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Review paper

# Energy production from biomass (part 1): overview of biomass

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**Abstract**

The use of renewable energy sources is becoming increasingly necessary, if we are to achieve the changes required to address the impacts of global warming. Biomass is the most common form of renewable energy, widely used in the third world but until recently, less so in the Western world. Latterly much attention has been focused on identifying suitable biomass species, which can provide high-energy outputs, to replace conventional fossil fuel energy sources. The type of biomass required is largely determined by the energy conversion process and the form in which the energy is required. In the first of three papers, the background to biomass production (in a European climate) and plant properties is examined. In the second paper, energy conversion technologies are reviewed, with emphasis on the production of a gaseous fuel to supplement the gas derived from the landfilling of organic wastes (landfill gas) and used in gas engines to generate electricity. The potential of a restored landfill site to act as a biomass source, providing fuel to supplement landfill gas-fuelled power stations, is examined, together with a comparison of the economics of power production from purpose-grown biomass versus waste-biomass. The third paper considers particular gasification technologies and their potential for biomass gasification. © 2002 Elsevier Science Ltd. All rights reserved.

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## 1. Background

Biomass is a term for all organic material that stems from plants (including algae, trees and crops). Biomass is produced by green plants converting sunlight into plant material through photosynthesis and includes all land- and water-based vegetation, as well as all organic wastes. The biomass resource can be considered as organic matter, in which the energy of sunlight is stored in chemical bonds. When the bonds between adjacent carbon, hydrogen and oxygen molecules are broken by digestion, combustion, or decomposition, these substances release their stored, chemical energy. Biomass has always been a major source of energy for mankind and is presently estimated to contribute of the order 10–14% of the world's energy supply.

This paper is the first in a three-part series examining the use of biomass as a fuel source, with emphasis on its potential use as a supplementary fuel for power generation, using landfill gas fuelled, spark ignition gas engines.

The conversion of biomass into energy can be achieved in a number of ways. To provide a fuel suitable for direct use in spark ignition gas engines (s.i.g.e.), the fuel must be provided in either a gaseous, or a liquid form. Production of a gaseous fuel from biomass can be achieved by the application of a number of technologies, each with its specific requirements, advantages and disadvantages.

## 2. Introduction

Biomass is the plant material derived from the reaction between $CO_2$ in the air, water and sunlight, via photosynthesis, to produce carbohydrates that form the building blocks of biomass. Typically photosynthesis converts less than 1% of the available sunlight to stored, chemical energy. The solar energy driving photosynthesis is stored in the chemical bonds of the structural components of biomass. If biomass is processed efficiently, either chemically or biologically, by extracting the energy stored in the chemical bonds and the subsequent 'energy' product combined with oxygen, the carbon is oxidised to produce $CO_2$ and water. The process is cyclical, as the $CO_2$ is then available to produce new biomass.

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The value of a particular type of biomass depends on the chemical and physical properties of the large molecules from which it is made. Man for millennia has exploited the energy stored in these chemical bonds, by burning biomass as a fuel and by eating plants for the nutritional content of their sugar and starch. More recently, fossilised biomass has been exploited as coal and oil. However, since it takes millions of years to convert biomass into fossil fuels, these are not renewable within a time-scale mankind can use. Burning fossil fuels uses "old" biomass and converts it into "new" $CO_2$, which contributes to the "greenhouse" effect and depletes a non-renewable resource. Burning new biomass contributes no new carbon dioxide to the atmosphere, because replanting harvested biomass ensures that $CO_2$ is absorbed and returned for a cycle of new growth.

One important factor which is often overlooked when considering the use of biomass to assist alleviate global warming, is the time lag between the instantaneous release of $CO_2$ from burning fossil fuels and its eventual uptake as biomass, which can take many years. One of the dilemmas facing the developed word is the need to recognize this time delay and take appropriate action to mitigate against the lag period. An equal dilemma faces the developing world as it consumes its biomass resources for fuel but does not implement a programme of replacement planting.

Numerous crops have been proposed or are being tested for commercial energy farming. Potential energy crops include woody crops and grasses/herbaceous plants (all perennial crops), starch and sugar crops and oilseeds.

In general, the characteristics of the ideal energy crop are:

- high yield (maximum production of dry matter per hectare),
- low energy input to produce,
- low cost,
- composition with the least contaminants,
- low nutrient requirements.

Desired characteristics will also depend on local climate and soil conditions. Water consumption can be a major constraint in many areas of the world and makes the drought resistance of the crop an important factor. Other important characteristics are pest resistance and fertiliser requirements. Only UK climatic conditions are considered in this study.

## 3. Drivers for biomass

In the past 10 years, there has been renewed interest, world-wide, in biomass as an energy source. There are several reasons for this situation:

- Firstly, technological developments relating to the conversion, crop production, etc. promise the application of biomass at lower cost and with higher conversion efficiency than was possible previously. For example, when low cost biomass residues are used for fuel, the cost of electricity is already now often competitive with fossil fuel-based power generation. More advanced options to produce electricity are looking promising and allow a cost-effective use of energy crops e.g. production of methanol and hydrogen by means of gasification processes.
- The second main stimulus is the agricultural sector in Western Europe and in the US, which is producing food surpluses. This situation has led to a policy in which land is set aside in order to reduce surpluses. Related problems, such as the de-population of rural areas and payment of significant subsidies to keep land fallow, makes the introduction of alternative, non-food crops desirable. Demand for energy will provide an almost infinite market for energy crops grown on such (potentially) surplus land.
- Thirdly, the potential threat posed by climate change, due to high emission levels of greenhouse gases ($CO_2$ being the most important one), has become a major stimulus for renewable energy sources in general. When produced by sustainable means, biomass emits roughly the same amount of carbon during conversion as is taken up during plant growth. The use of biomass therefore does not contribute to a build up of $CO_2$ in the atmosphere.

