Energy Values of Unprocessed Biomass, Charcoal and other Biomass Fuels and their role in Greenhouse Gas Mitigation and Energy Use

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Abstract. The energy value of biomass depends on its carbon and hydrogen contents, its non-combustibles and the water content. For unprocessed biomass, namely wood, residues and dung, the C and H contents are more or less constant for each group of fuels on an ash-free and moisture-free basis. Using this information, a method is given to calculate the low heat values of unprocessed biomass at different moisture and ash contents. While most wood species have an ash content of about 1%, the ash content of crop residues vary according to species from about 1 to 20%. Similarly dung varies from about 20 to 30% ash. However, moisture is the most important factor when determining the available energy. Tables and graphs are given of unprocessed biomass energy at different ash and moisture contents. Charcoal is the most important processed biomass. A method to calculate the energy value of charcoal from biomass is given. The energy values of other forms of biomass are also given. Finally, the role of biomass as a renewable energy (RE) source as well as it being an important tool to capture and reduce greenhouses gases (GHG) is discussed.

Key words. Biomass energy content; biomass energy determination; RE source; GHG reduction.

1 Introduction

For some people, there is confusion regarding the energy values of biomass. For example in the publication *Firewood Crops*, National Academy of Sciences (NAS). 1980 [1] some species of wood are stated to have 'high' energy values and others 'low' energy values. This could be due to the fact that the energy value was determined on a volume, not weight, basis and/or at different moisture contents. The density of wood species varies considerably with some species having a density of 1 and others of 0.5. Thus, on a volume basis, at the same moisture content, the latter species will have half the energy value of the former. Because of the density variations in biomass, it is important to measure the energy value by weight. This article tries to dispel such confusion and gives standard formats for calculating the energy value (in Joules) of biomass types. There are two energy standards, namely the high heat value and the low heat value. The difference between these two values is the amount of energy required when during the combustion process, the hydrogen in biomass combines with oxygen to produce water in the form of steam. The heat required to turn this water into vapour, assuming the average hydrogen content of wood and crop residues is 6% on an ash free and moisture free basis, is about 1.3 MegaJoule (MJ), (2.44 MJ kg^{-1} of water). Normally the water vapour escapes and its heat content is lost and therefore, not available as energy. The high heat value of ash-free dry wood is on average 20.2 MJ kg^{-1}. Thus, its low heat value is 18.9 MJ kg^{-1}. However, the ash content of wood is about 1 percent. Therefore, the low heat value of dry wood is 99 percent of 18.9, namely 18.7 $MJkg^{-1}$. It is this low heat value that is used when the energy content of wood and other fuels containing hydrogen is given.

The energy value of processed and unprocessed biomass depends on three factors, the carbon (and hydrogen) content, the moisture content and the content of other non-energy releasing elements such as silica, usually defined as the ash content. The less moisture and the smaller the ash content per unit weight of biomass, the more energy it will release when burnt. This is for two reasons: the first is that it will have a higher percentage of combustibles and the second is that less energy will be used to drive off the water in the biomass: 2.44 MJ of energy are required to drive off 1 kg of water, Bialy J. 1979 [2]. Therefore, one kg of biomass that contains 50 percent water will expend 1.22 MJ to expel this

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water, whereas if the biomass has 15 percent water, only 0.37 MJ of energy per kg of biomass will be used to drive off the water. Also for the same species of biomass, the latter specimen will have 70 percent more combustible material per unit weight than the former. This is why people prefer to collect dry biomass, or at least let it dry before burning. There are exceptions to this. Sugar cane waste (bagasse) is usually burnt with about 30 to 40 percent moisture. This is because it has a tendency to combust spontaneously if left to dry in a pile. It is a fallacy to say that on a weight basis, certain species of wood have a higher energy value than other species at the same moisture content. Dense wood burns more slowly than less dense wood, but both release the same amount of energy per unit weight, but not per unit volume!

2 Phyllis

This publication gives a 'rule of thumb' to determine high heat and low heat energy values for groups of unprocessed biomass, namely wood, crop residues and dung and charcoal from unprocessed biomass. There is a resource called *Phyllis*, Energy Research Centre of the Netherlands (ECN). 2012 [3], which amongst other things is collecting the energy values of different species of wood and crop residues and different varieties of dung. It also gives a more precise method to determine the high and low energy values. Many of the listed energy values especially for woody biomass are in close agreement with the general energy values given in this text. It also gives charcoal values for a few species of wood, and char values for different kinds of biomass.

