THE BRILLIANCE OF BIOENERGY – ENVIRONMENTALLY SOUND TECHNOLOGIES – OR NOT?

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Abstract
Biomass can be used to provide heat, power and transport fuels via a wide variety of energy conversion processes. It is a store of chemical energy which, in all its wide variety of forms, originates from the process of photosynthesis. Whether the use of biomass is sustainable and environmentally sound is determined by the source of the biomass, production methods and land use, alternative treatments when biomass is in the form of organic wastes, and the type of energy conversion processes involved. In all cases the level of greenhouse gas emissions is low or zero. Life cycle analyses to determine the environmental impacts of modern biomass have shown the overall system can be environmentally benign. In the longer term there are good opportunities for biomass to be used in environmentally sound, small scale, distributed generation systems including fuel cells and micro-turbines, suitable for both developed and developing countries. For the many rural communities still dependent on traditional biomass (firewood and dung) for cooking and heating, the uptake of more efficient conversion technologies but using these familiar fuels should be relatively easy to achieve.

Introduction
Biomass covers a wide range of chemical energy resources, all originating from plant material. It can therefore be considered as a store of solar energy. Conversion into useful energy services and products can be undertaken using a wide range of technological pathways (Fig. 1). Biomass projects can vary in scale from simple combustion in domestic open fires; to 5-10MW bio-fermentation processes owned by municipalities for the treatment of organic waste materials; to fully commercial complex thermo-chemical reactors in the form of 100MWₑ combined heat and power stations.

It is not possible in this paper to cover the specific potential environmental impacts of each of the biomass conversion routes as outlined in Figure 1 and to identify which of the systems are environmentally sound and which are less so. The issue is further complicated by environmental impacts usually being project specific and therefore difficult to define in general terms. Details and case studies for each technology are published elsewhere (Sims, 2002). Therefore the objective of this paper is to outline some generic environmental issues relating to biomass use.

Brief history of biomass
Traditionally biomass has been used to provide the basic human needs of cooking and warmth for many centuries. This is still the case particularly in many developing countries. Biomass currently contributes around 12-13% of global primary energy demand based mainly on the burning of 2 billion tonnes a year of firewood, 1.3 billion tonnes of crop residues and 1 billion tonnes of animal dung (Pimental, 2001). Removal of this material from the land robs the soil of
Figure 1. A wide range of biomass resources can be converted using several routes to provide heat, power, or transport fuels.

recycled nutrients, exposes it to water and wind erosion, reduces the organic matter content and reduces the soil rooting depth. It is clearly not a sustainable practice, especially as population increases add to the biomass demand. By contrast modern and efficient, large scale bioenergy conversion plants, in part fuelled by specially grown energy crops, have been developed in OECD countries during the past 20 or so years. These produce acceptably low levels of emissions which generally meet the ever more stringent legislation requirements such as the Clean Air Act (1991) of the USA and the Resource Management Act (1990) of New Zealand.

Global environmental trends are slowly moving towards more sustainable production methods, waste minimisation, reduced vehicle pollution, distributed electricity generation, conservation of native forests, and reduction of greenhouse gas (GHG) emissions. Development and equity, as sought by the 2 billion people with no access to electricity, are also linked to sustainability goals. Modern biomass has a major role to play in each one of these environmental and social drivers as is clear from the Intergovernmental Panel on Climate Change, Third Assessment Report (IPCC 2001).
**Technology application**

New and improved bioenergy conversion technologies such as gasification, pyrolysis and enzymatic hydrolysis of ligno-cellulose, are being further developed to help solve some of the problems relating to environmental impacts from biomass use. The aim should be to ensure that, once proven, these are made available as “leapfrog technologies” for uptake in developing countries at prices they can afford in order to provide a more healthy and enjoyable quality of life. Biomass resources and wastes are already widely distributed and people living in rural communities are familiar with their use. However in many places firewood is becoming scarce and in future the biomass resource will need to be managed in a more sustainable manner. The challenge is to encourage sustainable production of biomass together with the uptake of efficient conversion technologies, ranging from domestic wood stoves with low smoke production, to large power plants with flue gas emission controls to minimize particulates and dioxins. This will take time, effort, investment and political will to achieve.

