ENERGY FROM BIOMASS

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Keywords: Biomass, Phytomass, Photosynthesis, Thermochemical conversion, Combustion, Gasification, Pyrolysis, Charcoal, Biotechnology, Anaerobic fermentation, Ethanol, Biodiesel, Energy crops.

Contents

Summary

Biomass is the World's fourth fuel in importance, after oil, coal and natural gas, contributing about 12% of the world's total primary energy supply. Usually what is

meant by biomass is the vegetable matter or phytomass produced by the action of solar energy on plant photosynthesis, which builds plant cell walls and other components such as seeds and fruits. Bioenergy is the energy resulting from the use of biomass as a fuel or feedstock to produce heat, electricity, liquid and solid fuels. As the only source of renewable carbon, whose use does not increase the atmospheric concentrations of carbon dioxide, biomass is a major component of future strategies to address the global concerns of climate change.

The physical, chemical and fuel properties of biomass are described along with the end-use patterns of biomass use. The key technologies are the thermochemical processes of combustion, pyrolysis, gasification, as well as the emerging biotechnologies of anaerobic fermentation to biogas, and conversion via fermentation of sugars, starches and cellulose to ethanol- an increasingly important biofuel.

Biomass and bioenergy are used in the daily living sector to provide cooking fuels and heat energy for daily living for over 3 billion people in both developing and industrial countries. Industrial use of bioenergy is common in the forest industries (paper and solid products) and the food processing industries such as sugar cane and palm oil. Byproduct residues are used to generate electricity and process heat needs in combined power and heat facilities. The largest of these is over 300 MW$_{th}$. Biomass energy is increasingly derived from post consumer residues produced by urban centers, and as a result of the application of environmental control technologies such as anaerobic digestion producing biogas to displace natural gas and other fuels. Modern biomass applications to produce electricity and liquid fuels are the most rapidly growing field both in terms of implementation and research and development. While the majority of biomass is the product of other agricultural and forestry activities, increasing attention is being paid to energy crops grown to provide sustainable resources for an expanded bio-industry.

1. Biomass

Biomass is the mass of the living flora and fauna on the earth. With the exception of some organisms that obtain their energy from chemosynthetic processes, by far the majority of life forms obtain their energy directly or indirectly from the sun. The photosynthesis process via solar energy builds phytomass (flora): polymers of carbon (C), hydrogen (H) and oxygen (O) to make cell walls and other plant parts. In addition to the main C, H, O constituents, biomass also contains minor concentration of phosphorous, nitrogen, and potassium as well as many other trace elements associated with cellular life processes. In the energy context biomass is a short hand form for phytomass which can be viewed as stored solar energy, and can be used as fuel or feedstock for processes that either produce energy - bioenergy, or a biofuel, which is an intermediate fuel such as charcoal, or ethanol. All applications of biomass involve a fuel chain with the following key steps:

- Production of biomass;
- Transportation of the biomass;
- Conversion directly to energy or a biofuel;
- Energy or biofuel transport;

- Its final utilization.

Prior to the industrialization of the 18th century, biomass was in fact the principal fuel for human existence, and most of the biomass used came from forests and woods as fuelwood. It was, and is, used for cooking, heating, and in industrial processes such as obtaining iron and steel from their ores after conversion of the fuelwood to charcoal as a reducing agent. Today biomass contributes about 12 % of the world's primary energy supply, though much of it is not commercially traded and is often missed from world energy statistics as a result.

1.1. Photosynthesis and Biomass Yields

The processes of photosynthesis can be summarized as the following chemical balance equation:

$$CO_2 + H_2O + sunlight \rightarrow CH_2O + O_2. \tag{1}$$
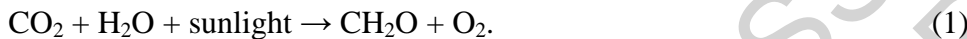
The carbon dioxide comes from the atmosphere and is absorbed by the leaf of the plant, while the plant's vascular system and roots supply the water. Light on the photosynthetic centers oxides water to produce oxygen, protons, and electrons. The leaves release oxygen back to the atmosphere and the protons react with carbon dioxide to produce a photosynthate identified in Eq. (1) as CH_2O. The CH_2O unit is the basic building block of sugars, starch and cellulose and is used internally in plants as a «fuel» for metabolic processes and as the building block for the polymers that make up the cell walls of the plant's structure. While cellulose is the most common natural polymer on the earth, the plant also is able to synthesize compounds that are more chemically reduced and the second most common polymer is lignin that is composed of phenyl propane units. Energy is obtained from biomass by means of combustion with oxygen as in a fire, or through metabolic processes e.g. respiration to provide chemical energy for muscles and other processes:

$$CH_2O + O_2 \rightarrow CO_2 + H_2O + Heat \tag{2}$$

Either way, the net result is a closed cycle in which carbon dioxide and water vapor are returned to the atmosphere. This solar energy powered closed loop supports all life on earth, providing food for humanity, feed for animals, fiber for clothing and material for buildings in addition to fuel.