But these three main issues are not the only stimuli: biomass is also an indigenous energy source, available in most countries and its application may diversify the fuel-supply in many situations, which in turn may lead to a more secure energy supply. Biomass production can generate employment and if intensive agriculture is replaced by less intensively managed energy crops, there are likely to be environmental benefits, such as reduced leaching of fertilisers and reduced use of pesticides. Moreover, if appropriate crops are selected, restoration of degraded lands may be possible. Depending on the crops used and the way the biomass is cultivated, increased biodiversity can be obtained, compared to current agricultural practice.

Biomass is available on a renewable basis, either through natural processes, or it can be made available as a by-product of human activities i.e. organic wastes. The potential of biomass energy derived from forest and agricultural residues world-wide, is estimated at about 30 EJ/yr, compared to an annual world-wide energy demand of over 400 EJ. If biomass is to contribute to a larger extent to the world's energy supply, then energy farming, the cultivation of dedicated crops for energy purposes, will be required, using fallow land and marginal lands, the latter being largely unsuited for food crops. When energy crops are considered as a source of biomass, the total energy potential of biomass for energy production may be considerably larger than the energy potential of biomass residues. In 1992 at the Rio United Nations Conference on environment and development, the renewable intensive global energy scenario (RIGES) suggested that, by 2050, approximately half the world's current primary energy consumption of about 400 EJ/yr, could be met by biomass and that 60% of the world's electricity market could be supplied by renewables, of which biomass is a significant component (Price, 1998).

In the UK, the Government's target is to generate 10% of the national electricity need of 60 GW/yr from renewable sources, of which biomass will form a significant part. To date, the 10 or so biomass projects working/under construction will generate about 100 MW.

Biomass can be converted into three main types of product:

- electrical/heat energy,
- transport fuel,
- chemical feedstock.

Of particular interest in this study is the generation of electricity but the two other end-products will be examined briefly.

## 4. Biomass types

Researchers characterise the various types of biomass in different ways but one simple method is to define four main types, namely;

- woody plants,
- herbaceous plants/grasses,
- aquatic plants,
- manures.

Within this categorisation, herbaceous plants can be further subdivided into those with high- and low-moisture contents. Apart from specific applications or needs, most commercial activity has been directed towards the lower moisture-content types, woody plants and herbaceous species and these will be the types of biomass investigated in this study. Aquatic plants and manures are intrinsically high-moisture materials and as such, are more suited to 'wet' processing techniques.

Based primarily upon the biomass moisture content, the type of biomass selected subsequently dictates the most likely form of energy conversion process. High-moisture content biomass, such as the herbaceous plant sugarcane, lends itself to a 'wet/aqueous' conversion process, involving biologically mediated reactions, such as fermentation, while a 'dry' biomass such as wood chips, is more economically suited to gasification, pyrolysis or combustion. Aqueous processing is used when the moisture content of the material is such that the energy required for drying would be inordinately large compared to the energy content of the product formed.

However, there are other factors which must be taken into consideration in determining the selection of the conversion process, apart from simply moisture content, especially in relation to those forms of biomass which lie midway between the two extremes of 'wet' and 'dry'. Examples of such factors are the ash, alkali and trace component contents, which impact adversely on thermal conversion processes and the cellulose content, which influences biochemical fermentation processes.

## 5. Plant characteristics

Biomass contains varying amounts of cellulose, hemicellulose, lignin and a small amount of other extractives. Woody plant species are typically characterised by slow growth and are composed of tightly bound fibres, giving a hard external surface, while herbaceous plants are usually perennial, with more loosely bound fibres, indicating a lower proportion of lignin, which binds together the cellulosic fibres: both materials are examples of polysaccharides; long-chain natural polymers. The relative proportions of cellulose and lignin is one of the determining factors in identifying the suitability of plant species for subsequent processing as energy crops.

Cellulose is a glucose polymer, consisting of linear chains of (1,4)-D-glucopyranose units, in which the units are linked 1–4 in the $\beta$-configuration, with an average molecular weight of around 100,000.

Hemicellulose is a mixture of polysaccharides, composed almost entirely of sugars such as glucose, mannose, xylose and arabinose and methylglucuronic and galaturonic acids, with an average molecular weight of <30,000. In contrast to cellulose, hemicellulose is a heterogeneous branched polysaccharide that binds tightly, but non-covalently, to the surface of each cellulose microfibril. Hemicellulose differs from cellulose, in consisting primarily of xylose and other five-carbon monosaccharides.

