CLIMATE CHANGE SOLUTIONS FROM BIOMASS, BIOENERGY AND BIOMATERIALS

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ABSTRACT

Bioenergy conversion technologies are well developed but mainly utilize feedstocks from solid and liquid organic waste streams which have limited supplies. The socio-economic potential for bioenergy is not always being fully realised in many countries and sector growth has been slower than anticipated. Energy cropping is becoming better understood but it must be ecologically sustainable, environmentally acceptable to the public, and the delivered costs ($/GJ) need to be lower than for fossil fuels. Production of biomaterials is also limited by the costs of the biomass feedstock which need to be reduced by higher crop yields, lower inputs, more sustainable production and improved transport methods. More efficient conversion plant designs, simplified resource consent procedures and feedstock supply security will reduce project investment risks and reduce reliance on government support mechanisms in the longer term. Carbon trading will provide additional revenue as will seeking higher value multi-products from the biomass resource. Future opportunities for biomass include development of bio-refineries, atmospheric carbon "scrubbing" and the growing trend towards small scale, distributed energy systems leading towards a hydrogen economy.

INTRODUCTION

The use of biomass to produce bioenergy in order to provide a wide range of energy services (heat, light, comfort, entertainment, information, mobility etc.), and to produce biomaterials as substitutes for those presently manufactured from petro-chemicals, is an integrating response to a number of global problems. These include equity, development, energy supply security, rural employment, and climate change mitigation. Biomass provides fuel flexibility to match a wide range of energy demands and is a renewable energy source that can be stored, which is an advantage over other forms of renewable energy. It has been identified by the European Union as a significant contributor to the 12% renewable energy target and to its ambitious goal of substituting 20% of road transport fuels with alternatives, including biofuels by 2020.

Currently solid biomass represents 45% of primary renewable energy in OECD countries[1]. Globally nearly 84 TWh of electricity was generated from biomass in 2000, half being in the USA, 11.3 TWh in Japan and 8.5 TWh in Finland. Growth has been around 2.5% per year. A further 565 PJ of heat (including cogeneration), 245 PJ of gaseous energy from biomass and 227 PJ of biofuels were also produced worldwide in 2000.

The term "biomass" relating to agriculture and as discussed in this paper includes:

- crop residues (e.g. cereal straw, rice husks and bagasse for cogeneration);
- animal wastes (e.g. anaerobic digestion to produce biogas or interesterification of tallow to give biodiesel);
- woodlot arisings (e.g. from agro-forestry and farm woodland silviculture and after log extraction and used mainly for heating); and
- energy crops (e.g. vegetable oil crops to produce biodiesel, or sugarcane, beet, maize and sweet sorghum for bioethanol, or miscanthus and short rotation coppice for heat and electricity generation).

Other non-agricultural sources of biomass such as municipal solid waste, landfill gas, large scale forest arisings, wood process residues and sewage gas are not considered here.

In developing countries, traditional biomass remains the main source of energy. Several countries particularly in Africa (e.g. Kenya) and Asia (e.g. Nepal) derive over 90% of their primary energy supply from traditional biomass. In India and China it provides 45% and 30% respectively. A report from the World Bank[2] concluded that energy policy makers in developing countries will need to be more concerned about the supply and use of biomass and should support methods for using it efficiently and sustainably. It is now better recognised that promising modern commercial biomass projects can provide opportunities for rural industries and rural employment[3]. The technical transfer of modern bioenergy technologies to developing countries will be encouraged by the Clean Development Mechanism, but it will remain a challenge to implement them successfully. Where this has occurred it has led to better and more efficient utilization of biomass that, in many instances, complements the use of traditional fuels. For example liquid fuels produced from corn husks in China by a small scale Fischer-Tropsch process is used for traditional cooking[4] but the electricity co-product can also be generated by passing unconverted syn-gas through a combined cycle gas turbine.

Wealthier countries such as Sweden, USA, Canada, Austria, and Finland better appreciate the benefits of biomass and are already using it widely to displace fossil fuels. Currently in the USA for example agricultural and forest product residues are utilized in hundreds of heat and power plants totalling almost 10 GW of installed capacity, the largest being the 54 MW_{th} McNeil generating station in Vermont[5] and in Sweden over 90PJ/yr of imported oil equivalent is displaced with biomass[6].

Calculations of the available biomass resource have been made in many regions. A range of mature conversion technologies exist which can be matched to the local resource characteristics including combustion for dry material, anaerobic digestion for wet material, and inter-esterification and fermentation of oils and sugars to produce liquid biofuels. Several less mature technologies are still being demonstrated but are considered to be close to full commercialisation (such as gasification). Others such as pyrolysis, enzymatic hydrolysis, bio-refining of chemicals, production of biomaterials and hydrogen production, show promise but are still at the pilot-plant stage of development.

Taking a proposed bioenergy project through the contractual and consenting processes that are needed to reach commercial reality can be a major challenge, even if based on a mature and well proven technology. Issues to be resolved include land availability, transporting large volumes of biomass, environmental impact consents, controlling emissions, producing energy crops sustainably, recycling nutrients, minimizing water demand, energy input/output ratios, employment opportunities, the growing public resistance towards monoculture cropping, and from using woody biomass (even if from managed plantation forests), perceived threats to indigenous forests, emissions and economic competition from cheap fossil fuels. When taking all of these into account and also attempting to obtain long term fuel supply contracts, then the *socio-economic potential*[7] for biomass becomes a lot lower than its technical potential which is based purely on simple resource analysis. This overview paper will discuss these issues and also identify some exciting future opportunities for biomass.

CARBON MITIGATION

Climate change is now generally accepted as a serious global problem and the world is waiting for the Kyoto Protocol to come into force as the first small step in solving it. The likelihood of Russia ratifying it to ensure this occurs seems, at the time of writing (mid May 2003), slightly greater than the possibility that it will not[8]. Once in force the Protocol will become a key driver for governments, local authorities, industries and communities to move towards a world with reduced dependence on fossil fuels. More sustainable methods of food and fibre production, including reducing the direct and indirect energy inputs, will also be an international goal.

Biomass will have an increasing role to play as a result of carbon trading activities. It may receive carbon offset credits from displacing fossil fuels; earn carbon sink credits from biological carbon sequestration; or enable physical sequestration of atmospheric carbon to occur by capturing carbon dioxide after biomass combustion and transporting it to permanent geological stores[9]. Overall bioenergy projects, if carefully planned and managed, can be carbon neutral, though there are circumstances where fossil fuel based energy inputs for growing, harvesting, transporting and processing large volumes of the biomass feedstock can exceed the bioenergy outputs obtained.

Biomass projects will be included in The Clean Development Mechanism (CDM) of the Kyoto Protocol. Special fast track procedures for small projects (<15MW) to keep the transaction costs low will help to encourage their uptake. In developing countries where traditional biomass (firewood and dung) continues to be the major energy source, cultural acceptance and understanding of modern biomass production and conversion technologies may be easier to achieve than for other renewable energy sources[10]. Developed countries must first increase their successful use of biomass domestically in order to demonstrate to governments of developing countries its reliability, environmental acceptance, social benefits and economic feasibility. The development of Joint Implementation bioenergy projects would certainly give them increased credibility when negotiating to build similar bioenergy plants in non-Annex 1 countries under the CDM.

THE BIOMASS RESOURCE

The annual global primary production of biomass is 220 billion oven dry tonnes (odt) or 4,500 EJ of solar energy captured each year. From this an annual bioenergy market of 270 EJ could be possible on a sustainable basis[3]. The challenge is to sustainably manage the resource, its conversion and the delivery of bioenergy to the market place in the form of modern and competitive energy services.

The agricultural biomass resource available arises from a wide range of sources. These can be classified into crop residues, animal wastes, woodland residues, food and fibre processing by-products and purpose grown energy crops. A large number of conversion routes to provide useful bioenergy products and services have been demonstrated (Fig. 1). Most have reached the commercial stage where under certain conditions their economic viability can compete with fossil fuel use (though often requiring government support mechanisms to do so).

