Bioenergy conversion technologies

There are five fundamental forms of biomass energy use.

(1) the "traditional domestic" use in developing countries (fuelwood, charcoal and agricultural residues) for household cooking (e.g. the "three stone fire"), lighting and space-heating. In this role-the efficiency of conversion of the biomass to useful energy generally lies between 5% and 15%.

(2) the "traditional industrial" use of biomass for the processing of tobacco, tea, pig iron, bricks & tiles, etc, where the biomass feedstock is often regarded as a "free" energy source. There is generally little incentive to use the biomass efficiently so conversion of the feedstock to useful energy commonly occurs at an efficiency of 15% or less.

(3) "Modern industrial." Industries are experimenting with technologically advanced thermal conversion technologies which are itemised below. Expected conversion efficiencies are between 30 and 55%.

(4) newer "chemical conversion" technologies ("fuel cell") which are capable of by-passing the entropy-dictated Carnot limit which describes the maximum theoretical conversion efficiencies of thermal units.

(5) "biological conversion" techniques, including anaerobic digestion for biogas production and fermentation for alcohol.

In general, biomass-to-energy conversion technologies have to deal with a feedstock which can be highly variable in mass and energy density, size, moisture content, and intermittent supply. Therefore, modern industrial technologies are often hybrid fossil-fuel/biomass technologies which use the fossil fuel for drying, preheating and maintaining fuel supply when the biomass supply is interrupted.

Direct combustion processes.

Co-firing.

Feedstocks used are often residues such as woodchips, sawdust, bark, hogfuel, black liquor, bagasse, straw, municipal solid waste (MSW), and wastes from the food industry.

Direct combustion furnaces can be divided into two broad categories and are used for producing either direct heat or steam. Dutch ovens, spreader-stoker and fuel cell furnaces employ two-stages. The first stage is for drying and possible partial gasification, and the second for complete combustion. More advanced versions of these systems use rotating or vibrating grates to facilitate ash removal, with some requiring water cooling.

The second group, include suspension and fluidised bed furnaces which are generally used with fine particle biomass feedstocks and liquids. In suspension furnaces the particles are burnt whilst being kept in suspension by the injection of turbulent preheated air which may already have the biomass particles mixed in it. In fluidised bed combustors, a boiling bed of pre-heated sand (at temperatures of 500 to 900°C) provides the combustion medium, into which the biomass fuel is either dropped (if it is dense enough to sink into the boiling sand) or injected if particulate or fluid. These systems obviate the need for grates, but require methods of preheating the air or sand, and may require water cooled injection systems for less bulky biomass feedstocks and liquids. {WEC, 1992}

Co-firing.

A modern practice which has allowed biomass feedstocks an early and cheap entry point into the energy market is the practice of co-firing a fossil-fuel (usually coal) with a biomass feedstock. Co-firing has a number of advantages, especially where electricity production is an output.

Firstly, where the conversion facility is situated near an agro-industrial or forestry product processing plant, large quantities of low cost biomass residues are available. These residues can represent a low cost fuel feedstock although there may be other opportunity costs. Secondly, it is now widely accepted that fossil-fuel power plants are usually highly polluting in terms of sulphur, CO_2 and other GHGs. Using the existing equipment, perhaps with some modifications, and co-firing with biomass may represent a cost-effective means for meeting more stringent emissions targets. Biomass fuel's low sulphur and nitrogen (relative to coal) content and nearly zero net CO_2 emission levels allows biomass to offset the higher sulphur and carbon contents of the fossil fuel. {Demeter et al. 1993} Thirdly, if an agro-industrial or forestry processing plant wishes to make more efficient use of the residues generated by co-producing electricity, but has a highly seasonal component to its operating schedule, co-firing with a fossil fuel may allow the economic generation of electricity all year round. Agro-industrial processors such as the sugarcane sugar industry can produce large amounts of electricity during the harvesting and processing season, however, during the off-season the plant will remain idle. This has two drawbacks, firstly, it is an inefficient use of equipment which has a limited life-time, and secondly, electrical distribution utilities will not pay the full premium for electrical supplies which can't be relied on for year round production. In other words the distribution utility needs to guarantee year round supply and may therefore, have to invest in its own production capacity to cover the off-season gap in supply with associated costs in equipment and fuel. If however, the agro-processor can guarantee electrical supply year-round through the burning of alternative fuel supplies (i.e. coal and bagasse in Mauritius, see section 3) then it will make efficient use of its equipment and will receive premium payments for its electricity by the distribution facility.{GEF, 1992}

Thermochemical processes.

These processes do not necessarily produce useful energy directly, but under controlled temperature and oxygen conditions are used to convert the original biomass feedstock into more convenient forms of energy carriers, such as producer gas, oils or methanol. These carriers are either more energy dense and therefore reduce transport costs, or have more predictable and convenient combustion characteristics allowing them to be used in internal combustion engines and gas turbines.