The closed cycle has, in the last two centuries, been augmented by the use of fossil fuels such as coal, petroleum and natural gas, increasing the amount of carbon dioxide in the atmosphere to over 370 ppmv compared with the pre-industrial level of 280 ppmv. On a carbon basis the atmosphere contains approximately 720 Gt, while the terrestrial biosphere contains about 2000 Gt of which about 50% is no longer living biomass. The aquatic biosphere is considered to contain about 1 - 2 Gt of living biomass, though the oceans also contain about 1000 Gt of organic material and almost 40 Tt of inorganic carbon. Each year the «natural» carbon flux between the terrestrial biosphere and the atmosphere is about 60 Gt, while the addition of fossil carbon and the loss of terrestrial stored biomass due to changes in land use such as conversion of forest to agricultural

land is about 8 Gt. It is this augmentation of the natural cycle that is responsible for the net increase in carbon dioxide, which is a green house gas that is implicated in climate change.

The process of photosynthesis that drives this flux of carbon has an instantaneous efficiency of converting sunlight into stored energy of about 5.5%. This estimate can be derived in the following way. If the solar energy reaching sea level is considered to be 100%, then there is an immediate loss of 50% of the incoming energy because only the photons contained in the solar spectrum between 400 and 700 nm are useable for photosynthesis. The plant leaves reflect, absorb and transmit part of this light for a loss of a further 20%. Of the 40% of the original incident light that is taken up in the photosynthetic apparatus of the leaf, the thermodynamics requires between 8 and 12 light quanta to fix one molecule of photosynthate CH_2O; this results in a loss of 77% (based on 10 quanta of 680 nm light per CO_2 molecule) due to quantum efficiency considerations. The photosynthate is then allocated between plant respiration and maintenance as well as the accumulation of biomass. Assuming a 40% respiration loss and 60% incorporation into biomass results in an overall efficiency of 5.5%.

An efficiency of 5.5% would imply a daily accumulation of woody biomass of around 0.75 t ha^{-1} in the tropics where the average daily solar input is 7 kWh m^{-2}, or an annual production of 270 t ha^{-1} of dry matter. Instantaneous crop yields have been measured at rates of about 0.3 t ha^{-1} per day; however, over a tropical growing season it is hard to exceed an annual production rate of 100 t ha^{-1} in a crop like sugar cane due to variations in leaf index (the area of leaf to capture the solar energy) and temperature which affects the photosynthetic process efficiencies. Temperature in fact has a major effect in what are known as C_3 species that include Northern temperature zone trees, in which high ambient temperatures increase the photorespiration rate and reduce the efficiency of photosynthesis. C_3 plants are adapted to cooler conditions and lower light inputs and use the 3 carbon phosphoglyceric acid pathway (Calvin cycle) to fix carbon dioxide for further processing and use in the plant. The C_4 plants are adapted to warmer and drier climates and process their carbon dioxide in both the Calvin cycle and a pathway via phosphoenol pyruvate to fix carbon dioxide in four carbon acids, oxaloacetate and malate. Adaptations of the leaf structure allow for lower photorespiration and thus higher yields. Sugar cane (*Saccharum officianarum*) and corn (*Zea mays*) are both C_4 plants.

Typical biomass yields vary considerably with the climate and soil zone and the application of technology to the production of plants. A mature boreal forest may be accumulating less than 1 t ha^{-1} per year of biomass due to the slow growth rates of mature plants, low temperatures, and short growing seasons. Agricultural crops can have very high yields, provided that there are no limitations with respect to water and fertilizer availability and the crop is protected from pests. The yield is normally quoted in the food product, such as the record yield of corn in the USA in 1999 that was 393.7 bushels of corn per acre. This corresponds to 24.7 t ha^{-1} of corn kernels. In addition there is the above ground biomass in the stalk, and the corncobs. In agriculture the fraction of the total biomass that is the desired food product is given by the term harvest index. For corn the harvest index is 0.5 so that the record above ground biomass yield for a C_4 plant growing in temperate climate was approximately 50 t ha^{-1} in 1999.