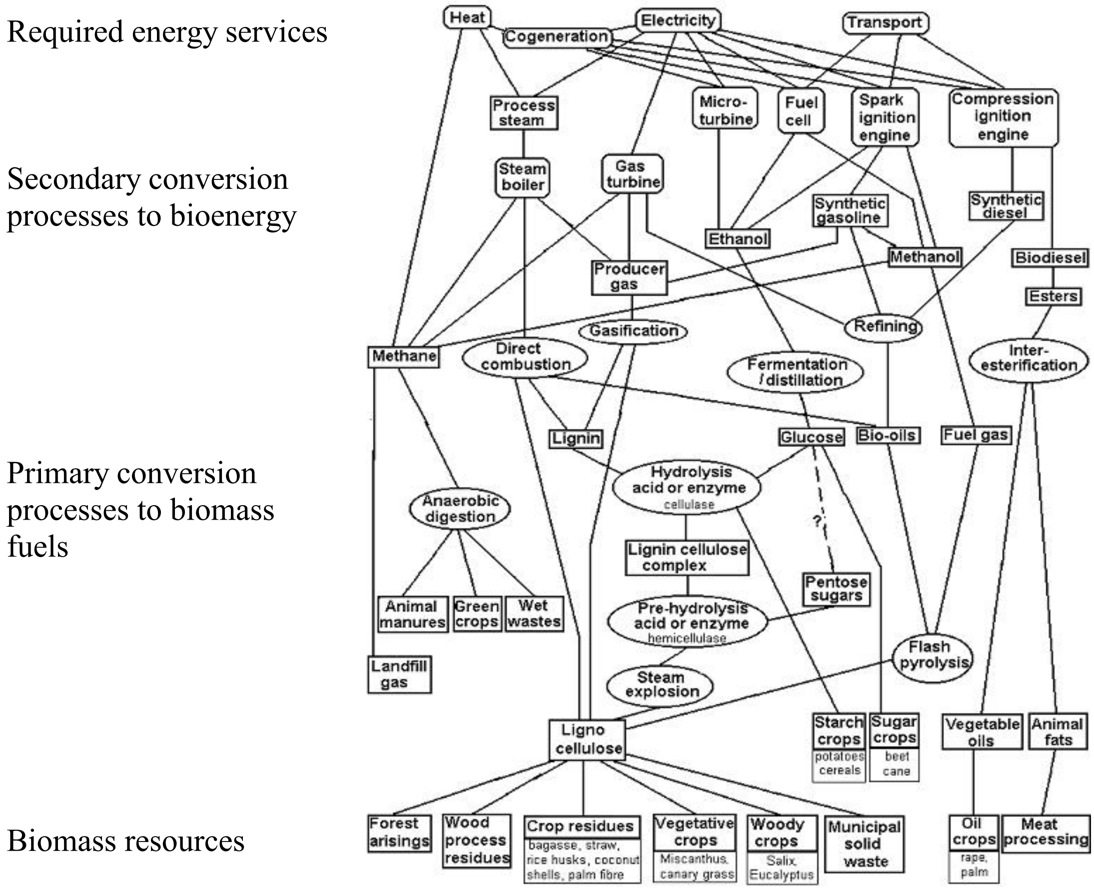
Biomass can also provide a renewable source of hydrogen and a wide range of bio-materials and chemical feedstocks[11]. In essence all products that currently result from the processing of petro-chemicals can, at least in theory, be produced from biomass feedstocks. These include lubricants, polymers, high matrix composites, textiles, biodegradable plastics, paints, adhesives, thickeners, stabilisers, and a range of cellulosics.

Agricultural residues and wastes

Wastes arising from agricultural production or farm woodlots often have a disposal cost. Therefore their conversion from waste-to-energy has good economic and market potential, particularly in rural community applications[3]. A significant portion of this waste resource is already utilised for energy purposes, but being the waste products of other processes, the supply is finite. It is also under possible threat from improved waste minimization practices. Energy crops can be grown to supplement this limited resource but they have higher delivered energy costs (in terms of $/GJ) compared with fossil fuels.

Large quantities of crop residues are produced annually worldwide and often dumped. These include rice husks, bagasse, maize cobs, coconut husks (copra), groundnut and other nut shells, sawdust, and cereal straw. Rice husks and bagasse are usually accumulated in large volumes at one site. These wastes tend to be relatively low in moisture content (10-30% wet basis - m.c.w.b.) and therefore are more suited to direct combustion than to anaerobic digestion which better suits wet wastes such as animal manures, meat cuttings or reject fruit.

Figure 1. Biomass resources and conversion routes available to produce bioenergy products and services[12]



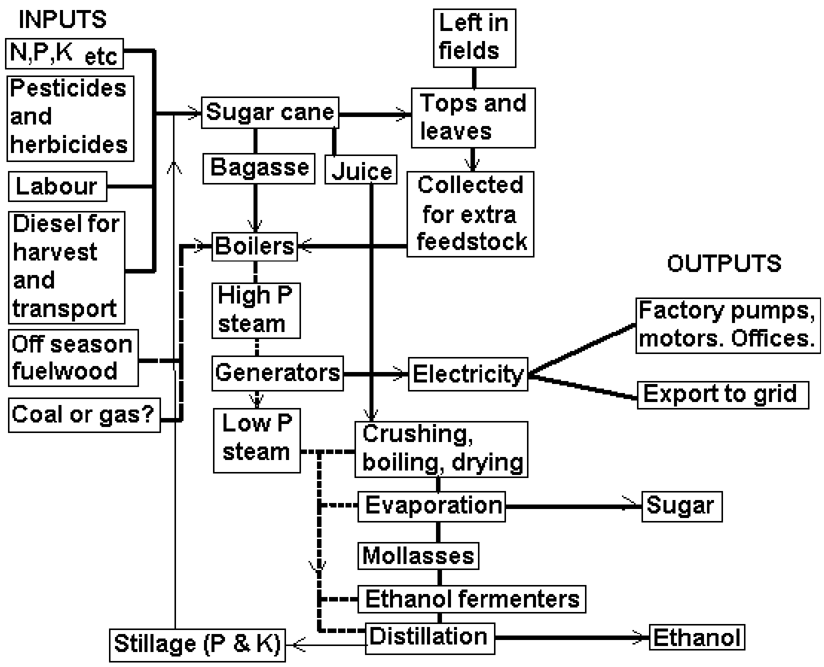
Rice husks are among the commonest agricultural residue. They make up 20-25% of the harvested rice grains on a weight basis and are usually separated out at the processing centre. Indonesia alone for example produces around 8Mt per year. The husks have a relatively high silica content that, on combustion, can cause an ash problem and possible slagging within the boiler. However their homogeneous nature lends this biomass resource to more efficient conversion technologies such as gasification that requires a uniform fuel quality for best results. Several commercial conversion plants exist.

Bagasse

Sugarcane is a C4 plant with a better photosynthetic efficiency than the more common C3 plants and it requires fewer inputs of pesticides and herbicides. Whether or not it is grown on a truly sustainable basis is debatable as nutrients need to be added to replace those removed with the crop. However if the stillage or effluent from the crushing and distillation process and the ash from the combustion of the bagasse (the residual fibre left after sugar extraction with an energy content of around 10MJ/kg) were to be returned to the fields, (particularly when the cane trash is also removed for biomass), then only nitrogen would be in deficit.

The flows of materials and energy in the sugarcane processing industry are worth highlighting with regard to potential bioenergy supplies as co-products (Fig. 2) in the form of heat, power or bioethanol production as in Brazil. Sugarcane factories from many decades have logistical experience of transporting and handling large bulky volumes of biomass, typically around 300,000 t/yr. Each fresh tonne of sugarcane brought into the factory for processing yields around 250kg of bagasse. Since there are such large volumes to dispose of, historically sugar companies have tended to "waste it efficiently" by burning it in large inefficient boilers but using only a portion of the available bioenergy to produce heat for raising steam to "cook" the cane and extract the sugar, and possibly to generate around 2-3MW of electricity for use on-site. This was a cheap form of disposal and avoided accumulation of surplus material. Any agricultural region that grows sugarcane therefore has a significant biomass energy resource available, already collected and delivered to the processing plant (in effect free-on-site).

