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Review paper

Energy production from biomass (part 2): conversion technologies

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Abstract

The use of biomass to provide energy has been fundamental to the development of civilisation. In recent times pressures on the global environment have led to calls for an increased use of renewable energy sources, in lieu of fossil fuels. Biomass is one potential source of renewable energy and the conversion of plant material into a suitable form of energy, usually electricity or as a fuel for an internal combustion engine, can be achieved using a number of different routes, each with specific pros and cons. A brief review of the main conversion processes is presented, with specific regard to the production of a fuel suitable for spark ignition gas engines. © 2002 Elsevier Science Ltd. All rights reserved.

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1. Introduction

The conversion of biomass to energy (also called bio-energy) encompasses a wide range of different types and sources of biomass, conversion options, end-use applications and infrastructure requirements. Biomass can be derived from the cultivation of dedicated energy crops, such as short rotation coppice (SRC), perennial grasses, etc.; by harvesting forestry and other plant residues (forest thinnings, straw, etc.); and from biomass wastes such as sludge from organic industrial waste and organic domestic waste or the wastes themselves. In each case the biomass feedstock has to be harvested/collected, transported and possibly stored, before being processed into a form suitable for the chosen energy conversion technology.

The use of biomass to produce energy is only one form of renewable energy that can be utilised to reduce the impact of energy production and use on the global environment. As with any energy resource there are limitations on the use and applicability of biomass and it must compete not only with fossil fuels but with other renewable energy sources such as wind, solar and wave power.

In a previous paper (McKendry, 2001) an overview of the sources and main types of biomass and typical plant characteristics was presented. In this paper, a brief review of the potential bio-energy conversion processes is outlined, with emphasis on producing a gaseous fuel for spark ignition gas engines (s.i.g.es). The purpose of the gaseous fuel is to supplement (diminishing) supplies of landfill gas, the methane-rich gas produced by the anaerobic degradation of organic wastes in a waste disposal (or landfill) site. Landfill gas is widely used in power generation schemes to produce electricity for export to the generating companies.

Electricity produced from landfill gas is classified as a renewable energy source and as such attracts a premium sale value per unit, i.e. per kW $h_{(e)}$. The typical power generation scheme uses s.i.g.es coupled to a generator, with the engine-generator combination packaged in a container. The use of landfill gas to produce electricity allows the opportunity to use the restored landfill surface to produce biomass for processing into a fuel for s.i.g.es, thereby helping to promote waste disposal by landfill as a sustainable form of waste management.

2. Bio-energy conversion: process options

Biomass can be converted into useful forms of energy using a number of different processes. Factors that influence the choice of conversion process are: the type and quantity of biomass feedstock; the desired form of the energy, i.e. end-use requirements; environmental standards; economic conditions; and project specific factors. In many situations it is the form in which the energy is required that determines the process route,

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followed by the available types and quantities of biomass.

Biomass can be converted into three main products: two related to energy – power/heat generation and transportation fuels – and one as a chemical feedstock. Amongst the options for energy conversion that form the basis of this study, only those that produce a fuel suitable for use in an s.i.g.e. are the main focus of this study. However, a brief overview of energy conversion options is presented by way of general background information.

Conversion of biomass to energy is undertaken using two main process technologies: thermo-chemical and bio-chemical/biological. Mechanical extraction (with esterification) is the third technology for producing energy from biomass, e.g. rapeseed methyl ester (RME) bio-diesel. Currently the cost of bio-diesel compared with fossil fuel makes the technology uncompetitive but increasing environmental pressures to improve air quality, especially in cities, may change this situation in the near future.

Within thermo-chemical conversion four process options are available: combustion, pyrolysis, gasification and liquefaction. Bio-chemical conversion encompasses two process options: digestion (production of biogas, a mixture of mainly methane and carbon dioxide) and fermentation (production of ethanol).

A distinction can be made between the energy carriers produced from biomass by their ability to provide heat, electricity and engine fuels. A useful means of comparing biomass and fossil fuels is in terms of their O:C and H:C ratios, known as a Van Krevlen diagram, shown in Fig. 1. The lower the respective ratios the greater the energy content of the material. The major conversion technologies and processes are discussed in the following sections.