However, at the same moisture content, the density and energy value of wood can vary by site, age and the percentage of bark. Therefore, even for a single species, there can be a range of energy values, e.g. eucalyptus spp. Chapola G.B.J. Ngulube M.R. 1991 [4]. At present, most wood energy is used in tropical countries by households, informal industries and the service sector. These sectors use a large variety of woody species ranging from shrubs to mature trees. There are very few tropical species listed in *Phyllis* and thus, ascribing specific energy values to intermediate or end use is not practical. There are species listed in *Phyllis* where the energy value is not stated, although the carbon and hydrogen content are given. Also, some of the stated values are suspect. For example, the low heat (LH) value of dry ash free coconut coir is given as 21.64 MJ kg^{-1}, but the carbon, hydrogen and oxygen contents are respectively given as 19.39, 2.74 and 77.26 percent. If these percentages are correct, it is highly unlikely that ash free coconut coir has such a large energy value. 6.9 MJ kg^{-1} may be nearer the truth! This is because for dry ash-free coconut coir fibre the LH energy value is given as 17.27 MJ kg^{-1} and the percentages for C, H and O is given as 48.58, 6.74 and 44.69 respectively. It is C and H that provide the energy, not O.

Regarding crop residues, not all the kinds of residues used by the various sectors, especially households, are listed in *Phyllis* and even though cow manure is given, in the tropics, especially in India, it is prepared as fuel by mixing it with straw and leaves then dried before being ignited. Thus, the energy value of such 'cow pats' may differ from that given in *Phyllis*.

For all these reasons, the rule of thumb calculations given in this paper are a good approximation for government departments, surveyors and planners etc., especially since many field measurements on which energy values are determined contain measurement errors of up to 10 percent or more. *Phyllis* is very useful when single species are being burnt such as in sugar mills (for bagasse) and tea drying factories where a single eucalyptus species may be used to dry the tea, but these are exceptions.

3 Energy Values of Biomass

Many publications specify calorific value when referring to the energy content of biomass etc., but give it in Joules not calories. This publication prefers the term energy value to avoid confusion. Table 1 gives the "low heat" energy values of wood, crop residues and dung at different moisture and ash contents, Openshaw K. 1986 [5]. It is assumed that each form of biomass contains about 6% hydrogen. Therefore, on an ash-free, moisture free basis, the difference in energy values is dependent on its carbon content. Irrespective of species, wood has about 50 percent carbon (C), 6 percent hydrogen (H) and 44 percent oxygen (O) per unit dry weight of combustible material. Similarly, crop residues have on average in percentage terms about 45 C, 6 H and 49 O. Finally, dung has about 58 C, 6 H and 36 O in percentage terms. Usually, wood has a low ash content, being of the order of 1 percent, with a range from about 0.3 to 3 percent, Bialy J. 1979 [2].

The ash content in crop residues varies considerably depending on the type of residues. In coconut shells it is about 1 percent whereas in rice husks it can be up to 20 percent. Table 2 gives the ash content of different residues. The ash content of dung is much higher than that of plants because many minerals in plant food are not absorbed by animals, but excreted in a concentrated form and as stated above it may have residues added before burning. Thus, the ash content of dung can range from about 20 to 30%.

Table 1. Energy Values of Plant Biomass and Dung at Different Moisture & Ash Contents[1].

Units: MJ kg^{-1}. (Low heat value)[2].

Biomass type	Ash content[4]	Moisture content[3]: dry basis [db] and wet basis [wb] percent ----- Fresh/Green	---- -----	-----	---- Air dry	----		----		Dry
	percent	db 150 wb 60	100 50	66.7 40.0	42.9 30.0	25.0 20.0	17.6 15.0	11.1 10.0	5.3 5.0	0 0
Wood	1	6.0	8.2	10.3	12.4	14.5	15.5	16.6	17.7	18.7
Crop residues	5	5.2	7.1	9.0	10.9	12.8	13.8	14.7	15.7	16.6
	10	4.9	6.7	8.5	10.3	12.1	13.0	13.9	14.8	15.8
	20	4.2	5.8	7.4	9.1	10.7	11.5	12.4	13.2	14.0
Dung	20	5.4	7.3	9.3	11.2	13.2	14.1	15.1	16.1	17.0
	25	5.0	6.8	8.6	10.5	12.3	13.2	14.1	15.1	16.0
	30	4.5	6.3	8.0	9.7	11.4	12.3	13.2	14.0	14.9