Figure 2. Energy and material flows during the sugar cane production and processing operation[12].



Where privatisation of the electricity industry has occurred, some sugar companies have become independent power producers (often in joint ventures with their local utilities). They now combust all their bagasse in efficient cogeneration plants and export significant quantities of surplus power to the grid. Operational and contractual difficulties from generating power only during the 6 to 7 month cane crushing season were solved by using forest or municipal solid green wastes in the non-crushing season. The potential to develop a new business from generating 20 to 30MW_e all year round has been realised. Bagasse combustion, in association with collecting and using the cane trash, could provide biomass fuel for up to 50GW of generating capacity world wide.

The growing links between the electricity industry and the sugar industry will lead to different sugar cane management practices and the need for partnerships and third party investments in capital plant. A power generating company also has to consider the risk that the sugar industry is not always buoyant and a sugar company it partners with in a new cogeneration development may not survive for the whole term of the project.

Cereal straw

Small cereal crops produce around 2.5 – 5 t/ha of straw depending on crop type, variety and the growing season. Maize and sorghum stover is higher yielding. These residues range from 10-40% m.c.w.b and have a heating value between 10-16 MJ/kg. In terms of comparative gross energy values, 1 tonne of straw approximately equates to 0.5 tonne of coal or 0.3 tonne of oil. It has a high silica content leading to ash contents of up to 10% by weight.

The utilisation of straw for energy purposes has increased following a ban on burning in the fields after harvest. Denmark has thousands of straw burning facilities for district heating (3-5MW), industrial processing (1-2MW), and domestic heating (10-100kW) purposes. At the on-farm scale, it can be utilised for grain drying or heating animal houses as well as supplying dwellings with space and water heating.

If straw is assumed to have zero economic value and the costs of collection are around $30/t for raking, baling etc., then large round or square bales would be around $3/GJ. Cartage of 25 kms to a central conversion plant site would add another $4-6/GJ. Conversion of straw to electricity would therefore cost around 7-10c/kWh which is viable only in OECD countries where wholesale power prices are relatively high. Direct combustion of the straw for process heat in nearby applications (such as barley malting plants) may be more viable except where cheap coal or natural gas are available.

A range of straw pellets and wafers with a greater mass density than bales have been produced in an attempt to try and reduce transport costs and also enable automatic feeding to occur, particularly at the smaller domestic scale (10-30kW heat output). Many specialist pellet burners are on the market but the cost of the total system is relatively high. The pellets can be delivered in bulk by small truck to the dwelling or small business as required. Pellets are also made from sawdust as no comminution is required and they are easy to manufacture. A large number of pellet stove manufacturing businesses have been established mainly in Canada, Austria and Scandinavia and the pellets are being exported in growing volumes.

Animal wastes

Pig manure, cattle manure and chicken litter are useful biomass sources because these animals are often reared in confined areas which produces a considerable concentration of organic matter. In the past many of these animal wastes have been recovered and sold as fertiliser or simply spread back onto agricultural land. However the introduction of tighter environmental controls on odour and water pollution means that better forms of waste management are now required. This provides incentives to consider anaerobic digestion of the material, but the annual supply volume, seasonal variations and specific characteristics of the resource should be carefully assessed before developing a plant.

ENERGY CROPPING

Growing energy crops is a non-traditional land use option which may boost farm incomes and the rural economy in general[13]. A number of annual and perennial species convert solar energy into stored biomass relatively efficiently. High yielding vegetative grasses, short rotation forest crops, and C4 crop plants grown on a commercial scale can produce over 400GJ/ha/yr under good growing conditions, leading to positive input/output energy balances for the overall system. Correct species selection to meet specific soil and climatic site conditions can result in even higher energy yields[14]. To exemplify what can be achieved as a result of traditional species selection, the average saccharose yield of sugarcane grown in Brazil for bioethanol production increased by 10% to 143kg/t of fresh cane (70% moisture content, wet basis) between 1990 and 2001.

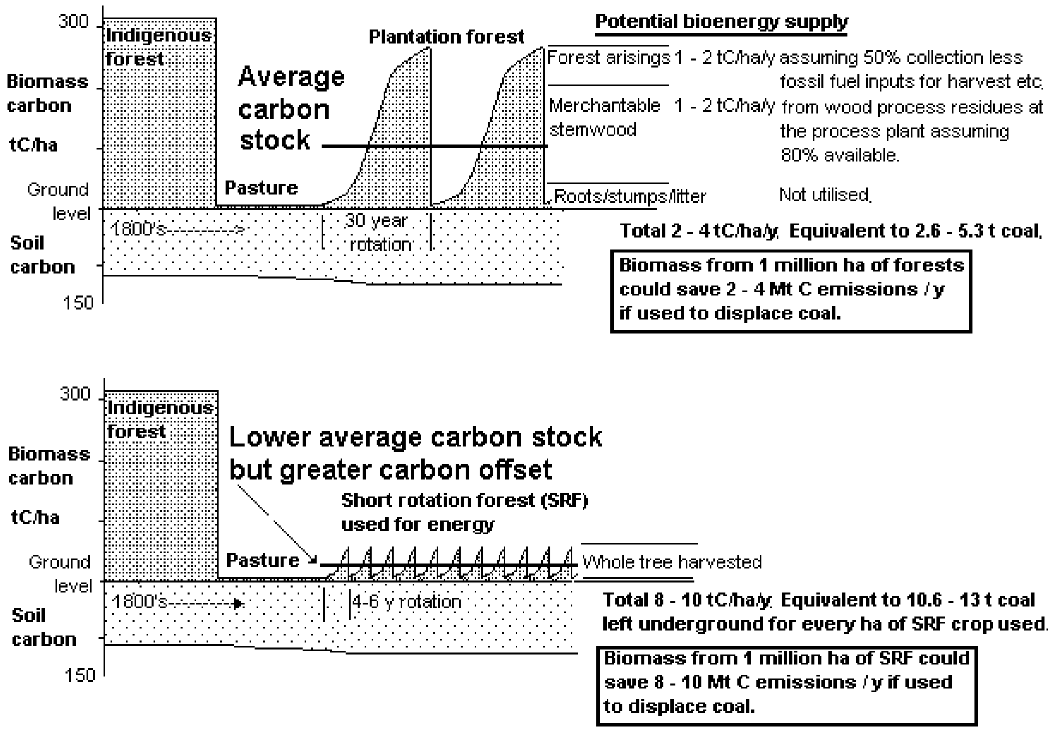
The future role for "Designer Biomass" by developing suitable genetically modified crops cannot be ignored. Certainly the possibility of genetically modified organisms entering the environment without full and proper evaluation are of considerable concern. However genetic modification does indeed hold great promise. Imagine having several attractive, high yielding, C4 plants which have nitrogen fixing ability, consume relatively little water, are easy to harvest and can be grown extensively to produce protein, carbohydrates, fibres and lignin which can all be processed through a "bio-refinery" into a range of industrial, edible and energy products. The issues of sustainable production, biodiversity and monocultures would still need to be carefully considered.

Agricultural grants and subsidies continue to be a major cost item of the EU budget under the Common Agricultural Policy and many energy crop producers have received considerable benefit as a result. Growers of oilseed rape for biodiesel in Europe and of maize and other cereals in the USA for ethanol depend upon continued government support as the crops are costly to grow and are prone to commodity price fluctuations. For example the costs of growing and producing biofuels in terms of $/GJ can be more than double the ex-refinery cost of petrol and diesel, even where the crop energy yield is high in terms of GJ/ha/yr. However trade reforms and continuing pressure to reduce subsidies which serve to encourage excess food and fibre production, means that in the future there can be no guarantees that agricultural support mechanisms will remain at their current levels. So bioenergy from energy crops may need to compete with fossil fuels on its own merits. Future carbon mitigation credits will help.

