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REVIEW

Energy crops: current status and future prospects

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Abstract

Energy crops currently contribute a relatively small proportion to the total energy produced from biomass each year, but the proportion is set to grow over the next few decades. This paper reviews the current status of energy crops and their conversion technologies, assesses their potential to contribute to global energy demand and climate mitigation over the next few decades, and examines the future prospects. Previous estimates have suggested a technical potential for energy crops of $\sim 400\,EJ\,yr^{-1}$ by 2050. In a new analysis based on energy crop areas for each of the IPCC SRES scenarios in 2025 (as projected by the IMAGE 2.2 integrated assessment model), more conservative dry matter and energy yield estimates and an assessment of the impact on non-CO_2 greenhouse gases were used to estimate the realistically achievable potential for energy crops by 2025 to be between 2 and $22\,EJ\,yr^{-1}$, which will offset $\sim$ 100–2070 Mt CO_2-eq. yr^{-1}. These results suggest that additional production of energy crops alone is not sufficient to reduce emissions to meet a $550\,\mu mol\,mol^{-1}$ atmospheric CO_2 stabilization trajectory, but is sufficient to form an important component in a portfolio of climate mitigation measures, as well as to provide a significant sustainable energy resource to displace fossil fuel resources. Realizing the potential of energy crops will necessitate optimizing the dry matter and energy yield of these crops per area of land through the latest biotechnological routes, with or without the need for genetic modification. In future, the co-benefits of bioenergy production will need to be optimized and methods will need to be developed to extract and refine high-value products from the feedstock before it is used for energy production.

Keywords: bioenergy, biofuel, biotechnology, climate change, energy crops

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Current status and trends

Concern about global warming in recent decades has stimulated interest in using biomass for energy. Biomass energy is close to 'carbon neutral', that is to say, it produces energy while only releasing carbon to the atmosphere that has been captured during the growing cycle of the plant, rather than emitting carbon that has been locked away from the atmosphere in fossil reserves for millions of years.

Bioenergy currently contributes 13.4% (IEA Statistics, 2005) of world primary energy use and currently is used mainly in Africa, Asia and China through use of wood and dung in rural areas as a fuel for heating and cooking. The impetus to invest in technology to use biomass for energy stemmed initially from the need of countries to substitute for imported coal, oil and gas with a locally produced fuel to either ensure security of supply or to improve trade balances. The development of the maize ethanol and soybean biodiesel market in the central USA is an example of the former. The US responded to the decline in its crude oil reserves and production rates, and its increasing dependency of oil imports, by investing in bioethanol production from maize, which also stimulated its agricultural economy. The conversion of Brazil's entire Otto cycle private car

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fleet in the 1980s to run on ethanol manufactured from the fermentation of cane sugar is an example of the latter. Ethanol was later partly displaced by gasoline as Brazil developed its offshore oil reserves but remains as a 20–25% blend in all gasoline today.

The pattern of energy use in the world is changing with the successive industrialization of the economies of South East Asia and Brazil, and more recently with the increasing pace of the industrialization of China and India. This has driven an increase in the demand for energy, and hence for fossil fuel, at the rate of 3% yr^{-1} (World Oil, 2005). The rate at which conventional oil production can be increased has been reduced by the lack of refining capacity, and the fact that nearly 50% of the world's proven and probable conventional light crude oil reserves have already been consumed (USGS, 2004). This flat topping in the availability of oil has been compensated for by the increased availability of natural gas and new reserves of cheap coal. Natural gas has been increasing its share of the energy supply mix as the infrastructure and technology of its transportation is put into place both by pipelines, liquefaction and conversion to methanol. In developed economies, gas has displaced both oil and coal, while coal use has increased in developing economies, particularly in China. At the same time the use of nuclear energy has stagnated because of public concerns about waste storage and disposal.

The use of biofuels for transport has increased in energy terms, but decreased in terms of total percentage energy use. An increase in price in fossil fuel will further encourage the development of alternative sources because higher energy prices will lead to carbon neutral energy sources, which include biomass, becoming increasingly economic. The development of technology to utilize biomass as a source of energy has advanced on many fronts, from the production of transport fuels such as biodiesel from vegetable oil and bioethanol from sugars, starch and cellulose rich crops, to the use of woody biomass to fuel integrated gasification combined cycle plants. The technologies have been shown to be effective, but their large-scale application has previously been limited by commercial economics. They have found applications, however, where national interests have created the political environment to facilitate the financial or tax regime to allow the technology to be used.

Many countries have ambitious, near term policy objectives for bioenergy (IEA, 2005). The available global economic potential from biomass residues and wastes, is estimated to be around 100 EJ yr^{-1} (World Energy Council, 2004). Increasing this biomass potential will require changes to agricultural and forestry production and the active growth of dedicated energy crops. Hall & Rosillo-Calle (1998) estimated 2900 EJ of potential biomass energy was available, of which only 270 EJ could be utilized on a sustainable basis at competitive prices. Hoogwijk (2004) analysed the use of biomass for 17 different scenarios and showed its 'research focus' potential by 2025–2050 was between 67 and 450 EJ, whereas the 'demand driven' potential was between 28 and 220 EJ. The global technical potential of bioenergy is therefore large and could provide around 200–400 EJ yr^{-1} at competitive costs by 2050 (IPCC, 2001).

Globally, biomass currently provides around 46 EJ of bioenergy in the form of combustible biomass and wastes, liquid biofuels, renewable municipal solid waste, solid biomass/charcoal, and gaseous fuels. This share is estimated to be 13.4% of global primary energy supply (IEA Statistics, 2005) but this is mainly from 'traditional biomass' estimated to provide 32 EJ in 2002 of non-commercial firewood, charcoal and dung used for cooking and heating in developing countries (IEA, 2004). Such low-grade biomass provides around 35% of primary energy in many developing countries, but more than 70% in Africa (Sims *et al*., 2003).

Residues from industrialized farming, plantation forests and food and fibre processing operations that are currently collected worldwide and used in modern bioenergy conversion plants contain approximately 9 EJ yr^{-1} of energy. Current combustion of over 130 Mt of municipal waste annually provides a further 6 EJ yr^{-1} (although this includes plastics, etc). Much more organic waste is deposited in landfills, which in turn create large volumes of greenhouse gases (GHGs), mainly methane. Annual C emissions to the atmosphere would be higher if the 46 EJ of energy from biomass were to be provided instead by a mix of fossil fuels. Taking the emission factor of oil (about 75 t CO_2 TJ^{-1}) as an average, then this would result in global emissions of 3.45 Gt CO_2 (0.94 Gt C). If we further assume that this average fossil fuel mix would be used with twice the efficiency of wood, then the figure is halved. Carbon emissions to the atmosphere would, therefore, increase by about 0.5–1 Gt C yr^{-1} if the current energy supplied by traditional biomass were instead supplied by fossil fuels. Biomass sources include specialist energy crops and short rotation forest plantations as well as 'wastes' including forest, agricultural and livestock residues, municipal solid waste and other organic waste streams. These are used as feedstocks to produce solid fuels (chips, pellets, briquettes, logs), liquid fuels (methanol, ethanol, diesel), gaseous fuels (synthesis gas, biogas, hydrogen) and heat. Dedicated energy crops, the focus of this review, at present contribute relatively little to the overall energy supply from biomass energy (Fig. 1) but are projected to grow substantially over the next few decades.

Energy crops can take many forms and can be converted to a number of different products. Many crop

