated moisture has not been condensed to return the heat back to the system. An estimate of the *LHV* or net heating value (*NHV*) is obtained from the measured *HHV* by subtracting the heat of vaporization of water in the products.

$$LHV = HHV(1 - M) - 2.447M \qquad 3$$

where *LHV* is the gross (or lower) heating value MJ/kg, M is the wet basis moisture content (mass fraction decimal). The constant 2.447 is the latent heat of vaporization of water in MJ/kg at 25^{o}C. A more accurate estimate of the net heating value from equation 3 can be obtained by including the heat released by the combustion of the hydrogen content of the biomass.

High and low heating value at constant pressure

In practice, the gases evolving from combustion of a biomass are expanded without much constraints. In other words during combustion the volume expands but the pressure in the combustion zone does not change much. This situation is often present in a boiler combustion chamber with unrestricted exhaust system. For these cases equation 3 developed from constant volume measurement is converted to heating value at constant pressure according to equation 4,

$$HHV_p = HHV - 0.212X_H - 0.0008(X_O + X_N) \qquad 4$$

where HHV_p is the high heating value at constant pressure for dry biomass. X_H, X_O, and X_N are the mass fraction (percent dry mass) of the biomass. For wet biomass, the net heating value at constant pressure is calculated from

$$LHV_{p,w} = HHV_p(1.0 - M) - 2.443M \qquad 5$$

M is the wet basis moisture content (mass fraction decimal). $LHV_{p,w}$ is the net heating value of biomass at constant pressure per unit of wet biomass.

Example of using equations 1 -5

The high heating values of two biomass species poplar and stover along with their ultimate analysis were measured. The moisture content of the samples was 35% wet mass basis. The table below lists the measured data.

Measured Moisture, Elements, and High Heating Value of Biomass								
	M (%)	Ash (%)	C (%)	H (%)	O (%)	N (%)	S (%)	HHV_d (MJ/kg)
Poplar	35	0.65	51.64	6.26	41.45	0.00	0.00	20.75
Stover	35	11.27	44.80	5.35	39.55	0.38	0.01	17.33

Estimation of HHV_d (constant volume)

Equation 2 is used to calculate high heating value

$$HHV_d = 0.35X_C + 1.18X_H + 0.10X_S - 0.02X_N - 0.10X_O - 0.02X_{ash}$$

Substituting from compositions listed in the table above

for poplar

$$HHV_d = 0.35(51.64) + 1.18(6.26) + 0.10(0.00) - 0.02(0.00) - 0.10(41.45) - 0.02(0.65)$$

$$= 21.3\ MJ/kg$$

and for stover,

$$HHV_d = 0.35(44.80) + 1.18(5.35) + 0.10(0.01) - 0.02(0.38) - 0.10(39.55) - 0.02(11.27)$$

$$= 17.8\ MJ/kg$$

The calculated HHV_d for both species are slightly higher than measured HHV_d in the table above.

Estimation of *LHV* (constant volume)

Equation 3 is used to calculate low heating value

$$LHV = HHV_d(1 - M) - 2.447M$$

Substituting for *HHV* and moisture content,

for poplar,

$$LHV = (20.8)(1 - 0.35) - 2.447(0.35)$$

$$= 12.7\ MJ/kg$$

and for stover,

$$LHV = (17.3)(1 - 0.35) - 2.447(0.35)$$

$$= 10.4\ MJ/kg$$

Calculations for HHV_p (constant pressure)

Equation 3 is used to calculate low heating value (or net calorific value) at constant pressure

$$HHV_p = HHV_d - 0.212X_H - 0.0008(X_O + X_N)$$

Substituting from the table above for HHV_d (for constant volume) and concentrations,

for poplar,

$$HHV_p = (20.8) - 0.212(6.26) - 0.0008(41.45 + 0.00)$$

$$= 19.4\ MJ/kg$$

and for stover,

$$HHV_p = (17.3) - 0.212(5.35) - 0.0008(39.55 + 0.38)$$
$$= 16.1\ MJ/kg$$

Calculations for LHV_p (constant pressure)

Equation 5 is used to calculate low heating value,

$$LHV_p = HHV_p(1.0 - M) - 2.443M$$

Substituting for HHV_p and moisture content,

for poplar,

$$LHV = (19.4)(1 - 0.35) - 2.443(0.35)$$
$$= 11.8\ MJ/kg$$

and for stover,

$$LHV = (16.1)(1 - 0.35) - 2.443(0.35)$$
$$= 9.6\ MJ/kg$$

The table below shows the application of equation 5 to calculate the net heating value of biomass at various levels of moisture content. Increasing moisture content diminished the net heat value of biomass to the point that at slightly higher than 80% moisture content, much of the heat content of the biomass is used up to evaporate its moisture.

Effect of Moisture Content on the Net Heating Value of Biomass at Constant Pressure

Biomass	Moisture content percent wet mass basis							
	0	10	20 3	0 40		50	60	70	80
Poplar	19.4	17.3	15.1	12.9	10.7	8.5	6.3	4.1	1.9
Stover	16.1	14.3	12.4	10.6	8.7	6.8	5.0	3.1	1.3

List and Definition of Symbols	
Symbol	Definition
LHV	Lower heating value
HHV	Higher heating value
GHV	Gross heating value
NHV	Net heating value
HHV_p	High heating value at constant pressure
HHV_d	Bone dry gross heating value of the biomass
M	Moisture content wet mass basis
X	Mass fraction percent dry mass basis
Subscripts	
ash	Ash
C	Carbon
d	Dry mass basis
H	Hydrogen
N	Nitrogen
O	Oxygen
p	Constant pressure
w	Moist biomass
Units	
Btu	British thermal unit
MJ	Mega (10^6) Joule (SI unit)
kg	Kilogram
lb	Pound mass

References

ASABE Standards. 2011. American Society for Agricultural & Biological Engineers, St. Joseph, MI: ASABE.

ASTM E870 - 82(2006) Standard Test Methods for Analysis of Wood Fuels. http://www.astm.org/Standards/E870.htm

Gaur, S., T. Reed. 1995. An atlas of thermal data for biomass and other fuels. NREL/TB-433-7965, UC Category: 1310, DE95009212, National Renewable laboratory, Golden Colorado, USA.

Obenberger, I. and G. Thek. 2010. The Pellet Handbook. IEA Bioenergy . Earthscan LLC, Washington, DC.

SIS-CENéTS14918:2005. Solid biofuels. Method of determination of calorific value. http://www.biomassenergycentre.org.uk/portal/page?_pageid=77,19836&_dad=portal&_schema=PORTAL

Sjaak, Van Loo, Jaap Koppejan. 2008. The handbook of biomass combustion and co-firing. Earthsacn, Washington, DC.

TAPPI Gross heating value of black liquor, Test Method T 684 om-11http://www.tappi.org/Bookstore/Standards--TIPs/Standards.aspx

Written by Shahab Sokhansanj, Oak Ridge National Laboratory, September 2011.

Forestry Volume Unit to Biomass Weight Considerations

Biomass is frequently estimated from forestry inventory merchantable volume data, particularly for purposes of comparing regional and national estimates of aboveground biomass and carbon levels. Making such estimations can be done several ways but always involves the use of either conversion factors or biomass expansion factors (or both combined) as described by figure 1 below. Figure 2 clarifys the issue further by defining what is included in each catagory of volume or biomass units.