A high gross margin is necessary to attract growers to change from traditional land uses, but this increases the relative price of the biomass when delivered to the conversion plant. Conversely plant operators want feedstock delivered as cheaply as possible to compete with low priced fossil fuels. Recognising the carbon sink and carbon offset values from producing and using the energy crops may enable the goals of both growers and plant operators to be met.

All forms of bioenergy, when substituted for fossil fuels, will directly reduce CO_2 emissions. Therefore, a combination of energy crop production with carbon sink and offset credits can result in maximum benefits from carbon mitigation strategies. This can be achieved by planting energy crops such as short rotation eucalyptus, miscanthus or reed canary grass into previously arable or pasture land, which will lead to an increase in the average carbon stock on that land, while also yielding a source of biomass (Fig.3). Utilising the accumulated carbon in the biofuels for energy purposes, and hence recycling it, alleviates the critical issue of maintaining the biotic carbon stocks over time, as is the case for a permanent forest. Increased levels of soil carbon may also result from growing perennial energy crops but the data is uncertain and further research including detailed life cycle assessments is needed for specific crops grown in various regions.

Figure 3. Carbon stocks in the biomass and top soil on a 1 hectare plot of land with land use changes over time from indigenous forest to pasture, to plantation forest or short rotation forests.



Land availability

Large-scale production of energy crops in future must not compete for land needed for food and fibre production. There have been careful calculations made that there is enough sutiable land available to provide the world's population with all its needs for food, fibre and energy throughout this century[15]. (Equitable distribution of these basic necessities is another issue yet to be resolved). In some regions the availability of water will be the constraining factor to growing energy crops rather than available land.

The global land area thought to be available for biomass production by 2050 is shown in Table 1. Of the 2.495Gha of total land area with crop production potential, 0.897Gha was cultivated for food and fibre production in 1990. The increasing world population will require an additional 0.416Gha by 2050 leaving 1.28Gha available for growing energy crops. The technical potential of producing biomass from energy crops grown on this available land is 396 EJ/yr based on current yield data and known water supplies. By 2100, the global land requirement for food and fibre production is estimated to reach about 1.7Gha, with a further 0.69-1.35Gha needed to support future biomass energy requirements in order to meet a high-growth energy scenario. This exceeds the 2.495Gha total cropping land available so land-use conflicts could then arise.

Table 1. Projection of technical energy potential from energy crops grown by 2050.

Region	Population in 2050 billion	Total land with crop production potential Gha	Cultivated land in 1990 Gha	Additional cultivated land required in 2050 Gha	Available area for biomass production in 2050 Gha	Maximum additional amount of energy from biomass[a] EJ/year
Industrialised[b]	-	0.820	0.670	0.050	0.100	30
Latin America						
Central & Caribbean	0.286	0.087	0.037	0.015	0.035	11
South America	0.524	0.865	0.153	0.082	0.630	189
Africa						
Eastern	0.698	0.251	0.063	0.068	0.120	36
Middle	0.284	0.383	0.043	0.052	0.288	86
Northern	0.317	0.104	0.04	0.014	0.050	15
Southern	0.106	0.044	0.016	0.012	0.016	5
Western	0.639	0.196	0.090	0.096	0.010	3
China[c]	-	-	-	-	-	2
Western	0.387	0.042	0.037	0.010	-0.005	0
South – Central	2.521	0.200	0.205	0.021	-0.026	0
Eastern	1.722	0.175	0.131	0.008	0.036	11
South – East	0.812	0.148	0.082	0.038	0.028	8
Total for all regions	8.296	2.495	0.897	0.416	1.28	396
TOTAL BIOMASS ENERGY POTENTIAL, EJ/year						**441**[d]

Source: [7] derived from [16.17.18]

[a] Assumed 15 odt/ha/y and 20GJ/odt
[b] OECD and Economies in Transition
[c] For China, the numbers are projected values[17] and not maximum estimates.
[d] Includes 45 EJ/year of current traditional biomass.

BIOENERGY CONVERSION

Combustion is well proven from 1kW to 100MW but is relatively inefficient when linked with power generation from steam turbines. New conversion technologies show promise but there are no international industry standards or consumer tests for developers to select which specific plant to purchase. Decisions are often based solely on the hearsay of experienced operators of other similar plants even though there are usually local variations in the biomass feedstocks used which have to be taken into account when determining plant design, handling and storage facilities.

Gasification

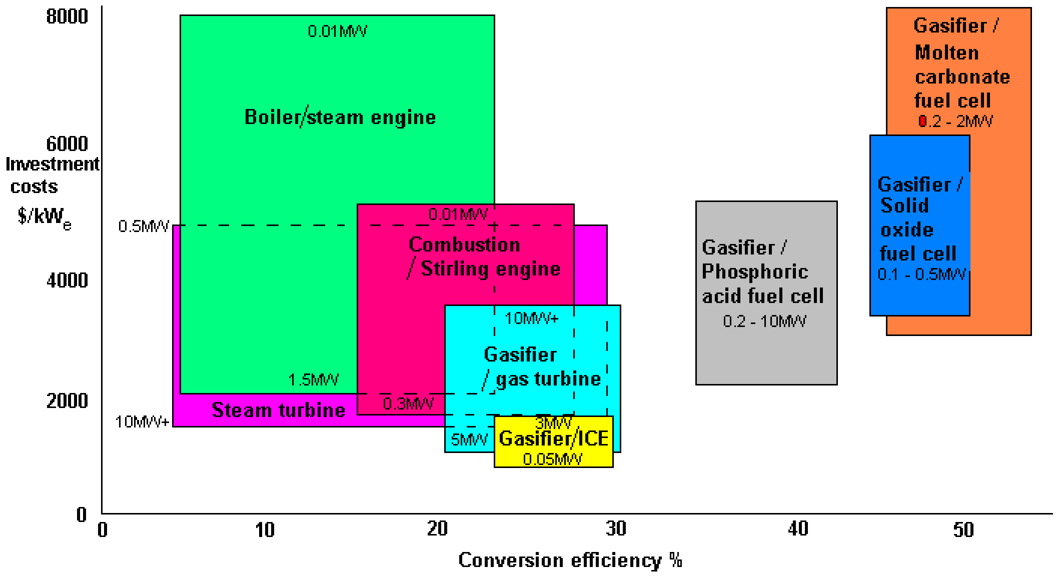
Development of efficient biomass integrated gasification combined cycle (BIGCC) plants using gas turbines are approaching commercial realization particularly for woody biomass and bagasse feedstocks. Several pilot and demonstration projects have been evaluated with varying degrees of success. BIGCC technology has good potential at the 10–75 MW_e range, with economies of scale and improvements in generation efficiency occurring at the top end[19]. However the low heat value gas usually requires modification of the turbines. Alternatively oxygen blown gasification systems produce a more suitable higher quality gas of 15-20 MJ/Nm^3.

Biomass resources are generally easier to gasify than coal at both the large and small scale and the process is well understood[20]. Development of 10 to 30MW_e efficient BIGCC systems is nearing commercial realization though gas cleaning problems still remain. Several pilot and demonstration projects have been evaluated with varying degrees of success[21,22,23,24]. Capital investment for a high pressure, direct gasification, combined-cycle power plant of this scale was anticipated to fall from the present $US2,000/kW to around $US1,100/kW by 2030 as a result of plant manufacturing and installation experience. Total operating costs (including supplying the biomass fuel), will also decline from 3.98c/kWh to 3.12c/kWh[25]. By way of comparison, capital costs for traditional combustion boiler/steam turbine technology were also predicted to fall from $US1,965/kW to $US1,100/kW in the same period with the operating costs of 5.50c/kWh lowering to 3.87c/kWh (reflecting the poor fuel efficiency compared with gasification).