There are sizable yield gaps between attainable and farm-level yields across climatic zones, regions within these zones and crop seasons. One definition of a practical yield gap is the difference between the optimum attainable yield and the farm-level yield. The optimum attainable yield is the yield of experimental on-farm plots with no physical, biological or economic constraints and managed with the best available practices for that season and ecology. The farm-level yield is the average yield that farmers achieve in the area in the same season and ecology. These gaps range from 10 to 60 % depending on the ecosystem and country. More adverse environments such as rain-fed and flood-prone areas subject to atmospheric weather cycles such as the ENSO (El Nino Southern Oscillation) have higher yield gaps. In addition to the biophysical causes there are other factors such as: technical/managerial, socio-economic, institutional/policy, technology transfer and adoption/linkage problems. Because of these factors only part of the yield gap can remedied by technologies such as developing new varieties with higher yield potential and lower levels of inputs.

1.2. Biomass Properties

Biomass properties that affect the biofuels, and materials utilization for energy, include the chemical and the polymeric composition, and the physical traits such as density, toughness and so on.

1.2.1. Polymeric and Chemical Composition

The traditional biomass used in energy applications has been fuelwood. It is a fiber composed of lignin, cellulose and hemicellulose or in short hand, wood is a lignocellulosic material resource. Cellulose, hemicellulose and lignin are carbon-hydrogen-oxygen polymers that serve different structural purposes in the construction of the cell walls of woody plants. Lignocellulosic include trees, most woody plants, the straw and stalks of cereal crops, and are the most important biomass materials and energy resource as they represent much more than half of the above ground biomass produced by photosynthesis. Other major plant components containing polymers of carbon, hydrogen and oxygen that are also used for energy include: starches that are the major part of the cereal grains, as well as the starch from tubers such as manioc and potatoes. Cellulose and starches can be hydrolyzed to simple sugars similar to those produced by sugar beet in temperate climates or sugar cane in the tropics and the sugars can be directly fermented to alcohols. Lipids are very low oxygen containing CHO polymers that are produced by oil seed bearing plants such as soya and rape or are in the fruits of oil palms and are possible diesel fuel substitutes when they are treated with simple alcohols such as methanol and ethanol;

In addition to the carbon-hydrogen-oxygen polymers, there are more complex polymers such as proteins (that can contain sulfur in addition to nitrogen), extractives, and inorganic materials. The inorganic materials range from anions such as chlorine, sulfate and nitrates, and cations such as potassium, sodium, calcium and magnesium as major constituents and there are also many trace elements including manganese, and iron that are the metallic elements in key enzyme pathways involved in cell wall construction.

1.2.2. Fuels Analysis

For combustion purposes there is not much need for information on the polymeric composition and the major analyses that are required are the proximate and ultimate analysis. The proximate analysis for fuels (Table 1) is usually of the material as received, includes the ash content (a reflection of the mineral content), moisture, the heating value and the fixed carbon.

Fuel	Ash content, %	Moisture, %	Volatile matter, %	HHV*, GJ t^{-1}
Bituminous Coal	2.72	2.18	33.4	34.5
Sub-bituminous	3.71	18.41	44.3	21.24
Softwood	1	20	85	18.6

*On a moisture and ash free basis (maf)

Table 1. Proximate analysis of representative solid fuels

The value of a proximate analysis is that it identifies the fuel value of the as-received biomass material, provides an estimate of the ash-handling requirement and describes something of the characteristics in burning. Generally fuels that are highly volatile such as biomass need to have specialized combustor designs to cope with the rapid evolution of gas when the fuel is heated, while those with low volatile matter or conversely a very high fixed carbon value need to be burnt on a grate as they take a long time to burn out or to be prior to combustion pulverized to a very small size.

An ultimate analysis that is most often given on a moisture and ash free (maf) basis gives information on the elemental composition (Table 2).

Material	C	H	N	S	O	Ash	HHV, GJ t^{-1}
Bituminous coal	75.5	5.0	1.2	3.1	4.9	10.3	31.67
Sub bituminous coal	77.9	6.0	1.5	0.6	9.9	4.1	32.87
Charcoal	80.3	3.1	0.2	0.0	11.3	3.4	31.02
Douglas fir	52.3	6.3	0.1	0.0	40.5	0.8	21.00
Douglas fir bark	56.2	5.9	0.0	0.0	36.7	1.2	22.00
Pine bark	52.3	5.8	0.2	0.0	38.8	2.9	20.40
Western hemlock	50.4	5.8	0.1	0.1	41.4	2.2	20.00
Eucalyptus grandis	48.3	5.9	0.15	0.01	45.13	0.4	19.35
Beech	51.6	6.3	0.0	0.0	41.5	0.6	20.30
Sugar cane bagasse	44.8	5.4	0.4	0.01	39.6	9.8	17.33
Wheat straw	43.2	5.0	0.6	0.1	39.4	11.4	17.51
Poplar	51.6	6.3	0.0	0.0	41.5	0.6	20.70
Rice hulls	38.5	5.7	0.5	0.0	39.8	15.5	15.30
Rice straw	9.2	5.1	0.6	0.1	35.8	19.2	15.80