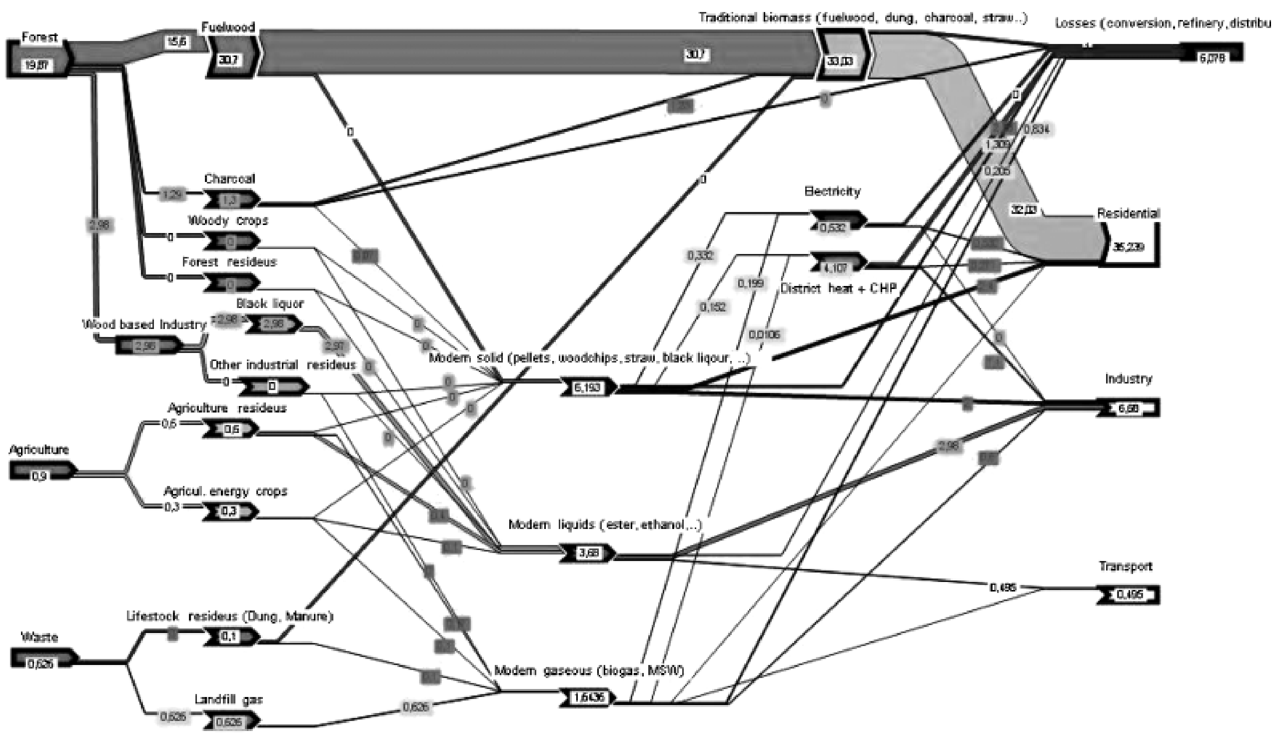

Fig. 1 Global biomass energy flows (EJ) to produce heat, power and transport fuels (the width of the line is proportional to the flow).

species are multipurpose in that they can be used to produce more than one type of energy product, for example, hemp (both oil and solid biomass) and cereals (ethanol and solid biomass from straw). Some of the more common energy crops are listed below.

Oil crops: (e.g. oilseed rape, linseed, field mustard, hemp, sunflower, safflower, castor oil, olive, palm, coconut and groundnut). Vegetable oils can be used directly as heating fuels or refined to transport biofuels such as biodiesel esters.

Cereals: (e.g. barley, wheat, oats, maize and rye): The grain can be used to produce ethanol and the straw can be used as a solid fuel. They can also be grown and harvested as a whole crop (grain plus straw) before the grain has ripened and used as a solid fuel or for biogas production feedstock.

Starch and sugar crops (e.g. potato, sugar beet, Jerusalem artichoke and sugarcane): Ethanol can be produced from the starch and glucose by fermentation then used directly as a fuel, as in Brazil, or more normally in blends with gasoline.

Cellulose crops (e.g. straw, wood, short rotation coppice (SRC), etc.): The hemicellulose can be reduced to sugar by acid or enzymatic hydrolysis and then fermented to produce ethanol. This has been pioneered in Sweden (Whitworth, 2005) where the ethanol was used by specially modified Ford Focus vehicles that can run on any mixture of ethanol and gasoline by adjusting the engine management parameter based upon sensing the exhaust gas composition.

Solid energy crops (e.g. cardoon, sorghum, kenaf, prickly pear, whole crop maize, reed canary grass, miscanthus and SRC willow, poplar and eucalyptus): These crops can be utilized whole to produce heat and electricity directly through combustion or indirectly through conversion for use as biofuels like methanol and ethanol.

Increasing bioenergy demand in future will be met to a greater degree by the active production of biomass crops from either surplus productive or marginal lands. Low production costs give significant potential for biomass production in the former USSR, Oceania, East and Western Africa and East Asia. It is estimated that in the long term (2050) about 130–270 EJ yr^{-1} of energy crops may be produced at costs below US\$2 GJ^{-1} (equivalent to the current highest cost level of coal; Hoogwijk, 2004). Such low costs presume significant land productivity improvements will occur over time together with technical learning and capital-labour substitution. Commercial energy crops are already grown extensively in Brazil (sugar cane for ethanol), USA (maize for ethanol) and Europe (oilseed rape for biodiesel) but such land use is often heavily subsidized and may involve nonsustainable agricultural practices (OECD, 2004). It is likely that bioenergy cropping systems of the future will have primary, secondary and even tertiary uses, propelling bioenergy systems

Table 1 A comparison of commonly used fuels from fossil and biological origins in terms of emissions of carbon dioxide per MJ energy accounting for the energy used in fuel production and assuming all carbon of the biomass derived fuels is mitigated. From the energy density (MJ kg^{-1}), the energy cost of fuel production (MJ MJ^{-1}), and the mass ratio of carbon in the fuel, the emissions (kg CO_2 MJ^{-1}) were calculated. To keep a singular comparison methodology it was assumed that the production energy was supplied by the fuel being produced.

Fuel	**Origin**	Energy density* (MJ kg^{-1})	Process energy cost† (process MJ MJ^{-1} fuel)	(kg‡ C kg^{-1} fuel)	C emitted fuel (kg CO_2 MJ^{-1})	C emitted fuel + proc (kg CO_2 MJ^{-1})	Bio-mitigation factor§ (%)	Carbon mitigated¶ (kg CO_2 MJ^{-1})	Effective C emitted (kg CO_2 MJ^{-1})
Low sulphur diesel	Crude	48.6	0.26	0.86	0.065	0.082	0%	0.000	0.082
Diesel	Crude	48.6	0.20	0.86	0.065	0.078	0%	0.000	0.078
Unleaded gasoline	Crude	51.6	0.19	0.86	0.061	0.072	0%	0.000	0.072
Fuel oil	Crude	54.2	0.19	0.86	0.058	0.069	0%	0.000	0.069
Anthracite	Coal	31.0	0.10	0.92	0.109	0.120	0%	0.000	0.120
Bitmumous coal	Coal	29.0	0.10	0.74	0.094	0.103	0%	0.000	0.103
Lignite	Coal	25.0	0.10	0.50	0.073	0.081	0%	0.000	0.081
Natural gas	Natural gas	55.7	0.20	0.75	0.049	0.059	0%	0.000	0.059
Methanol from NG	Natural gas	22.4	0.20	0.51	0.083	0.100	0%	0.000	0.100
Electricity	Bituminous coal	29.0	2.08	0.74	0.09	0.29	0%	0.000	0.288
Ethanol	Crude	35.0	0.20	0.52	0.05	0.07	0%	0.000	0.065
Rapeseed oil	Oil seed rape	43.0	0.29	0.55	0.047	0.061	100%	0.061	0.000
Biodiesel	Oil seed rape	43.7	0.44	0.61	0.051	0.074	100%	0.074	0.000
Biodiesel	Recycled veg oil	43.7	0.19	0.61	0.051	0.061	100%	0.061	0.000
Methanol	Pyrolysis/wood	25.0	1.00	0.51	0.075	0.150	100%	0.150	0.000
Ethanol	Wheat	35.0	0.46	0.52	0.054	0.080	100%	0.080	0.000
Ethanol	Maize	35.0	0.29	0.52	0.054	0.070	100%	0.070	0.000
Ethanol	Sugarcane	35.0	0.50	0.52	0.054	0.082	100%	0.082	0.000
Ethanol	Sugarbeet	35.0	0.50	0.52	0.054	0.082	100%	0.082	0.000
Ethanol	Wood chips	35.0	0.57	0.52	0.054	0.086	100%	0.086	0.000
Ethanol	Straw	35.0	0.57	0.52	0.054	0.086	100%	0.086	0.000
Wood	SRC	21.0	0.25	0.44	0.077	0.096	100%	0.096	0.000
Miscanthus		15.0	0.20	0.44	0.108	0.129	100%	0.129	0.000
Straw	Maize silage	20.0	0.21	0.44	0.081	0.097	100%	0.097	0.000
Charcoal	From wood	29.0	1.00	1.00	0.126	0.253	100%	0.253	0.000

*From Rose & Cooper (1977), UK DTI (2005) and Rodgers & Mayhew (1967). Energy density for 'electricity' is that of fuel of origin 'bituminous coal'.
†From Boyles (1984).
‡From Weast *et al.* (1966)
§Assumes that all carbon including production cost carbon is from same bio-source and that the net soil emission is zero, i.e. no C sequestration of emission.
¶Assumes all carbon is mitigated for biofuels.

into mainstream markets for bioproducts such as grain and pharmaceuticals that may help to improve financial viability in future (Perlack *et al*., 2005).

Table 1 shows a comparison of commonly used fuels from fossil and biological origins in terms of energy density (MJ kg^{-1}), the energy cost of production (Boyles, 1984) (MJ input MJ^{-1} fuel), the mass ratio of carbon in the fuel, and calculated emissions (kg CO_2 MJ^{-1} of the fuel). The kg of CO_2 per useful MJ of fuel was calculated and the production cost of the fuel also included. To keep a singular comparison methodology the production input energy was assumed to be generated by the fuel being produced.

Conversion technologies

Net carbon emissions from generation of a unit of bioenergy are 10–20 times lower than emissions from fossil fuel-based generation (Mann & Spath, 2000; Matthews & Mortimer, 2000). Biochemical technologies can convert cellulose to sugars and glycerides that, in turn, can be converted to bioethanol, biodiesel, hydrogen and chemical intermediates in biorefineries. However, the energy input/output ratios can be marginal. Fossil energy is usually consumed in producing bioenergy carriers, but usually this energy input is a small fraction of the total energy output. Typical energy ratios for bioenergy forestry and agriculture systems are 1 : 25 to 1 : 50 units (Matthews, 2001). Although energy output/input ratios are often quoted, they should be used with care. Biomass can be produced and converted independently of external fossil energy by using its own product. However, this means that less of the product can be sold to markets to displace fossil fuels. Also, energy ratios do not indicate any GHG mitigation potential because this depends on the fossil fuel reference system. Thus, in some cases it might be preferable to transport biomass over long distances if this means that a more carbon intensive and less efficient fossil fuel can be replaced. Overall, careful choice of system boundaries is necessary when analysing the GHG impacts of bioenergy systems and full life cycle analyses are essential.