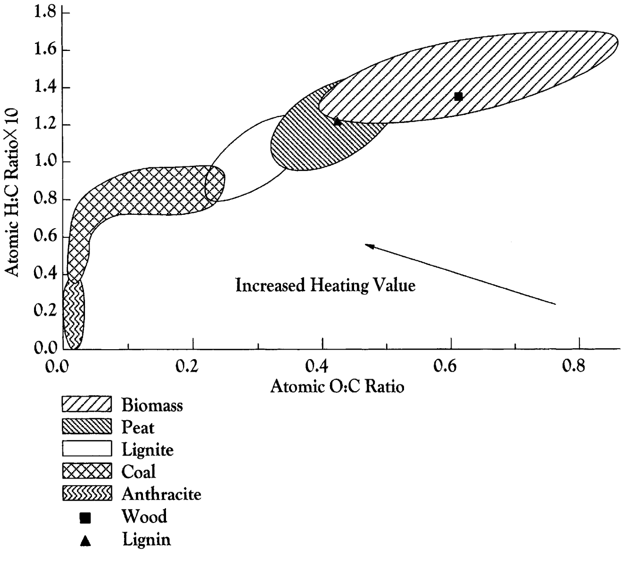

Fig. 1. Van Krevelen diagram for various solid fuels.

3. Thermo-chemical conversion

Three main processes are used for the thermo-chemical conversion of biomass, together with two lesser-used options. The main processes, the intermediate energy carriers and the final energy products resulting from thermo-chemical conversion are illustrated in the flowchart shown in Fig. 2.

3.1. Combustion

The burning of biomass in air, i.e. combustion, is used over a wide range of outputs to convert the chemical energy stored in biomass into heat, mechanical power, or electricity using various items of process equipment, e.g. stoves, furnaces, boilers, steam turbines, turbo-generators, etc. Combustion of biomass produces hot gases at temperatures around 800–1000 °C. It is possible to burn any type of biomass but in practice combustion is feasible only for biomass with a moisture content <50%, unless the biomass is pre-dried. High moisture content biomass is better suited to biological conversion processes.

The scale of combustion plant ranges from very small scale (e.g. for domestic heating) up to large-scale industrial plants in the range 100–3000 MW. Co-combustion of biomass in coal-fired power plants is an especially attractive option because of the high conversion efficiency of these plants (Mitsui Babcock, 1997; Aston University and DK Teknik, 1993; Warren Spring Laboratory, 1993a,b; EU, 1999; Aston University, 1986).

Net bio-energy conversion efficiencies for biomass combustion power plants range from 20% to 40%. The higher efficiencies are obtained with systems over 100 MWe or when the biomass is co-combusted in coal-fired power plants. Combustion per se is not considered any further in this study, as it does not produce a fuel suitable for use in either an s.i.g.e. or a gas turbine. One heat engine cycle, the Stirling cycle, uses combustion to provide shaft power directly but the development of the cycle is presently limited to small power outputs.

3.2. Gasification

Gasification is the conversion of biomass into a combustible gas mixture by the partial oxidation of biomass at high temperatures, typically in the range 800–900 °C. The low calorific value (CV) gas produced (about 4–6 $\mathrm{MJ/N\ m^3}$) can be burnt directly or used as a fuel for gas engines and gas turbines (LRZ, 1993; Natural Resources Institute, 1996). The product gas can be used as a feedstock (syngas) in the production of chemicals (e.g. methanol).