Pyrolysis.

The biomass feedstock is subjected to high temperatures at low oxygen levels, thus inhibiting complete combustion, and may be carried out under pressure. Biomass is degraded to single carbon molecules (CH_4 and CO) and H_2 producing a gaseous mixture called "producer gas." Carbon dioxide may be produced as well, but under the pyrolytic conditions of the reactor it is reduced back to CO and H_2O; this water further aids the reaction. Liquid phase products result from temperatures which are too low to crack all the long chain carbon molecules so resulting in the production of tars, oils, methanol, acetone, etc. Once all the volatiles have been driven off, the residual biomass is in the form of char which is virtually pure carbon.

Pyrolysis has received attention recently for the production of liquid fuels from cellulosic feedstocks by "fast" and "flash" pyrolysis in which the biomass has a short residence time in the reactor. A more detailed understanding of the physical and chemical properties governing the pyrolytic reactions has allowed the optimisation of reactor conditions necessary for these types of pyrolysis. Further work is now concentrating on the use of high pressure reactor conditions to produce hydrogen and on low pressure catalytic techniques (requiring zeolites) for alcohol production from the pyrolytic oil.

Carbonisation.

This is an age old pyrolytic process optimised for the production of charcoal. Traditional methods of charcoal production have centred on the use of earth mounds or covered pits into which the wood is piled. Control of the reaction conditions is often crude and relies heavily on experience. The conversion efficiency using these traditional techniques is believed to be very low; on a weight basis Openshaw estimates that the wood to charcoal conversion rate for such techniques ranges from 6 to 12 tonnes of wood per tonne of charcoal. {Openshaw, 1980}.

During carbonisation most of the volatile components of the wood are eliminated; this process is also called "dry wood distillation." Carbon accumulates mainly due to a reduction in the levels of hydrogen and oxygen in the wood.

The wood undergoes a number of physico-chemical changes as the temperature rises. Between 100 and 170°C most of the water is evaporated; between 170°C and 270°C gases develop containing condensible vapours, CO and CO_2. These condensible vapours (long chain carbon molecules) form pyrolysis oil, which can then be used for the production of chemicals or as a fuel after cooling and scrubbing. Between 270°C and 280°C an exothermic reaction develops which can be detected by the spontaneous generation of heat {Emrich, 1985}.

The modernisation of charcoal production has lead to large increases in production efficiencies with large-scale industrial production in Brazil now achieving efficiencies of over 30% (by weight).

There are three basic types of charcoal-making: a) internally heated (by controlled combustion of the raw material), b) externally heated (using fuelwood or fossil fuels), and c) hot circulating gas (retort or converter gas, used for the production of chemicals).

Internally heated charcoal kilns are the most common form of charcoal kiln. It is estimated that 10 to 20% of the wood (by weight) is sacrificed, a further 60% (by weight) is lost through the conversion to, and release of, gases to the atmosphere from these kilns. Externally heated reactors allow oxygen to be completely excluded, and thus provide better quality charcoal on a larger scale. They do, however, require the use of an external fuel source, which may be provided from the "producer gas" once pyrolysis is initiated.

Recirculating heated gas systems offer the potential to generate large quantities of charcoal and associated by-products, but are presently limited by high investment costs for large scale plant. {Emrich, 1985}

The main characteristics of a typical charcoal kiln in Brazil (internally heated) are shown in table 12.

Gasification.

High temperatures and a controlled environment leads to virtually all the raw material being converted to gas. This takes place in two stages. In the first stage, the biomass is partially combusted to form producer gas and charcoal. In the second stage, the $C0_2$ and H_2O produced in the first stage is chemically reduced by the charcoal, forming CO and H_2. The composition of the gas is 18 to 20% H_2, an equal portion of CO, 2 to 3% CH_4, 8 to 10% CO_2, and the rest nitrogen. {Makunda, 1992}. These stages are spatially separated in the gasifier, with gasifier design very much dependant on the feedstock characteristics.

Gasification requires temperatures of about 800°C and is carried out in closed top or open top gasifiers. These gasifiers can be operated at atmospheric pressure or higher. The energy density of the gas is generally less than 5.6 MJ/m^3, which is low in comparison to natural gas at 38 MJ/m^3 {WEC, 1992}, providing only 60% the power rating of diesel when used in a modified diesel engine {Makunda, 1992}.

Gasification technology has existed since the turn of the century when coal was extensively gasified in the UK and elsewhere for use in power generation and in houses for cooking and lighting. Gasifiers were used extensively for transport in Europe during World War II due to shortages of oil, with a closed top design predominating.