A wide range of conversion technologies to produce bioenergy carriers and useful energy are under continuous development both for small- and large-scale applications. The use of biomass for combined heat and power (CHP or cogeneration) and industrial, domestic and district heating continues to expand (Martinot, 2005). Combustion of biomass for heat and steam generation remains the state of the art, but advanced technologies including second-generation biomass integrated gasification combined cycle (BIGCC) systems, cofiring (with coal or gas), and pyrolysis, are awaiting further technical breakthroughs and demonstrations to bring down the costs. Power generation has improved its efficiency from the 6% thermal energy conversion of the 1882 Holburn Viaduct to the 85% of modern CHP plants. Most electricity power supply is from large-scale grids supplied by electricity generators using a plethora of technologies with thermal energy conversion efficiencies ranging from 35% for a medium size coal-fired turbine power station (Rodgers & Mayhew, 1967) to 58% for a modern combined cycle gas turbine (CCGT) power station. Distribution grids are only 83% efficient (Hughes, 1967) and reduce the efficiency of the system. Smaller CHP stations have an advantage as although they have a lower thermal-electricity conversion efficiency, they use the rejected heat for district heating or industrial processes, have low transmission network losses as they supply a smaller area, and are suitable for bioenergy as the catchment area for the biomass can be compact and the transportation energy and costs reduced. Efficiencies of the power generation technologies for different fuels determine carbon emissions per MJ of electricity generated (Table 2). The emissions of each can be compared with the 1996 average UK grid emissions and the impact of the closure of medium sized coal stations and their replacement by CCGT stations is demonstrated. The future emissions average will increase as nuclear stations close, unless they are replaced by renewable energy forms.

Biomass tends to have low-energy density compared with equivalent fossil fuels which makes transportation, storage and handling more costly per unit of energy (Sims, 2002). These costs will be minimized if biomass can be sourced from a location where it is already concentrated and converted nearby (IEA, 2005). The reason bioenergy projects using forest residues and crop residues are often not competitive at present lies in the resource being dispersed over large areas leading to high collection costs.

More than 30% of total energy consumption in industrialized countries is for space heating for offices, factories and homes. Some countries with a preexisting network of district heating such as in Eastern Europe, Scandinavia or cities like New York can use CHP technology to replace district heating boilers. Other smaller scale CHP systems for large single facilities like hospitals, factories and military camps can also replace the existing heating boilers. This captures more of the heat energy released during combustion and also lends itself to adaptation to biomass, like the many plants in use in Sweden today fuelled by chipped wood waste from the forestry industry.

Many domestic home heating systems are inefficient. In Table 3 the CO_2 emissions per MJ of useful heat are compared for many heating systems of different efficiencies for commonly used fossil and biomass fuels.

Table 2 Comparative efficiencies of a range of methods and fuels for electricity generation including the efficiency of heat to mechanical energy conversion and heat loss, conversion of mechanical energy to electrical energy and electrical transmission losses to provide actual carbon emissions per useful unit of electrical energy at the point of use ($kg\,CO_2\,kWh^{-1} = kg\,CO_2\,MJ^{-1}*3.6$

Type of power station	Engine efficiency* (%)	Generator efficiency† (%)	Generation efficiency† (%)	Transmission efficiency† (%)	Total efficiency† (%)	Fuel emissions ($kg\,CO_2\,MJ^{-1}$)‡	Electricity emissions ($kg\,CO_2\,MJ^{-1}$)§,¶
Oil-fired steam turbine theoretical maximum	61	97	59	83	49	0.069	0.141
Medium coal-fired steam turbine	36	97	35	83	29	0.103	0.355
Large coal-fired steam turbine	40	97	39	83	32	0.103	0.320
Oil-fired steam turbine	40	97	39	83	32	0.069	0.215
Gas-fired combined cycle theoretical maximum	80	97	78	83	64	0.059	0.092
Gas-fired combined cycle turbines	60	97	58	83	48	0.059	0.123
Large marine/stationary diesel theoretical	60	97	58	83	48	0.069	0.144
Large marine/stationary diesel actual	52	97	50	83	42	0.069	0.166
Nuclear steam turbine (Magnox/AGC)	41	97	40	83	33	0.000	0.000
Nuclear steam turbine (boiling water)	36	97	35	83	29	0.000	0.000
Nuclear steam turbine (pressurized water)	32	97	31	83	26	0.000	0.000
Nuclear steam turbine (pebble bed)	50	97	49	83	40	0.000	0.000
Wind		97	97	83	81	0.000	0.000
Wave and Tide and Hydro		97	97	83	81	0.000	0.000
Combined heat and power coal	36	97	35		85	0.103	0.121
Combined heat and power oil	36	97	35		85	0.069	0.082
Combined heat and power gas	36	97	35		85	0.059	0.070
Combined heat and power wood	36	97	35		85	0.000	0.000
Combined heat and power miscanthus	36	97	35		85	0.000	0.000
Combined heat and power straw	36	97	35		85	0.000	0.000
UK grid 1996 average for comparison							0.288

*Rodgers & Mayhew (1967).
†Hughes (1967).
‡From Table 1.
§Wind, nuclear, wave and hydro power have relatively large infrastructure carbon cost.
¶Excluding carbon cost of infrastructure.

Table 3 Comparative emissions of carbon dioxide per MJ of useful heat for a range of fuels and space heating technologies

Fuel	Fuel CO_2 emission* ($kg\,CO_2\,MJ^{-1}$) Heating efficiency	Flued open fire ($kg\,CO_2\,MJ^{-1}$) 10% *Emissions per unit of useful heat*	Enclosed stove ($kg\,CO_2\,MJ^{-1}$) 50%	Enclosed stove forced convection ($kg\,CO_2\,MJ^{-1}$) 70%	CH Boiler ($kg\,CO_2\,MJ^{-1}$) 78%	CH Boiler Condensing ($kg\,CO_2\,MJ^{-1}$) 90%	Electrical† ($kg\,CO_2\,MJ^{-1}$) 100%
Diesel	0.078		0.156	0.112	0.100	0.087	
Fuel oil	0.069		0.139	0.099	0.089	0.077	
Anthracite	0.120	1.197	0.239	0.171	0.153		
Bitmumous coal	0.103	1.029	0.206	0.147	0.132		
Lignite	0.081	0.807	0.161	0.115	0.103		
Natural gas	0.059	0.593	0.119	0.085	0.076	0.066	
Methanol from NG	0.100					0.111	
Electricity	0.288						0.288
Methanol from wood	0.000					0.000	
Ethanol from wheat	0.000					0.000	
Wood	0.000	0.000	0.000	0.000	0.000	0.000	
Miscanthus	0.000	0.000	0.000	0.000	0.000		
Straw	0.000						
Charcoal	0.000	0.000	0.000	0.000	0.000		

*From Table 1.
†Assumes heating 100% efficient and that electricity is average from UK grid in 1996 (Table 2).

The progression from open fire to condensing boiler for central heating (CH) takes the efficiency from 10% to 90% with the emissions correspondingly reduced. This migration to higher efficiency systems and lower emission fuels can have a large impact on overall carbon emissions but it can be seen that using electricity from fossil fuel fired plants for space heating can be a waste of resources as it generates the highest emissions per MJ. Hence, the conversion to oil and gas-fired condensing boilers is currently the best option for areas where the use of biomass fired CHP plants for district heating systems is impractical. The development of pelletized biomass for use in auto-feed condensing boilers can also replace fossil fuels.

Bioenergy carriers range from simple crop residues to highly refined transport biofuels. Different biomass products suit different situations and specific objectives for using biomass are affected by the quantity, quality and cost of feedstock available, location of the consumers, type and value of energy services required, and whether there are any co-products or benefits (IEA, 2005).

Combustion and cofiring

Combustion is by far the most commonly applied conversion route for biomass. Improved insight into fundamental aspects relating to combustion performance and ash behaviour could lead to further increases in plant reliability and efficiency. Emission levels and specific investment costs will be reduced and better understanding of the combustion of challenging fuels such as straw is needed (IEA, 2002). Cogeneration through combustion to generate useful heat and power is increasing. Commercial options using small-scale steam turbines, Stirling engines, organic Rankin cycle systems, etc. can generate power for between US\$0.07 and 0.12 kWh^{-1}, but with the opportunity to further reduce the capital costs by mass production and experience (Martinot, 2005).

Biomass pellet and briquette heating systems for domestic and small industrial heat supply are experiencing growing demand in OECD countries because of their convenience. They also provide good potential for developing countries to export their surplus biomass as pellets which are portable, flowable, have consistent quality with a low moisture content, good energy density, and can be made from a range of feed stocks such as sawdust.