One promising concept is the biomass integrated gasification/combined cycle (BIG/CC), where gas tur-

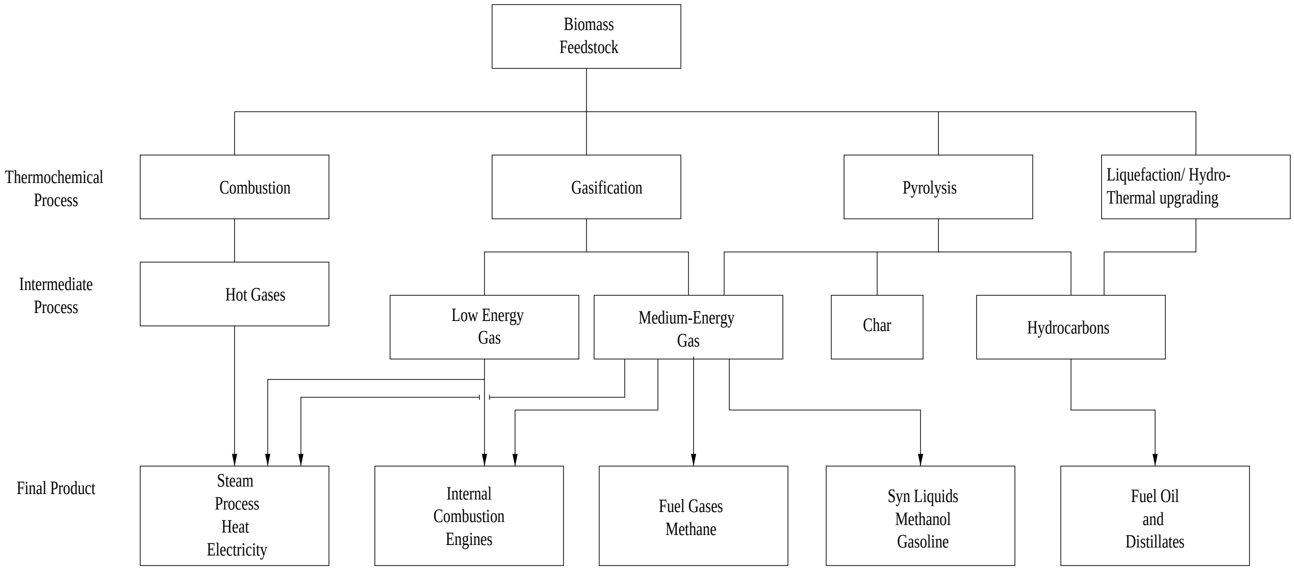

Fig. 2. Main processes, intermediate energy carriers and final energy products from the thermo-chemical conversion of biomass.

bines convert the gaseous fuel to electricity with a high overall conversion efficiency. An important advantage of BIG/CC systems is that the gas is cleaned before being combusted in the turbine, allowing more compact and less costly gas cleaning equipment to be used, as the volume of gas to be cleaned is reduced. The integration of gasification and combustion/heat recovery ensures a high conversion efficiency, producing net efficiencies of 40–50% (based on the lower heating value of the incoming gas) for a plant of 30–60 $MW_{(e)}$ capacity. However, BIG/CC technology is currently only at the demonstration stage (Mitsui Babcock, 1997; EU, 1999; Aston University, 1986).

The production of syngas from biomass allows the production of methanol and hydrogen, each of which may have a future as fuels for transportation. In the production of methanol, either hydrogen-indirect or oxygen-blown gasification processes are favoured, because of the higher value CV gas (typically 9–11 MJ/N m^3) produced by these processes: such schemes are currently close to demonstration.

3.3. Pyrolysis

Pyrolysis is the conversion of biomass to liquid (termed bio-oil or bio-crude), solid and gaseous fractions, by heating the biomass in the absence of air to around 500 °C: Fig. 3 depicts the range and possible yields of pyrolysis energy products. Pyrolysis can be used to produce predominantly bio-oil if flash pyrolysis is used, enabling the conversion of biomass to bio-crude with an efficiency of up to 80% (Aston University and DK Teknik, 1993; EU, 1999; Aston University, 1996). The bio-oil can be used in engines and turbines and its use as a feedstock for refineries is also being considered.