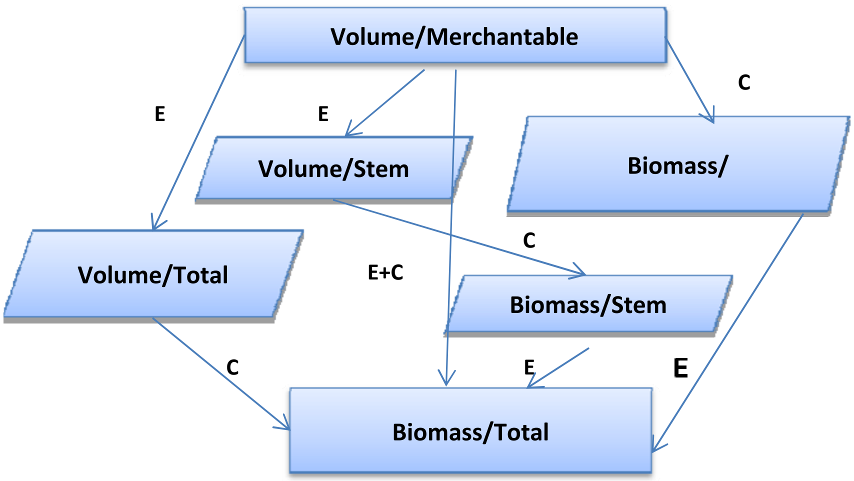

Figure 1 Source: Somogyi Z. et al. Indirect methods of large-scale biomass estimation. Eur J Forest Res (2006) DOI 10.1007/s10342-006-0125-7

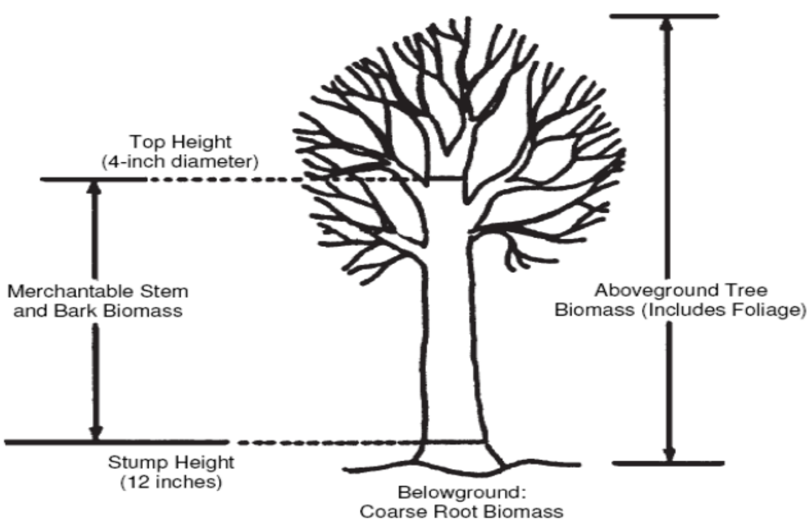

Figure 2 Source: Jenkins, JC, Chojnacky DC, Heath LS, Birdsey RA. Comprehensive Database of Diameter-based Biomass Regressions for North American Tree Species. United States Department of Agriculture, Forest Service General Technical Report NE-319, pp 1-45 (2004)

Unfortunately definitions used in figure 1 are not standardized worldwide, but figure 2 below demonstrates definitions used in the United States for forest inventory data. The <u>merchantable volume</u> provided by forest inventory reports commonly refers only to the underbark volume or biomass of the main stem above the stump up to a 4 inch (10 cm) top. Merchantable stem volume can be converted (symbolized by C in Fig. 1) to merchantable biomass. Both merchantable volume and biomass must be expanded (symbolized by E in Figure 1) to include the bark for stem volume or biomass. Further expansion is needed to obtain the <u>total volume or biomass</u> which includes stem, bark, stump, branches and foliage, especially if evergreen trees are being measured. When estimating biomass available for bioenergy, the foliage is not included and the above-ground portion of the stump may or may not be included depending on whether harvest occurs at ground level or higher.

Both conversion and expansion factors can be used together to translate directly between merchantable volumes per unit area and total biomass per unit area (see table A5, Appendix A) .

Section: Appendix A
Estimation of Biomass Weights from Forestry Volume Data

Simple volume to weight conversion

An equation for estimation of merchantable biomass from merchantable volume assuming the specific gravity and moisture content are known and the specific gravity basis corresponds to the moisture content of the volume involved.

Weight = (volume) * (specific gravity) * (density of H_2O) * ($1+MC^{od}/100$)

where volume is expressed in cubic feet or cubic meters,

where the density of water is 62.4 lb/ft^3 or 1000 kg/$m^{3,}$

where MC^{od} equals oven dry moisture content.

for example the weight of fiber in an oven dry log of 44 ft^3 with a specific gravity of 0.40 =

40 ft^3*0.40 * 62.4 lb ft^3 * (1+0/100) equals 1,098 lb or 0.549 dry ton

Source: Briggs D. 1994. Forest Products Measurements and Conversion Factors, Chapter 1. College of Forest Resources University of Washington. http://www.ruraltech.org/projects/conversions/briggs_conversions/briggs_book.asp

Specific gravity (SG) is a critical element of the volume to biomass estimation equation. The SG content should correspond to the moisture content of the volume involved. SG varies considerably from species to species, differs for wood and bark, and is closely related to the moisture content as explained in graphs and tables in Briggs (1994). The wood specific gravity of species can be found in several references though the moisture content basis is not generally given. Briggs (1994) suggests that a moisture content of 12% is the standard upon which many wood properties measurements are based.

Biomass expansion factors for estimating total aboveground biomass Mg ha^{-1} from growing stock volume data (m^3 ha^{-1})

Methods for estimating total aboveground dry biomass per unit area from growing stock volume data in the USDA ForestService FIA database were described by Schroeder et. al (1997). The growing stock volume was by definition limited to trees > than or equal to 12.7 cm diameter. It is highly recommended that the paper be studied for details of how the biomass expansion factors (BEF) for oak-hickory and beech-birch were developed.

The BEFs for the two forest types were combined and reported as:

BEF = EXP (1.912 - 0.344*lnGSV) **GSV = growing stock volume m^3 ha^{-1}**

R2 = 0.85, n = 208 forest units , std. error of estimate = 0.109.

The result is curvilinear with BEF values ranging from 3.5 to 1.5 for stands with very low growing stock volume and approaching the value of 1 at high growing stock volumes. Minimum BEFs for the forest types evaluated are estimated to be about 0.61 to 0.75.

Source: Schroeder P, Brown S, Mo J, Birdsey R, Cieszewski C. 1997. Biomass estimation for temperate broadleaf forests of the US using forest inventlry data. Forest Science 43, 424-434.

Forestry Volume Unit to Biomass Weight Examples

(selected examples from the north central region)

Species Group	Specific gravity wood[a]	Specific gravity bark[a]	Green MC wood & bark (%)	Green weight wood & bark lb/ft^3	Dry weight wood & bark lb/ft^3	Green weight of solid cord[b] (lbs)	Green weight of solid cord[b] (tons)[c]	Air-dry tons per solid cord[b] 15% MC[c]	Oven-dry tons per solid cord 0% MC[c]
Softwood									
Southern Pine	0.47	0.32	50	64	32	5,056	2.5	1.5	1.3
Jack Pine	0.40	0.34	47	54	29	4,266	2.1	1.3	1.1
Red Pine	0.41	0.24	47	54	29	4,266	2.1	1.3	1.1
White Pine	0.37	0.49	47	53	28	4,187	2.1	1.3	1.1
Hardwood									
Red Oak	0.56	0.65	44	73	41	5,767	2.9	1.9	1.6
Beech	0.56	0.56	41	64	38	5,056	2.5	1.7	1.5
Sycamore	0.46	0.45	55	62	28	4,898	2.4	1.3	1.1
Cottonwood	0.37	0.43	55	59	27	4,661	2.3	1.2	1.0
Willow	0.34	0.43	55	56	25	4,424	2.2	1.1	1.0

Source:

Smith, B. Factors and Equations to Estimate Forest Biomass in the North Central Region. 1985. USDA Forest Service, North Central Experimental Station. Research Paper NC-268 (This paper quotes many original literature sources for the equations and estimates.)