**Reasons for using biomass**

Biomass resources include energy crops, agricultural crops and forestry residues, animal, food and fibre processing wastes, landfill gas and municipal solid wastes. These are widely distributed so have good potential to provide many areas with a renewable source of energy. Globally, terrestrial plant growth provides an annual primary production of $220 \times 10^9$ oven-dry tonnes (odt) containing $4,500$EJ of chemical energy of which $270$EJ/y might become available for bioenergy use on a sustainable basis. Whether or not it does depends on the economics of production and utilization, as well as on the availability of suitable land. The challenge is to provide sustainable management, efficient conversion and economic delivery of the bioenergy to the market place in the form of modern and competitive energy services.

Municipal solid wastes, and residues such as bagasse, rice husks, and sawdust often have a disposal cost and, when dumped or land-filled, can lead to toxic fungal spore and methane production during the natural decomposition process. If burnt in the open air, high atmospheric pollution results. Therefore, waste-to-energy conversion may have good economic potential to provide heat and power as well as transport fuels, and hence give environmental benefits as well.

Energy crops have less immediate potential than using wastes and residues because of their higher delivered costs in terms of S/GJ of available energy. By 2100 the global land requirement to be used for agriculture to feed and clothe the growing world population is estimated to reach about 1.7Gha, whereas 0.69-1.35Gha would also be needed to support future biomass energy crop requirements in order to meet a high-growth scenario (IPCC, 2001). Up until this time, even with a growing world population, there may well be sufficient land to supply all demands for food, fibre and energy. However at some stage after that land-use conflicts could arise, though before this stage is reached, competition for water may be a greater constraint for energy cropping in some regions.

Harvesting operations, transport methods, and cartage distances to the conversion plants significantly impact on the environmental impacts and energy balance of an overall biomass system. The generating plant or ‘biorefinery’ must be located near to the resource to minimize roading impacts and transport costs of the low energy density biomass, and also to minimize
impacts on air and water use. However, economies of scale of a larger plant can outweigh the benefits of reduced transport distances, so careful analysis is necessary for any given project.

Recent commercial developments in biomass cogeneration, co-firing in coal-fired boilers, biomass-fueled integrated gasification combined-cycle (BIGCC) units for the forest industry, and bio-ethanol from the hydrolysis of lingo-cellulosic material all show good technical and socio-economic potential, with co-firing giving the lowest cost and technical risk. In all cases the capital investment costs continue to decline with project experience. For example, present investment costs for a pressurised BIGCC plant of 20-30MW scale are estimated by 2030 to fall from over $US2000/kW now to around $US1100/kW when lower fuel supply and operating costs are also predicted.

Liquid and gaseous transport fuels derived from a range of biomass sources are used commercially in a number of countries. These “biofuels” include methanol, ethanol, di-methyl esters, pyrolytic oil, Fischer-Tropsch gasoline and distillate, and biodiesel from vegetable oil crops or tallow. Overall, biofuels can only become competitive with currently cheap crude oil products if significant government support is provided by way of fuel tax exemptions or subsidies, and if a value is placed on the resulting environmental benefits. These can include reduced exhaust emissions in terms of carbon, NO₅ and particulates, leading to reduced respiratory complaints for city dwellers. However with certain biofuels additional emissions can result, such as aldehydes from bio-ethanol use.

Carbon sinks

A key point in favour of using woody biomass is the link with biological carbon sequestration. Take for example a 1 hectare plot of native forest land. When it was first deforested for agricultural production, the carbon content of the soil and standing biomass was reduced (Fig. 2). Reafforestation with managed plantation forests will partly replace the carbon. It is recognised that such “Kyoto forest” plantations established after 1990 into pasture or crop land are biological carbon sinks and may therefore earn additional revenue from carbon credits. However such sinks can only be a temporary solution to climate change mitigation and even when properly managed, can only allow time for other mitigation options to be developed. Only when the stored carbon is recycled by utilising these sustainably produced forest crops to displace fossil fuels (as well as for low energy intensive construction materials) can carbon sink and carbon offset benefits result.