A Swedish TPS atmospheric circulating fluidized bed gasifier using hot gas cleaning was successfully tested using a range of fuels including short rotation *Salix*. The English 10MW_e ARBRE project, supported by a 15 year NFFO (non fossil fuel obligation) contract, went into liquidation when nearing completion. The ALSTOM turbine was run successfully for short periods but the problems of gas clean-up, feed handling and the evaporator cooler had not been fully resolved[24]. These technologies were in the process of being upgraded by Kelda, the developer, when the plant was sold to Energy Power Resources Ltd (along with other projects) who decided to terminate the project. Capital costs of the plant were high at around $US2,700/kW but it was anticipated this would be halved with further project experience.

A review of combined heat and power technologies at the smaller 2-3 MW_e scale more suited for rural community use[20] confirmed the inefficiency of steam turbines compared with other technologies. Emerging small scale, distributed bioenergy power technologies have a wide range of claimed manufacturing costs and efficiencies as shown by the ranges given in Fig. 4. The typical range of investment costs for a single plant is shown for each technology. Using several modular devices in parallel enables a greater capacity to be achieved. Many of these technologies are at the prototype or demonstration stage but once demand increases and mass production occurs, then the investment costs could well decline.

Figure 4. Investment cost and conversion efficiency ranges based on manufacturers' claims for a selection of small (<10MW) capacity bioenergy conversion devices and hydrogen or methane-powered fuel cells suitable for on-farm or rural community use and compared with a gasifier/internal combustion engine (ICE)[1,20].



(Note: $/kWe are New Zealand dollars: NZ$1 = $US0.50 approximately)

Small scale biomass systems show good potential to become significant contributors to distributed energy systems and a possible source of "green" hydrogen for use in fuel cells. Increased integration of bioenergy with other distributed energy resources such as wind and solar could further enhance technology improvement in this sector but the environmental impacts from use of such small scale systems is not clear. For example gasification in poorly designed down-draft plants can lead to the formation of carcinogenic condensates that would need careful disposal.

Co-firing of biomass

Combustion of woody biomass is common when blended with pulverized coal at up to 10- 15% of the fuel mix based on total thermal input. Several studies however have shown co-firing to be uneconomic due to the very cheap coal price compared with growing, harvesting, storing, and delivering the biomass, plus the additional combustion plant feed conveyors and conversion costs[26]. However major environmental benefits can result including the reduction of SO_2 and NO_x emissions as was demonstrated when operating a small 350 kW_t bubbling fluidized bed plant[27]. In this study various blends of both anthracite and bituminous coals were mixed with hardwood chips and co-combusted. For all blends, emissions of CO, NO_x and SO_2 were reduced significantly, decreasing as the blend of wood fuel was increased by volume in steps from 10% to 100%.

Crop residues, woody biomass and vegetative grasses can also be used successfully when co-combusted with coal or natural gas in appropriately designed conversion plants[28]. Although co-firing is well understood the plant may require specialist feedstock and ash handling equipment and the ash may contain heavy metals from the coal and preclude its use in fertilisers. Where biomass fuel is free on-site and has a negative disposal cost, or environmental benefits are factored into the economic analysis, it is likely that co-firing will be viable, even with low fossil fuel prices. Under these conditions, in the US alone co-firing of biomass has the potential to generate 10-20GWh of electricity by 2015[25].

Anaerobic Digestion

There have been few if any significant technological developments in anaerobic digestion for either small scale plants suitable for on-farm use or at the larger scale requiring up to 500m^3 feedstock per day. Several of the large centralized biogas plants in Denmark have been closely monitored[29] and technical problems have not been uncommon. A gas production level of 30-35 m^3 per m^3 of feedstock is necessary for economic viability but it is not always achieved. Nevertheless over 25 plants continue to operate in Denmark.

India and China are both moving away from traditional small scale family biogas plants to the more efficient community and industrial scales, assisted by financial incentives, technology advances, their dissemination, and training of operating personnel[15].

Transport biofuels

Transport fuel production from biomass is technically feasible and liquid and gaseous biofuels can be derived from a range of biomass sources. For example biomethanol, bioethanol, di-methyl esters, pyrolytic oil, and biodiesel can all be produced from a variety of energy crops. Bioethanol production using sugarcane fermentation techniques has been commercially undertaken in Brazil since the 1980s[30]. Production from maize and other cereals has occurred in several US states for over a decade. Ethanol can be used as a straight fuel, as an oxygenate, or blended with petrol at up to 26% by volume as in Brazil. In the USA anhydrous bioethanol is used as a 10% blend to reduce ozone emissions and replace the octane enhancer MTBE (methyl tertiary butyl ether) which has possible carcinogenic properties. ETBE (ethyl tertiary butyl ether) production from bioethanol has a promising market in Europe but the production costs for hydrolysing cereals or sweet sorghum crops followed by fermentation of the sugars remain high. The process of enzymatic hydrolysis of ligno-cellulosic feedstocks such as bagasse, rice husks, municipal green waste, wood and straw[25] has been evaluated in a 1t/day pilot plant at the National Renewable Energy

Laboratory, Golden, Colorado. The project successfully reached the commercial scale-up phase[31] and several companies such as the Canadian IOGEN Corporation, supported by Shell, have since made substantial investments. A wide range of bacteria and fungi actinomytes and their genetic manipulation are also being investigated but all have found only limited commercial success to date[32].

The cost of producing biofuels from crops usually far exceeds the current price of diesel or petrol due mainly to the high cost of growing the crops, even if grown on set-aside land. In Brazil the production of dedicated ethanol fuelled cars running on 95% ethanol / 5% water produced from sugarcane fermentation achieved 96% market share in 1985 but declined to 3.1% in 1995 and to 0.1% in 1998. Meanwhile the Brazilian government approved a 26% blend level in petrol and hence the production of bioethanol continued to increase, achieving a peak of 15,300m^3 in the 1997/98 sugarcane harvesting season. This represented 42.73% of the total fuel consumption in all Brazilian Otto cycle engines giving an annual net carbon emission abatement of 11% of the national total from the use of fossil fuels[7].

Research into producing biomethanol from woody biomass continues and several different processes have been evaluated[33]. Successful conversion of around 50% of the original chemical energy stored in the biomass to methanol has been obtained in the USA at a cost estimate of around $US0.90 per litre of methanol ($US34/GJ)[34]. In Sweden production of methanol from either short rotation *Salix* or forest residues was estimated to cost only $0.22/litre whereas bioethanol would cost $0.54/litre[35]. At these costs, using woody biomass feedstocks for heat and power generation would be a preferable alternative[36]. In addition since the volumetric energy density (MJ/l) of biomethanol is around 50% that of petrol, and bioethanol around 65%, then larger storage tanks would be needed to give the same vehicle range between refills. By comparison biodiesel has an energy content around 90% of standard mineral diesel.

Commercial biodiesel processing plants have been constructed in France, Germany, Italy, Austria, Slovakia and USA[37] and many small scale plants also exist[38]. Around 1.5 million tonnes is produced each year with the largest plant having a capacity of 120,000t/yr. A compression ignition engine needs no modification to run efficiently on biodiesel either as a neat fuel or blended with mineral diesel. National biodiesel fuel standards are in place in Germany and many engine manufacturers such as Volkswagen now maintain existing warranties when biodiesel is used[39,40]. Environmental benefits from running biodiesel rather than mineral diesel in the same engine include a 99% reduction of sulphur oxide emissions, a reduction in greenhouse gas emissions of at least 3.2kg of CO_2 per kilogram of biodiesel, a 39% reduction in particulate matter and a high level of biodegradability[41].

A positive energy ratio was claimed in that each energy unit from the fossil fuel inputs to produce the biodiesel from an oilseed rape crop gave 3.2 biodiesel energy units[41]. Conversely other older studies suggest more energy is consumed during the process than is produced[42]. The differences in the two analyses between the oilseed crop grown, the oil yield obtained, and the assumed method of production and processing are the reasons for this discrepancy so further life-cycle analyses are required.