Table 2. Ultimate Analysis Data for Biomass and Selected Solid Fuels (Dry Basis, % by weight)

The energy content of biomass is always reported for dry material; however, many of the lignocellulosic species are harvested fresh in a so-called green condition and contain as much as 50 % of their mass as water. There are also two different energy content reporting conventions in use. The term higher heating value HHV refers to the energy

released in combustion when the water vapor resulting from the combustion is condensed thus realizing the latent heat of evaporation; much of the data from North America is reported in this way. The lower heating value or LHV reports the energy released when the water vapor remains in a gaseous state. For pure carbon, which only produces carbon dioxide when burned, the HHV and LHV are equal, while for methane when it is burned there are two molecules of water produced for each molecule of carbon dioxide, and the HHV is 11.1 % greater than the LHV.

1.2.3. Physical Properties

In addition to the moisture content and chemical properties the physical properties are also important in the design of systems to handle biomass fuels and feed stocks. Compared with fossil fuels biomass in the raw state has a relatively low bulk energy density. Bituminous coal or crude oil for example, has a volumetric energy density of 30 dm^3 GJ^{-1}, solid wood has around 90 dm^3 GJ^{-1}, while in chip form the volume increases to 250 dm^3 GJ^{-1} for hardwood species and 350 dm^3 GJ^{-1} for coniferous species. Cereal straw has even less energy density and ranges from 450 dm^3 GJ^{-1} for large round bales to 1.2 m^3 GJ^{-1} for chopped straw, similar to that of sugar cane bagasse which is the fiber and pith left over after the extraction of sugar juice from green cane.

Size reduction of biomass resources is often more difficult than with minerals as the materials are naturally strong fibers, and the production of uniform particle size feed stocks is correspondingly difficult.

1.2.4. Biomass Briquettes and Pellets

One of the ways in which both transportation and handling problems of biomass fuels can be minimized is to produce densified fuels, either by pelletizing or briquetting. Both processes produce fuels that have volumetric densities in the range of 0.8 - 1.2 kg dm^{-3}, the volumetric energy density as a result is of the order of 50 dm^3 GJ^{-1}. While pelletizing uses the natural waxes and extractives in the biomass to bind the densified pellet, briquetting is usually accomplished with water and an added binder (often a starch based compound) and can include other materials such as coal dust or clay, and when used with low-grade coals it is also possible to add desulfurizing agents such as limestone. Briquettes can also be carbonized in kilns to drive off the volatiles and produce a charcoal like fuel. The processing steps for both pellets and briquettes are first to reduce the particle size of the biomass to less than 3 mm, and to dry the material. In the case of briquettes the fibers are then blended with the filler, binder and a small amount of water and the mixture is put into a piston press or a screw extruder at around 1 - 3 MPa applied pressure, and the resulting compacted material is then air dried before packaging or using it. Piston presses produce a solid briquette, while the screw extruder pellet has a hollow core. Pelletizing occurs in high-pressure dies and requires considerably more mechanical energy input than briquetting (between 50 and 100 kWh of electricity is required per 1 t of pellets). Nevertheless, the mass and energy efficiency of pellet production is very high at over 95%, and the process adds a cost of about $ 50 t^{-1} to the cost of the biomass feedstock. In the USA pellet production has doubled in the last decade and the product is marketed for prices of about $6 GJ^{-1}. Specialized high efficiency low emissions pellet stoves are available and when used for domestic heating

are competitive with heating oil or natural gas in the Northern USA. The total annual production of pellets in the USA is around 700 kt with an energy content of about 12 PJ.