Note: *A caution:* In extensive online research for reference sources that could provide guidance on estimating biomass per unit area from volume data (eg m^3, ft^3 or board ft), several sources of conversion factors and "rules of thumb" were found that provided insufficient information to discern whether the reference was applicable to estimation of biomass availibility. For instance moisture contents were not associated with either the volume or the weight information provided. These "rule of thumb" guides can be useful when fully understood by the user, but they can be easily misinterpreted by someone not understanding the guide's intent. For this reason, most simple "rules of thumb guides" are not useful for converting forest volume data to biomass estimates.

---

[a] The SG numbers are based on weight oven-dry and volume when green (Smith, 1985; table 1) of wood and bark respectively. Wood and bark are combined for other columns (Smith, 1985, table 2).

[b] A standard solid cord for the north central region was determined by Smith, 1985 to be 79 ft^3 rather than the national average of 80 ft^3 as used in table A9 in appendix A..

[c] The green weight values in lbs provided by the Smith (1985) paper were converted to green tons, air-dry tons and oven-dry tons for convenience of the user.

Section: Appendix A
Stand Level Biomass Estimation

Biomass estimation at the individual field or stand level is relatively straight forward, especially if being done for plantation grown trees that are relatively uniform in size and other characteristics. The procedure involves first developing a biomass equation that predicts individual tree biomass as a function of diameter at breast height (dbh) , or of dbh plus height. Secondly, the equation parameters (dbh and height) need to be measured on a sufficiently large sample size to minimize variation around the mean values, and thirdly, the mean individual tree weight results are scaled to the area of interest based on percent survival or density information (trees per acre or hectare). Regression estimates are developed by directly sampling and weighing enough trees to cover the range of sizes being included in the estimation. They often take the form of:

ln Y (weight in kg) = -factor 1 + factor 2 x ln X (where X is dbh or dbh^2 +height/100) Regression equations can be found for many species in a wide range of literature. Examples for trees common to the Pacific Northwest are provided in reference 1 below. The equations will differ depending on whether foliage or live branches are included, so care must be taken in interpreting the biomass data. For plantation trees grown on cropland or marginal cropland it is usually assumed that tops and branches are included in the equations but that foliage is not. For trees harvested from forests on lower quality land, it is usually recommended that tops and branches should not be removed (see reference 2 below) in order to maintain nutrient status and reduce erosion potential, thus biomass equations should assume regressions based on the stem weight only.

Sources:

(1) Briggs, D. Forest Products Measurements and Conversion Factors. College of Forest Resources University of Washington. Available as of 9/29/2008 at: http://www.ruraltech.org/projects/conversions/briggs_conversions/briggs_book.asp

(2) Pennsylvania Department of Conservation and Natural Resources. Guidance on Harvesting Woody Biomass for Energy in Pennsylvania. September, 2007. Available as of 9-29-08 at: http://www.dcnr.state.pa.us/PA_Biomass_guidance_final.pdf

Section: Appendix A
Number of Trees per Acre and per Hectare by Various Tree Spacing Combinations

Spacing (feet) =	Trees per Acre =	Spacing (meters)=	Trees per Hectare[a]	Spacing (meters)=	Trees per Hectare	Spacing (ft and in) =	Trees per Acre[b]
1 x 1	43,560	0.3 x 0 .3	107,637	0.1 x 0.1	1,000,000	4" x 4 "	405,000
2 x 2	10,890	0.6 x 0.6	26,909	0.23 x 0.23	189,035	9" x 9 "	76,559
2 x 4	5,445	0.6 x 1.2	13,455	0.3 x 0.3	107,593	1' x 1'	43,575
3 x 3	4,840	0.9 x 0.9	11,960	0.5 x 0.5	40,000	1'8" x 1'8"	16,200
4 x 4	2,722	1.2x 1.2	6,726	0.5 x 1.0	20,000	1'8" x 3'3"	8,100
4 x 5	2,178	1.2 x 1.5	5,382	0.5 x 2.0	10,000	1'8" x 6'7"	4,050
4 x 6	1,815	1.2 x 1.8	4,485	0.75 x 0.75	17,778	2'6" x 2'6"	7,200
4 x 7	1,556	1.2 x 2.1	3,845	0.75 x 1.0	13,333	2'6" x 3'3"	5,400
4 x 8	1,361	1.2 x 2.4	3,363	0.75 x 1.5	8,889	2'5" x 4'11"	3,600
4 x 9	1,210	1.2 x 2.7	2,990	1.0 x 1.0	10,000	3'3" x 3'3"	4,050
4 x 10	1,089	1.2 x 3.0	2,691	1.0 x 1.5	6,667	3'3" x 4'11"	2,700
5 x 5	1,742	1.5 x 1.5	4,304	1.0 x 2.0	5,000	3'3" x 6'6"	2,025
5 x 6	1,452	1.5 x 1.8	3,588	1.0 x 3.0	3,333	3'3" x 9'10"	1,350
5 x 7	1,245	1.5 x 2.1	3,076	1.5 x 1.5	4,444	4'11"x4'11"	1,800
5 x 8	1,089	1.5 x 2.4	2,691	1.5 x 2.0	3,333	4'11"x 6'6"	1,350
5 x 9	968	1.5 x 2.7	2,392	1.5 x 3.0	2,222	4'11"x9'10"	900
5 x 10	871	1.5 x 3.0	2,152	2.0 x 2.0	2,500	6'6" x 6'6"	1,013
6 x 6	1,210	1.8 x 1.8	2,990	2.0 x 2.5	2,000	6'6" x 8'2"	810
6 x 7	1,037	1.8 x 2.1	2,562	2.0 x 3.0	1,667	6'6" x 9'10"	675
6 x 8	908	1.8 x 2.4	2,244	2.0 x 4.0	1,250	6'6" x 13'1"	506
6 x 9	807	1.8 x 2.7	1,994	2.5 x 2.5	1,600	8'2" x 8'2"	648
6 x 10	726	1.8 x 3.0	1,794	2.5 x 3.0	1,333	8'2" x 9'10"	540
6 x 12	605	1.8 x 3.7	1,495	3.0 x 3.0	1,111	9'10"x9'10"	450
7 x 7	889	2.1 x 2.1	2,197	3.0 x 4.0	833	9'10"x13'1"	337
7 x 8	778	2.1 x 2.4	1,922	3.0 x 5.0	666	9'10"x13'1"	270
7 x 9	691	2.1 x 2.7	1,707	4.0 x 4.0	625	13'1" x 13'1'	253
7 x 10	622	2.1 x 3.0	1,537	5.0 x 5.0	400	16'5" x 16'5'	162
7 x 12	519	3.1 x 3.7	1,282				
8 x 8	681	2.4 x 2.4	1,683				
8 x 9	605	2.4 x 2.7	1,495				
8 x 10	544	2.4 x 3.0	1,344				
8 x 12	454	2.4 x 3.7	1,122				
9 x 9	538	2.7 x 2.7	1,329				
9 x 10	484	2.7 x 3.0	1,196				
9 x 12	403	2.7 x 3.7	996				
10 x 10	436	3.0 x 3.0	1,077				
10 x 12	363	3.0 x 3.7	897				
10 x 15	290	3.0 x 4.5	717				
12 x 12	302	3.7 x 3.7	746				
12 x 15	242	3.7 x4.6	598				

[a] The spacing is approximated to nearest centimeter but trees per hectare = trees per acre x 2.471

[b] The spacing is approximated to nearest inch but trees per acre = trees per hectare x 0.405

The conversions in this table are only suitable for converting volume units of harvested roundwood or processed sawtimber to approximate alternative volume units, but not for estimating standing volume of biomass.