Due to the low oil yields and relatively high production costs, biodiesel has only been commercially implemented in countries and states where significant government incentives exist. Biodiesel production from purpose grown oilseed crops exceeds the ex-refinery costs of mineral diesel by a factor of three or four. This is mainly due to the high costs of crop production, even when grown in the USA or Europe on set-aside land receiving additional farm subsidies[43]. Production is unlikely to become more cost effective for several years[44]. However modified pressurized continuous production facilities such as that at Zistersdorf, Vienna[45], which processes 40,000t/yr, could help drive the production costs down. The use as feedstock of inedible tallow, a by-product from the meat industry, would be a cheaper proposition[46].

Increasing the oil yield per hectare would also bring down the costs. Energy yields from oilseed crops grown under temperate climatic conditions tend to be only around 1500-2000 litres of oil per hectare so production costs per litre are relatively high. These energy yields of around 60 to 80 GJ/ha/yr are low compared with growing short rotation forests or starch/sugar crops on the same land which can produce 300 to 400 GJ/ha/yr. This, together with the poor energy ratios of some systems, led the US National Research Council to advise against any further research investment[47].

Most transport biofuels, other than perhaps those produced from waste by-products from other processes, will likely become competitive with cheap mineral oil products if significant government support is provided by way of fuel tax exemptions or subsidies (such as when using set-aside land to grow energy crops), or if additional values are placed on the resulting environmental benefits. New biomass developments such as growing specialist energy crops, producing transport biofuels and designing small scale distributed generation systems will often require some form of government mechanism or subsidy to incentivise the implementation of such innovative projects. The expectation is that they will become fully commercial over time as they follow down the standard experience curve. This will also be the case should biomass be used as a renewable source of hydrogen in the future[48,49].

BIOMASS PROJECT CONTRACTS

A bioenergy project developer will need to secure a fuel supply over a term of 10-20 years if the project investment risk is to be reduced. For plants depending on energy crops as feedstocks this will often be challenging as landowners are not used to fulfilling such long term contracts. The British Project ARBRE successfully achieved contracting over 2000ha of coppice willow for 15 years but it needed considerable effort to convince the growers. (After the liquidation of the project in July 2002, the farmers have since formed their own company, "Renewable Energy Growers" to supply the new US plant owners, Biodevelopment International). Securing crop or process residues over this long period may also be a challenge since crop rotations and processes change over time which may affect the total annual residual biomass volume available. In addition other competing markets for the biomass material may eventuate (for example biomaterials, composting mulch, building panels) so that the existing "waste" product then has a higher value.

Developing a bioenergy project often proves more difficult to achieve than when developing a new wind farm or small hydro scheme of similar capacity. For example a cogeneration plant recently constructed at a sugar mill in New South Wales, Australia, using bagasse in the 7 month cane crushing season and municipal green waste in the 5 month off season required four fuel supply contracts and several other contracts and agreements to be negotiated[50]. These included a power purchase agreement, electrical connection provision contract, steam sales contract, water supply contracts, five joint venture agreements with plant manufacturers, financing information memoranda, finance agreements, site leases, site subdivisions, fuel supply and transmission easements, grid connection agreements, development consent licence, operating licence, asset management agreement, and an operation and maintenance agreement. It may be easier to obtain project closure more easily in less regulated countries but the time and effort required should not be under-estimated.

Resource Consenting Process

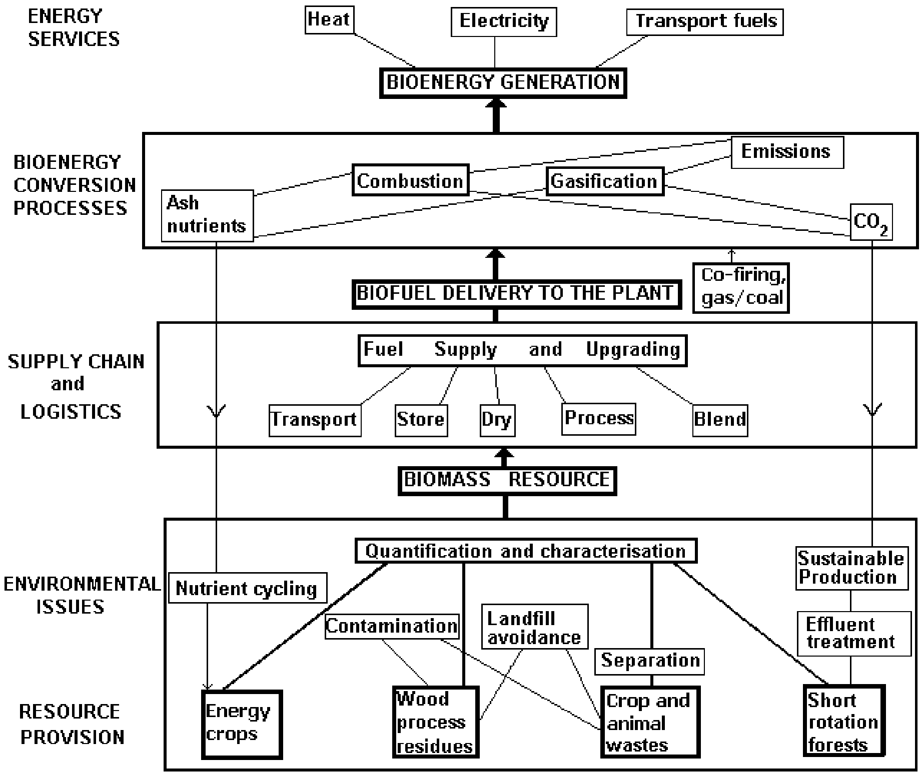
The time and costs involved in obtaining resource consents to operate and supply a bioenergy
plant can be very expensive for a developer since often the objections are numerous and the process is lengthy. To reduce this cost and to enable the biomass industry to expand responsibly in the UK, British Biogen (the industry association) jointly developed a series of planning "Good Practice Guidelines" based on a consensus procedure with all stakeholders. Three were produced (short rotation crops[51], anaerobic digestion[52] and forest wood products[53]) by what proved to be a very successful approach. It included planners, developers, equipment manufacturers, researchers and environmental groups working together over a 4 to 6 month period. Initially they all met for a one day meeting to outline the issues; a sub-group was formed to prepare a draft assisted by a facilitator; the draft was circulated several times for comment and amendment; and a final meeting held at which consensus was reached on all issues. The documents are now a useful tool for developers to use to shorten the consents process as many of the concerns expressed by individual local authorities will have already been agreed by all stakeholders.

Specific reoccurring issues such as emissions resulting from biomass combustion (especially dioxins from municipal solid waste) need further research studies to determine the extent of the problem and enable comparisons to be made with other sources. Atmospheric emissions are also a source of debate for transport biofuels and further analysis is also required.

TRANSPORTING THE BIOMASS

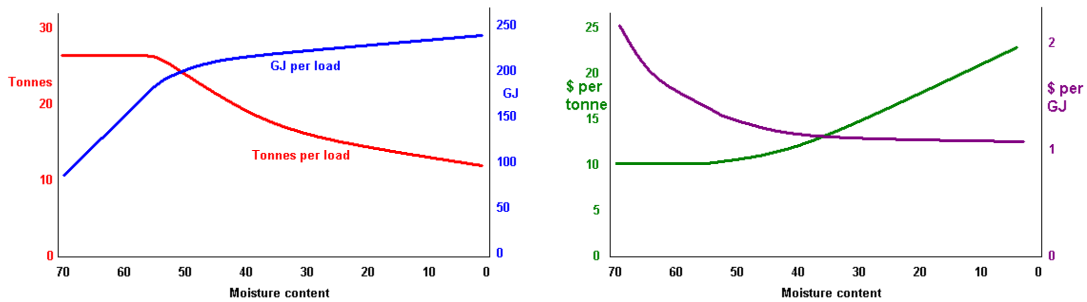
A key part of a biomass system involves delivering the material to the energy conversion plant or biomaterial processing plant as cheaply as possible. The supply chain link between biomass resource and bioenergy plant is shown in Figure 5. The interactions between biomass moisture content, dry matter loss, bulk density, delivered energy content, drying rate, storage location and period, distance between resource and plant, and truck payload constraints are complex but need to be evaluated in order to deliver the material cheaply and efficiently.