2. The Biomass and Bioenergy System

Biomass for bioenergy use comes either directly from the land or is a residue that is generated in primary processing of raw materials such as the production of pulp and paper from wood, or sugar from sugar cane. Another important contribution is from post consumer residue streams such as construction and demolition wood, pallets used in transportation and the clean fraction of MSW (municipal solid waste). In many respects the biomass and bioenergy system is part of the management of the solar generated flow of materials, food and fiber in society. These inter-relationships are illustrated in Figure 1, which shows the various resource types and their applications, and the cascade of their harvest, process and use residues to bioenergy applications. Not all biomass applications directly produce energy, but rather convert it into biofuels such as charcoal (a high energy density solid fuel) or ethanol (an automotive fuel that is used in Brazil and the United States).
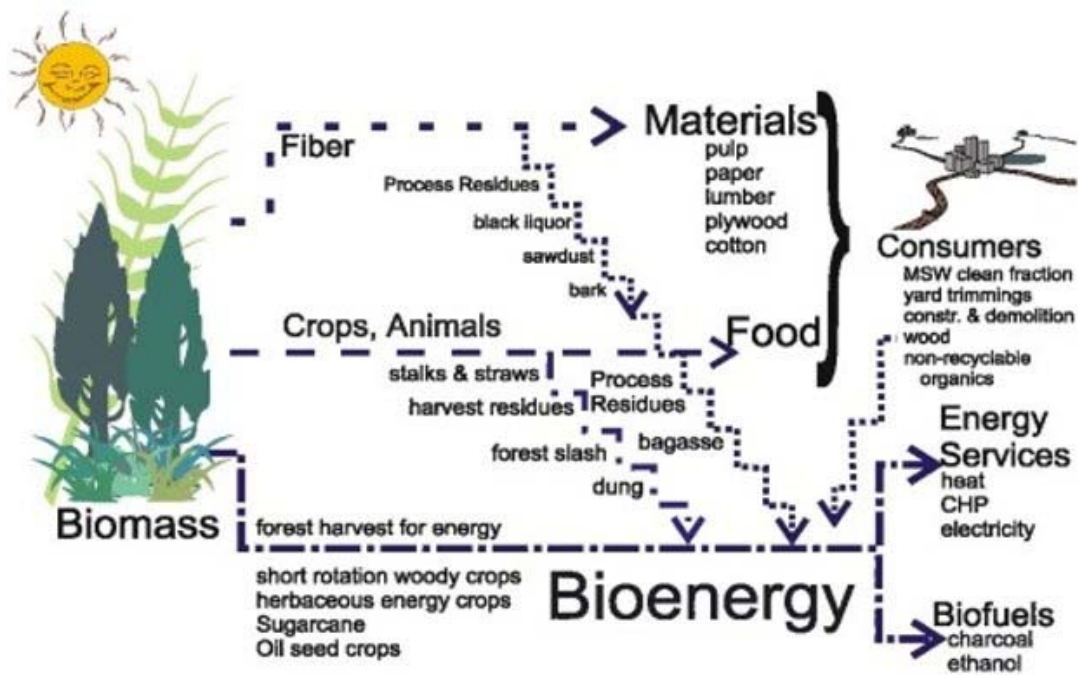
Figure 1. The flow of biomass produced by photosynthesis and human activity

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Biographical Sketch

Ralph P. Overend, NREL Research Fellow, was trained in physical chemistry, and worked in bioenergy and renewable energy since 1973 as a researcher, research manager, and coordinator of research and development in both Canada and the United States. His nearly 20 years with the National Research Council of Canada, was as manager of the Bioenergy program, and advisor to the Department of Energy Mines and Resources on biomass energy. In addition, he served as coordinator of Canadian renewables R&D for several years. He joined the United States Department of Energy Biomass Power program at the National Renewable Energy Laboratory in 1990, and has worked extensively in the development of long-range plans and strategies for biomass power and biofuels since that time. His major technical activity at the present time is assisting the development of the Vermont Gasification project—a 60 MW thermal indirect gasification system attached to the McNeil station in Burlington, Vermont.

He was the Chairman of the American Chemical Society Cellulose Division 1993-94. He edits the journal, *Biomass and Bioenergy*, and the biomass section of the Journal, *Solar Energy*, in addition to being a member of several editorial boards. He has also served as a United Nations, World Bank, and FAO lecturer/advisor in the USSR, China, Pakistan, and Mexico. He recently completed the biomass component of a renewable energy atlas for the Government of the Philippines.

Significant recognitions for outstanding scientific contributions in biomass and bioenergy include: Fellow of the Chemical Institute of Canada, 1990; Johannes Linneborn Prize, 1996; H.M. Hubbard Award, 1997; R&D 100 Award, 1998; NREL Research Fellow, 2000; the Thomas R. Miles Award, 2001, and the World Renewable Energy Network, Pioneer Award, 2002.