Section: Appendix A
Wood and Log Volume to Volume Conversion Factors

	TO						
FROM	**standard cord**	**solid cord**	**cunit**	**board foot**	**1,000 board feet**	**cubic foot average**	**cubic meters average**
standard cord	1	1.6	1.28	1,536	1.536	128	3.6246
solid cord	0.625	1	0.8	960	0.96	80[a]	2.2653
cunit	0.7813	1.25	1	1,200	1.2	100	2.832
board foot	0.00065	0.00104	0.00083	1	0.001	0.0833	0.0024
1,000 board feet	0.651	1.0416	0.8333	1,000	1	83.33	2.3598
cubic foot	0.0078	0.0125	0.01	12	0.012	1	0.0283
cubic meters	0.2759	0.4414	0.3531	423.77	0.4238	35.3146	1

Source:
http://www.unitconversion.org/
(Verified with several other sources.)

Brief Definitions of the Forestry Measures
A standard cord is 4 ft x 4 ft x 8 ft stack of roundwood including bark and air
A solid cord is the net volume of roundwood in a standard cord stack
A cunit is 100 cubic feet of solid wood
1 board foot (bf) is a plank of lumbar measuring 1 inch x 1 foot x 1 foot (1/12 ft^3)
1000 board feet (MBF) is a standard measure used to buy and sell lumber
1 cubic foot of lumber or roundwood is a 1 ft x 1 ft x 1 ft cube
1 cubic meter of lumber or roundwood is a 1 m x 1 m x 1 m cube

[a] The estimate of 80 cubic feet (or 2.26 cubic meters) in a solid cord is an average value for stacked lumber and also for hardwood roundwood with bark. Values for all roundwood wood types with and without bark can range from 60 to 95 cubic feet or (1.69 to 2.69 cubic meters) depending on wood species, moisture content and other factors.

To use these conversion factors, first decide the mill type, which is based on equipment; then determine the average scaling diameter of the logs. If the equipment indicates a mill type B and the average scaling diameter is 13 inches, then look in section B, line 2. This line shows that for every thousand board feet of softwood lumber sawed, 0.42 tons of bark, 1.18 tons of chippable material, and 0.92 tons of fines are produced, green weight. Equivalent hard hardwood and soft hardwood data are also given. Converting factors for shavings are omitted as they are zero for sawmills.

Section: Appendix A
Estimating Tons of Wood Residue Per Thousand Board Feet of Lumber Produced by Sawmills, by Species and Type of Residue

		Softwood[c]						Hard hardwood[c]						Soft hardwood[c]					
		Bark		Chippable		Fine[f]		Bark		Chipable		Fine		Bark		Chipable		Fine	
Mill Type[a]	Small end diameter[b]	G[d]	OD[e]	G	OD	G	OD	G	OD	G	OD	G	OD	G	OD	G	OD	G	OD
A, B, C, H, and I	1	0.46	0.31	1.57	0.78	0.98	0.48	0.84	0.59	1.84	1.04	1.26	0.71	0.58	0.41	1.27	0.72	0.86	0.49
	2	0.42	0.29	1.18	0.58	0.92	0.45	0.72	0.51	1.53	0.87	1.34	0.76	0.50	0.35	1.06	0.60	0.91	0.52
	3	0.41	0.28	1.07	0.53	1.00	0.49	0.56	0.39	1.17	0.66	1.08	0.61	0.39	0.27	0.81	0.46	0.74	0.42
	4	0.31	0.21	0.88	0.43	0.91	0.45	0.49	0.35	1.03	0.58	1.05	0.60	0.34	0.24	0.72	0.41	0.72	0.41
D and E	1	0.29	0.20	1.57	0.78	0.90	0.45	0.84	0.59	1.84	1.04	0.92	0.52	0.58	0.41	1.27	0.72	0.63	0.36
	2	0.29	0.20	1.18	0.58	0.76	0.38	0.72	0.51	1.53	0.87	0.84	0.48	0.50	0.35	1.06	0.60	0.58	0.33
	3	0.29	0.20	1.07	0.53	0.71	0.35	0.56	0.39	1.17	0.66	0.84	0.48	0.39	0.27	0.81	0.46	0.58	0.33
	4	0.29	0.20	0.88	0.43	0.64	0.32	0.49	0.35	1.03	0.58	0.80	0.45	0.34	0.24	0.72	0.41	0.55	0.31
F	1	0.29	0.20	1.57	0.78	0.98	0.48	0.84	0.59	1.84	1.04	1.26	0.71	0.58	0.41	1.27	0.72	0.86	0.49
	2	0.29	0.20	1.18	0.58	0.92	0.45	0.72	0.51	1.53	0.87	1.34	0.76	0.50	0.35	1.06	0.60	0.91	0.52
	3	0.29	0.20	1.07	0.53	1.00	0.49	0.56	0.39	1.17	0.66	1.08	0.61	0.39	0.27	0.81	0.46	0.74	0.42
	4	0.29	0.20	0.88	0.43	0.91	0.45	0.49	0.35	1.03	0.58	1.05	0.60	0.34	0.24	0.72	0.41	0.72	0.41
G	1	0.29	0.20	1.90	0.94	0.57	0.28	0.84	0.59	2.23	1.28	0.53	0.28	0.58	0.41	1.54	0.88	0.36	0.20
	2	0.29	0.20	1.34	0.66	0.60	0.30	0.72	0.51	1.72	0.98	0.65	0.37	0.50	0.35	1.19	0.68	0.45	0.25
	3	0.29	0.20	1.17	0.58	0.61	0.30	0.56	0.39	1.29	0.73	0.72	0.41	0.39	0.27	0.89	0.51	0.50	0.28
	4	0.29	0.20	0.98	0.48	0.54	0.28	0.49	0.35	1.15	0.65	0.68	0.38	0.34	0.24	0.80	0.46	0.47	0.26

Source:
Ellis, Bridgette K. and Janice A. Brown, Tennessee Valley Authority. "Production and Use of Industrial Wood and Bark Residues in the Tennessee Valley Region," August 1984.

[a] Mill Type
- A. Circular headsaw with or without trim saw
- B. Circular headsaw with edger and trim saw.
- C. Circular headsaw with vertical band resaw, edger, trim saw.
- D. Band headsaw with edger, trim saw.
- E. Band headsaw with horizontal band resaw, edger, trim saw.
- F. Band headsaw with cant gangsaw, edger, trim saw.
- G. Chipping head rig.
- H. Round log mill.
- I. Scragg mill.

[b] Average small-end log (scaling) diameter classes.
1. 5-10 inches.
2. 11-13 inches.
3. 14-16 inches.
4. 17 inches and over

[c] See Appendix A for species classification, i.e., softwood, hard hardwood, and soft hardwood.
[d] G = green weight, or initial condition, with the moisture content of the wood as processed
[e] OD = Oven Dry. It is the weight at zero percent moisture.
[f] Fine is sawdust and other similar size material.