Figure 5. The biomass *system* includes delivering the biomass resource to the conversion plant gate.



The importance of this interaction is illustrated by a 40 m^3 capacity high sided, truck and trailer unit but with a 26 tonne maximum payload. When used for carrying biomass at high moisture contents between 50 to 70% m.c.w.b. (Fig. 6a) the load is weight constrained whereas below around 50% m.c.w.b it becomes volume constrained and the energy carried per load remains between 200 to 250 GJ. Based on a cartage distance of 35kms and a charge of $0.60/t/km, the cost per tonne delivered increases as the load lightens due to the lower moisture content (Fig 6b) but the more important $/GJ delivered cost is reduced. It stabilises when the load is below around 50% m.c.w.b.

Figure 6. Example of the delivered energy content of a truck load of biomass being carted a distance of 35kms at various moisture contents[54].

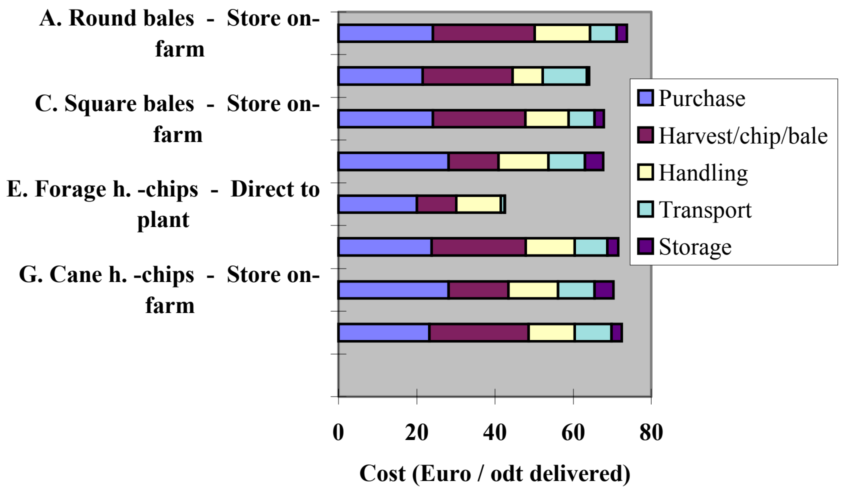


(a) (b)

(Note: $ are New Zealand dollars: NZ$1 = $US0.50 approx.)

Detailed modelling studies of biomass transport options have been carried out for a range of harvesting and processing systems[55,1]. Each study has shown there to be a wide range of delivered costs resulting from selecting different supply chain systems to harvest, collect and deliver the biomass material. For example short rotation coppice *Salix* based on British conditions, was compared using several harvesting options (Fig. 7). Delivered costs varied between $45 to $75/odt. Purchase price for the biomass was taken to be $20/odt, the slight variations shown resulting from the model calculating the need to purchase a greater quantity to overcome any dry matter losses during transport and storage in order to end up with the same total energy being delivered to the plant gate.

Figure 7. Comparative costs of short rotation coppice *Salix* delivered an average of 40.5kms to the power plant[55].



SUSTAINABLE PRODUCTION

A major challenge when using biomass is for it to be produced and used in a sustainable manner in order to provide an acceptable future supply of bioenergy and biomaterials with minimal inputs of water, agri-chemicals, fertilisers or fossil fuel energy. With careful design of the overall system this might be achieved by recycling nutrients through the ash, optimising (rather than maximising) crop yields per hectare, linking effluent treatment with energy crop production, growing mixed species tree crops, and returning to the traditional crop rotations including use of leguminous species. Increasing public concerns cannot be ignored regarding monoculture crops nor can scientific evidence that some biomass crops such as short rotation *Eucalyptus* consume an excessive amount of fertiliser and water (over 35 litres per day uptake for only a 2 year old tree on a sunny day[56].

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. Life cycle analyses to determine the environmental impacts of modern biomass have shown that the overall system can be relatively benign in terms of greenhouse gases. 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.

Genetically modified energy crops are under investigation and may well become an acceptable means of capturing and storing solar energy in future decades. Their impact on the environment and "sustainable" production is complex and requires careful evaluation before widespread energy crop production begins.

The international collaborative IEA Bioenergy Agreement aims to realize the use of environmentally sound and cost competitive bioenergy on a sustainable basis[57]. The program has moved towards commercialization of bioenergy systems and with particular emphasis on greenhouse gas balances. Biomass use is not a panacea for the huge problems of climate change, development and equity. However it certainly will have a key role to play throughout this century to help mitigate these problems.

Analysing the socio-economic impacts of biomass produced from agriculture is a major, but often under-estimated component when aiming to implement more bioenergy projects[58]. The question needs to be addressed as to whether people really want biomass and bioenergy or are scientists and developers just assuming they do? The social benefits from the use of biomass include improved health from reduced air pollution, employment opportunities, social cohesion in rural communities and greater security of energy supply.

COMPARATIVE COSTS OF BIOENERGY

The economic benefits of utilising biomass feedstocks are often viable where a waste product is produced and utilised on site (as in a bagasse cogeneration plant or an on-farm biogas plant). The alternative cost of disposal is therefore avoided. In such commercially viable projects, there can be win/win opportunities in terms of saving energy costs and avoiding greenhouse gas emission reductions. These result in a good comparative return on investment in terms of "$/t of carbon equivalent avoided". For example when comparing alternative power generation options with constructing a new pulverised coal power station (Table 2), the opportunity for BIGCC plants to produce power at competitive prices and also reduce carbon emissions compared with coal becomes apparent.

Where high costs for collection, transport and processing are involved, (as when using straw or plantation woodlot arisings such as thinnings, prunings and branches), it is difficult to compete with cheap fossil fuels. Improved economic viability for bioenergy and biomaterial production will result from carbon charges already being imposed globally on fossil fuel use.

Table 2. Cost ranges for greenhouse gas reduction technologies compared with a conventional coal-fired power plant, and the potential for carbon reduction[7,59]

Power station type	Carbon emissions (gC/kWh)	Emission savings (gC/kWh)	Generating costs (cents/kWh)	$/t carbon avoided. ($/t)	Reduction potential to 2010 - 2020 (MtC/yr)
Pulverised coal – as base case	229		4.9		
IGCC[a] – coal	190 - 198	31 - 40	3.6 - 6.0	-10 - 40	49 - 140
Pulverised coal + CO_2 capture	40 – 50	179 - 189	7.4 - 10.6	136 - 165	10 - 100
CCGT[b] - natural gas	103 - 122	107 - 126	4.9 - 6.9	0 - 156	38 - 240
CCGT gas + CO_2 capture	14 – 18	211 - 215	6.4 - 8.4	71 - 165	Uncertain
Hydro	0	229	4.2 - 7.8	-31 - 127	26 - 92
Solar thermal and solar PV	0	229	8.7 - 40.0	175 - 1400	2.5 - 28
Wind – good to medium sites	0	229	3.0 - 8.0	-82 - 135	63 - 173
Bioenergy IGCC–wood wastes	0	229	2.8 - 7.6[c]	-92 - 117	14 - 90

[a] Integrated gasification combined cycle
[b] Combined cycle gas turbine
[c] Biomass fuels as delivered range from $0/GJ for on-site waste requiring disposal costs to $4/GJ for purpose grown energy crops.

In addition a range of fiscal and non-fiscal government policy support mechanisms exist including renewable energy certificates and feed-in tariffs for electricity and heat; excise tax reduction for transport fuels; and research support for say the integrated production of multi-products from one resource through a bio-refinery process.