Note. 1. This is a straight-line relationship (energy value/mc [wb]). Thus, the value at any moisture content can be calculated and/or read from a graph (below). At a wbmc of between 86 and 89 percent the low heat value for all biomass is zero; that is all the energy in the 11 to 14 percent of fibre is used to drive off the 86 to 89 percent of water.
2. One (1) MJ =239 kcal or 948 Btu. 1 kcal = 4.187 kJ. 1Btu = 1,055 J. 1 J = 1 W; 1 kWhr = 3.6 MJ.
3. The formula for measuring moisture content (MC) is as follows:
Dry basis. Wet weight – Dry weight/Dry weight. The dry basis MC can be greater than 100%.
Wet basis. Wet weight – Dry weight/Wet weight. This MC cannot be greater than 100%.
The formula for converting from dry to wet is: D (%)/[1 + D%/100] = W%. W%/[1 – W%/100] = D%.
4. The ash content is measured on a dry basis; therefore the percentage of ash in the fibre remains constant irrespective of moisture content
Source. Openshaw K. 1986 [5].
The different energy values in Table 1 can be calculated using the formula: $Y_1 = Y_2 – C(X_1-X_2)$, where:
X_1 = the moisture content (wb) in percent of the unknown energy value; X_2 = the moisture content (wb) in percent of a known energy value;
Y_1 = the energy value in MJ kg^{-1} to be determined; Y_2 = the known energy value in MJ kg^{-1};
C = a constant at a specific ash content, representing the negative slope of the line.
C is determined from knowing two energy values. E.g. at 50% mcwb, wood with a 1% ash content has an energy value of 8.1 MJ kg^{-1}. At 0% mcwb, its energy value is 18.7 MJ kg^{-1}. The slope of the line C = minus (18.7 – 8.1)/(50 - 0) = minus 0.212
This formula can be applied to determine any (biomass) energy value at different ash and moisture contents, provided two values are known so that C can be determined. The constants for the crop residues in Table 1 are respectively minus 0.190; 0.182; and 0.164 for ash contents of 5, 10 & 20 %. Likewise for dung with ash contents of 20, 25 & 30 percent respectively, they are minus 0.194; 0.184; and 0.172.

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The low heat energy value at different ash and moisture contents has been calculated as follows. The average high heat value for bone-dry wood, crop residues and dung was determined on an ash free basis. For wood it is 20.2 MJ kg^{-1}, for crop residues 18.8 MJ kg^{-1} and for dung 22.6 MJ kg^{-1}.

As stated above, the difference between high and low heat values is approximately 1.3 MJ kg^{-1} of biomass at zero moisture content. This amount was deducted from the high heat value to obtain the low heat value, namely 18.9, 17.5 and 21.3 MJ kg^{-1} respectively for wood, crop residues and dung. These are the basic values that are used to determine the low heat values of the three forms of biomass at different moisture and ash contents. If wood has a moisture content of 40 percent wet basis (wb), or 67 percent dry basis (db), it contains 60 percent fibre and 40 percent water. If all the fibre is burnable, the energy content is 0.60 x 18.9 = 11.34 MJ. However, 1 percent of this total is non-combustible, so the energy content is 0.60 x 18.9 x 99 = 11.23 MJ. Some of this energy is used to expel the water. It takes about 2.44 MJ to remove one kilogram of water. Thus, to expel 0.40 kg will take 2.44 x 0.40 = 0.98 MJ. For wood with 40 % mc, the net energy available for heating is 11.23 – 0.98 = 10.25 MJ kg^{-1}. As a group, coniferous species have slightly higher energy contents than broadleaves, because of their resin content. It may be up to 5 percent greater than the average, but the errors involved in estimating the moisture and ash contents may negate consideration of this, Bialy J. 1979 [2].

Table 1 can be represented in a graphical form and may be easier for some people to visualize. Graphs 1a, 1b, and 1c, give the energy values of wood, residues and dung at different moisture and ash contents. Before burning, ‘green’ biomass, if allowed to dry say to 10 to 20 percent moisture content (wet basis), will improve its energy content for reasons stated above. It will be observed that air-dry wood has over twice the energy value per unit weight of green or fresh wood; likewise for other forms of biomass.