Biomass can easily be combined with fossil fuel technologies by cofiring solid biomass particles with coal; mixing synthesis gas, landfill gas or biogas with natural gas before combustion; blending diesel with biodiesel and gasoline with bioethanol; and using flexible fuel engines in vehicles. There has been rapid progress in recent years in the development of the co-utilization of biomass materials in coal-fired boiler plants. Commercially significant lignites, bituminous and subbituminous coals, anthracites, and petroleum coke have all been co-fired up to 15% by energy content with a very wide range of biomass material, including herbaceous and woody materials, wet and dry agricultural residues and energy crops (Laux *et al*., 1999). This experience has shown how the technical risks associated with cofiring in different types of coal-fired power plants can be reduced to an acceptable level through proper selection of biomass type and co-firing technology. It is a relatively low cost, low risk means of adding biomass capacity, particularly in countries where old coal-fired plants are prevalent.

Gasification

Gasification of dry biomass is generally easier than for coal. It has a higher conversion efficiency (40–50%) than combustion, can generate electricity through a gas turbine, or the synthesis gas produced can be used as feedstock to produce a range of liquid biofuels. Development of efficient BIGCC systems of around 5–20 MW_e is nearing commercial realization but the challenges of gas clean-up remain. Several pilot and demonstration projects have been evaluated with varying degrees of success (Pitcher *et al*., 2002). Capital investment for a high pressure, direct gasification combined-cycle plant of this scale is estimated to fall from over US\$2000 kW^{-1} to around US\$1100 kW^{-1} by 2030, with operating costs, including delivered fuel supply, also declining to give generation costs around US\$0.10 to 0.12 kWh^{-1} (Martinot, 2005). A life cycle assessment of the production of electricity in a BIGCC plant showed 95% of carbon delivered was recycled (Mann & Spath, 1997). From the energy ratio analysis, one unit of fossil fuel input produced approximately 16 units of carbon neutral electricity exported to the grid.

Biofuels for transport

Global biofuel consumption in 2002 was between 0.35 EJ (IEA, 2004) and 0.50 EJ (UNDP, 2004). This has potential to rise to over 50 EJ in 2050 based on economic estimates (Fischer & Schrattenholzer, 2001). Biochemical and thermochemical conversion technologies can convert CO_2 neutral biomass feedstocks into carbon containing biofuels such as biodiesel, dimethyl esters and Fischer–Tropsch liquids as well as to hydrogen. The primary feedstock for ethanol production worldwide remains sugar or starch from agricultural crops, and its primary use is as an oxygenate within gasoline at 5–22% blends. Reacting ethanol with butylene produces ETBE also used as an 8–10% blend with gasoline. Fermentation techniques are commercially undertaken in a number of jurisdictions, including Brazil from sugar cane at over 300 distilleries (Moreira & Goldemberg, 1999; Martinot, 2005), the USA, Spain and France from maize and other cereal crops (Jeanroy, 2000), and more recently in Canada and Sweden from ligno-cellulosic sources (Lawford & Rousseau, 2003). The bioethanol market is likely to continue to expand as the processing of ligno-cellulose to sugars and glycerides matures. These carriers can be converted to ethanol, diesel, hydrogen and chemical intermediates to displace petro-chemicals (Sims, 2004). Process demonstration units have been installed in several locations including the National Renewable Energy Laboratory, USA (Nguyen *et al*., 1996), University of British Columbia, Canada (Boussaid *et al*., 2000), and northern Sweden (Wingren *et al*., 2004). Commercial ventures for ligno-cellulosic-based ethanol include Iogen (Canada) and Abengoa (Spain and USA). Anaerobic digestion and Fischer–Tropsch processes can also be used for producing gaseous and liquid fuels at the small scale (Larson & Jin, 1999).

The technology to burn ethanol as an automotive fuel is based upon the Otto cycle because it can be used as a direct substitute for gasoline in spark ignition (SI) engines. It is more corrosive and engines that run on 100% ethanol require special ethanol resistant plastic and rubber components and also hardened valve seats to resist the more corrosive ignition products. But most modern engines designed for unleaded gasoline can use up to 10% ethanol in gasoline without modification. As pure ethanol has an octane rating of 115 it can be used as an octane enhancer in gasoline to replace more polluting MTBE. To use ethanol efficiently and to take advantage of the increased octane level the ignition timing has to be advanced to optimize the combustion efficiency. Several vehicle manufacturers have developed engine management software that can detect the variable mixtures of gasoline and ethanol by using sensors to measure the exhaust gas properties and then adjust the engine management parameters accordingly (Whitworth, 2005). This low-cost modification (~ US\$230) enables flexible vehicle use not limited by the availability of a particular fuel.

Otto cycle technology advancements in recent years have moved from the naturally aspirated, contact spark timing engines with thermal efficiency of 26% to more modern turbo charged, fuel injected engines with electronic ignition controlled by engine management systems giving thermal efficiencies of 32%. Materials science and new friction surface and bearing designs as well as the increased use of lighter structural materials such as aluminium, alloys and plastics have contributed to this gain. Recent developments pioneered by Toyota have led to the Atkinson cycle for SI engines and the uptake of the hybrid transmission system which has increased the thermal efficiency to 36%. (Table 4). Based upon these efficiencies and the fuel C emissions per MJ, a notional CO_2 emission per km was calculated for comparison purposes based upon a vehicle that requires 513 KJ km^{-1}, equivalent to a car requiring 15 kW (20 HP) to run at 100 km h^{-1} on the level. The effective carbon emissions per MJ of fuel consumption (Table 1) included those emitted during extraction, production and processing of the transport fuel, and assumed that the same fuel was consumed in the 'well to wheels' analysis.

Ethanol manufactured from crude oil has approximately 2/3 the emissions of gasoline produced when using the same engine technology. Methanol, derived from natural gas has a very high process energy and carbon cost and, therefore, has higher effective emissions compared with ethanol, even though it is similar in its combustion properties. Ethanol is also less toxic for human health with an exposure limit of 1900 mg m^{-3} over a 40 h working week compared with 260 mg m^{-3} for methanol and 900 mg m^{-3} for gasoline. When the ethanol is derived from annual plants the effective emissions are negligible, but when derived from wood it has a higher production energy cost, but lower emissions than gasoline. Methanol from wood has a high production energy cost.

The theoretical maximum efficiency of the diesel cycle is 62% compared with 59% for the Otto cycle (although the best efficiency achieved with large marine or stationary diesel cycle engines greater than 30,000 kW is only 52%). Automotive diesel cycle engines have undergone a metamorphism from heavy, low-speed, naturally aspirated engines with a thermal efficiency of 35% to today's light common rail injection turbo-charged engines with a thermal efficiency of 42%. This increase in efficiency has been achieved by improvements in turbo chargers, intercoolers, injection systems, engine management systems, bearings, friction reduction and material sciences. The use of aluminium and ceramics has reduced engine weight considerably. Comparing current technologies, the diesel cycle produces lower emissions per MJ output than Otto cycle engines. It should be noted that the process energy costs for ultra-low sulphur diesel are higher than regular diesel and therefore the effective emissions become higher than for the Otto cycle. For both cycles, automatic gearboxes have around a 90% energy transmission efficiency and hence increase emissions by around 11% and four-wheel drive transmissions can increase losses further by up to 5%.

Biodiesel can be substituted directly as a fuel in modern diesel engines, giving similar thermal efficiencies but with a slightly lower carbon content than diesel leading to lower actual CO_2 emissions per km.

Railway transport emissions can also be improved by using biofuels. Energy use by trains has been reduced over the years by moving from DC traction motors and generators to AC systems. Rolling stock has become lighter with new designs and materials and rail tracks have improved giving less friction. The move from diesel to electric trains has also reduced energy consumption as this has reduced the moving mass of the engines. However, most electricity comes from the national grid and this has a significant efficiency penalty because of the distribution network. When a comparison of emissions is made between diesel/electric and fossil fuel power plant, grid supplied electric trains, the former have lower carbon emissions (Table 5). It was assumed that it takes 3.7 kW (5 HP) to transport one person at 100 km h^{-1} on the flat for all technologies.

Comparisons were made for train traction from electricity generated by different fuels for both CHP and combined cycle where appropriate which demonstrated the emission gains of new generation technologies. Having numerous distributed power generating systems instead of a large central power plant eliminates a portion of the distribution losses, all of which have less emissions than diesel traction. Biomass in a CHP to supply the electric railway, or using biodiesel to fuel a diesel/electric train, would achieve a carbon neutral transport system.

Biofuel costs

For ethanol the cost of the raw material is usually between 25% and 40% of total production costs. The wide range is due to the local price of feedstock being impacted by local agricultural subsidies and hence is between US\$22–61 dry t^{-1} in Europe and US\$12–18 dry t^{-1} in North America (von Sivers & Zacchi, 1996; S&T^2, 2004). Because of the recovery of distillers grains for animal feed as a coproduct, ethanol from cereals has an average price of around US\$0.32 L^{-1} (S&T^2, 2004). Ethanol from sugarcane is down to US\$0.20 L^{-1} in Brazil and since 1999 has remained below the equivalent Rotterdam gasoline price (Goldemberg *et al.*, 2004). The estimated cost of producing bioethanol from wood varies between US\$0.50 and 0.76 L^{-1} with lower costs coming from plants with capacities above 600 000 t yr^{-1} (Galbe & Zacchi, 2002; AEA Technology, 2003; S&T^2, 2004).