Life cycle analysis assessments of the environmental impacts of bioenergy

Biomass utilization produces zero or low net carbon dioxide emissions as it is recycled between crop production and combustion. However other parts of the biomass supply chain produce other emissions. If the true effects of emissions from bioenergy use are to be evaluated accurately, so that for example woody biomass can be compared with coal, the emissions from all stages of the life cycle need to be included. This “well to wheel” analysis for fossil fuel products would need to include plant construction, mining, processing, transportation and storage as well as the more widely monitored and measured emissions released during combustion. For biomass it would include cultivating the land to grow the crops, fertilizer and chemical applications, harvesting and
transport, processing operations, construction of the conversion plant and future decommissioning. Since biomass typically has a lower energy density (MJ/kg) compared to the more energy concentrated fossil fuels, the delivery and conversion of this bulkier material requires more machinery and larger structures per unit of energy produced. This in turn involves more embedded energy in their manufacture and construction. The elements to be analysed in detail in such a life cycle framework would need to include:

- whether the biomass was produced as the main product of a system such as short rotation forests, or as a by-product such as wood process residues;
- what other by-products also need to be considered such that appropriate emissions and offsets can be allocated between them;
- the factors and fluxes relating to biological carbon storage in forest sinks;
- the balances between reforestation, afforestation and conservation of forests against utilisation of resources for bioenergy;
- whether bioenergy provides an irreversible mitigation effect by reducing CO₂ at its source, whereas afforestation and forest conservation are mitigation options subject to future management regimes;
- efficiencies of bioenergy conversion systems which in many cases are low compared with fossil fuel systems, though technology improvements such as BIGCC plants have the potential to improve this;
- leakage of carbon emissions, whereby biomass fuels simply provide a new energy source adding to the total energy consumption of “business as usual” rather than displacing the use of fossil fuels to the extent anticipated; and
- the emission of other GHG emissions associated with both fossil fuels and bioenergy fuel chains, particularly methane and nitrous oxides.
The volumes of GHG emissions arising from the collection, transport and processing of biomass are dependent on a range of complex factors which vary with specific projects including:
- the system used to collect, transport and process the biomass feedstock materials including equipment used and types of biomass collected;
- fuel consumption for the trucks and machinery used for each type of operation;
- haul distances for supplying the biomass fuel to the conversion plant gate; and
- whether any electricity consumed comes from thermal, nuclear or hydro sources.

Life cycle analysis of bioenergy is a complex process but there are some basic guidelines that have been developed. In theory the indirect energy and related emissions embodied in the machinery, buildings, equipment and fertilizers used should also be taken into account, but this becomes even more complex and it is difficult to know where to put a boundary around the analysis.

Transporting biomass gives rise to a major component of the total GHG emissions. For example transporting 2.9 million m³ of forest arisings over a maximum haul distance of 120km resulted in 26,400t of carbon being emitted, whereas the collection and chipping of the same material produced only 8,000tC. To be thorough, the analysis should also include an allocation of any GHG arising from the establishment and management of the forests as well as at harvest.

During the conversion of bioenergy several GHGs may be emitted depending on the fuel source, the type of technology and the plant efficiency. If conversion plants are operating at high efficiencies and achieving complete conversion of fuel to energy, then the emissions will be low or negligible. Combustion of coal gives similar values to biomass for methane but is far higher for nitrous oxide, sulphur dioxide and carbon dioxide emissions, at approximately 220gC/kWh of electricity generated compared with 5-10gC/kWh for biomass (Table 1).

Table 1. Typical life cycle emissions for a range of conversion technologies for electricity generation (g/kWh).

<table>
<thead>
<tr>
<th>Technology</th>
<th>C</th>
<th>SO₂</th>
<th>NOₓ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Woody biomass gasification</td>
<td>5-10</td>
<td>0.05-0.10</td>
<td>0.5-0.6</td>
</tr>
<tr>
<td>Coal – pulverised IGCC</td>
<td>190-220</td>
<td>11.00-12.00</td>
<td>4.0-4.5</td>
</tr>
<tr>
<td>Natural gas – CCGT</td>
<td>90-120</td>
<td>0</td>
<td>0.5-0.6</td>
</tr>
<tr>
<td>Onshore wind farms</td>
<td>10-15</td>
<td>0.05-0.10</td>
<td>0.01-0.03</td>
</tr>
<tr>
<td>De-centralised solar PV</td>
<td>150-170</td>
<td>1.6-1.9</td>
<td>0.5-0.6</td>
</tr>
</tbody>
</table>

The output values from a life cycle analysis will vary depending on the technologies used and plant location, and also allowing for differences in extraction, processing, regional distribution and generation. Where biomass is substituted for natural gas to be used for electricity generation, carbon emissions can also be reduced significantly. More efficient biomass conversion systems can further improve emission reductions.