Lignin can be regarded as a group of amorphous, high molecular-weight, chemically related compounds. The building blocks of lignin are believed to be a three carbon chain attached to rings of six carbon atoms, called phenyl-propanes. These may have zero, one or two methoxyl groups attached to the rings, giving rise to three structures, termed I, II and III, respectively. The proportions of each structure depend on the source of the polymer i.e. structure I is found in plants such as grasses; structure II in the wood of conifers; while structure III is found in deciduous wood.

Cellulose is generally the largest fraction, representing about 40–50% of the biomass by weight; the hemicellulose portion represents 20–40% of the material by weight.

Both woody and herbaceous plant species have specific growing conditions, based on the soil type, soil moisture, nutrient balances and sunlight, which will determine their suitability and productive growth rates for specific, geographic locations. Many types of perennial grasses, such as sugarcane and cereals like wheat and maize, have widely different yields, depending on the growing conditions: thus wheat can be grown in both hot and temperate climates with a wide range of rainfall, whereas sugarcane can be grown successfully only in warm, moist climatic conditions.

## 6. Photosynthesis

Photosynthesis is the process by which chlorophyll-containing organisms – green plants, algae, and some bacteria – capture energy in the form of light and convert it to chemical energy. Virtually all the energy available for life in the Earth's biosphere, the zone in which life can exist, is made available through photosynthesis.

A generalised, unbalanced, chemical equation for photosynthesis is

$$CO_2 + 2H_2A + \text{light energy} = (CH_2O) + H_2O + A_2$$

The formula $H_2A$ represents a compound that can be oxidised, i.e. from which electrons can be removed and $CH_2$ is a general formula for the carbohydrates incorporated by the growing organism. In the vast majority of photosynthetic organisms – that is, algae and green plants – $H_2A$ is water ($H_2O$) and $A_2$ is oxygen ($O_2$); in some photosynthetic bacteria however, $H_2A$ is hydrogen sulphide ($H_2S$). Photosynthesis involving water is the most important and best understood and therefore will be discussed in more detail.

Photosynthesis consists of two stages: a series of light-dependent reactions that are temperature-independent and a series of temperature-dependent reactions that are light independent. The rate of the first series, called the light reaction, can be increased by increasing light intensity (within certain limits) but not by increasing temperature. In the second series, called the dark reaction, the rate can be increased by increasing temperature (within certain limits) but not by increasing light intensity.

Another differentiator amongst plant species is the type of photosynthetic pathway utilised by the plant. Most plants utilise the $C_3$ photosynthesis route, the $C_3$ determining the mass of carbon contained in the plant material. Another photosynthesis pathway is represented by $C_4$ plants, which accumulate a significantly greater dry mass of carbon than do $C_3$ plants, giving a biomass with increased potential for energy conversion. Examples of $C_3$ species are poplar, willow, wheat and most other cereal crops, while the perennial grass, *Miscanthus*, sweet sorghum, maize and artichoke, all use the $C_4$ route.

Traditionally, the biochemical conversion of biomass into liquids, such as ethanol, has been undertaken using sugar/starch feedstocks, such as cereals. The conversion of cellulose into glucose via acid/enzymatic hydrolysis and the subsequent conversion of glucose into alcohol, using fermentation, is more easily undertaken with high-cellulose content biomass, than with lignin-rich biomass i.e. woody species, which is not so easily converted (Coombs, 1996).

## 7. Plant species

The choice of plant species depends upon the end-use, bio-conversion option of interest e.g. combustion, gasification, pyrolysis, fermentation or mechanical extraction of oils. Some plant species are amenable to nearly all of the potential conversion technologies: e.g. oil seed rape can be processed via combustion, gasification, pyrolysis or mechanical extraction, while others such as wood and cereal crops, are suitable for combustion, gasification, pyrolysis and fermentation.

It is important to note that, while particular plant species may have specific benefits for subsequent processing technologies, the amount of energy potentially available from a given biomass source is the same, irrespective of the conversion technology used. What will vary between conversion technologies is the actual amount of energy recovered from the biomass source and the form of that energy.

The attention paid to particular woody/herbaceous plant species varies around the world, taking account of the soil and climatic factors that affect growth. In the context of northern Europe, much attention has been focused on the $C_3$ woody species, especially those grown as short rotation coppice (SRC) e.g. willow and poplar and forestry residues (Ove Arup and Partners, 1989). Herbaceous $C_3$ species, such as cereals, are of less interest in the UK due to limited interest in the bio-conversion of carbohydrate-rich biomass to alcohol (ethanol) fuels, which is not the case in the USA and some parts of Europe. Similarly oil seed rape, for producing bio-diesel fuel, is of wide interest in Europe but not so in the UK (Culshaw and Butler, 1992). In tropical climates where sugarcane can be grown, Brazil has been one of the pioneers of large-scale fuel–alcohol production derived from sugarcane.

Of the herbaceous plant species, the perennial $C_4$ grass, *Miscanthus*, has created considerable interest (ADAS, 1992). *Miscanthus* has been identified as the ideal fuel crop, providing an annual crop, being easy to grow and harvest and when harvested dry, gives a high dry-matter yield. Light, arable soils give a good yield, provided there is adequate rainfall, which would not be a problem in the UK: dark-coloured soils produce a better yield than light-coloured soils and the plant is pH tolerant. In the UK, yields would overall be greater in the wetter West than the drier East of the country. This thin-stemmed grass has been evaluated as a bio-energy crop in Europe for over 10 years, having been grown experimentally in over 10 countries. The combination of an annual harvest, low inherent mineral content and a good energy yield/ha (similar to that for wood species), gives the plant considerable potential as a bio-energy crop in the UK.