The costs of producing biodiesel from vegetable oils range between US\$0.62 and 0.80 L^{-1}, with higher crop production costs found in countries with restricted growing seasons and high food demand (AEA Technology, 2003). Used cooking oil and animal fat feedstocks produce cheaper biodiesel at around US\$0.40–0.60 L^{-1} (S&T^2, 2004; EECA, 2005). More efficient interesterifica-

Table 4 Comparative efficiencies of automotive movers and emissions per vehicle km compared for a range of technologies and fuels

Prime mover	Fuel	Origin	Cycle	Fuel CO_2 emission* ($kg\,CO_2\,MJ^{-1}$)	Work/heat conversion theoretical maximum† (%)	Work/heat conversion effective† (%)	Transmission efficiency† (%)	Actual CO_2 emission‡ ($kg\,CO_2\,MJ^{-1}$)	Emission per vehicle km§ ($g\,CO_2\,km^{-1}$)
Petrol naturally aspirated	Gasoline	Crude	Otto	0.072	59	26	90	0.309	159
Petrol turbo and management system	Gasoline	Crude	Otto	0.072	59	32	90	0.251	129
Petrol turbo and management system hybrid	Gasoline	Crude	Atkinson	0.072	59	36	100	0.201	103
Petrol turbo and management system	Methanol	N gas	Otto	0.100	53	38	90	0.293	150
Petrol turbo and management system	Ethanol	Crude	Otto	0.065	53	38	90	0.191	98
Automotive diesel	Diesel	Crude	Diesel	0.078	62	35	90	0.248	127
Automotive turbo diesel	Diesel	Crude	Diesel	0.078	62	42	90	0.207	106
Automotive turbo diesel	Lo S Diesel	Crude	Diesel	0.082	62	35	90	0.260	134
Automotive diesel	Biodiesel	Oil seed rape	Diesel	0.000	62	35	90	0	0
Automotive turbo diesel	Biodiesel	Oil seed rape	Diesel	0.000	62	42	90	0	0
Petrol turbo and management system	Methanol	Wood	Otto	0.000	53	38	90	0	0
Petrol turbo and management system	Ethanol	Wheat	Otto	0.000	53	38	90	0	0
Petrol turbo and management system	Ethanol	Straw	Otto	0.000	53	38	90	0	0
Petrol turbo and management system	Ethanol	Wood	Otto	0.000	53	38	90	0	0
Theoretical best petrol	Gasoline	Crude	Otto	0.072	59	59	90	0.136	70
Theoretical best diesel	Diesel	Crude	Diesel	0.078	62	62	90	0.140	72
Theoretical best methanol	Methanol	Natural gas	Otto	0.100	53	53	90	0.212	109
Theoretical best ethanol	Ethanol	Crude	Otto	0.065	53	53	90	0.138	71

*From Table 1.

†Rodgers & Mayhew (1967).

‡No infrastructure carbon cost in included for the roads nor for the vehicle.

§Assuming 513 kJ km^{-1} traveled with car requiring 15 kW (20 HP) to keep vehicle running at 100 km h^{-1} on level terrain

Table 5 Comparative efficiencies of railway traction prime movers and emissions per passenger km compared between diesel and electric power technologies using a range of fuels

Prime mover type	Fuel	Origin	Cycle	Fuel CO_2 emission* ($kg\,CO_2\,MJ^{-1}$)	Maximum possible work/heat conversion †(%)	Effective work/heat conversion †(%)	Effective generator efficiency ‡(%)	Effective motor efficiency ‡(%)	Total efficiency cumulative (%)	CO_2 emission§ ($kg\,CO_2\,MJ^{-1}$)	Carbon emissions per kilometer¶ ($g\,CO_2\,km^{-1}$)
Diesel electric DC–DC	Diesel	Crude	Diesel	0.078	62	49	85	85	35	0.221	28
Diesel electric AC–DC	Diesel	Crude	Diesel	0.078	62	49	95	85	40	0.197	25
Diesel electric AC–AC	Diesel	Crude	Diesel	0.078	62	49	95	95	44	0.177	23
Electric DC	Electricity	UK grid		0.288				85	85	0.245	31
Electric AC	Electricity	UK grid		0.288				95	95	0.274	35
Electric AC	Electricity	Natural gas CC		0.123				95	95	0.117	15
	Electricity	Coal CHP		0.121				95	95	0.115	15
	Electricity	Oil CHP		0.082				95	95	0.078	10
Electric AC	Electricity	Natural Gas CHP		0.084				95	95	0.080	10
	Electricity	Wood CHP		0.000				95	95	0.000	0
Electric AC	Electricity	Miscanthus CHP		0.000				95	95	0.000	0

*From Tables 1 and 3.
†Rodgers & Mayhew (1967).
‡Hughes (1967).
§No carbon cost is added for infrastructure cost such as the tracks and the trains.
¶Emissions for $128\,kJ\,km^{-1}\,passenger^{-1}$, assuming 3.7 kW (5 HP) is required to transport one person on level terrain at $100\,km\,h^{-1}$.

tion processes will reduce these costs further (Körbitz *et al*., 2004).

In order to prove the suitability of biodiesel fuel and to develop compatible engine technology, several engine manufacturers carried out extensive fleet tests with various blends in the 1970s following the oil price shocks and also more recently. Governments and industry have cooperated in the development of quality parameters, and national standards have been established. European wide standards, created by the European Standardization Organization (CEN) at the behest of the European Commission, are used by engine manufacturers to approve the use of consistent quality biodiesel for their vehicles.

The EC Biofuels Directive of 2003 required a voluntary market share of 5.75% biofuels for each member state by 2010. Other countries (including Netherlands, India, China, Thailand and New Zealand) and individual states in the USA and Canada have since established mandatory biofuels targets and yet others have removed excise taxes. Such policies should see additional capacity for bioethanol and biodiesel production developed.

Cobenefits, constraints, trade-offs and barriers to market penetration

Growing energy crops is a nontraditional land use option which may boost farm incomes and the rural economy in general (Askew & Holmes, 2001). A number of annual and perennial species convert solar energy into stored biomass relatively efficiently. High yielding vegetative grasses, short rotation forests and C4 plants when grown on a commercial scale can produce over $400\,\mathrm{GJ\,ha^{-1}\,yr^{-1}}$ 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 (Sims *et al*., 1999). 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 $143\,\mathrm{kg\,t^{-1}}$ of fresh cane (70% moisture content, wet basis) between 1990 and 2001.

Energy crop production has a number of other potential cobenefits relating to social, environmental and economic aspects of production (Table 6).

In spite of the large potential for biomass and the significant cobenefits available, there are often practical difficulties when implementing bioenergy projects. These result particularly from its dirty and low technology image by the public; the challenge to secure biomass fuel supplies; its relative low-energy density compared with fossil fuels; the high demand for water and nutrients by some energy crops; and the difficulties for conversion plants in achieving economies of scale when using widespread feed stocks, negotiating financing and contractual arrangements, and obtaining resource and planning consents. Climate change effects in some regions from more frequent or extreme droughts, floods, typhoons, etc. may also impact on future biomass production potential.

Table 6 Potential co-benefits of biomass uptake and energy crop production can be social, environmental as well as economic (based on IEA, 2005)

Social aspects	Environmental aspects	Economic aspects
Improved access to basic services (pumped water, electric lighting). Creation of jobs, livelihoods. Increase of labour, power, access to resources. Pride and independence. Support for rural communities. Improved social cohesion. Reduced dependency on imported oil.	Reduced pressure on finite natural resources. Reduced landfill waste and associated issues. Protection of groundwater supplies. Reduced dryland salinity and soil erosion. Maintenance of logging sites in a clean state for reforestation. Increased terrestrial carbon sinks and reservoirs. The return of derelict land into production with enhanced biodiversity. Improved quality of degraded soils if grown as riparian strips. Quality of waterways and lakes can be improved by reducing nutrient loadings. Reduced GHG emissions via fossil fuel substitution.	Concentrated sources of biomass (e.g. residues from sawmills, landfill gas), can already compete with fossil fuels. Trade of 'carbon credits' will impact the economics of biomass and other energy systems. $/GJ of biomass delivered to the conversion plant gate will be secure if contracted for the medium to long term. Cycling of goods and services within the local economy instead of outsourcing keeps money in the economy.

Among other constraints are the competition for land and the economics of implementation, which depend upon the market for products and the availability of subsidies. In an economic analysis, McCarl & Schneider (2001) showed that the implementation of bioenergy projects also depends upon the price of carbon. At low prices, climate mitigation focuses on practices that are most consistent with existing production (e.g. changes in energy efficiency, tillage practices and livestock diets). At higher prices, activities that generate higher rates of emissions offsets, such as energy cropping, soil carbon uptake and afforestation, are introduced.

Agricultural grants and subsidies in the EU under the Common Agricultural Policy have delivered considerable benefits to many energy crop producers. 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 US$GJ^{-1} can be more than double the exrefinery cost of petrol and diesel, even where the crop energy yield is high in terms of GJ ha^{-1} yr^{-1}.