Biomass has to compete not only with fossil fuels but with other renewable energy sources to gain a share of the electricity markets. In the longer term it must also compete with “clean” technologies for fossil fuels and physical carbon sequestration. These can all be compared in terms of $ investment per tonne of carbon emissions avoided. The IPCC Third Assessment
Report compared a range of electricity generating technologies on a global basis as summarised in Table 2. Details of the many complex assumptions used for this global assessment are not discussed here, but the point made is relatively simple. In terms of $/tC avoided, it may under certain circumstances be cheaper from a national long term perspective to replace an old coal-fired boiler with a bioenergy plant with virtually zero carbon emissions than with a cheaper combined cycle gas-fired plant having moderate carbon emissions.

Table 2. Cost ranges for greenhouse gas reduction technologies compared with a conventional coal-fired power plant, and the potential cost of carbon reduction.

<table>
<thead>
<tr>
<th>Power station type</th>
<th>Carbon emissions (gC/kWh)</th>
<th>Emission savings (gC/kWh)</th>
<th>Generating costs (USc/kWh)</th>
<th>$/t carbon avoided. (US$/t)</th>
<th>Reduction potential 2010 / 2020 (MtC/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulverized coal – as base case</td>
<td>229</td>
<td></td>
<td></td>
<td>4.9</td>
<td>49 / 140</td>
</tr>
<tr>
<td>IGCC – coal</td>
<td>190 – 198</td>
<td>31 – 40</td>
<td>3.6 – 6.0</td>
<td>-10 – 40</td>
<td>49 / 140</td>
</tr>
<tr>
<td>Pulverised coal + CO2 capture</td>
<td>40-50</td>
<td>179-189</td>
<td>7.4-10.6</td>
<td>136 – 165</td>
<td>10 / 100</td>
</tr>
<tr>
<td>CCGT - natural gas</td>
<td>103 – 122</td>
<td>107 – 126</td>
<td>4.9 – 6.9</td>
<td>0 – 156</td>
<td>38 / 240</td>
</tr>
<tr>
<td>CCGT gas + CO2 capture</td>
<td>14 – 18</td>
<td>211 – 215</td>
<td>6.4 – 8.4</td>
<td>71 – 165</td>
<td>Uncertain</td>
</tr>
<tr>
<td>Hydro</td>
<td>0</td>
<td>229</td>
<td>4.2 – 7.8</td>
<td>-31 – 127</td>
<td>26 / 92</td>
</tr>
<tr>
<td>Bioenergy IGCC–wood wastes</td>
<td>0</td>
<td>229</td>
<td>2.8 – 7.6&lt;sup&gt;a&lt;/sup&gt;</td>
<td>-92 – 117</td>
<td>14 / 90</td>
</tr>
<tr>
<td>Wind – good to medium sites</td>
<td>0</td>
<td>229</td>
<td>3.0 – 8.0</td>
<td>-82 – 135</td>
<td>63 / 173</td>
</tr>
<tr>
<td>Solar thermal and solar PV</td>
<td>0</td>
<td>229</td>
<td>8.7 – 40.0</td>
<td>175 – 1400</td>
<td>2.5 / 28</td>
</tr>
</tbody>
</table>

<sup>a</sup> Biomass fuels as delivered range from $0/GJ for on-site waste requiring disposal costs to $4/GJ for purpose grown energy crops.

Environmental and social benefits.

Past assessments of potential energy projects have been based mainly on the economic return on investment. The “triple bottom line” approach now being taken by many energy companies gives greater weighting to social and environmental issues as well as profit. Environmental benefits from using biomass, in addition to reducing GHG emissions, include reducing local emissions, using limited resources better, improving biodiversity and protecting the habitat and landscape by reducing the need for harvesting native forests (which growing short rotation forests can do well if planned and designed carefully). Reducing waste disposal into landfills and waterways, avoiding the noise, maintenance and inconvenience of diesel generating sets, and minimizing the need for power lines are other benefits that bioenergy can provide.