In OECD countries where agricultural and energy subsidies are minimal or do not exist, biomass produced from purpose grown crops (rather than from waste organic products) competes better with coal and natural gas in the heat market rather than with traditional forms of generation in the electricity market. In the transport fuel market there is a considerable gap between the ex-refinery price for diesel and petrol and the cost of producing biodiesel and bioethanol (though this gap is closed somewhat when biodiesel is produced from the tallow by-product of the meat industry and bioethanol from the whey by-product of the dairy industry). In order to stimulate the modern biomass industry when in its infancy, government financial incentives have often been required. This is partly because the environmental externalities from competing fossil fuel use have not been accounted for in comparative economic analyses. Rather than offer grants and subsidies over the longer term, the value of carbon mitigation and waste disposal avoidance should be included when comparing energy supply options. As a result more potential bioenergy and biomaterial production projects would become viable without depending on government support mechanisms that can change over time. This approach could result in a more secure investment.

FUTURE OPPORTUNITIES FOR BIOMASS

Biomass and biofuels were identified by a US Department of Energy inter-laboratory study as critical technologies for minimizing the costs of reducing carbon emissions. Co-firing in coal-fired boilers, biomass fuelled integrated gasification combined-cycle units for the forest industry, and ethanol from the hydrolysis of ligno-cellulosics, were the three areas specifically recognized as having most potential. Estimates of annual carbon offsets in the US alone for each technology ranged between 16-24 Mt, 4-8 Mt, and 12.6-16.8 Mt respectively by the year 2010. The near term energy savings from the implementation of each of these technologies should cover the associated costs[60] with co-firing giving the highest return and lowest technical risk. They have each been discussed above.

Bio-refining

The concept of using different fractions of the whole crop for food, stock feed, industrial and chemical feedstocks and energy is under development and a wide range of products and materials could be produced[61]. For example a closed loop pilot plant was constructed in New Zealand to fractionate biomass into a number of components[62]. After washing and pre-heating, the hemicellulose was hydrolysed to produce chemicals such as furfural, and the lignin and cellulose dried and prepared for hardboards, activated carbon, animal feed or bioenergy feedstock. The concept was based on the entrained flow drying of biomass particles suspended in superheated steam passing through several distinct sets of pressure and temperature conditions. Unfortunately the pilot plant was closed down in 1999 due to lack of further funding but it had successfully demonstrated the technical potential for jointly producing biomaterials and bioenergy.

Multi-product benefits

Where feasible it makes sense that a biomass resource be "value-added" by producing a range of products and benefits and not just bioenergy which tends to have a lower value. For example the "Integrated Oil Mallee" project in Western Australia, with the state utility company Western Power as a major joint venture partner, is based on more than heat and power generation. The biomass resource will come from growing short rotation eucalyptus mallee crops in 4-5m wide strips to help solve the growing dryland salinity problem on cropping lands that are rapidly becoming infertile by driving the water table (and hence the salt) back down. A carbon credit from the forest sink benefit may also be claimed in future (once Australia ratifies the Kyoto Protocol). Harvesting the trees on a 3 to 4 year cycle will provide feedstock for a pilot plant currently under development and designed to obtain revenue from extracting fine oils for pharmaceutical purposes, producing activated carbon for use in air filters, generating heat and power for export, and consequently earning tradeable renewable energy certificates for the "green" power produced. It is anticipated other larger scale plants will follow since the dryland salinity problem resulting from tree removal by early settlers extends over millions of hectares of arable land and across several states.

A less ambitious multi-product example perhaps is the growing of oilseed crops to provide a biodiesel feedstock, a high protein animal feed after oil extraction, and using the straw to provide heat and power to drive the process and then export any electricity surpluses off-site.

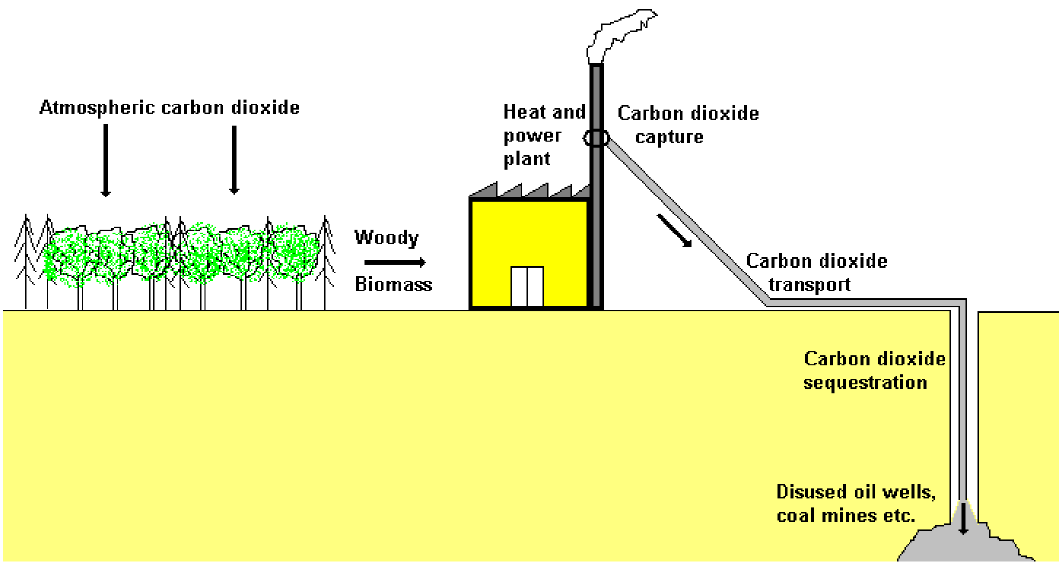
Carbon sequestration

Growing energy crops may be linked with an atmospheric carbon "scrubbing" process The trees or crops in effect act as carbon pumps by absorbing atmospheric carbon dioxide as they grow then releasing it during combustion when it is captured, transported and permanently sequestered underground or in deep saline aquifers (Fig 8), based on a similar process being advocated for fossil fuels[7]. Atmospheric concentrations are therefore reduced over time. The concept hinges on the development of reliable and cheap methods of physical geological carbon storage which is being intensively researched as a means of utilizing "clean coal". However confidence in the developing technology remains low at this stage.

Hydrogen and distributed energy

In the longer term, the key to sustainability, equity and development, (which are inextricably linked with climate change mitigation[7]), will be the development of new and affordable small scale "distributed generation" conversion technologies such as fuel cells, Stirling engines, and micro-turbines as well as internal combustion engines running on landfill gas or biodiesel. If fuelled by these or other biofuels such as

Figure 8. Carbon dioxide removal from the atmosphere through the production and use of woody biomass in an energy or hydrogen plant followed by physical sequestration.



hydrogen, methane and methanol[63], then a move towards a decarbonised world based partly on the greater use of biomass will be enhanced.

The move towards the hydrogen economy, from which many countries stand to benefit in the longer term, partly depends on being able to produce the hydrogen using renewable and sustainable resources. This could be from coal or natural gas, but only if the resulting carbon can be captured, transported and physically sequestered underground or in deep saline aquifers. Since the cost for this exercise may be high and the concept is not yet proven, it is perhaps more likely that in the longer term hydrogen will come from sustainably produced biomass or from renewable energy powered electrolysis of water[48].

CONCLUSIONS

The biomass resource is abundant based on organic waste products and a wide range of energy crops. Many conversion technologies exist and are largely well understood. Currently preventing the bioenergy sector from reaching its full potential and therefore providing additional revenue for the agricultural community are the high biomass production costs; the difficulties in securing adequate fuel supplies at an early stage of project development; and the stringent planning constraints, partly from a lack of understanding by some of the stakeholders. Developing a bioenergy project is therefore usually a challenge. The future prospects for carbon trading, distributed energy systems and hydrogen, multi-product benefits from bio-refining of the biomass feedstock, and the Clean Development Mechanism should enable the sector to develop as originally envisaged by policy makers. For this to happen, the biomass industry will have to improve its image, ensure it is using only sustainably produced material, and become more efficient in biomass delivery and bioenergy conversion operations and less reliant on government incentives.

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