The quantity of land available for the growth of energy crops is limited by land suitability, and the need to provide food and fibre for an increasing global population which increasingly expects the level and quality of diet and goods currently mainly enjoyed in industrialized countries. Given this competition for land, energy crops will need to be assessed in terms of the energy that can be created per unit of land.

The world average yields of wheat and maize (FAO, 2005), the Brazilian average for sugarcane, the US average for maize and the EU averages for sugar beet, SRC wood and miscanthus, together with the energy inputs and the amount of raw material required to produce the final biomass fuel, were used to calculate the fuel energy density ha^{-1} knowing the energy density of the fuel. These values are shown for various forms of bioenergy in Table 7. Yield can vary greatly as does the energy density being proportional to the yield. However, this comparison shows the highest energy density crops are wood, miscanthus, sugarcane and sugar beet.

Trade reforms and continuing pressure to reduce subsidies that lead to excess food and fibre production, means that agricultural support mechanisms may well change in the future. Biomass sourced from energy crops may then need to compete with fossil fuels on its own merits. Future carbon mitigation credits will help.

Energy cropping also gives new risks to land managers. Traditionally, annual food crops are sold within a year of planting. By contrast perennial energy crops such as miscanthus and SRC do not produce economic yields until a few years after establishment and even then commercial yields tend to be below what is theoretically possible, given variations in rainfall, soil types, interception radiation and conversion efficiencies. For example, the theoretical yield of short rotation poplar is in excess of 30 oven dry tonnes(odt) ha^{-1} yr^{-1}, and that of miscanthus grown in research plots, in excess of 40 odt ha^{-1} yr^{-1} (Clifton-Brown *et al*., 2001; Heaton *et al*., 2004). However, at the commercial scale 7–12 odt ha^{-1} yr^{-1} is more likely (Rae *et al*., 2004). The risks associated with potential changes in market for product are therefore greater and a high gross margin is necessary to attract growers to change from traditional land uses. 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. Recognizing 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.

Another potential barrier to implementation is the power generation and distribution infrastructure. Some countries (e.g. Scandinavian nations) have a power generation system with many small power stations distributed widely, and not all grid connected. Others (e.g. Western Europe, USA) have a centralized transmission grid in which large power generation occurs at relatively few locations and is then distributed widely. The former energy distribution infrastructure is more favourable for bioenergy use, and in such countries the market penetration of bioenergy is significantly higher than in countries with centralized power generation. This is particularly the case where municipal district heating schemes enable efficient CHP systems to be incorporated.

At present, there are few ethical or environmental issues associated with energy crops, but widespread use of bioenergy may raise concerns in the future. Examples include the impact of monocultures of often nonnative energy crops grown on large areas of land. There are potential implications for biodiversity (both positive and negative) and the perception by the public of what rural landscapes should look like. In some regions there may be ethical issues and public opposition to energy crops if genetically modified, and if using land when there are likely to be food shortages elsewhere in the world.

The role of energy crops in mitigating climate change

The potential contribution of energy crops to climate change mitigation can be assessed by multiplying the area planted by the fossil fuel carbon offset per area (minus any increases in non-CO_2 GHGs). Using the

Table 7 Energy density of useable fuel energy per unit of land area for a selection of solid biomass fuels and liquid biofuels

Fuel	Origin	Energy density of fuel* ($MJ\,kg^{-1}$)	Process energy cost for fuel (process* $MJ\,MJ^{-1}$ fuel)	Carbon density of fuel (kg c kg fuel)	Crop yield,‡† ($t\,ha^{-1}$)	Weight of crop to make fuel (kg (raw) kg $(fuel)^{-1}$)	Crop required including process† (kg (raw) kg $(fuel)^{-1}$)‡,§	Fuel produced per ha ($t\,ha^{-1}$†)	Fuel energy per ha. ($GJ\,ha^{-1}$†)
Biodiesel	Oil seed rape	43.7	0.44	0.61	3.00	3.28	4.72	0.64	28
Methanol	Pyrolysis/wood	25.0	1.00	0.51	10.00	1.00	2.00	5.00	125
Ethanol	Wheat	35.0	0.46	0.52	2.64	4.23	6.19	0.43	15
Ethanol	Maize	35.0	0.29	0.52	4.17	3.04	3.92	1.06	37
Ethanol	Sugarcane	35.0	0.50	0.52	61.84	12.60	18.90	3.27	115
Ethanol	Sugarbeet	35.0	0.50	0.52	60.00	12.60	18.85	3.18	111
Ethanol	Wood chips	35.0	0.57	0.52	10.00	5.50	8.64	1.16	41
Ethanol	Wheat straw	35.0	0.57	0.52	1.92	5.00	7.85	0.25	9
Wood	SRC	21.0	0.25	0.44	10.00	1.00	1.25	8.02	168
Miscanthus	Miscanthus	15.0	0.20	0.44	16.22	1.00	1.20	13.52	203
Straw	Maize silage	20.0	0.21	0.44	20.50	1.00	1.21	16.98	340
Charcoal	from wood	29.0	1.00	1.00	10.00	1.00	2.00	5.00	145

*Assumes all energy for production comes from the product fuel – straw/residue is returned to soil for carbon neutral agriculture.
†Table 1.
‡ Taken from world average for wheat, maize, average Brazil for sugarcane, average Europe for sugarbeet, wood SRC and miscanthus & average New Zealand for maize silage.
§ Dry weight for all crops except sugarcane and sugarbeet.

Table 8 Energy crop areas in 2025 projected for each region and globally based on the IMAGE 2.2 model for four IPCC scenarios

	Energy crop area in 2025 (ha $\times 10^{-3}$) under each scenario			
Region	B1	A1b	B2	A2
North America	14 992	31 004	41 132	34 985
Central America	3406	6489	10 047	7550
South America	8521	8722	15 687	8219
Northern Africa	182	0	0	0
Western Africa	182	257	142	102
Eastern Africa	101	137	80	53
Southern Africa	549	791	1376	706
OECD Europe	7266	19 681	17 886	15 092
Eastern Europe	514	1826	2715	1647
Former USSR	3534	8916	7296	6092
Middle East	526	0	0	0
South Asia	5788	12469	12726	5171
East Asia	10 068	18 097	21 609	12 163
Southest Asia	1854	4501	7406	3521
Oceania	198	537	1594	1057
Japan	650	1150	1510	855
World	58 332	114 577	141 206	97 212

areas of energy crops projected under IPCC scenarios for 2025 (IPCC, 2000) by the IMAGE 2.2 integrated assessment model (Strengers *et al*., 2004; Table 8), the global and regional GHG mitigation potential of energy crops can be calculated.

In calculating the GHG mitigation potential of energy crops, the following assumptions were used:

- mean regional yields range between 4 and 12 odt ha^{-1} (Andersen *et al*., 2005);
- savings of 1.61 t of oil CO_2-eq odt^{-1} of biomass consumption (Cannell, 2003);
- conversion plant efficiencies giving energy outputs of 7.4 GJ odt^{-1} biomass for electricity generation and 12.95 GJ odt^{-1} biomass for CHP production (Cannell, 2003); and
- increased GHG emissions of methane and nitrous oxide from biomass combustion using IPCC defaults equivalent to 1.73 and 2.97 t CO_2-eq. ha^{-1} yr^{-1}, respectively (Smith *et al*., 2001).

Using the range of total areas (58–141 Mha) of energy crops projected for each IPCC scenario, then a low mean annual yield of 4 odt ha^{-1} across all scenarios would produce 230–700 M odt of biomass yr^{-1}. At the other end of the yield range, 12 odt ha^{-1} yr^{-1} would produce 560–1700 M odt yr^{-1}. Thus, energy crop production could deliver fossil fuel CO_2 savings between $\sim$ 360 and $\sim$ 2730 Mt CO_2 yr^{-1}, but this is offset by the increased GHG emissions of 270–660 Mt CO_2-eq. yr^{-1} from biomass combustion. Net GHG benefits were therefore estimated to be between $\sim$ 100 and 2070 Mt CO_2-eq. yr^{-1} (shown for each region in Fig. 2).

The 4.6–34 EJ of biomass energy potential depends upon yield and would generate $\sim$ 2–22 EJ yr^{-1} of useful energy, depending on the proportion of the energy used for generating heat, electricity or CHP. This is considerably less than the estimated technical potential by 2050 reported in the IPCC Third Assessment Report (TAR) (IPCC, 2001) of $\sim$ 400 EJ yr^{-1} which assumed 15 odt ha^{-1}, 20 GJ odt^{-1} and a higher maximum cultivated land area possibly being available (Table 9).

The estimates calculated here for biomass energy mitigation are also somewhat lower than those in the IPCC Second Assessment Report (SAR) of 1100–4800 Mt CO_2-eq. yr^{-1} (IPCC, 1996) because non-CO_2 GHGs are also accounted for. The estimates were also based on more conservative projected energy crop areas than the assumed 10–15% of agricultural land used in the SAR and the maximum 1.58 Gha land area available as quoted in the TAR. The projected emissions of carbon and also the emissions allowable for various atmospheric CO_2 stabilization trajectories were presented for each IPCC scenario (IPCC, 2000). From this the 'emission gaps' between projected emissions and the emissions necessary for 550 μmol mol^{-1} CO_2 stabilization were calculated. These were then compared with the GHG mitigation potentials offered by the range of projected energy crop areas. The additional land areas needed to be devoted to energy crops to close the emission gaps under high and low yields were then calculated (Table 10).