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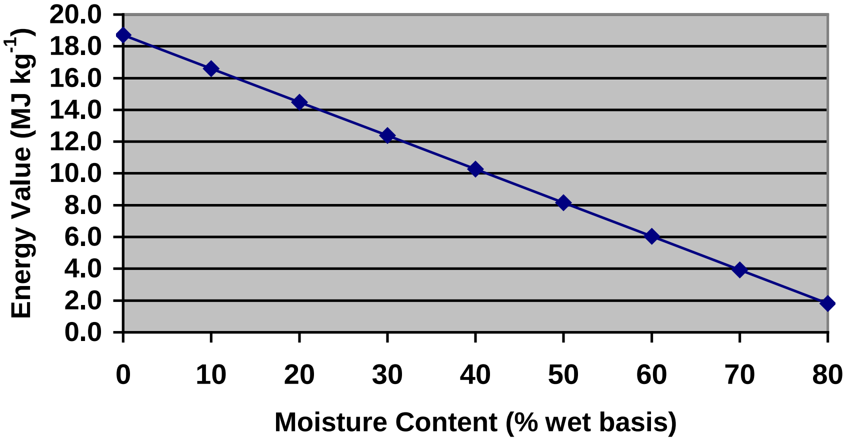
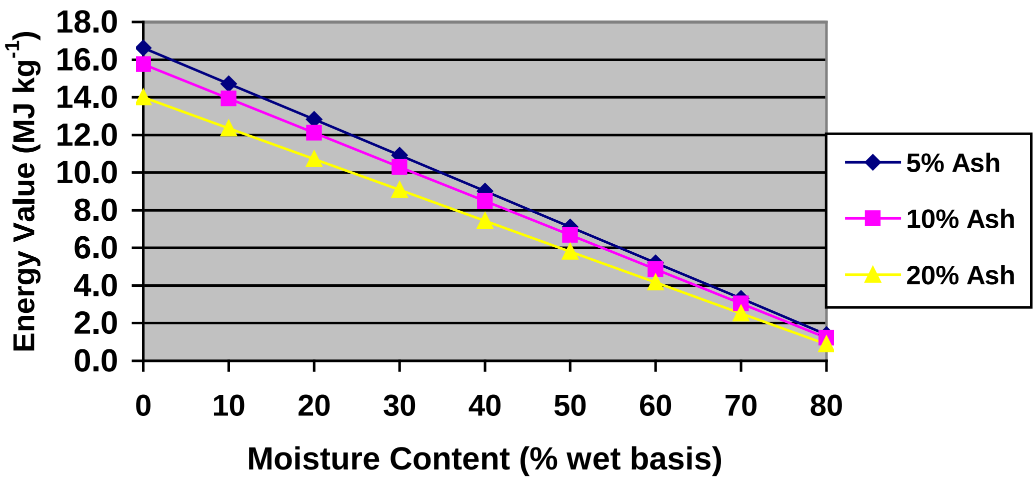
Graph 1a. Energy Values of Wood (1% ash content)



Graph 1b. Energy Values of Crop Residues



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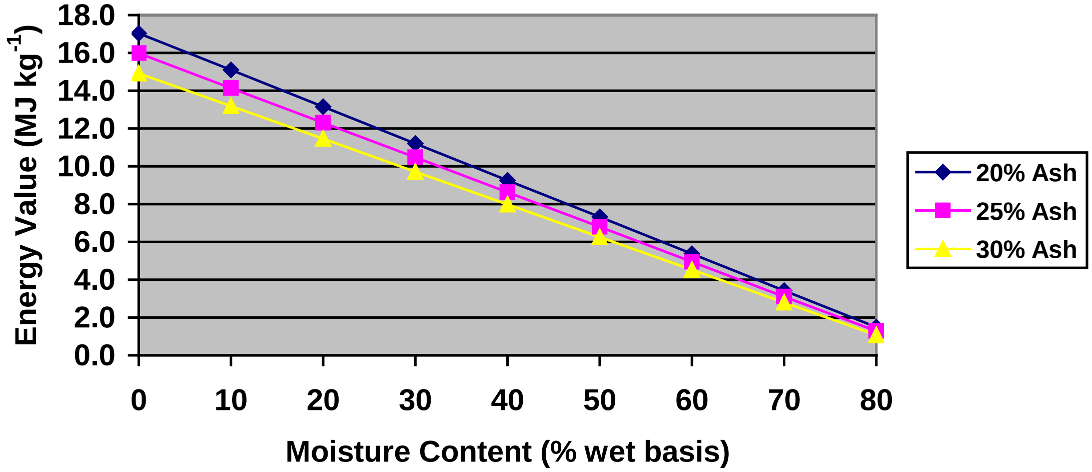
Graph 1c. Energy Values of Dung



4 Ash Content of Wood and Residues

As stated above, the ash content of wood can be taken as 1 percent, whereas for crop residues it differs from species to species and within a species it varies depending on the type of residue (rice straw, rice husk). Table 2 gives the average ash content of various residues from selected crops, Openshaw K. 1986 [5], Barnard G. Kristoferson L. 1985 [6], Commonwealth Science Council. 1986 [7]. In some estimates there is a large difference between the low and high measure, therefore, caution should be used when applying such figures. It may be best to undertake spot measurements on the residues.