Estimating Tons of Wood Residue Per Thousand Board Feet of Wood Used for Selected Products

Type of Plant	Bark	% MC	Chipable[b]	% MC	Shavings	% MC	Fine[c]	%MC
				Softwood[a]				
Planing mill	-	-	0.05	19	0.42	19	-	-
Wood chip mill[d]	0.60	50	-	-	-	-	-	-
Wooden furniture frames	-	-	0.22	12	0.25	12	0.05	12
Shingles & cooperage stock	0.42	50	1.29	100	-	-	1.01	100
Plywood	-	-	0.13	9	-	-	0.21	9
Veneer	0.42	50	1.77	100	-	-	-	-
Pallets and skids	-	-	0.42	60	0.21	60	0.07	60
Log homes	-	-	0.17	80	-	-	0.05	80
Untreated posts, poles, and pilings	0.46	50	0.40	100	-	-	0.05	100
Particleboard	0.60	60	-	-	-	-	0.21	6
Pulp, paper, and paperboard	0.60	70	-	-	-	-	-	-
				Hard hardwood[a]				
	Bark	% MC	Chipable[b]	% MC	Shavings	% MC	Fine[c]	%MC
Planing mill	-	-	0.06	19	0.54	19	-	-
Wood chip mill	0.90	60	-	-	-	-	-	-
Hardwood flooring	-	-	0.12	6	0.57	6	-	-
Wooden furniture frames	-	-	0.31	9	0.36	9	0.07	9
Shingles & cooperage stock	0.56	60	1.66	70	-	-	1.47	70
Plywood	-	-	0.16	9	-	-	0.26	9
Veneer	0.72	60	2.70	70	-	-	-	-
Pallets and skids	-	-	0.50	60	0.25	60	0.08	60
Pulp, paper, and paperboard	0.90	60	-	-	-	-	-	-
				Soft hardwood[a]				
	Bark	% MC	Chipable[b]	% MC	Shavings	% MC	Fine[c]	%MC
Planing mill	-	-	0.04	19	0.40	19	-	-
Wood chip mill	0.62	88	-	-	-	-	-	-
Wooden furniture frames	-	-	0.22	9	0.26	9	0.05	9
Plywood	-	-	0.13	9	-	-	0.21	9
Veneer	0.50	88	2.13	95	-	-	-	-
Pallets and skids	-	-	0.34	60	0.17	60	0.06	60
Particleboard	0.60	60	-	-	-	-	0.21	6
Pulp, paper, and paperboard	0.62	88	-	-	-	-	-	-

Source:

Ellis, Bridgette K. and Janice A. Brown, Tennessee Valley Authority. "Production and Use of Industrial Wood and Bark Residues in the Tennessee Valley Region", August 1984.

Notes:

For shingles and cooperage stock the table indicates that for every thousand board feet of softwood logs used, 1.29 tons of chippable material could be expected, with an average moisture content (MC) of 100%, based on oven dry weight. If the Average MC of the wood used is greater or less than 100%, proportionally greater or lesser weight of material could be expected.

[a] For definitions of species, see next page

[b] Chippable is material large enough to warrant size reduction before being used by the paper, particleboard, or metallurgical industries.

[c] Fines are considered to be sawdust or sanderdust.

[d] For chipping mills with debarkers only

Section: Appendix A
Area and Length Conversions

Area

Multiply	by	To Obtain
acres (ac)[a]	0.4047	hectares
hectares (ha)	2.4710	acres
hectares (ha)	0.0039	square miles
hectares (ha)	10000	square meters
square kilometer (km^2)	247.10	acres
square kilometer (km^2)	0.3861	square miles
square kilometer (km^2)	100	hectares
square mile (mi^2)	258.9990	hectares
square mile (mi^2)	2.5900	square kilometers
square mile (mi^2)	640	acres
square yards (yd^2)	0.8361	square meters
square meters (m^2)	1.1960	square yards
square foot (ft^2)	0.0929	square meters
square meters (m^2)	10.7639	square feet
square inchs (in^2)	6.4516	square centimeters (exactly)
square decimeter (dm^2)	15.5000	square inches
square centimeters (cm^2)	0.1550	square inches
square millimeter (mm^2)	0.0020	square inches
square feet (ft^2)	929.03	square centimeters
square rods (rd^2), sq pole, or sq perch	25.2930	square meters

Length

Multiply	by	To Obtain
miles (mi)	1.6093	kilometers
miles (mi)	1,609.34	meters
miles (mi)	1,760.00	yards
miles (mi)	5,280.00	feet
kilometers (km)	0.6214	miles
kilometers (km)	1,000.00	meters
kilometers (km)	1,093.60	yards
kilometers (km)	3,281.00	feet
feet (ft)	0.3048	meters
meters (m)	3.2808	feet
yard (yd)	0.9144	meters
meters (m)	1.0936	yards
inches (in)	2.54	centimeters
centimeters (cm)	0.3937	inches

Source:
National Institute of Standards and Technology, General Tables of Units and Measurements
http://ts.nist.gov/WeightsAndMeasures/Publications/upload/h4402_appenc.pdf

[a] An acre is a unit of area containing 43,560 square feet. It is not necessarily square, or even rectangular. If a one acre area is a perfect square, then the length of a side is equal to the square root of 43,560 or about 208.71 feet.

Section: Appendix A
Mass Units and Mass per Unit Area Conversions

Mass

Multiply	by	To Obtain
ounces (oz)	28.3495	grams
grams (gm)	0.0353	ounces
pounds (lbs)	0.4536	kilograms
pounds (lbs)	453.6	grams
kilograms (kg)	2.2046	pounds
kilograms (kg)	0.0011	U.S. or short tons
metric tons or tonne (t)[a]	1	megagram (Mg)
metric tons or tonne (t)	2205	pounds
metric tons or tonne (t)	1000	kilograms
metric tons or tonne (t)	1.102	short tons
metric tons or tonne (t)	0.9842	long tons
U.S. or short tons, (ts)	2000	pounds
U.S. or short tons, (ts)	907.2	kilograms
U.S. or short tons, (ts)	0.9072	megagrams
U.S. or short tons, (ts)	0.8929	Imperial or long tons
Imperial or long tons (tl)	2240	pounds
Imperial or long tons (tl)	1.12	short tons
Imperial or long tons (tl)	1016	kilograms
Imperial or long tons (tl)	1.016	megagrams

Mass per Unit Area

Multiply	by	To Obtain
megagram per hectare (Mg ha^{-1})	0.4461	short tons per acre
kilograms per square meter (kg m-1)	4.461	short tons per acre
tons (short US) per acre (t ac^{-1})	2.2417	megagram per hectare
tons (short US) per acre (t ac^{-1})	0.2241	kilograms per square meter
kilograms per square meter (kg m-1)	0.2048	pounds per square foot
pounds per square foot (lb ft^2)	4.8824	kilogram per square meter
kilograms per square meter (kg m-1)	21.78	short tons per acre
kilogram per hectare (kg ha^{-1})	0.892	pounds per acre
pounds per acre (lb ac^{-1})	1.12	kilogram per hectare

Sources:
www.gordonengland.co.uk/conversion and
http://www.convert-me.com/en/convert/weight
and the Family Farm Series Publication, "Vegetable Crop Production" at
http://sfp.ucdavis.edu/pubs/Family_Farm_Series/Veg/Fertilizing/appendix.html

[a] The proper SI unit for a metric ton or tonne is megagram (MG) however "t" is commonly used in practice as in dt ha^{-1} for dry ton per hectare. Writers in the US also normally use "t" for short ton as in dt ac^{-1} for dry ton per acre, so noting the context in the interpretation of "t" is important.