*Miscanthus* is currently propagated as rhizomes (no fertile seed is presently available), planted in double rows about 75 cm apart, with 175 cm gaps between double rows. Weed control is vital for crop establishment but the plant faces negligible disease problems within Europe. Yields of 3–10 years old plantations grown in Germany and Denmark are 13–30 t/ha: if a yield of 20 t/ha could be achieved, this would give a gross energy yield equivalent to 7 t/ha of oil over the life of each crop.

On the basis of a 20 t/ha yield of dry matter, the value as an energy crop would be about £620/ha, compared with wheat at £400 ha; this equates to a value of one third that of oil and about half that of coal. Overall, the production costs of *Miscanthus*, based on a 20 t/ha yield, compare favourably with wood chips from SRC forestry and with whole crop cereals.

In the USA, another thin-stemmed, herbaceous plant, switchgrass, (*Pancium virgatum*) has been selected as a model herbaceous crop for the Oak Ridge National Laboratory, Biofuels Feedstock Program (McLaughlin et al., 1996). Switchgrass is also a $C_4$ species and has a calorific value comparable to wood but with a much lower moisture content. The purpose of the program is to develop ethanol for petrol replacement and switchgrass has been identified as being suitable for conversion processes based on saccharification and fermentation technology, which yields high amounts of ethanol. The low ash and alkali content indicates that it should also be a suitable fuel for combustion, with a low, potential for slagging.

A more radical proposal for a low moisture content biomass feedstock, with a high-cellulose content, is the use of hemp (Dewey, 1916). Hemp, a member of the mulberry family (*Moraccae*), which includes the mulberry, paper mulberry and the hop plant, has a cellulose content of about 80% and has long been grown for a variety of uses, providing material for medicinal, nutritional and chemical production. It has been used to produce paper for cardboard/paper bags; the cannabis hemp seeds contain all the essential amino acids and essential fatty acids to maintain healthy human life; linseed oil is a widely used derivative in the manufacture of paint and varnish; and hemp is the earliest recorded plant cultivated for the production of a textile fibre.

The association with marijuana caused the demise of the hemp industry in the USA in the late 1930s. This association continues today to prevent its widespread cultivation, despite its potential as a feedstock for a wide range of uses. Its revival as a biomass feedstock may arise due to the environmental pressures.

In general, most attention on biomass-to-energy schemes to date, in the UK, has been focused on woody, rather than herbaceous plant species, due to the emphasis on electricity production compared with the production of alternative, i.e. liquid, transport fuels.

## 8. Biomass properties

It is the inherent properties of the biomass source that determines both the choice of conversion process and any subsequent processing difficulties that may arise. Equally, the choice of biomass source is influenced by the form in which the energy is required and it is the interplay between these two aspects that enables flexibility to be introduced into the use of biomass as an energy source.

As indicated above, the categories of biomass considered in this study are woody and herbaceous species; the two types examined by most biomass researchers and technology providers. Dependent on the energy conversion process selected, particular material properties become important during subsequent processing.

The main material properties of interest, during subsequent processing as an energy source, relate to:

- moisture content (intrinsic and extrinsic),
- calorific value,
- proportions of fixed carbon and volatiles,
- ash/residue content,
- alkali metal content,
- cellulose/lignin ratio.

For dry biomass conversion processes, the first five properties are of interest, while for wet biomass conversion processes, the first and last properties are of prime concern. The quantification of these materials properties for the various categories of biomass is discussed in the following section.

### 8.1. Moisture content

Two forms of moisture content are of interest in biomass:

- intrinsic moisture: the moisture content of the material without the influence of weather effects,
- extrinsic moisture: the influence of prevailing weather conditions during harvesting on the overall biomass moisture content.

In practical terms, it is the extrinsic moisture content that is of concern, as the intrinsic moisture content is usually only achieved, or applicable, under laboratory conditions. Table 1 lists the typical (intrinsic) moisture contents of a range of biomass materials. Also of im-

Table 1
Proximate analysis of some biomass feedstocks (wt%)

| Biomass | Moisture[a] (%) | VM (%) | FC (%) | Ash (%) | LHV (MJ/kg) |
|---|---|---|---|---|---|
| Wood | 20 | 82 | 17 | 1 | 18.6 |
| Wheat straw | 16 | 59 | 21 | 4 | 17.3 |
| Barley straw | 30 | 46 | 18 | 6 | 16.1 |
| Lignite | 34 | 29 | 31 | 6 | 26.8 |
| Bituminous coal | 11 | 35 | 45 | 9 | 34 |

[a] Intrinsic.

portance in respect of the prevailing weather conditions at the time of harvesting, is the potential contamination of the harvested biomass by soil and other detritus, which can in turn have a significant deleterious impact on other 'material' properties during subsequent treatment or processing. The parameters of interest that are affected by such contamination are the ash and alkali metal content of the material.