Table 2. Ash Content of Selected Crop Residues.

Units. Percentage of dry weight.

Residue	Ash content	Residue	Ash content
Maize stover (stalk)	3 – 7	Coffee husk, parchment & cherry	8 –10
Maize cobs	1 – 2	Coconut fronds	3 – 5
Rice straw	18 – 19	Coconut husks	6
Rice husk	15 – 20	Coconut shells	1
Wheat straw	4 – 9	Palm nut shells	1
Alfalfa straw	6 - 10	Walnut shells	1
Sugar bagasse	10 – 12	Almond shells	5
Papyrus	6 – 8	Groundnut shells	4 – 14
Cotton stalks	3 - 17	*Jatropha curcas* seed cake	5

Source. Openshaw K. 1986 [5], Barnard G. Kristoferson L. 1985 [6], Commonwealth Science Council. 1986 [7].

Air-dry rice straw (15% moisture content [wb]) will have an energy value of about 11.8 MJ kg^{-1}, whereas wheat straw at the same moisture content will have an energy value of 13.5 $MJkg^{-1}$, some 15 percent more than that of rice straw. The various nutshells with 1 percent ash will have an energy value of about 14.4 MJ kg^{-1} at 15 percent moisture content (wb). Thus, knowing the ash content of residues is important. For some of the stated values, there is a considerable range. This infers that the testing methodology could be at fault.

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Table 3. Energy Value of Charcoal made from Wood and Crop Residues.
Units: MJ kg^{-1}. (Low heat value).

Raw material	Ash content	Percentage moisture content: wet basis [wb]; (dry basis [db])			
	percent	9.0 (db. 9.9)	7.0 (7.5)	5.0 (5.3)	0
Fully carbonized (92 percent)					
Wood	2	29.9	30.6	31.4	33.1
	4	29.3	30.0	30.7	32.4
	6	28.7	29.4	30.1	31.8
Crop residues	10	27.5	28.1	28.8	30.4
	20	24.4	25.0	25.6	27.0
	30	21.3	21.8	22.4	23.7
85 percent carbonized					
Wood	2	28.2	28.9	29.6	31.3
	4	27.7	28.3	29.0	30.6
	6	27.1	27.7	28.4	30.0
Crop residues	10	25.9	26.5	27.2	28.7
	20	23.0	23.6	24.1	25.5
	30	20.1	20.6	21.1	22.3
75 percent carbonized					
Wood	2	25.7	26.3	26.9	28.4
	4	25.1	25.7	26.3	27.8
	6	24.6	25.2	25.8	27.3
Crop residues	10	23.5	24.1	24.7	26.1
	20	20.9	21.4	21.9	23.2
	30	18.3	18.7	19.2	20.3

Note. It is assumed that the energy value of all fully carbonized charcoal (92% carbon), irrespective of raw material, on an ash free, moisture free basis is 33.8 MJ/kg^{-1}. It is also assumed that the energy value of partially carbonized charcoal (85% carbon) on an ash free, moisture free basis is 31.9 MJ/kg^{-1} and that of partially carbonized charcoal (75% C) on an ash free, moisture free basis is 29.0 MJ/kg^{-1}.
Source. Openshaw K. 1986 [5].

5 Energy Values of Charcoal

Table 3 gives the values for charcoal from wood and residues, Openshaw, K. 1986 [5]. There are three variables that determine the energy value of charcoal, namely the moisture content, the ash content and the degree of carbonization. The average moisture content of charcoal is about 5 percent (wb). It will absorb moisture only gradually unless deliberately wetted or left out in the rain, so the moisture content can be treated as constant. The ash content depends on the parent material. In the conversion process the ash accumulates. Thus, wood with one percent ash and 20 percent conversion (based on dry weight) will have about 5 percent ash in the charcoal. However, some of this ash may fall to the bottom of the kiln as fines or be expelled as particulates, so the average ash content of lump charcoal made from wood is about 4 percent. Coffee husk charcoal has 30 to 40% ash.