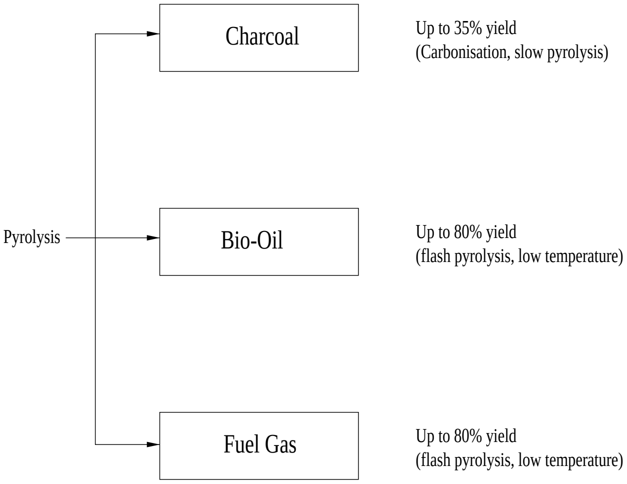

Fig. 3. Energy products from pyrolysis.

Problems with the conversion process and subsequent use of the oil, such as its poor thermal stability and its corrosivity, still need to be overcome. Upgrading bio-oils by lowering the oxygen content and removing alkalis by means of hydrogenation and catalytic cracking of the oil may be required for certain applications. Possible treatment and upgrading options for bio-oil are shown in Fig. 4.

3.4. Other processes

Other processes that produce bio-oils are hydro thermal upgrading (HTU) and liquefaction. HTU converts biomass in a wet environment at high pressure to partly oxygenated hydrocarbons: the process is believed to be almost at the pilot stage. The interest in liquefaction is

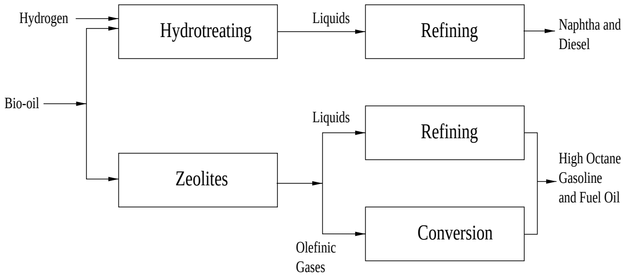

Fig. 4. Treatment and upgrading options for bio-oil.

low because the reactors and fuel-feeding systems are more complex and more expensive than pyrolysis processes. Liquefaction is the conversion of biomass into a stable liquid hydrocarbon using low temperatures and high hydrogen pressures (Warren Spring Laboratory, 1993a). A generalised conceptual flow sheet for liquefaction is shown in Fig. 5.

4. Bio-chemical conversion

Two main processes are used, fermentation and anaerobic digestion (AD), together with a lesser-used process based on mechanical extraction/chemical conversion.

4.1. Fermentation

Fermentation is used commercially on a large scale in various countries to produce ethanol from sugar crops (e.g. sugar cane, sugar beet) and starch crops (e.g. maize, wheat). The biomass is ground down and the starch converted by enzymes to sugars, with yeast then converting the sugars to ethanol. Purification of ethanol by distillation is an energy-intensive step, with about 450 l of ethanol being produced per ton of dry corn. The solid residue from the fermentation process can be used as cattle-feed and in the case of sugar cane, the bagasse can be used as a fuel for boilers or for subsequent gasification (Coombs, 1996).

The conversion of lignocellulosic biomass (such as wood and grasses) is more complex, due to the presence of longer-chain polysaccharide molecules and requires acid or enzymatic hydrolysis before the resulting sugars can be fermented to ethanol. Such hydrolysis techniques are currently at the pre-pilot stage.