Other factors aside, such as conversion to alcohol or gas/oil, the relationship between biomass moisture content and appropriate bio-conversion technology is essentially straight forward, in that thermal conversion requires low moisture content feedstock (typically <50%), while bio-conversion can utilise high moisture content feedstocks. Thermal conversion technologies can also use feedstocks with high moisture content but the overall energy balance for the conversion process is adversely impacted.

On this basis, woody and low moisture content herbaceous plant species are the most efficient biomass sources for thermal conversion to liquid fuels, such as methanol. For the production of ethanol by biochemical (fermentation) conversion, high moisture herbaceous plant species, such as sugarcane, are more suited: such species can also be fermented via another biochemical process, anaerobic digestion (AD), to produce methane.

### *8.2. Calorific value*

The calorific value (CV) of a material is an expression of the energy content, or heat value, released when burnt in air. The CV is usually measured in terms of the energy content per unit mass, or volume; hence MJ/kg for solids, MJ/l for liquids, or $MJ/Nm^3$ for gases. The CV of a fuel can be expressed in two forms, the gross CV (GCV), or higher heating value (HHV) and the nett CV (NCV), or lower heating value (LHV).

The HHV is the total energy content released when the fuel is burnt in air, including the latent heat contained in the water vapour and therefore represents the maximum amount of energy potentially recoverable from a given biomass source. The actual amount of energy recovered will vary with the conversion technology, as will the form of that energy i.e. combustible gas, oil, steam, etc. In practical terms, the latent heat contained in the water vapour cannot be used effectively and therefore, the LHV is the appropriate value to use for the energy available for subsequent use.

Table 1 lists the CV of a range of biomass materials. When quoting a CV, the moisture content needs to be stated, as this reduces the available energy from the biomass. It appears normal practice to quote both the CV and crop yield on the basis of dry matter tonnes (dmt), which assumes zero percent moisture content. If any moisture is present, this reduces the CV proportional to the moisture content.

### *8.3. Proportions of fixed carbon and volatile matter*

Fuel analysis has been developed based on solid fuels, such as coal, which consists of chemical energy stored in two forms, fixed carbon and volatiles:

- the volatiles content, or volatile matter (VM) of a solid fuel, is that portion driven-off as a gas (including moisture) by heating (to 950 °C for 7 min)
- the fixed carbon content (FC), is the mass remaining after the releases of volatiles, excluding the ash and moisture contents.

Laboratory tests are used to determine the VM and FC contents of the biomass fuel. Fuel analysis based upon the VM content, ash and moisture, with the FC determined by difference, is termed the proximate analysis of a fuel. Table 1 gives the proximate analyses of some typical biomass sources: values for lignite and coal are given for reference.

Elemental analysis of a fuel, presented as C, N, H, O and S together with the ash content, is termed the ultimate analysis of a fuel. Table 2 gives the ultimate analyses for some biomass materials.

The significance of the VM and FC contents is that they provide a measure of the ease with which the biomass can be ignited and subsequently gasified, or oxidised, depending on how the biomass is to be utilized as an energy source. This type of fuel analysis is of value for biological conversion processes only once the fuel is produced, enabling a comparison of different fuels to be

Table 2
Ultimate analyses for typical biomass materials (wt%)

| Material | C | H | O | N | S | Ash |
|---|---|---|---|---|---|---|
| Cypress | 55.0 | 6.5 | 38.1 | – | – | 0.4 |
| Ash | 49.7 | 6.9 | 43.0 | – | – | 0.3 |
| Beech | 51.6 | 6.3 | 41.4 | – | – | – |
| Wood (average) | 51.6 | 6.3 | 41.5 | 0 | 0.1 | 1 |
| Miscanthus | 48.1 | 5.4 | 42.2 | 0.5 | <0.1 | 2.8 |
| Wheat straw | 48.5 | 5.5 | 3.9 | 0.3 | 0.1 | 4 |
| Barley straw | 45.7 | 6.1 | 38.3 | 0.4 | 0.1 | 6 |
| Rice straw | 41.4 | 5 | 39.9 | 0.7 | 0.1 | |
| Bituminous coal | 73.1 | 5.5 | 8.7 | 1.4 | 1.7 | 9 |
| Lignite | 56.4 | 4.2 | 18.4 | 1.6[a] | – | 5 |

[a] Combined N and S.

Table 3
Properties of selected biomass materials (wt%)

| Material | Moisture content (%$H_2O$) | HHV[a] (MJ/kg) | FC content (%) | VM content (%) | Ash content (%) | Alkali metal content (as Na and K oxides) (%) |
|---|---|---|---|---|---|---|
| Fir | 6.5 | 21 | 17.2 | 82.0 | 0.8 | – |
| Danish pine | 8.0 | 21.2 | 19.0 | 71.6 | 1.6 | 4.8 |
| Willow | 60 | 20.0 | – | – | 1.6 | 15.8 |
| Poplar | 45 | 18.5 | – | – | 2.1 | 16 |
| Cereal straw | 6 | 17.3 | 10.7 | 79.0 | 4.3 | 11.8 |
| Miscanthus | 11.5 | 18.5 | 15.9 | 66.8 | 2.8 | – |
| Bagasse | 45–50 | 19.4 | – | – | 3.5 | 4.4 |
| Switchgrass | 13–15 | 17.4 | – | – | 4.5 | 14 |
| Bituminous coal | 8–12 | 26–2 | 57 | 35 | 8 | – |

[a] Dry basis, unless stated otherwise.

undertaken. Table 3 summarises the fuel properties of selected biomass materials.