Section: Appendix A
Distance and Velocity Conversions

1 inch (in)	= 0.0833 ft	1 centimeter (cm)	= 0.3937 in
	= 0.0278 yd		= 0.0328 ft
	= 2.54 cm		= 0.0109 yd
	= 0.0254 m		= 0.01 m
1 foot (ft)	= 12.0 in.	1 meter (m)	= 39.3700 in
	= 0.3333 yd		= 3.2808 ft
	= 30.48 cm		= 1.0936 yd
	= 0.3048 m		= 100 cm
1 mile (mi)	= 63360 in.	1 kilometer (km)	= 39370 in.
	= 5280 ft		= 3281 ft
	= 1760 yd		= 1093.6 yd
	= 1609 m		= 0.6214 mile
	= 1.609 km		= 1000 m

1 in/hr = 2.54 cm/hr
1cm/hr = 0.3937 in/hr
1 ft/sec = 0.3048 m/s = 0.6818 mph = 1.0972 km/h
1 m/sec = 3.281 ft/s = 2.237 mph = 3.600 km/h
1 km/h = 0.9114 ft/s = 0.2778 m/s = 0.6214 mph
1 mph = 1.467 ft/s = 0.4469 m/s = 1.609 km/h

Source:
Davis, S.C., S.W. Diegel and R.G. Boundy. 2008, *Transportation Energy Data Book: Edition 27* , ORNL-6981, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

Capacity, Volume and Specific Volume Conversions[a]

Capacity and Volume

1 U.S. gallon (gal)	=	3.785	liters (L)	1 liter (L)	=	0.2642	US gal
	=	4	US quarts (qt)		=	0.22	UK gal
	=	0.8327	UK gallon (gal)		=	1.056	US qt
	=	0.0238	barrels oil (bbl)		=	0.00629	bbl (oil)
	=	0.0039	cubic meters (m^3)		=	61.02	in^3
	=	0.1337	cubic feet (ft^3)		=	0.03531	ft^3
	=	231	cubic inches (in^3)		=	0.001	m^3
1 imperial (UK) gallon (gal)	=	4.546	liters	1 barrel (bbl) oil	=	158.97	L
	=	4.803	US qt		=	168	US qt
	=	1.201	US gal		=	42	US gal
	=	0.0286	bbl (oil)		=	34.97	UK gal
	=	0.0045	m^3		=	0.15897	m^3
	=	0.1605	ft^3		=	5.615	ft^3
	=	277.4	$in.^3$			9702	$in.^3$
1 cubic meter (m^3)	=	264.172	US gal	1 cubic foot (ft^3)	=	7.4805	US gal
	=	1000	L			28.3168	L
	=	1056	US qt			29.9221	US qt
	=	6.2898	bbl (oil)			0.1781	bbl (oil)
	=	35.3145	ft^3			0.0283	m^3
		1.3079	yd^3			0.037	yd^3
1 cubic centimeter (cm^3)	=	0.061	in^3	1 cubic inches (in^3)	=	16.3872	cm^3
1 Liter (L) dry volume	=	1.8161	US pint (pt)	1 US bushel	=	64	US pt
	=	0.908	US qt		=	32	US qt
	=	0.1135	US peck (pk)		=	35.239	L
	=	0.1099	UK pk		=	4	US pk
	=	0.0284	US bushel (bu)		=	3.8757	UK pk
	=	0.0275	UK bu		=	0.9700	UK bu
	=	0.0086	US bbl dry		=	0.3947	US bbl dry
1 barrel (dry)	=	13.1248	US pk	1 barrel (dry)	=	12.7172	UK pk
	=	3.2812	US bu		=	3.1793	UK bu

Specific Volume

1 US gallon per pound	=	0.8326	UK gal/lb	1 liter per kilogram	=	0.0997	UK gal/lb
(gal/lb)	=	0.1337	ft^3/lb	(L/kg)	=	0.1118	US gal/lb
	=	8.3454	L/kg		=	0.016	ft^3/lb
	=	0.0083	L/g		=	0.0353	ft^3/kg
	=	0.0083	m^3/kg		=	1	m^3/kg
	=	8.3451	cm^3/g		=	1000	cm^3/g

Sources:

Websites www.gordonengland.co.uk/conversion/power.html and www.unitconversion.org were used to make or check conversions.

[a] Forestry unit relationships are provided in table A.9.

Section: Appendix A
Power Unit Conversions

Per second basis

FROM	TO: hp	hp-metric	kW	kJ s^{-1}	Btu_{IT} s^{-1}	$kcal_{IT}$ s^{-1}
Horsepower	1	1.014	0.746	0.746	0.707	0.1780
Metric horsepower	0.986	1	0.736	0.736	0.697	0.1757
Kilowatt	1.341	1.360	1	1	0.948	0.2388
kilojoule per sec	1.341	1.359	1	1	0.948	0.2388
Btu_{IT} per sec	1.415	1.434	1.055	1.055	1	0.2520
Kilocalories $_{IT}$ per sec	5.615	5.692	4.187	4.187	3.968	1

Per hour basis

FROM	TO: hp	hp- metric	kW	J hr^{-1}	Btu_{IT} hr^{-1}	$kcal_{IT}$ hr^{-1}
Horsepower	1	1.014	0.746	268.5×10^{4}	2544	641.19
Metric horsepower	0.986	1	0.736	265.8×10^{4}	2510	632.42
kilowatt	1.341	1.360	1	360×10^{4}	3412	859.85
Joule per hr	3.73×10^{-7}	3.78×10^{-7}	2.78×10^{-7}	1	9.48×10^{-4}	2.39×10^{-4}
Btu_{IT} per hr	3.93×10^{-4}	3.98×10^{-4}	2.93×10^{-4}	1055	1	0.2520
Kilocalories $_{IT}$ per hr	1.56×10^{-3}	1.58×10^{-3}	1.163×10^{-3}	4187	3.968	1

Sources:
www/unitconversion.org/unit_converter/power.html and
www.gordonengland.co.uk/conversion/power.html were used to make conversions

Note: The subscript "IT" stands for International Table values, which are only slightly different from thermal values normally subscripted "th". The "IT" values are most commonly used in current tables and generally are not subscripted, but conversion calculators ususally include both.

Section: Appendix A

Small and Large Energy Units and Energy per Unit Weight Conversions

Energy Units

	TO:				
FROM:	MJ	J	k W h	Btu_{IT}	cal_{IT}
megajoule (MJ)	1	1×10^{6}	0.278	947.8	238845
joule (J)[a]	1×10^{-6}	1	0.278×10^{-6}	9.478×10^{-4}	0.239
Kilowatt hours (k W h)	3.6	3.6×10^{6}	1	3412	859845
Btu_{IT}	1.055×10^{-3}	1055.055	2.93×10^{-4}	1	251.996
$calorie_{IT}$ (cal_{IT})		4.186	1.163×10^{-6}	3.97×10^{-3}	1

Energy per Unit Weight

	TO:			
FROM:	$J\ kg^{-1}$	kJ kg-1	$cal_{IT}\ g^{-1}$	$Btu_{IT}\ lb^{-1}$
joule per kilogram ($J\ kg^{-1}$)	1	0.001	2.39×10^{-4}	4.299×10^{-4}
kilojoules per kilogram($kJ\ kg^{-1}$)	1000	1	0.2388	0.4299
calorieth per gram ($cal_{IT}\ g^{-1}$)	4186.8	4.1868	1	1.8
BtuIT per pound ($Btu_{IT}\ lb^{-1}$)	2326	2.326	0.5555	1