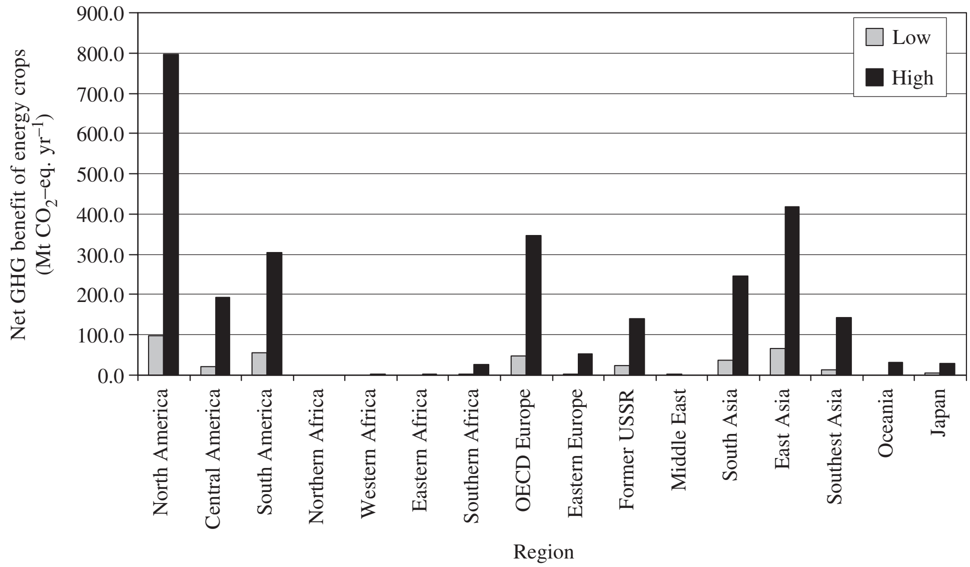

Fig. 2 Net GHG benefits from energy crops (Mt CO_2-eq. yr^{-1}) by region over a range of yields between 4 and 12 odt ha^{-1} yr^{-1}.

Table 9 Low and high estimates of the CO_2 emissions for each of four IPCC scenarios to reach the 550 μmol mol^{-1} stabilization trajectory in 2025; 'emission gaps' for each scenario; GHG mitigation potential offered by biomass options for each scenario; additional biomass energy necessary to reach 550 μmol mol^{-1} stabilization; and the area of energy crops necessary to close the emission gap under assumptions of low and high yields (4–12 odt ha^{-1} yr^{-1})

550 μmol mol^{-1} stabilization and other scenarios	550 μmol mol^{-1}	B1	A1b	B2	A2
Emission (Gt CO_2 yr^{-1})	35–40	30–60	35–65	35–50	45–50
Gap (comparing high-high yields) (Gt CO_2 yr^{11})	–	20	25	10	10
Biomass GHG mitigation in each scenario (Gt CO_2-eq. yr^{-1})	–	0.10–0.86	0.20–1.68	0.25–2.07	0.17–1.43
Additional biomass energy necessary for 550 μmol mol^{-1} stabilization (Gt CO_2-eq. yr^{-1})	–	19–20	23–25	8–10	8–10
Additional energy cropping area needed (ha × 10^6)	–	445–1750	610–2550	134–711	244–1090

By 2025, energy cropping could contribute GHG mitigation equivalent to between 0.5% and 20% of the emission gap. For each of the A1b, A2, B1 and B2 IPCC scenarios, to close the gap, the additional energy crop area in 2025 would need to be ∼5–20, ∼2–11, ∼8–30 and ∼1–5 times the projected area, respectively. If crop yields could be increased above the assumed 4–12 odt ha^{-1} yr^{-1}, the land area could be reduced accordingly.

Given that there will be increasing pressure on land to provide more food and fibre (Bruinsma, 2003), and given that the energy crop areas projected by IMAGE 2.2 are already ambitious, energy cropping alone by 2025 cannot close the projected emission gaps to achieve atmospheric CO_2 stabilization at 550 μmol mol^{-1}. In the longer term energy crops have the potential to form an important component in any portfolio of measures to tackle climate change which may also include the use of other renewable energy sources (e.g. Andersen *et al.*, 2005), carbon sequestration (Smith, 2004) and a range of other measures (IPCC, 2001).

Future prospects

Improving energy crop yields

Dedicated bioenergy crops are largely undomesticated and have not undergone the centuries of improvement that characterize our major food crops (Tuskan, 1998). Selection of appropriate crop species and genotypes for given locations to suit specific soil types and climate may be possible, but is at an early stage of under-

Table 10 Projection of *technical* energy potential from energy crops grown by 2050 (IPCC, 2001)

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* (EJ year^{-1})
Industrialized†	0.750	0.820	0.670	0.050	0.100	30
Latin America						
Central and 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‡	–	–	–	–	–	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	9.046	3.315	1.499	0.466	1.313	396
Total biomass energy potential, EJ year^{-1}						441§

Source: IPCC (2001).
*Assumed 15 odt ha^{-1} yr^{-1} and 20 GJ odt^{-1}.
†OECD and Economies in Transition.
‡For China, the numbers are projected values are not maximum estimates.
§Includes 45 EJ yr^{-1} of current traditional biomass.

standing for some energy crops and is unlikely to provide the magnitude of productivity gains necessary to allow the industry to develop. The genus *Eucalyptus,* for example, has over 600 species and identifying the most appropriate species and provenance for a given site is not well understood. Similarly inputs of agrichemicals and fertilizers, including returning nutrients and minerals in combustion ash, will require further analysis if energy crops are to be produced in a sustainable manner. Bioenergy crops must be optimized not maximized as low input systems requiring limited nutrients and chemical inputs are needed.

Traditional plant breeding, selection and hybridization techniques are slow, particularly in woody crops but also in vegetative grasses where even germplasm is in short supply. Much of the miscanthus currently being grown in Europe, for example, is from a sterile triploid that is propagated through expensive cuttings that may be susceptible to late frosts. In the USA, some long-term breeding of switch grass has produced large yield gains and this crop may begin to make a large contribution to biofuel production (Pedersen *et al*., 2005). Because of the limited breeding experience to date it is likely that large advances in bioenergy crops yields can be expected over the next few decades. New biotechnological routes as a result of the production of both nongenetically modified (non-GM) and GM plants are possible. In Table 11, target traits for improvement are identified.

Perennial crops are considered favourable to annual as establishment costs are reduced and soil chemistry and structure maintained. Both the quantity (the amount of biomass yield) and the quality (for example, the structure of the plant or the chemical nature of the feedstock) are identified as targets. Productivity gains are likely in C4 grasses such as miscanthus although the sensitivity of these grasses to low temperature must be resolved (Naidu & Long, 2004). A straightforward GM modification to improve yield in a tree such as poplar