A major future role is envisaged for electricity production from biomass plantations and agricultural residues using large scale gasifiers with direct coupling to gas turbines. The potential gains in efficiency using such hybrid gasifier/gas turbine systems make them extremely attractive for electricity generation once commercial viability has been demonstrated. Such systems take advantage of low grade and cheap feedstocks (residues and wood produced using short rotation techniques) and the high efficiencies of modern gas turbines to produce electricity at comparable or less cost than fossil-fuel derived electricity. Net atmospheric CO_2 emissions are avoided if growth of the biomass is managed to match consumption. The use of BIG/STIG (Biomass Integrated Gasifier Steam Injected Gas turbine) initially and BIG/GTCC (Biomass integrated Gasifier Gas Turbine Combined Cycle) as the technology matures, is predicted to allow energy conversion efficiencies of 40% to 55%. Modern coal electrical plants have efficiencies of about 35% or less. Combined Heat and Power systems could eventually provide energy at efficiencies of between 50% to 80%. The use of low-grade feedstocks combined with high conversion efficiencies makes these systems economically competitive with cheap coal-based plants and energetically competitive with natural gas-based plants. {Johansson et al., 1992; Williams and Larson, 1992} (see figs. 7 & 8).

Studies are continuing in the use of such technologies for the cost effective treatment of MSW e.g. in the Netherlands a study by Faaij et al. {1992} considers that "gasification can become a strong competitor to anaerobic digestion, composting and incineration for biomass waste treatment." This is based on the use of BIG/STIG technology with the system gasification using Atmospheric Circulating Fluidized Bed (ACFB) technology. They expect the potential to be "realised within 4 to 7 years". {Faaij et al., 1992}

Catalytic Liquefaction.

This technology has the potential to produce higher quality products of greater energy density. These products should also require less processing to produce marketable products.

Catalytic liquefaction is a low temperature, high pressure thermochemical conversion process carried out in the liquid phase. It requires either a catalyst or a high hydrogen partial pressure. Technical problems have so far limited the opportunities of this technology.

Biochemical processes.

Anaerobic Fermentation.
Methane Production in Landfills.
Ethanol Fermentation.
Biodiesel.

The use of micro-organisms for the production of ethanol is an ancient art. However, in more recent times such organisms have become regarded as biochemical "factories" for the treatment and conversion of most forms of human generated organic waste. Microbial engineering has encouraged the use of fermentation technologies (aerobic and anaerobic) for use in the production of energy (biogas) and fertiliser, and for the use in the removal of unwanted products from water and waste streams.

Anaerobic Fermentation.

Anaerobic reactors are generally used for the production of methane rich biogas from manure (human and animal) and crop residues. They utilise mixed methanogenic bacterial cultures which are characterised by defined optimal temperature ranges for growth. These mixed cultures allow digesters to be operated over a wide temperature range i.e. above 0°C up to 60°C.

When functioning well, the bacteria convert about 90% of the feedstock energy content into biogas (containing about 55% methane), which is a readily useable energy source for cooking and lighting. The sludge produced after the manure has passed through the digester is non-toxic and odourless. Also, it has lost relatively little of its nitrogen or other nutrients during the digestion process thus, making a good fertiliser. In fact, compared to cattle manure left to dry in the field the digester sludge has a higher nitrogen content; many of the nitrogen compounds in fresh manure become volatised whilst drying in the sun. On the other hand, in the digested sludge little of the nitrogen is volatised, and some of the nitrogen is converted into urea. Urea is more readily accessible by plants than many of the nitrogen compounds found in dung, and thus the fertiliser value of the sludge may actually be higher than that of fresh dung.

Anaerobic digesters of various types were widely distributed throughout India and China. Extension programmes promote biogas plants as ideal candidates for rural village use due to their energy and fertiliser production potential along with their improved health benefits. Health benefits primarily arise from the cleaner combustion products of biogas as opposed to other biomass or fossil fuels which may be used in the domestic environment, (see section 5) These two countries now have an estimated 5 to 6 million units in use.

Reliability problems have arisen from a number of problems i.e. construction defects, the mixed nature of the bacterial population, the digesters requirements for water and the maintenance of the optimum nitrogen ratio of the medium. Another problem is the digester's demand for dung, which may have alternative uses.

Modern designs have answered many of these problems and digesters are again becoming useful, especially with regard to the potential of digesters to remove toxic nutrients such as nitrates from water supplies; levels of which are now much more stringently controlled in many industrialised countries. The combination of energy production with the ability to enhance crop yields make biogas technology a good candidate for more widespread use now that reliable operation can be demonstrated. Recent Danish commercial experience with large scale digesters provides a useful example. (Section 3)

Methane Production in Landfills.