Large Energy Unit Conversions

	TO:				
	Terajoules	**Giga-calories**	**Million tonnes of oil equivalent**	**Million Btu**	**Gigawatt-hours**
FROM:	*multiply by:*				
Terajoules	1	238.8	2.388×10^{-5}	947.8	0.2778
Gigacalories	4.1868×10^{-3}	1	10^{-7}	3.968	1.163×10^{-3}
Million tonnes of oil equivalent	4.1868×10^{4}	107	1	3.968×10^{7}	11,630
Million Btu	1.0551×10^{-3}	0.252	2.52×10^{-8}	1	2.931×10^{-4}
Gigawatthours	3.6	860	8.6×10^{-5}	3412	1

Sources:

www.gordonengland.co.uk/conversion/power.html and www.convert-me.com/en/convert/power and www.unitconversion.org/unit_converter/fuel-efficiency-mass were used to make or check conversions

Davis, S.C., S.W. Diegel and R.G. Boundy. 2008. *Transportation Energy Data Book: Edition 27,* Appendix B.7. ORNL-6981, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

Note:
The subscript "IT" stands for International Table values, which are only slightly different from thermal values normally subscripted "th". The "IT" values are most commonly used in current tables and generally are not subscripted, but conversion calculators ususally include both.

[a] One Joule is the exact equivalent of one Newton meter (Nm) and one Watt second.

Section: Appendix A
Most Commonly Used Biomass Conversion Factors

1 Quadrillion Btu's (Quad) = 1 x 10^{15} Btu = 1.055 Exajoules (EJ) = 1.055 x 10^{18} Joules (J)

1 Million Btu's (MMbtu) = 1 x 10^{6} Btu = 1.055 Gigajoules (GJ) = 1.055 x 10^{9} J

1000 Btu per pound x 2000 lbs per ton = 2 MMbtu per ton = 2.326 GJ per Megagram (Mg)

8500 Btu per pound (average heating value of wood) = 17 MMbtu per ton = 19.8 GJ per Mg

Section: Appendix A
Alternative Measures of Greenhouse Gases

1 pound methane, measured in carbon units (CH_4)	=	1.333 pounds methane, measured at full molecular weight (CH_4)
1 pound carbon dioxide, measured in carbon units (CO_2-C)	=	3.6667 pounds carbon dioxide, measured at full molecular weight (CO_2)
1 pound carbon monoxide, measured in carbon units (CO-C)	=	2.333 pounds carbon monoxide, measured at full molecular weight (CO)
1 pound nitrous oxide, measured in nitrogen units (N_2O-N)	=	1.571 pounds nitrous oxide, measured at full molecular weight (N_2O)

Source:
Davis, S.C., S.W. Diegel and R.G. Boundy. 2008. *Transportation Energy Data Book: Edition 27* , Appendix B.9. ORNL-6981, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

Section: Appendix A
Fuel Efficiency Conversions

MPG	Miles/liter	Kilometers/L	L/100 kilometers
10	2.64	4.25	23.52
15	3.96	6.38	15.68
20	5.28	8.50	11.76
25	6.60	10.63	9.41
30	7.92	12.75	7.84
35	9.25	14.88	6.72
40	10.57	17.00	5.88
45	11.89	19.13	5.23
50	13.21	21.25	4.70
55	14.53	23.38	4.28
60	15.85	25.51	3.92
65	17.17	27.63	3.62
70	18.49	29.76	3.36
75	19.81	31.88	3.14
80	21.13	34.01	2.94
85	22.45	36.13	2.77
90	23.77	38.26	2.61
95	25.09	40.38	2.48
100	26.42	42.51	2.35
105	27.74	44.64	2.24
110	29.06	46.76	2.14
115	30.38	48.89	2.05
120	31.70	51.01	1.96
125	33.02	53.14	1.88
130	34.34	55.26	1.81
135	35.66	57.39	1.74
140	36.98	59.51	1.68
145	38.30	61.64	1.62
150	39.62	63.76	1.57
Formula	MPG/3.785	MPG/[3.785/1.609]	235.24/MPG

Source:

Davis, S.C., S.W. Diegel and R.G. Boundy. 2008. *Transportation Energy Data Book: Edition 27*, Appendix B.13. ORNL-6981, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

Section: Appendix A
SI Prefixes and Their Values

	Value	Prefix	Symbol
One million million millionth	10^{-18}	atto	a
One thousand million millionth	10^{-15}	femto	f
One million millionth	10^{-12}	pico	p
One thousand millionth	10^{-9}	nano	n
One millionth	10^{-6}	micro	μ
One thousandth	10^{-3}	milli	m
One hundredth	10^{-2}	centi	c
One tenth	10^{-1}	deci	d
One	10^{0}		
Ten	10^{1}	deca	da
One hundred	10^{2}	hecto	h
One thousand	10^{3}	kilo	k
One million	10^{6}	mega	M
One billion[a]	10^{9}	giga	G
One trillion[a]	10^{12}	tera	T
One quadrillion[a]	10^{15}	peta	P
One quintillion[a]	10^{18}	exa	E

Source:

Davis, S.C., S.W. Diegel and R.G. Boundy. 2008. Transportation Energy Data Book: Edition 27, Appendix B.14. ORNL-6981, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

[a] Care should be exercised in the use of this nomenclature, especially in foreign correspondence, as it is either unknown or carries a different value in other countries. A "billion," for example, signifies a value of 10^{12} in most other countries.

Section: Appendix A
Metric Units and Abbreviations

Quantity	Unit name	Symbol
Energy	joule	J
Specific energy	joule/kilogram	J/kg
Specific energy consumption	joule/kilogram•kilometer	J/(kg•km)
Energy consumption	joule/kilometer	J/km
Energy economy	kilometer/kilojoule	km/kJ
Power	kilowatt	kW
Specific power	watt/kilogram	W/kg
Power density	watt/meter^3	W/m^3
Speed	kilometer/hour	km/h
Acceleration	meter/second^2	m/s^2
Range (distance)	kilometer	km
Weight	kilogram	kg
Torque	newton•meter	N•m
Volume	meter^3	m^3
Mass; payload	kilogram	kg
Length; width	meter	m
Brake specific fuel consumption	kilogram/joule	kg/J
Fuel economy (heat engine)	liters/100 km	L/100 km

Source:
Davis, S.C., S.W. Diegel and R.G. Boundy. 2008. *Transportation Energy Data Book: Edition 27* , Appendix B.15. ORNL-6981, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

Section: Appendix A
Cost per Unit Conversions

Multiply	by	To Obtain
$/ton	1.1023	$/Mg
$/Mg	0.9072	$/ton
$/Mbtu	0.9407	$/GJ
$/GJ	1.0559	$/Mbtu

Appendix B - Biomass Characteristics

Biomass feedstocks and fuels exhibit a wide range of physical, chemical, and agricultural process engineering properties. Despite their wide range of possible sources, biomass feedstocks are remarkably uniform in many of their fuel properties, compared with competing feedstocks such as coal or petroleum. For example, there are many kinds of coals whose gross heating value ranges from 20 to 30 GJ/tonne (gigajoules per metric tonne; 8600-12900 Btu/lb). However, nearly all kinds of biomass feedstocks destined for combustion fall in the range 15-19 GJ/tonne (6450-8200 Btu/lb). For most agricultural residues, the heating values are even more uniform – about 15-17 GJ/tonne (6450-7300 Btu/lb); the values for most woody materials are 18-19 GJ/tonne (7750-8200 Btu/lb). Moisture content is probably the most important determinant of heating value. Air-dried biomass typically has about 15-20% moisture, whereas the moisture content for oven-dried biomass is around 0%. Moisture content is also an important characteristic of coals, varying in the range 2-30%. However, the bulk density (and hence energy density) of most biomass feedstocks is generally low, even after densification – between about 10 and 40% of the bulk density of most fossil fuels – although liquid biofuels have comparable bulk densities.