The significance of the O:C and H:C ratios on the CV of solid fuels can be illustrated using a Van Krevelen diagram (Fig. 1). Comparison of biofuels with fossil fuels, such as coal, shows clearly that the higher proportion of oxygen and hydrogen, compared with carbon, reduces the energy value of a fuel, due to the lower energy contained in carbon–oxygen and carbon–hydrogen bonds, than in carbon–carbon bonds.

### *8.4. Ash/residue content*

The chemical breakdown of a biomass fuel, by either thermo-chemical or bio-chemical processes, produces a solid residue. When produced by combustion in air, this solid residue is called 'ash' and forms a standard measurement parameter for solid and liquid fuels. The ash content of biomass affects both the handling and processing costs of the overall, biomass energy conversion cost. During biochemical conversion, the percentage of solid residue will be greater than the ash content formed during combustion of the same material.

For a biochemical conversion process, the solid residue represents the quantity of non-biodegradable carbon present in the biomass. This residue will be greater than the ash content because it represents the recalcitrant carbon which cannot be degraded further biologically but which could be burnt during thermo-chemical conversion.

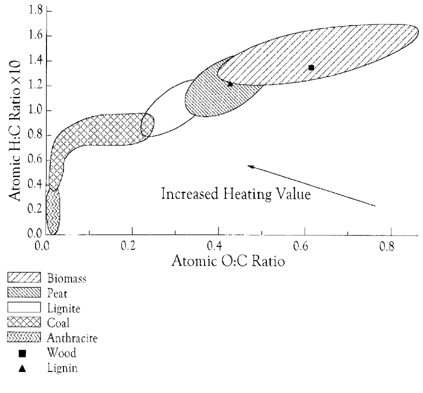

Fig. 1. Van Krevelen diagram for various solid fuels.

Dependent on the magnitude of the ash content, the available energy of the fuel is reduced proportionately. In a thermo-chemical conversion process, the chemical composition of the ash can present significant operational problems. This is especially true for combustion processes, where the ash can react to form a 'slag', a liquid phase formed at elevated temperatures, which can reduce plant throughput and result in increased operating costs.

### *8.5. Alkali metal content*

The alkali metal content of biomass i.e. Na, K, Mg, P and Ca, is especially important for any thermo-chemical conversion processes. The reaction of alkali metals with silica present in the ash produces a sticky, mobile liquid phase, which can lead to blockages of airways in the furnace and boiler plant. It should be noted that while the intrinsic silica content of a biomass source may be low, contamination with soil introduced during harvesting can increase the total silica content significantly, such that while the content of intrinsic silica in the material may not be a cause for concern, the increased total silica content may lead to operational difficulties.

### *8.6. Cellulose/lignin ratio*

The proportions of cellulose and lignin in biomass are important only in biochemical conversion processes. The biodegradability of cellulose is greater than that of lignin, hence the overall conversion of the carbon-containing plant material present as cellulose is greater than for plants with a higher proportion of lignin, a determining factor when selecting biomass plant species for biochemical processing. Table 4 gives the proportions of cellulose/hemicellulose/lignin for softwoods and hardwoods and for comparison, wheat straw and switchgrass.

Table 4
Cellulose/lignin content of selected biomass (wt%)

| Biomass | Lignin (%) | Cellulose (%) | Hemi-cellulose (%) |
|---|---|---|---|
| Softwood | 27–30 | 35–40 | 25–30 |
| Hardwood | 20–25 | 45–50 | 20–25 |
| Wheat straw | 15–20 | 33–40 | 20–25 |
| Switchgrass | 5–20 | 30–50 | 10–40 |

For the production of ethanol, a biomass feedstock with a high, cellulose/hemi-cellulose content is needed to provide a high, l/t, yield. While the lignin content represents a potentially large energy source, current techniques involving hydrolysis/enzymatic systems cannot convert the lignin to syngas. To illustrate the effect of cellulose content on yield, up to 280l/t of ethanol can be produced from switchgrass, compared with 205l/t from wood, an effect largely due to the increased proportion of lignin in wood.

### *8.7. Bulk density*

An important characteristic of biomass materials is their bulk density, or volume, both as-produced and as-subsequently processed (Table 5). The importance of the as-produced, bulk density is in relation to transport and storage costs. The density of the processed product impacts on fuel storage requirements, the sizing of the materials handling system and how the material is likely to behave during subsequent thermo-chemical/biological processing as a fuel/feedstock. As an example, taking wood as a reference material for transport and storage costs at about £20/m$^3$, for straw to be competitive on the same density basis, it needs either to be baled, or processed into a cubed/pelleted form, with a concomitant increase in costs.