Wood is by far the dominant feedstock for charcoal production and the bulk is made in earth kilns. Usually, the operator moves from site to site where there are sufficient supplies of suitable wood. A skilled earth kiln operator can achieve a carbonization rate of about 85 percent. The energy values for ‘earth kiln’ charcoal are shown in Graph 2 by moisture and ash contents. If the average ash content is 4 percent with a moisture content of 5 percent, the energy value is estimated to be 28.9 MJ kg^{-1}. Higher energy values can be achieved in metal and brick kilns and in retorts. However, the biomass feedstock has to be transported to the kilns and of course the capital costs are higher. Such kilns are suitable where there is a nearby steady supply of feedstock such as at sawmills, coffee processing units or dedicated plantations. A good technical book of charcoal making in developing countries is by Earthscan, Foley G. 1986 [8].

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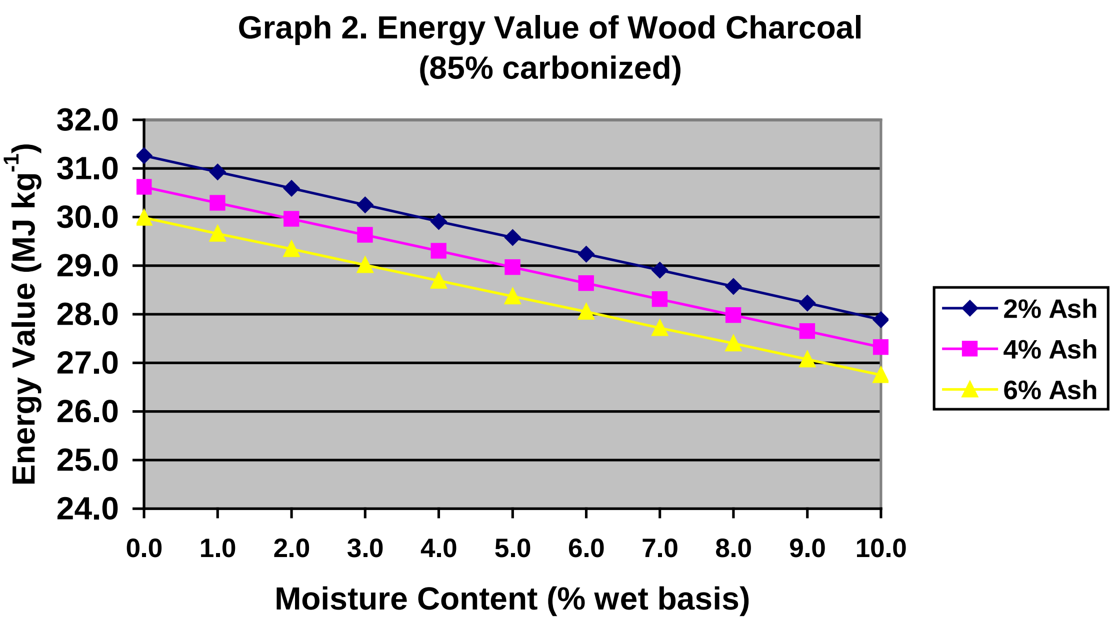

Apart from the ash content, the degree of carbonization has the greatest impact on the energy value. If wood is only charred rather than carbonized, then it will have an ash free energy value of about 20 MJ kg^{-1} (bone dry) and a recovery rate of about 90 percent (dry wood/dry 'char'). The carbon content of the char is about 52 percent. In a brick kiln or a retort, the carbon content of the charcoal may be about 92 percent and the recovery rate may be between 25 and 30 percent including fines (dry wood/dry charcoal) of which the fines are about 10 percent of the weight. The energy content of this ash free dry charcoal is 33.8 MJ kg^{-1}.

If it is assumed that the moisture content of wood is 15 percent (wb) and that of charcoal is 5 percent, then if the recoverable lump charcoal is 90 percent, the conversion rate of air-dry wood to lump charcoal is between 21 and 25 percent. The energy value of the charcoal assuming 4 percent ash and 5 percent moisture is an estimated 30.7 MJ kg^{-1}. In an earth kiln, the degree of carbonization is usually lower, with an average carbon content of the charcoal between 75 and 85 percent, and lump charcoal being about 85 percent. The recovery rate can vary from about 15 to 25 percent, depending on the skill of the operator and the degree of carbonization; the lower the carbonization rate the higher the recovery percentage, other things being equal.

The recovery percentage of charcoal from earth or pit kilns depends on the moisture content of the raw material, the size and layout of the kiln, whether or not it has a chimney and the skill of the operator. A skilled operator can obtain between 20 and 25 percent lump charcoal containing about 85 percent carbon (energy value about 29.0 MJ kg^{-1} with 4% ash and 5% moisture). On the other hand, an unskilled operator may obtain charcoal with only 75 percent lump carbon (energy value about 26.4 MJ kg^{-1} with 4% ash and 5% moisture) or if badly controlled, the operator may just finish up with wood ash!