Most biomass materials are easier to gasify than coal, because they are more reactive, with higher ignition stability. This characteristic also makes them easier to process thermochemically into higher-value fuels such as methanol or hydrogen. Ash content is typically lower than for most coals, and sulphur content is much lower than for many fossil fuels. Unlike coal ash, which may contain toxic metals and other trace contaminants, biomass ash may be used as a soil amendment to help replenish nutrients removed by harvest. A few herbaceous feedstocks stand out for their peculiar properties, such as high silicon or alkali metal contents – these may require special precautions for harvesting, processing and combustion equipment. Note also that mineral content can vary as a function of soil type and the timing of feedstock harvest. In contrast to their fairly uniform physical properties, biomass fuels are rather heterogeneous with respect to their chemical elemental composition.

Among the liquid biomass fuels, biodiesel (vegetable oil ester) is noteworthy for its similarity to petroleum-derived diesel fuel, apart from its negligible sulfur and ash content. Bioethanol has only about 70% the heating value of petroleum distillates such as gasoline, but its sulfur and ash contents are also very low. Both of these liquid fuels have lower vapor pressure and flammability than their petroleum-based competitors – an advantage in some cases (e.g. use in confined spaces such as mines) but a disadvantage in others (e.g. engine starting at cold temperatures).

The tables on the following 3 pages show some "typical" values or a range of values for selected compositional, chemical and physical properties of biomass feedstocks and liquid biofuels. Figures for fossil fuels are provided for comparison.

Sources for further information:

US DOE Biomass Feedstock Composition and Property Database.
http://www1.eere.energy.gov/biomass/feedstock_databases.html

PHYLLIS - database on composition of biomass and waste.
http://www.ecn.nl/phyllis/

Nordin, A. (1994) Chemical elemental characteristics of biomass fuels. Biomass and Bioenergy 6, 339-347.

Source: All information in Appendix B was taken from a fact sheet by Jonathan Scurlock, Oak Ridge National Laboratory, Bioenergy Feedstock Development Programs. P.O. Box 2008, Oak Ridge, TN 37831-6407

Section: Appendix B
Characteristics of Selected Feedstocks and Fuels

		Cellulose (Percent)	Hemi-cellulose (Percent)	Lignin (Percent)	Extractives (Percent)
Bioenergy Feedstocks	Corn stover[a]	30 - 38	19 - 25	17 - 21	3.3 - 11.9
	Sweet sorghum	27	25	11	
	Sugarcane bagasse[a]	32 - 43	19 - 25	23 - 28	1.5 - 5.5
	Sugarcane leaves	b	b	b	
	Hardwood	45	30	20	
	Softwood	42	21	26	
	Hybrid poplar[a]	39 - 46	17 - 23	21 - 8	1.6 - 6.9
	Bamboo	41-49	24-28	24-26	
	Switchgrass[a]	31 - 34	24 - 29	17 - 22	4.9 - 24.0
	Miscanthus	44	24	17	
	Giant Reed	31	30	21	
Liquid Biofuels	Bioethanol	N/A	N/A	N/A	N/A
	Biodiesel	N/A	N/A	N/A	N/A
Fossil Fuels	Coal (low rank; lignite/sub-bituminous)	N/A	N/A	N/A	N/A
	Coal (high rank bituminous/anthracite)	N/A	N/A	N/A	N/A
	Oil (typical distillate)	N/A	N/A	N/A	N/A

Source:
Oak Ridge National Laboratory, Bioenergy Feedstock Development Program. P.O. Box 2008, Oak Ridge, TN 37831-6407 (compiled by Jonathon Scurlock in 2002, updated by Lynn Wright in 2008).

Notes:
N/A = Not Applicable.
[a]Updated using http://www1.eere.energy.gov/biomass/feedstock_databases.html
[b] Data not available.

Characteristics of Selected Feedstocks and Fuels (Continued)

		Ash %	Sulfur (Percent)	Potassium (Percent)	Ash melting temperature [some ash sintering observed] (C)
Bioenergy Feedstocks	Corn stover[a]	9.8 - 13 5	0.06 - 0.1	b	b
	Sweet sorghum	5.5	b	b	b
	Sugarcane bagasse[a]	2.8 - 9.4	0.02 - 0.03	0.73-0.97	b
	Sugarcane leaves	7.7	b	b	b
	Hardwood	0.45	0.009	0.04	[900]
	Softwood	0.3	0.01	b	b
	Hybrid poplar[a]	0.4 - 2.4	0.02 - 0.03	0.3	1,350
	Bamboo	0.8 - 2.5	0.03 - 0.05	0.15 - 0.50	b
	Switchgrass[a]	2.8 - 7.5	0.07 - 0.11	b	1,016
	Miscanthus	1.5 - 4.5	0.1	0.37 - 1.12	1,090 [600]
	Giant reed	5 - 6	0.07	b	b
Liquid Biofuels	Bioethanol	b	<0.01	b	N/A
	Biodiesel	<0.02	<0.05	<0.0001	N/A
Fossil Fuels	Coal (low rank; lignite/sub-bituminous)	5 - 20	1.0 - 3.0	0.02 - 0.3	~1,300
	Coal (high rank bituminous/anthracite)	1 - 10	0.5 - 1.5	0.06 - 0.15	~1,300
	Oil (typical distillate)	0.5 - 1.5	0.2 - 1.2	b	N/A

Source:

Oak Ridge National Laboratory, Bioenergy Feedstock Development Program. P.O. Box 2008, Oak Ridge, TN 37831-6407 (compiled by Jonathon Scurlock in 2002, updated by Lynn Wright in 2008).

Notes:

N/A = Not Applicable.

[a]Updated using http://www1.eere.energy.gov/biomass/feedstock_databases.html

[b] Data not available.

Characteristics of Selected Feedstocks and Fuels (Continued)

		Cellulose fiber length (mm)	**Chopped density at harvest (kg/m³)**	**Baled density [compacted bales] (kg/m³)**
Bioenergy Feedstocks	Corn stover[a]	1.5	b	b
	Sweet sorghum	b	b	b
	Sugarcane bagasse[a]	1.7	50 - 75	b
	Sugarcane leaves	b	25 - 40	b
	Hardwood	1.2	b	b
	Softwood	b	b	b
	Hybrid poplar[a]	1 - 1.4	150 (chips)	b
	Bamboo	1.5 - 3.2	b	b
	Switchgrass[a]	b	108	105 - 133
	Miscanthus	b	70 - 100	130 - 150 [300]
	Giant reed	1.2	b	b
Liquid Biofuels				(typical bulk densities or range given below)
	Bioethanol	N/A	N/A	790
	Biodiesel	N/A	N/A	875
Fossil Fuels	Coal (low rank; lignite/sub-bituminous)	N/A	N/A	700
	Coal (high rank bituminous/anthracite)	N/A	N/A	850
	Oil (typical distillate)	N/A	N/A	700 - 900

Source:

Oak Ridge National Laboratory, Bioenergy Feedstock Development Program. P.O. Box 2008, Oak Ridge, TN 37831-6407 (compiled by Jonathon Scurlock in 2002, updated by Lynn Wright in 2008).

Notes:

N/A = Not Applicable.

[a]Updated using http://www1.eere.energy.gov/biomass/feedstock_databases.html

[b] Data not available.