From the social perspective there can be little doubt that bioenergy projects protect existing employment, provide new jobs, give learning opportunities, transfer skills, introduce new skills, and provide training and educational opportunities. The trend towards independent power production using smaller scale plants and embedded generation should result in a decline in urban drift once rural communities are able to develop and grow using the new sources of bioenergy available to them. This in turn will produce a sense of pride and independence, of particular importance to many indigenous or aboriginal communities who are struggling to maintain their cultural identities (IEA, 2002). Local health benefits can also result, from having better wood stove designs for people living in rural areas of developing countries, to reducing particulates from vehicle emissions for those living in the centre of London, Tokyo or New York.
Barriers to implementation

The role that biomass will play in future consumer energy supplies depends on the many commercial opportunities which exist to overcome the barriers to progress and commercial investment. A significant barrier is the popular concern that some forms of biomass are non-sustainable. In some instances this view is correct. There are some sources of biomass that for a variety of reasons should never be used for energy purposes. The industry needs to clarify this issue since growing public concerns at biomass use include the following.

- Will an increasing number of wood-fired heat and power plants lead to an incentive for investors and shareholders to support the cutting down of existing native forests?
- Will stack emissions from municipal solid waste-to-energy plants, and also possibly from wood-fired biomass plants, contain toxic substances such as dioxins?
- Will planting large areas with fast growing trees for energy forests reduce both water run-off and percolation into the groundwater, thereby affecting downstream users?
- Will soil nutrient levels be depleted by continually removing large quantities of biomass material such as crop residues from the land?
- Will biodiversity be further threatened and agri-chemical use increased if ever greater areas of monoculture crops are grown?
- Will genetically engineered trees and crops be developed specifically for use for biomass energy supplies?
- Will transport of large quantities of biomass to a power plant result in increased traffic congestion, noise, dust, road damage etc?
- Will the use of land for energy cropping reduce the area available for food and fibre production so that scarcities will result?
- Will using waste for energy purposes reduce the desirable incentives to minimize and recycle waste materials if it is cheaper to burn them?
- Is biomass production truly sustainable as well as renewable?

Also to be considered in the debate must be any beneficial environmental impacts such as avoiding methane emissions from landfills; reducing odours from direct application of animal wastes to land rather than after anaerobic digestion; improving sewage treatment prior to discharge to waterways or oceans; obtaining dry salinity soil improvements; reducing the GHG emissions from fossil fuels; and planting of energy forests which encourage bird life and biodiversity.

Concerns by the public and environmental groups, often due to a lack of understanding, will continue to arise whenever a new bioenergy project is first proposed. This often leads to prolonged debate and a ruling by the environmental courts. Developing Good Practice Guidelines by a consensus process involving all potential stakeholders is the recommended approach that should be taken to avoid repeated conflicts.