Anaerobic digestion in landfills is brought about by the microbial decomposition of the organic matter in refuse. The levels of organic matter produced per capita vary considerably from developed to developing countries e.g. the percentage of Municipal Solid Waste (MSW) which is putrescible in Sierra Leone is about 90% {Steele, 1992}, compared to about 60% for US MSW. The reduced levels of putrescibles in US MSW are a result of the increased proportions of plastics, metals and glass, mostly from packaging {Slivka et al., 1992}. Landfill-generated gas is on average half methane and half carbon dioxide with an energy content of 18 to 19 MJ/m^3. Its production does not occur under pressure, and thus recovery processes must be active.

Commercial production of land-gas can also aid with the leaching problems now increasingly associated with landfill sites. Local communities neighbouring land fill sites are becoming more aware of the potential for heavy metals and nutrients to leach into aquifers. Landfill processing reduces the volume of sludge to be disposed of, and the nutrient content, thus facilitating proper disposal.

Methane is a powerful greenhouse gas, with substantial amounts being derived from unutilized methane production from landfill sites. Its recovery therefore, not only results in the stabilisation of the landfill site, allowing faster reuse of the land, but also serves to lessen the impact of biospheric methane emissions on global warming.

Ethanol Fermentation.

Ethanol is mainly used as a substitute for imported oil in order to reduce their dependence on imported energy supplies. The substantial gains made in fermentation technologies now make the production of ethanol for use as a petroleum substitute and fuel enhancer, both economically competitive (given certain assumptions) and environmentally beneficial. For example, subsidies for alcohol production in Brazil are now becoming regarded as detrimental to the stability of the ethanol market, and thus obsolete, (section 3) In Zimbabwe, foreign exchange savings are seen as a major bonus, which along with the employment and environmental benefits have made the long term future and expansion of the this programme a priority for the Zimbabwean government. (see section 3; Sugarcane Electricity, Jobs)

The most commonly used feedstock in developing countries is sugarcane, due to its high productivity when supplied with sufficient water. Where water availability is limited, sweet sorghum or cassava may become the preferred feedstocks. Other advantages of sugarcane feedstock include the high residue energy potential and modern management practices which make sustainable and environmentally benign production possible whilst at the same time allowing continued production of sugar {Scurlock et al., 1992}. Other feedstocks include saccharide-rich sugarbeet, and carbohydrate rich potatoes, wheat and maize.

One of the most promising fermentation technologies to be identified recently is the "Biostil" process which uses centrifugal yeast reclamation, and continuous evaporative removal of the ethanol. This allows the fermentation medium to be continuously sterilised and minimises water use. The Biostil process markedly lowers the production of stillage, whilst the non-stop nature of the fermentation process allows substrate concentrations to be constantly kept at optimal levels and therefore fermentation efficiency is maximised. {Hall, 1991} Improved varieties of yeast, produced through clonal selection techniques have also raised the tolerance levels of the yeast to alcohol concentrations, again improving efficiency.

Recent advances in the use of cellulosic feedstock, may allow the competitive production of alcohol from woody agricultural residues and trees to become economically competitive in the medium term. (table 13) Since 1982, prices have fallen from about US$ 45 per GJ (95 c/l) to about US$ 13 per GJ (28 c/l) for ethanol, and for methanol, projected prices have been reduced from US$ 16 per GJ (27 c/l) to $15 per GJ (25 c/l) and could fall to prices competitive with gasoline produced from oil priced at US$ 25 per barrel. {Wyman et al., 1992}

Biodiesel.

The use of vegetable oils for combustion in diesel engines has occurred for over 100 years. In fact, Rudolf Diesel tested his first prototype on vegetable oils, which can be used, "raw", in an emergency. Whilst it is feasible to run diesel engines on raw vegetable oils, in general the oils must first be chemically transformed to resemble petroleum - based diesel more closely.

The raw oil can be obtained from a variety of annual and perennial plant species. Perennials include, oil palms, coconut palms, physica nut and Chinese Tallow Tree. Annuals include, sunflower, groundnut, soybean and rapeseed. Many of these plants can produce high yields of oil, with positive energy and carbon balances.

Transformation of the raw oil is necessary to avoid problems associated with variations in feedstock. The oil can undergo thermal or catalytic cracking, Kolbe electrolysis, or transesterification processes in order to obtain better characteristics. Untreated oil causes problems through incomplete combustion, resulting in the build up of sooty residues, waxes, gums etc. Also, incorrect viscosities can result in poor atomization of the oil also resulting in poor combustion. Oil polymerisation can lead to deposition on the cylinder walls. {Shay, 1993}

Generally, the chemical processing required to avoid these problems is simple, and in the case of soybean oil may be carried out in existing petroleum refineries. The use of diesel powered vehicles is widespread throughout agriculture, and biodiesel provides an environmentally friendly, CO_2-neutral alternative. It is now being widely promoted in the EC and elsewhere, as its use does not require major modification to existing diesel engines. {Shay, 1993}