Table 5
Bulk volume and density of selected biomass sources

| Biomass | Bulk volume (m$^3$/t, daf)[a] | Bulk density (t/m$^3$, daf) |
|---|---|---|
| *Wood* | | |
| Hardwood chips | 4.4 | 0.23 |
| Softwood chips | 5.2–5.6 | 0.18–0.19 |
| Pellets | 1.6–1.8 | 0.56–0.63 |
| Sawdust | 6.2 | 0.12 |
| Planer shavings | 10.3 | 0.10 |
| *Straw* | | |
| Loose | 24.7–49.5 | 0.02–0.04 |
| Chopped | 12.0–49.5 | 0.02–0.08 |
| Baled | 4.9–9.0 | 0.11–0.20 |
| Moduled | 0.8–10.3 | 0.10–1.25 |
| Hammermilled | 9.9–49.5 | 0.02–0.11 |
| Cubed | 1.5–3.1 | 0.32–0.67 |
| Pelleted | 1.4–1.8 | 0.56–0.71 |

[a] Dry, ash-free tonnes.

## 9. Harvesting

Establishment costs for SRC willow are currently estimated to be about £1800/ha, including cuttings, planting, weed control and rabbit/deer fencing (Anon, 1999). It is expected that as more schemes come to fruition, establishment costs will fall, perhaps by as much as 50%.

Harvesting biomass represents one of the significant cost factors in the production of biomass energy crops. The harvesting process is both energy-intensive – due primarily to transport fuel costs – and can introduce contaminants, such as soil, which can subsequently lead to operational problems during processing to produce energy. The moisture content of the biomass varies with the time of harvest and for some crops can introduce additional processing costs, due to the need to pre-dry, before processing further.

Woody species are harvested as felled-timber and cut into lengths or chipped, depending on the subsequent energy conversion technology. Woody biomass can be obtained as felling residues from traditional forestry timber growing activities, or as SRC timber, specially grown for 3–4 years and then harvested. Herbaceous plant species are harvested as baled straw or grasses, or as seeds/grains.

In addition to the establishment and maintenance of a biomass resource such as an energy plantation, the associated harvesting and transport costs of a commercial scheme are considerable. The harvesting costs depend also on the type of biomass being produced and the processing costs necessary to provide a feedstock suitable for use in whichever biomass conversion process is to be used.

Transport costs are largely a function of the distance travelled and the energy density, e.g. MJ/m$^3$, of the biomass being transported. In turn, the transport cost depends also on the type of biomass and the form in which it is being transported e.g. chopped or coppiced timber, compared with baled cereal straw.

Quoted data (Transport Studies Group, 1996) for fuel delivered to a thermal power station operating on biomass, indicates that road transport accounts for about 70% of the total delivered biomass-fuel cost i.e. growing, harvesting and transport to the user end-point. The lowest delivered cost is for cereal straw (as Hesston bales) at £28/t (dry matter), with forest fuel systems

Table 6
Typical biomass harvesting costs

| Biomass type | Harvested form | Cost (£/dmt)[a] |
|---|---|---|
| Forest residues | Timber off-cuts | 32–37 |
| Cereal straw | Hesston bales[b] | 28 |
| SRC | Chipped timber | 47–54 |

[a] Dry matter tonnes.

[b] Large rectangular bales, typically 1 t weight.

costing between £32 and 37/t and SRC and *Miscanthus* at £47 and 54/t. These costs are summarised in Table 6.

The type of harvesting used also influences costs e.g. baled *Miscanthus* is about 80% of the cost compared with direct cut and chop systems (Transport Studies Group, 1996).

## 10. Yields

The quantity of dry matter produced by a biomass species per unit area of production, determines the potential energy production capacity, or yield, of the available land area. Production is measured in dmt/ha and combined with the HHV of the biomass, the energy yield of the cultivated crop can be calculated. Table 7 indicates the range of energy yields for a number of types of biomass.

There is intensive research and development into increasing biomass yields using hybrid plants. Experimental work on hybrid poplar species in the US Pacific NW, has produced yields of 43 dmt/ha/a and in Brazil, eucalyptus yields of 39 dmt/ha/a have been reported (Hislop and Hall, 1996).

The development of dedicated plantations to grow biomass – energy plantations – is likely to take two main forms: species with a high dmt/ha, grown ideally on good quality agricultural land e.g. set aside and species capable of reasonably high dmt/ha yields, grown on marginal land. Table 8 below identifies potential species for the land quality referred to above.

Table 7
Energy yields from selected biomass

| Biomass | Crop yield (dmt/ha/a) | HHV (MJ/kg, dry) | Energy yield (GJ/ha) |
|---|---|---|---|
| Wheat | 7 grain/7 straw (14 total) | 12.3 (straw) | 123 |
| Poplar | 10–15 | 17.3 | 173–259 |
| SRC willow | 10–15 | 18.7 | 187–280 |
| Switchgrass | 8 | 17.4 | 139 |
| *Miscanthus* | 12–30 | 18.5 | 222–555 |

Table 8
Plant species for energy plantations

| High dmt/ha (set aside) | | Moderate dmt/ha (marginal/degraded land) |
|---|---|---|
| Woody species | Herbaceous | |
| Poplar | Sweet sorghum | Alder |
| Willow | Sugar cane | Black locust |
| Eucalyptus | *Miscanthus* | Birch |
| | Switchgrass | *Castanea saturia* |
| | Cord grasses | *Plantanus* |
| | | *Nicotania* |

## 11. Energy production

It is acknowledged that each species of biomass has a specific yield/output, dependent on climate, soil, etc. However, to provide data for outline process designs, it is useful to assume some general biomass properties.