Mitigation of environmental barriers from biomass use

- Health problems arising from open fires or from poorly designed bioenergy plants which produce high levels of particulate emissions can be overcome by proper installation of clean burning combustors that meet modern air emission standards.
• There is a lack of information available to potential bioenergy plant investors regarding environmental effects and many rely on their own limited knowledge rather than seek and pay for quality advice. In addition relatively few senior business managers possess good information about their own processing plant, its energy requirements and the emissions. So there is a need to publish information that will assist investors make appropriate equipment selection.
• Monocultural production of energy crops is deemed unacceptable by many environmental agencies and there could be public rejection due to changing landscape values and lack of biodiversity. An environmental impact assessment should address these issues. Planting a mix of species is sometimes worth considering, not only for landscape benefits but also for added resistance to the spread of pests and diseases and to provide a supply of fuel over a longer period.
• Continuous large scale production of forest plantations and energy crops could reduce soil fertility levels, impact on downstream water use, and lead to leaching of nutrients and increased use of agri-chemicals. Nutrient recycling through the return of the combustion ash and sustainable crop production methods should be practiced.
• The energy balance of biomass is not always favourable, especially for biofuels produced from annual energy crops (Pimental, 2001) than for wastes or woody biomass from perennial crops where the energy output is at least 10 – 20 times greater than the energy input. In addition the collection and transport of biomass often results in increased use of vehicles, higher exhaust air emissions and greater wear and tear on the roading infrastructure. Research to further reduce energy inputs and to maximise truck payloads is necessary.
• Land requirements for future energy crop and forest plantations will compete with land used for the traditional production of food and fibre products. The land area used will ultimately depend on biomass crop yields as achieved on a sustainable basis, water availability, and the conversion plant efficiency. For example, for a 20% efficiency, steam turbine plant fuelled by a forest energy crop yielding 15 oven dry tones (odt) /ha/y, 360ha of energy plantation would be needed per MW_e of installed capacity when running the plant for 6000 hours per year. If a 40% efficiency gasification plant was built instead and crop yields rose to 20odt/ha/y, then only 135ha would be needed per MW_e.
• There may be a future shortage of skilled workers for harvesting and collecting biomass. So although employment opportunities from greater bioenergy uptake are often quoted, finding willing workers for what can be somewhat arduous and repetitive work may not be easy in either developed or developing countries.

Future opportunities for bioenergy technologies

Small scale bioenergy power generation technologies are emerging to meet the growing distributed generation market. They include landfill gas engines, biodiesel fuelled stationary engines, micro-turbines, Stirling engines, fuel cells, and small modular bioenergy systems packaged as cogeneration (CHP) units. Since several of these are still at an early stage of development and many are commercially protected, in the literature a wide range of manufacturing costs and efficiencies is claimed (Fig. 3). Increased integration of bioenergy with other distributed energy resources could further enhance technology improvement in this sector but the overall environmental impacts from use of such small scale systems is not clear. For
example wood gasification in poorly designed down-draft plants can lead to the formation of carcinogenic condensates that would need careful disposal. This is rarely mentioned, but once the problem is solved, then small scale biomass will have good potential to become a significant fuel for distributed energy systems and a possible source of “green” hydrogen.

Figure 3. Installed cost estimates ($US/kW_e) and claimed conversion efficiency ranges of selected existing and emerging small scale bioenergy technologies.

Conclusions

Traditional biomass continues to provide a significant amount of global consumer energy but it is in scarce supply, is not produced sustainably and has adverse environmental impacts. To improve public health of rural communities and reduce atmospheric emissions, the use of firewood and dung for fuel should be replaced by the many new and improved modern biomass technologies reaching the market. In some cases these are successfully competing with fossil fuels even without government incentives.

The use of biomass for conversion to energy is constrained principally by cost. Fossil fuels remain the fuel of choice where available because useful energy can commonly be produced cheaper from a fossil fuel conversion facility than from one fuelled by biomass. In the future bioenergy facilities are likely to be most popular in the 5–100MWth range, though many heat supply projects will be below 5MWth. The global trend towards distributed electricity generation will provide further opportunities for bioenergy at the smaller scale, and provide future employment in rural areas in both developed and developing countries. In developed countries the use of biofuels for transport will continue to grow slowly, but only with government support as petroleum fuels will remain comparatively cheaper for some time. The opportunity for biofuels to provide hydrogen for fuel cells is a particularly exciting option.
Over the next decade as the carbon dioxide mitigation benefits of biomass become better understood by investors and international carbon emissions trading begins, there is likely to be a significant increase in the total installed capacity of biomass fuelled plants, including cogeneration facilities for heating and cooling. Increases in the cost of disposal of wastes and residues, driven by growing environmental concerns, will necessitate the need to find alternative options. Waste-to-energy projects not only avoid the cost of disposal but will provide useful and valuable outputs in the form of heat and electricity.

Within the wide range of commercial and developing bioenergy technologies are many that, after careful life cycle analysis, could be classified as environmentally sound. Others can create major environmental impacts. The difficulty in assessing the technologies is that projects are very fuel and site specific in this regard. Establishing a set of standard project guidelines for use by environmental consenting and project funding agencies to indicate the points to consider for each of a range of bioenergy technologies would be a useful approach. Undertaking detailed life cycle analyses following a standard method would then be easier to apply on a project by project basis.

References