6 Energy Values of other Biomass-derived Fuels

Besides charcoal there are other biomass-derived fuels, the most common ones being biogas, producer gas, methanol, ethanol, gelfuel and black liquor from pulp production. Over the last ten years and especially recently, plant oils are being used directly

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as fuels or processed into bio-diesel. Also, there are techniques to turn biomass into products similar to petroleum and synthetic gas whose energy value is comparable to natural gas. However, at present the production costs of these latter fuels are relatively high. Table 4 gives the energy value of the above-mentioned fuels and for comparison, the energy of pure methane is also given, Openshaw, K. 1986 [5].

Methane is considered to be a 'clean' fossil fuel, because it gives off the least amount of carbon dioxide (CO_2) per unit of energy burnt, but if vented to the atmosphere without burning, it is a very potent greenhouse gas (GHG), for it has a global warming potential (forcing factor) 22 times that of carbon dioxide. In terms of grams of carbon dioxide emitted per MJ of energy used, methane gives off 55g, liquid petroleum gas (LPG) 65g, kerosene 70g and 'standard' coal 88g. There is a concerted effort to improve the end use efficiency of fossil fuels and electricity, but it is imperative that more effort be applied to biomass energy as well, so as to reduce its pollution effects and improve its competitiveness with these other fuels.

Table 4. Energy Value of Biomass Products and Methane.

Fuel	Unit	Energy value MJ	Unit	Energy value MJ
Methane (natural gas) (CH_4)	m^3	35.8	kg	50.1
Biogas (60% methane) (CH_4, CO_2, H_2, NO_x)	m^3	22.6	kg	30.5
Producer gas (CO, H_2, CH_4)	m^3	3.6 to 5.5	kg	10.6 to 16.2
Methanol (wood alcohol) (CH_3OH)	litre	15.7	kg	19.9
Ethanol (C_2H_5OH)	litre	21.5	kg	26.8
Gelfuel (ethanol/cellulose mix, + 10% H_2O)	litre	18.0	kg	22.3
Plant oil (*Jatropha curcas* oil)	litre	37.4	kg	40.7
Black liquor	litre	11.8 to 12.2	kg	12.5 to 13.0

Source. Openshaw K. 1986 [5].

7 Global Warming and Biomass fuels

Unlike fossil fuels, biomass fuels are more or less "greenhouse gas" benign if they are from a sustainable supply. This is because the emission of carbon dioxide would have occurred through decomposition, wild fires or respiration if the biomass was not used for energy or other purposes. Every year, land and sea plants absorb about 100 giga tonnes (10^9t) of atmospheric carbon (367 Gt CO_2) and an equal quantity is returned to the atmosphere through respiration, decay and burning, (the carbon cycle), Hall, D.O. Rao, K.K. 1994 [9]. Over half of this total is from land plants. Each year, only about 1.4 giga tonnes of this carbon from land plants (5.1 Gt CO_2) are used for energy purposes, whereas about 9 giga tonnes of carbon (33 Gt CO_2) are emitted to the atmosphere annually through the burning of fossil fuels. It is this fossil fuel burning that is the main cause of atmospheric carbon dioxide accumulation. One way to reduce this accumulation is to use more of the potentially available biomass, estimated to be 50 giga tonnes per year of carbon equivalent (183 Gt CO_2), Hall, D.O. Rao, K.K. 1994 [9], about eight times the quantity of carbon given off annually by fossil fuels.

Practically all climate scientists and climate diplomats agree that to avoid catastrophic damage to the earth biosphere, which may spell doom for *Homo sapiens*, global temperatures should not rise by more than 2^0C compared to pre-industrial levels. It is agreed that the emissions of CO_2 from fossil fuel burning and land use changes as well as methane production from plants and animals are the main causes of this accumulation of atmospheric greenhouse gases (GHG). It is difficult, both economically and practically to reduce the consumption of fossil fuels in the short run. Indeed the International Energy Agency (IEA) forecast that coal and oil will only plateau by 2040 and natural gas consumption will still be increasing. The total emissions from fossil fuels my reach 12 GtC by 2050 (44 $GtCO_2$) IEA 2014. [10].