4.2. Anaerobic digestion

AD is the conversion of organic material directly to a gas, termed biogas, a mixture of mainly methane and carbon dioxide with small quantities of other gases such as hydrogen sulphide (EU, 1999). The biomass is converted by bacteria in an anaerobic environment, producing a gas with an energy content of about 20–40% of the lower heating value of the feedstock. AD is a commercially proven technology and is widely used for treating high moisture content organic wastes, i.e. +80–90% moisture. Biogas can be used directly in s.i.g.e. and gas turbines and can be upgraded to higher quality i.e. natural gas quality, by the removal of CO_2. Used as a fuel in s.i.g.e. to produce electricity only, the overall

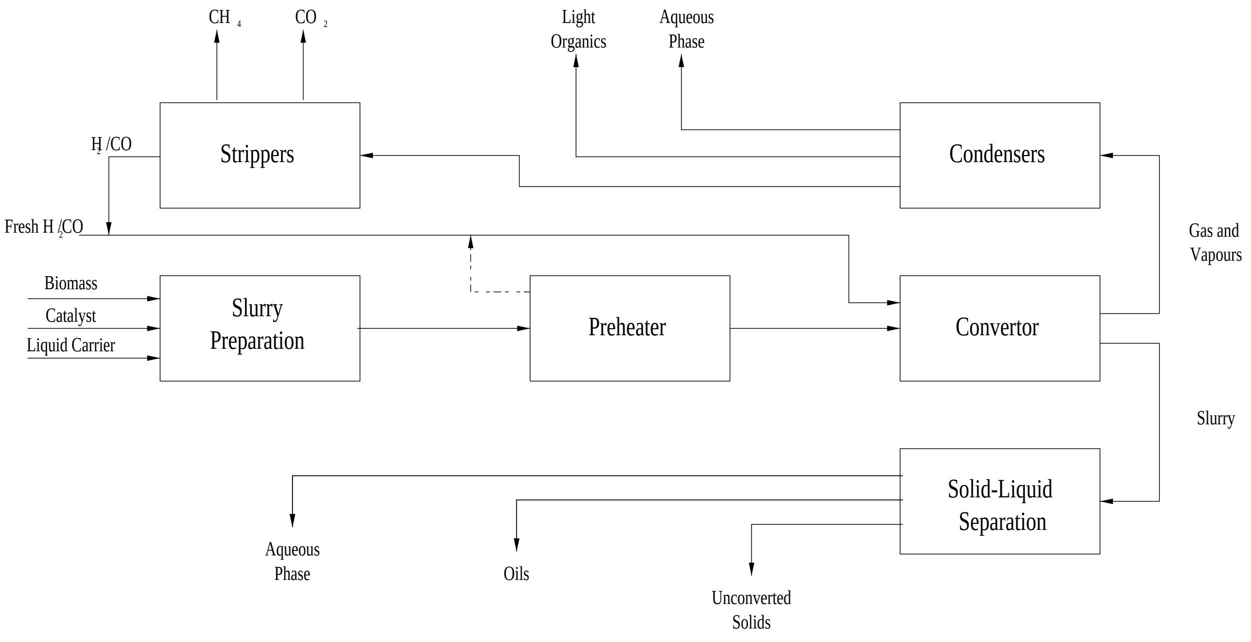

Fig. 5. Flow sheet for liquefaction.

conversion efficiency from biomass to electricity is about 10–16%. As with any power generation system using an internal combustion engine as the prime mover, waste heat from the engine oil and water-cooling systems and the exhaust could be recovered using a combined heat and power system. A typical flow sheet for processing biomass using AD is shown in Fig. 6.

4.3. Mechanical extraction

Extraction is a mechanical conversion process used to produce oil from the seeds of various biomass crops, such as oilseed rape, cotton and groundnuts. The process produces not only oil but also a residual solid or 'cake', which is suitable for animal fodder. Three tons of rapeseed are required per ton of rapeseed oil produced. Rapeseed oil can be processed further by reacting it with alcohol using a process termed esterification to obtain RME or bio-diesel (Warren Spring Laboratory, 1993a). RME is used in some European countries as a supplementary transport fuel. Fig. 7 depicts a generalised flow sheet for the production of methyl ester bio-diesel and the by-product glycerine.