In the case of wood derived from SRC, it is assumed that the average LHV is 18 MJ/kg. At full generation rate, 1 kg of woodchips converts to 1 kWh(e) via use in a gasifier/gas engine generator, giving an overall efficiency of conversion to electricity of about 20%: this takes no account of the potentially useful heat available from the gasifier/gas engine (Warren et al., 1995).

At yields of 15 dmt/ha/a and with 1dmt equal to 1 MWh(e), 1ha (based on a 3 yr. harvesting cycle) of SRC biomass would provide 15 MWh(e)/a. Assuming an annual operating time of 95%, a 100 kW(e) gas engine generator set would require about 55 ha to provide the necessary biomass feedstock: for a 1 MW(e) gas engine generator set, the land take would be about 550 ha.

The above calculation suggests that a significant land-take is required to produce a relatively modest energy output as electricity, due to the low overall efficiency of conversion i.e. 20%, of biomass to electricity. Combustion processes using high-efficiency, multi-pass, steam turbines to produce electricity, can achieve an overall efficiency of 35–40%, reducing the necessary land-take for a 1 MW(e) output to between 270–310 ha. Integrated gasification combined cycle (IGCC) gas turbines can achieve about 60% efficiency. However, the object of the study was to provide gas to supplement existing LFG supplies. Assuming a 20% supplement for a 1 MW(e) LFG power generation scheme, the land-take required for SRC is about 110 ha, large for most (closed) landfill sites but more realistic in terms of being able to use the existing site in combination with additional, adjacent land.

It can be seen that if biomass with an equivalent CV to SRC willow but with a greater crop yield were available, the necessary land-take would reduce in proportion to the increased yield. The reported range of yields for *Miscanthus* is quoted as being equivalent to SRC willow at the lower end, while the upper end is about twice that for SRC willow. If this were the case, the land-take for a 20% energy supplement for a 1 MW(e) LFG power scheme would reduce from 110 ha for SRC willow, to 55 ha for *Miscanthus*. The effect of energy yield on land-take requirements can be seen clearly to be a significant factor in any biomass power generation scheme.

It should also be noted that in terms of the energy produced, or available, from a biomass source, the maximum value is equivalent to the biomass CV i.e. as measured by combustion in air. While a given biomass source may be burnt in air, gasified, pyrolysed, fermented, digested, or undergo mechanical extraction, the total energy available (or extractable) from the resource is the same. In practice the actual amount of energy obtained and the form of that energy, will vary from one conversion process technology to another.

Two examples may help to illustrate the above point:

- Gasifying wood gives the same potential release of energy as burning the wood in a combustor but the form of the energy released by gasification may be of more use than that derived from combustion e.g. a useable, low CV gas, that could be used to fuel a gas engine, rather than hot air, which can only provide process heat/steam, or power a steam turbine to generate electricity.
- Fermenting wheat to produce ethanol provides a fuel suitable for vehicles, which is not possible via combustion or gasification processes.

Apart from energy being available in a more suitable or convenient form, the overall conversion efficiency from biomass source to alternative energy product, for each type of conversion process, is of interest. For example, while combustion releases all of the ‘available’ chemical energy stored in the biomass source, converting the hot gases (via a boiler) to produce steam (at an efficiency of 88%) and subsequent conversion to electricity (via a turbo-generator), gives an overall thermal efficiency of about 40% for large plant and as low as 10–15% for simple, steam plant. The importance of these thermodynamic considerations will depend on the particular economic factors associated with specific projects.

## 12. Conclusions

- The use of biomass, as a traditional energy source for the third world, can play a pivotal role in helping the developed world reduce the environmental impact of burning fossil fuels to produce energy but only if significant areas of replanting are actioned immediately.
- Biomass is an accepted form of renewable energy and is seen as a means of helping to reduce global warming, by displacing the use of fossil fuels: up to 10% of the UK’s electricity needs is targeted to be generated from renewable forms of energy by 2010.
- Of the four main types of biomass, woody plants and herbaceous plants and grasses are the main types of interest for producing energy, with attention focused on the $C_4$ plant species.
- The stored chemical energy in plants is contained in the cellulose, hemicellulose and lignin components of the plant, the proportions varying with the type of plant.
- The relative proportions of cellulose/hemicellulose/lignin are, *inter alia*, key factors in determining the optimum energy conversion route for each type of biomass.
- The exception to energy yield being the primary selection criterion for biomass, is the form in which the energy is required.
- All biomass can be burned in thermo-chemical conversion plant i.e. combustion, to produce steam for use in a turbo-generator to produce electricity: some biomass species are better suited for biochemical conversion processes to produce gaseous or liquid fuels.
- The energy content of biomass (on a dry, ash-free basis) is similar for all plant species, lying in the range 17–21 MJ/kg. The principal selection criteria for biomass species are growth rate, ease of management, harvesting and intrinsic material properties, such as moisture/ash/alkali content, the latter properties influencing the operational characteristics of thermal-conversion plant.
- Based on annual energy yields in temperate climates, biomass species of interest in the UK for thermal conversion processes are the woody species, willow and poplar and the $C_4$ herbaceous species, switchgrass and *Miscanthus*.

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