At present carbon sequestration is a priority for many (industrialized) countries. However, only 'high tech' solutions are being considered, such as capturing CO_2 emissions from refineries, power plants, combined heat and power units (CHP) and from cement factories etc. Governments have offered up to one billion dollars or more to provide commercial options for carbon capture and storage (CCS), but they are still in the experimental stage.

Such CCS are site specific and do nothing to capture CO_2 emissions from vehicles, homes, small fossil-fuel burning plants, and land clearing operations etc. However, there is a ‘low tech’ solution that can capture CO_2 emissions from all sources and is relatively cheap. This solution is capturing CO_2 in perennial plants, principally trees. Capturing atmospheric CO_2 in plants, especially in woody biomass, not only sequesters C in wood, but increases the C content in the soil beneath the trees. It also gives an annual yield of renewable carbon in wood that can be used for energy, converted into organic compounds or stored in wood products such as building materials, joinery and furniture. This can be done worldwide through improving existing forests, woodlands, grasslands and arable systems, but especially with plantations, woodlots and farm trees using improved stock/cloning etc. As mentioned above, about 9 Gt/yr of carbon (33 Gt CO_2) is emitted to the atmosphere by burning fossil fuels: this could increase to about 12 Gt/yr^{-1} by 2050. Also today, deforestation, caused by land use changes, results in about 1.4 Gt C being emitted each year; this may drop to about 1.0 Gt/yr^{-1} C by 2050. Thus, to capture all the CO_2 emissions, on average about 12 Gt of carbon would have to be sequestrated each year in wood and soil from 2016 to 2050.What would it take to capture all this carbon in woody biomass and forest/plantation soils? Beside carbon capture and storage, at least three other interventions are required: tempering population increase, especially in Africa; increasing agricultural productivity for subsistence and cash agriculture; and increasing forest/tree productivity.

A simple model has been constructed assuming that plantation trees in tropical/sub-tropical areas on a 10 year rotation will sequester on average a net of $54.8tC/ha^{-1}$ in wood and forest soils over a period of 35 years to 2050, assuming that the planting is staggered over a 10-year period. Plantation trees in temperate areas on a 35 year rotation will sequester a net of $92.1tC/ha^{-1}$ to 2050 again staggering the planting over a 10-year period. If two-thirds of the planting takes place in tropical countries and one-third in temperate countries, then the average annual sequestration rate would be a net of $67.23tC/ha^{-1}$. Thus, an area of 178.5 million ha (119 million ha in tropical areas and 59.5 million ha in temperate areas) would be required to capture an annual emission of 12GtC or 420GtC for the period 2016 to 2050.

Assuming the capital cost for tropical species is between \$500 and \$750 per ha, and for temperate species between \$1,000 and \$1,500 per ha, then the cost for 178.5 million ha would be between \$119 and \$178.5 billion. This excludes the cost of land, but includes overheads. Therefore, the capital cost for sequestering 420Gt carbon is equal to between \$0.283 and \$0.425 per tonne C! Assumed that the growth rates are $2/3^{rd}$ of that given above, and the costs are double, then 267 million ha will be required to capture 420GtC. This would raise the cost of carbon sequestration to between \$ 0.869 and \$1.271 per tC or \$0.24 to \$0.35 per tCO_2. Even this ‘worst case’ scenario is considerably lower than the international ‘target’ price of \$10 per t CO_2.

Besides sequestrating carbon, there can be an annual removal from thinning and the final felling from year 10. Over the period 2026 to 2050, the removals will be an estimated 23,954 million tC equivalent to 48,392 million t of wood or 82,266 million m^3. This is equivalent to over 900 EJ. In comparison, the 9 Gt of carbon burnt in fossil fuels today have an annual energy value of about 450 EJ. However, when the plantations are in rotation, the annual removals will be an estimated 6,880 million m^3, equivalent to over 75 EJ per year. This could be used for energy or other purposes.

An area of 119 million ha represents 3.4% of the arable and pasture land in tropical countries and 1.8% of the land including forests and woodlands. This is a relatively large amount of land to consider for tree planting, but there is much ‘abandoned’ land that should be recovered. Similarly an area of 59.5 million ha represents 2.3% of the arable, grasslands and unproductive land in temperate countries and 1.3% if forests and woodlands are included. Therefore, it is imperative that full consideration be given to using (woody) biomass for carbon capture, storage and use.

It is proposed that rural people willing to plant and manage trees, especially in the tropics should be paid the above amount of money on a per-ha basis and once the carbon is fully captured in the wood and forest soils an additional amount of money could be paid from a ‘carbon fund’. This could assist many people, especially the rural poor in developing nations in the quest for truly sustainable development.

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