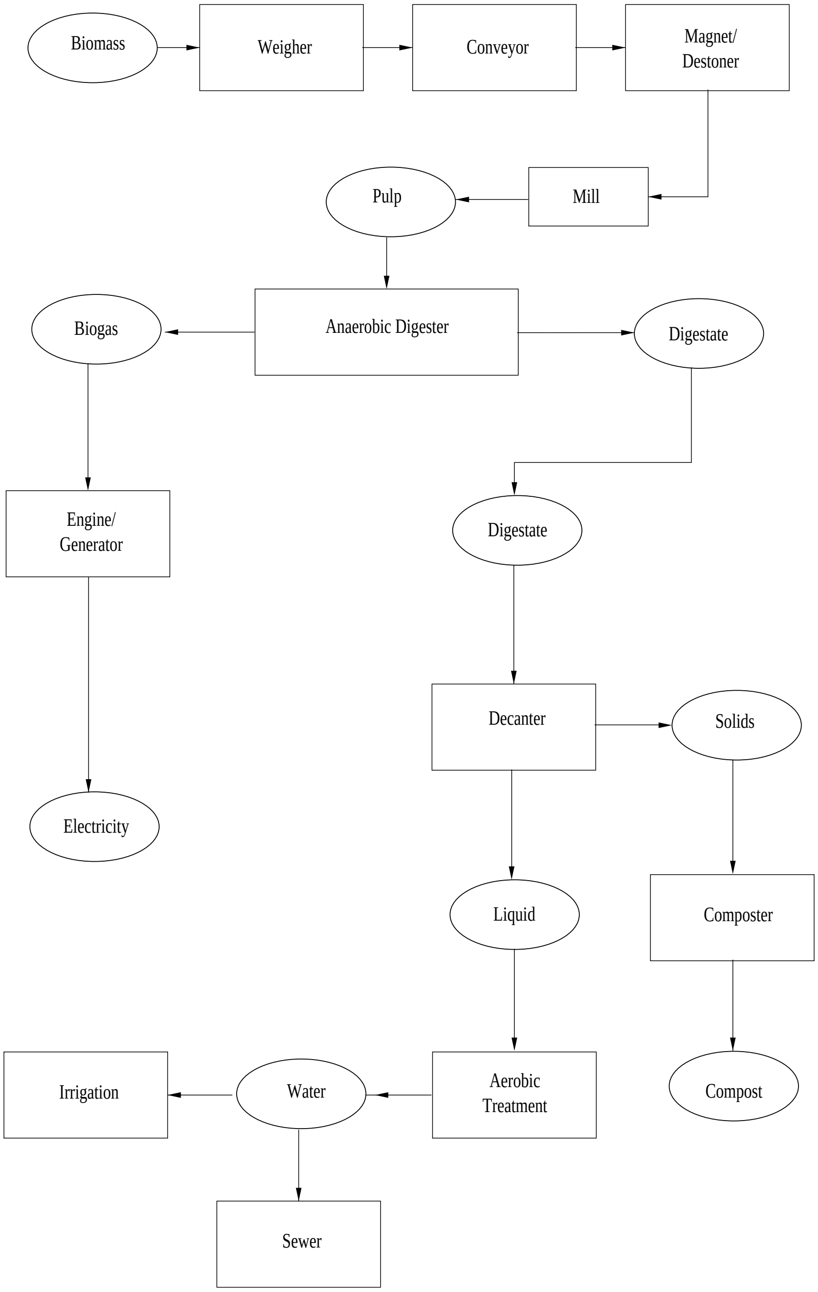

Fig. 6. Flow sheet for the AD of biomass.