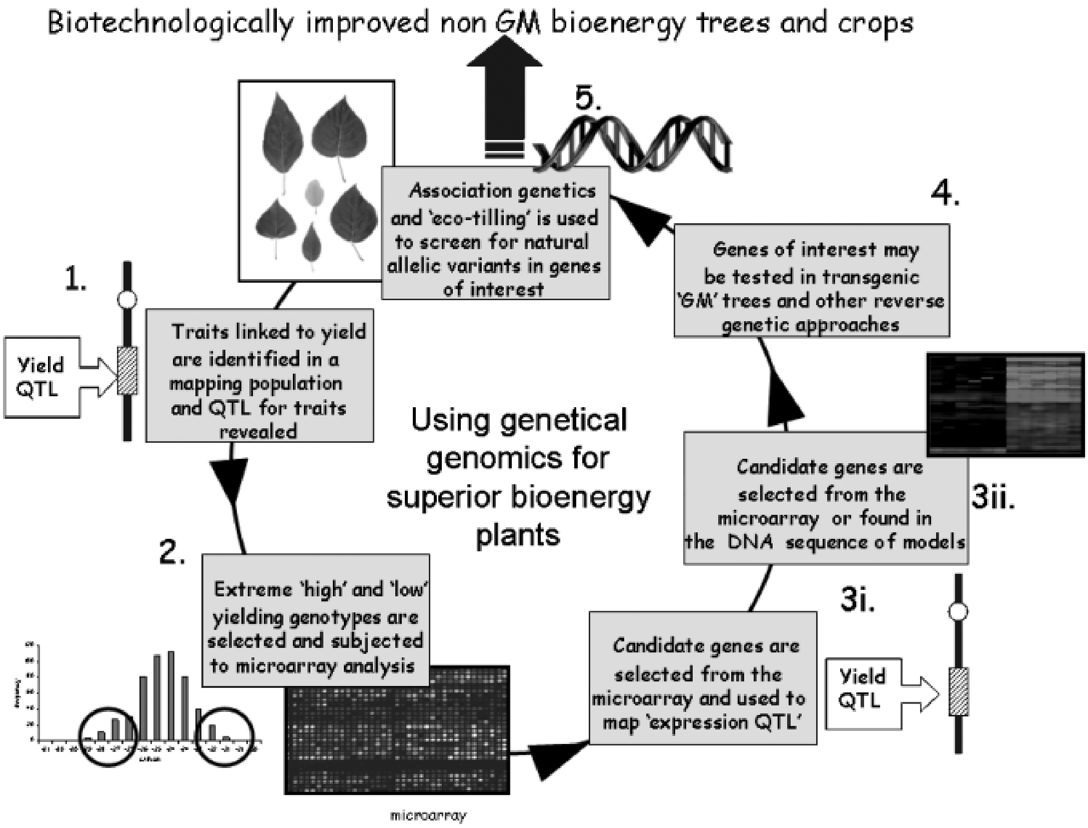

Fig. 3 Biotechnological improvement of energy crops links a molecular genetic and genomic approach and may produce biotechnological improved 'non-genetic modification (GM)' or 'GM' crops. (1) Areas of the genome responsible for complex traits such as yield and lignin quantity are identified as quantitative trait loci (QTL). (2) The population used to identify these QTL may be subjected to microarray analysis. (3) Genes associated with high yield are identified. Once candidate genes are available their colocation to QTL may be determined. (4) Genes can then be tested using GM approaches for over expression of knock-out. (5) Such GM plants could be marketed commercially. However, other approaches now exist to identify the genes in natural or mutagenized populations, and these plants are consequently non-'GM'.

has already been achieved. Hu *et al*. (1999) showed that down regulation of the genes for lignin synthesis resulted in taller trees although the structure of the trees was somewhat altered. Similar improvements using 'over expression' (increase in the activity of targeted genes) have also been performed with some success (Busov *et al*., 2003). Although GM energy crop species will perhaps be more acceptable to the public than will GM food crops, there are still concerns with the potential environmental impacts of such plants, including gene flow from nonnative to native plant relatives. As a result non-GM biotechnologies may remain particularly attractive. Early work to use molecular biology in plant improvement was focussed on molecular markers that could be used in the rapid screening of germplasm within a breeding population. Although this approach offers great potential to bioenergy crops (Tuskan, 1998), it has yet to be realized, often because linking these molecular markers or fingerprints to complex traits such as yield is extremely difficult because yield is likely to be controlled by many rather than single genes.

In contrast, a 'systems biology' approach using the latest technologies in genomics, particularly microarrays, can provide links between plant and crop performance and gene, cell and protein controls. Microarrays are solid surfaces (often glass slides) where DNA fragments representing genes are 'spotted'. The spots represent large efforts in sequencing. Currently for bioenergy crops, microarray resources only exist in poplar. However, willow has more than a 95% similarity at the level of DNA sequence and so transferability of the technology may be possible. Similarly transfer between maize and miscanthus is likely. The major advantage of microarrays is that they can be used to look at 'global gene expression' – to assess the importance of every gene to a process simultaneously. It should therefore be possible to differentiate many genes very quickly that are responsible for high tree yield (Fig. 3). A distinct advantage of poplar over any other tree, is that both physical and molecular genetic maps are available from which to deduce links between phenotypic traits and genes. These maps are important tools for the tree breeder because they enable identification of many areas of the genome controlling a trait, often termed quantitative trait loci (QTL). On a physical map the locations of identifiable landmarks (such as genes or molecular markers) are positioned regardless of inheritance, and usually measured in base pairs. Poplar is the only tree for which linkage information can be directly associated to the real physical sequence of DNA and the genes coding for traits. QTL for yield traits can be readily turned into underlying genes – or at least a long list of possible candidates can be identified by linking the microarray and QTL data (Boerjan, 2005). Once these genes are identified they can then be tested using a GM approach, both in the laboratory and in small controlled trials. Linking molecular genetic and genomic information is termed 'genetical genomics' and is beginning to provide a glimpse of what might be possible in the future. The latest ideas suggest that this genetical genomics information could be used in much wider natural populations to allow 'associations' between genes and phenotypic traits to be confirmed. Hence, 'non-GM' trees and grasses, improved through biotechnological advances, may finally become available to the grower.

Extracting high value products from energy crops

The future of energy may be intimately linked with the extraction of additional high value products from the biomass resource. Biomass can also provide a renewable source of hydrogen and a wide range of biomaterials and chemical feed stocks (Chisholm, 1994). All products that currently result from the processing of petrochemicals can be produced from biomass feedstocks. These include lubricants, polymers, high matrix composites, textiles, biodegradable plastics, paints, adhesives, thickeners, stabilizers and a range of cellulosics (Sims, 2004). Energy crops may become more economic if high value products are first extracted from them, with the residues used for lower value energy production.

The concept of using different fractions of the whole crop for food, stock feed, industrial and chemical feed stocks and energy is under development and a wide range of products and materials could be produced (Rexen & Blicher-Mathiesen, 1998). For example, a closed-loop pilot plant was constructed in New Zealand to fractionate biomass into a number of components (Sims, 2002). After washing and preheating, 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. The project successfully demonstrated the technical potential for jointly producing biomaterials and bioenergy.

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

Table 11 Potential targets for bioenergy crop improvement in future and their functional components and gene targets. Gene targets are mostly identified in model plants such as *Arabidopsis*

Trait targets for bioenergy crop improvement	Functional target (genes of potential interest)
Quantity traits	
Improve photosynthetic efficiency	Photosynthesis (Rubisco), photorespiration and other respiratory losses
Improve low-temperature tolerance in miscanthus and other vegetative grasses	Photosynthetic(Rubisco/PPDK)and leaf expansion control (XTHs)
Improve light interception through increased canopy greenness, longevity and branching	Understand bud flush and senescence and bud set in trees (phytochrome genes and others).
	Understand 'stay green' in grasses and seasonality of growth (phytochrome genes)
	Understand branching control (MAX)
Quality traits	
Modify ligno-cellulosic quality and quantity relative to whole plant	Lignin biosynthetic pathway (CAD)
Improve partitioning of carbon to roots	Phyto-hormone control of partitioning and rooting (IAA and cytokinin regulation genes)
Improve above-ground carbon capture	Leaf area development
	Genes controlling cell expansion (XTHs), and cell production (cylins and CDKs)
Improve water-use efficiency	Better stomatal regulation (ABA responsive genes, Ca^{2+} signaling). Increase fine root biomass.
Improve nitrogen use efficiency	Nitrogen metabolizing enzymes and mycorrhizal associations
Improve stress tolerance	Gene expression studies from model plants used to identify gene targets (LEAs for example)

Carbon offsets

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 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. Utilizing the accumulated carbon in the biomass 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.

If no policies are in place for supporting sustainable biomass production schemes or for incentivizing advanced bioenergy technologies, then the global share of bioenergy may decrease in the next few decades. The right criteria need to be in place to avoid serious negative impacts in terms of water use, biodiversity, and socio-economic issues. Long-term analyses using integrated assessment models (Read & Lermit, 2005) suggest that a combination of biomass technologies together with carbon capture and storage, will have an important bearing on the attainability and costs of low atmospheric CO_2 stabilization levels (below $450\,\mu mol\,mol^{-1}$). Where biomass is used as a feedstock for combustion, gasification or hydrogen production at a large-scale plant, it would be physically possible to capture, transport and sequester the CO_2. For solid biomass gasification projects at a smaller, more dispersed scale, the incorporation of the resulting charcoal into the soil to enhance crop growth, soil water holding capacity, and increase in soil carbon content could be feasible (Okimori *et al*., 2003). The potential to reduce atmospheric CO_2 concentrations relatively rapidly is the reason these options are being espoused as a possible solution to abrupt climate change.

Conclusions

The choice of measure to use when assessing the GHG mitigation of bioenergy partly depends on the limiting resource. Where the volume of residues available is restricted, the GHG mitigation per tonne of biomass used should be maximized. This suggests finding uses for biomass where carbon intensive fossil fuels can be replaced. When extra land is used to produce biomass, then the GHG mitigation potential per unit of land area is of greatest interest. When subsidies, tax exemptions, feed-in tariffs or similar measures are in place, then the GHG mitigation per unit of monetary support is relevant, taking into account cobenefits that may help to justify this support.

The social and environmental cobenefits, including carbon sequestration opportunities, will be drivers to future energy cropping uptake. The socio-economic potential for bioenergy is not always fully realized and sector growth has been slower than anticipated. Conversion technologies are well developed but mainly utilize feedstocks from solid and liquid organic waste streams which have limited supplies. Energy cropping is becoming better understood but it must be ecologically sustainable, environmentally acceptable to the public, and the delivered costs (US$GJ^{-1}) need to be competitive with fossil fuels.

Overall, bioenergy is envisaged to maintain its position as the highest contributor to global renewable energy in the short to medium term with dedicated energy crops set to provide a larger proportion of the biomass feedstock in the coming decades. Costs vary widely due to the complex characteristics of the resource, their site specificity, national policies, labour costs and efficiency of the conversion technologies used, but they are expected to continue to decline over time. Future opportunities for energy crops include development of biorefineries, atmospheric carbon 'scrubbing' and the growing trend towards small scale, distributed energy systems leading eventually perhaps towards a hydrogen economy.

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