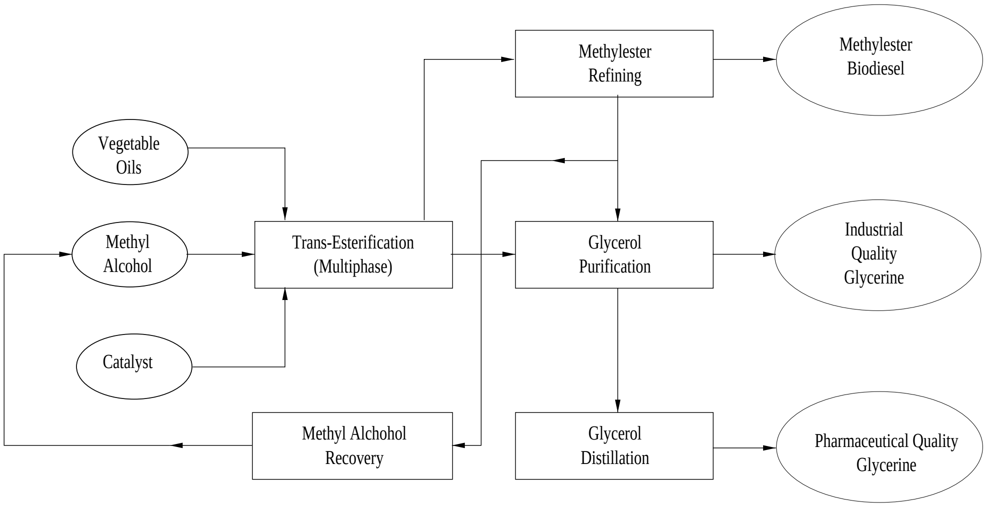

Fig. 7. Flow sheet for the production of methylester bio-diesel and glycerin.

5. Total bio-energy systems, energy ratios and energy yields

To evaluate the performance of a bio-energy conversion system, the entire chain from biomass production up to the end-use needs to be considered. A major criterion for comparing the total bio-energy systems is the net energy yield per hectare. The term net energy yield refers to the gross energy produced by the biomass, less the energy provided from the fossil fuels used in the production and processing of the biomass, including components of agricultural fuels, agricultural chemicals, transport fuels, process fuels and process chemicals.

If the net yield value is low, the amount of land required for the production of a given quantity of net energy is high and vice versa. As land is often a scarce commodity in many parts of the world, a high net energy yield per hectare is favoured. The environmental impact of a specific energy crop is also an important criterion in the selection process, together with the cost of the biomass per GJ of energy produced (or per GJ of fossil energy replaced). The relative significance of the net energy yield and the environmental impact of a particular biomass species will vary from one country to another and also from one region to another in the same country, depending on the relative socio-economic and political factors.

5.1. Energy ratios

The International Energy Agency (IEA, 1994) has made a comprehensive comparison of the bio-energy production chains for: ethanol from maize and sugar beet; RME from rapeseed; and methanol and electricity production from wood.

The energy ratio of a bio-energy chain is expressed as the ratio of the energy output versus the energy input, compared to the conventional fuel life cycle. Therefore an energy ratio below 1 implies that the energy input is higher than the energy output. Ethanol production from maize, wheat and beet, gives energy ratios between 0.9 and 1.5, indicating that there may be no net energy production in certain situations, if the required energy input is provided by fossil fuels. Projections, based on improved technologies and low-input, high-yield crops, indicate possible energy ratios between 2 and 3. Current production of RME from rapeseed has an energy ratio of about 1.5 and assuming an improved production system, up to 3. By comparison electricity produced from burning wood has an energy ratio 6–7 and values of 10–15 are considered feasible. For methanol, an energy ratio 6–12 is foreseen as possible in the longer term.

5.2. Energy yields

Table 1 compares the net energy yield per hectare of ethanol produced from wheat and beet, RME production and electricity-from-wood. Electricity-from-wood is the favoured option in the IEA study, although in the

Table 1
Net energy yields per hectare per year of some energy crops (IEA for NW Europe) (IEA, 1994)

Bio-energy type	Cxurrent context (GJ/ha/yr)	Future technology (GJ/ha/yr)
Ethanol from grain (replaces petrol)	Average 2	36
Ethanol from sugar beet (replaces petrol)	Average 30	139
RME production (replaces diesel)	17	41
Electricity from wood (replaces power generation)	110	165

longer- term ethanol from beet may also provide a relatively high value of energy production per hectare.

Other studies on energy yields however give a different ranking which serves to highlight the potential variations that can be obtained for apparently identical bio-energy systems. One study obtained higher net energy yields for ethanol produced from wheat and from RME but in the longer term, the net energy yields of the selected crops are of the same order of magnitude. The main explanations for the reported differences appear to be due to pessimistic estimates of the yield for wood production by SRC (e.g. willow) and optimistic assumptions associated with energy production from wheat straw and oilseed rape. For example, the IEA study assumed 10 odt/ha/yr for SRC in the current context and 12 odt for the longer term, while other studies used 8 odt/ha/yr as the current yield and 10 odt/ha/yr for the longer-term yield. The large difference between the energy yields for RME and wheat is caused by the difference in the assumed production of additional energy derived from utilisation of the straw residue.

To put biomass fuels into perspective in relation to conventional fossil fuels, Table 2 gives the energy densities for some fossil fuels compared with a typical biomass source, i.e. wood. It can be seen that in terms of transport and storage, biomass incurs considerable disadvantages in relation to fossil fuels (Transport Studies Group, 1996).

Comparing the energy yield data shown in Table 1 on a cost basis with conventional fuel costs produces the cost ratios shown in Table 3. The large cost ranges are due to the variation in the performance ranges of bio-energy systems. Fossil fuel prices are assumed constant and calculations assume a 5% discount rate. It can be seen that in the long term the most economic bio-energy system will be the one based on the production of electricity from wood, equalling or bettering electricity production from traditional fossil fuels. Similarly, on an economic basis alone, bio-energy replacements for petrol or diesel do not presently appear able to compete with fossil sources.

Table 2
Comparison of biomass and fossil fuel energy densities

Liquefied natural gas	56 GJ/t
Mineral oil	42 GJ/t
Coal	28 GJ/t
Biomass (wood, 50% moisture)	8 GJ/t

6. Conclusions

Based on the information and data presented, the following findings are suggested:

- the two main technologies presently used to convert biomass into energy are thermo-chemical and bio-chemical;
- selection of a conversion technology for biomass depends upon the form in which the energy is required;
- pyrolysis, fermentation and mechanical extraction (trans-esterification) all produce liquid fuels suitable for use as transportation fuels;
- other conversion processes produce energy in a form that is best used at the point of production i.e. hot air/steam or a gas;
- pyrolysis oils and liquid fuels (such as RME) are suitable only for diesel cycle engines;
- alcohol-based liquid fuels and combustible gases are suitable for use in s.i.g.e.;
- alcohol-based liquid fuels produced by fermentation are considered too costly for use in stationary s.i.g.e.;
- only gas from gasification/pyrolysis and AD is currently a cost-effective fuel for use in static s.i.g.e.

Having identified that gasification, pyrolysis and AD are the most likely cost-effective processes to produce a fuel suitable for an s.i.g.e., further consideration indicates that while all of the processes are (technically) able to produce a suitable fuel, only gasification is likely to be commercially viable. This finding is based on consideration of the greater overall conversion efficiency of gas production via gasification and the proven operational history and performance of gasifiers using purpose-grown, biomass feedstock.

Pyrolysis is a rapidly developing technology with great potential but the process is inherently better suited to producing a fuel oil, more suited to use in diesel engines and gas turbines. AD also has its place both as a conversion process to provide a gaseous fuel and as a treatment process for high moisture content industrial organic wastes, such ’difficult’ or wet biomass wastes like MSW and sewage sludge. In terms of providing a

Table 3
Cost ratios of bio-energy systems compared to conventional fuel costs (within the EU) (IEA, 1994)

Bio-energy system	Biofuel production cost (1991 crop prices)	Possible future biofuel production (based on world market/lowest prices)
Ethanol production from wheat (replacing petrol)	4.7–5.9	2.9–3.5
Ethanol production from beet (replacing petrol)	5–5.7	4.2–4.5
RME production (replacing diesel)	5.5–7.8	2.8–3.3
Methanol production from wood (replacing petrol)	n/a	1.9–2.2
Electricity production from wood (replacing grid electricity)	1.3–1.9	0.8–1.1

cost-effective process route to produce a gaseous fuel for stationary s.i.g.e., gasification is the preferred conversion process.

In a subsequent paper, gasification processes are examined in more detail.

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