# Potential Contribution of Bioenergy to the World's Future Energy Demand

This publication highlights the potential contribution of bioenergy to world energy demand. It summarises the wide range of biomass resources available and potentially available, the conversion options, and end-use applications. Associated issues of market development, international bioenergy trade, and competition for biomass are also presented. Finally, the potential of bioenergy is compared with other energy supply options.

IEA Bioenergy

IEA Bioenergy: ExCo: 2007:02

# ABSTRACT

Biomass is a versatile raw material that can be used for production of heat, power, transport fuels, and bioproducts. When produced and used on a sustainable basis, it is a carbon-neutral carrier and can make a large contribution to reducing greenhouse gas emissions. Currently, biomass-driven combined heat and power, co-firing, and combustion plants provide reliable, efficient, and clean power and heat. Production and use of biofuels are growing at a very rapid pace. Sugar cane-based ethanol is already a competitive biofuel in tropical regions. In the medium term, ethanol and high-quality synthetic fuels from woody biomass are expected to be competitive at crude oil prices above US$45 per barrel.

Feedstocks for bioenergy plants can include residues from agriculture, forestry, and the wood processing industry, as well as biomass produced from degraded and marginal lands. Biomass for energy may also be produced on good quality agricultural and pasture lands without jeopardising the world's food and feed supply if agricultural land use efficiency is increased, especially in developing regions. Revenues from biomass and biomass-derived products could provide a key lever for rural development and enhanced agricultural production. Certification schemes are already established to ensure sustainable production of forest biomass and could be adopted to guide residue recovery and energy crop production. Biomass utilisation will be optimised by processing in biorefineries for both products and energy carriers.

Given these possibilities, the potential contribution of bioenergy to the world energy demand of some 467 EJ per year (2004) may be increased considerably compared to the current 45-55 EJ. A range from 200-400 EJ per year in biomass harvested for energy production may be expected during this century. Assuming expected average conversion efficiencies, this would result in 130-260 EJ per year of transport fuels or 100-200 EJ per year of electricity.

# INTRODUCTION

Global energy demand is growing rapidly. The total current (2004) commercial energy use amounts to some 467 EJ [IEA, 2006a], and about 88% of this demand is met by fossil fuels. Energy demand is expected to at least double or perhaps triple during this century.

At the same time, concentrations of greenhouse gases (GHGs) in the atmosphere are rising rapidly, with fossil fuel-derived $CO_2$ emissions being the most important contributor. In order to minimise related global warming and climate change impacts, GHG emissions must be reduced to less than half the global emission levels of 1990. In addition, security of energy supply is a global issue. A large proportion of known conventional oil and gas reserves are concentrated in politically unstable regions, and increasing the diversity in energy sources is important for many nations to secure a reliable and constant supply of energy.

In this context, biomass for energy can play a pivotal role. Energy from biomass, when produced in a sustainable manner, can drastically reduce GHG emissions compared to fossil fuels. Most countries have biomass resources available, or could develop such a resource, making biomass a more evenly spread energy supply option across the globe. It is a versatile energy source, which can be used for producing power, heat, liquid and gaseous fuels, and also serves as a feedstock for materials and chemicals.

This publication has been produced by the IEA Bioenergy Executive Committee based on the considerable information available from Member Countries. It highlights the contribution of bioenergy in meeting the world's future energy demand, through state-of-the-art research and market development. It also explores the routes for bioenergy to achieve its potential.

*Mechanised harvesting of small trees for biofuel (Courtesy Dr Arto Timperi, Timberjack)*

## Current use of biomass for energy

Over the past decades, the modern use of biomass has increased rapidly in many parts of the world. In the light of the Kyoto GHG reduction targets, many countries have ambitious targets for further biomass utilisation. Oil price increases have also increased the level of interest in bioenergy.

Current global energy supplies are dominated by fossil fuels (388 EJ per year), with much smaller contributions from nuclear power (26 EJ) and hydropower (28 EJ). Biomass provides about 45 ± 10 EJ, making it by far the most important renewable energy source used. On average, in the industrialised countries biomass contributes less than 10% to the total energy supplies, but in developing countries the proportion is as high as 20-30%. In a number of countries biomass supplies 50-90% of the total energy demand. A considerable part of this biomass use is, however, non-commercial and relates to cooking and space heating, generally by the poorer part of the population. Part of this use is commercial, i.e., the household fuelwood in industrialised countries and charcoal and firewood in urban and industrial areas in developing countries, but there are very limited data on the size of those markets. An estimated 9 ± 6 EJ are included in this category [WEA, 2000 and 2004].

Modern bioenergy (commercial energy production from biomass for industry, power generation, or transport fuels) makes a lower, but still very significant contribution (some 7 EJ per year in 2000), and this share is growing. It is estimated that by 2000, 40 GW of biomass-based electricity production capacity was installed worldwide (producing 0.6 EJ electricity per year) and 200 GW of heat production capacity (2.5 EJ heat per year) [WEA, 2000]. Biomass combustion is responsible for over 90% of the current production of secondary energy carriers from biomass. Combustion for domestic use (heating, cooking), waste incineration, use of process residues in industries, and state-of-the-art furnace and boiler designs for efficient power generation all play their role in specific contexts and markets.

Biofuels, mainly ethanol produced from sugar cane and surpluses of corn and cereals, and to a far lesser extent biodiesel from oil-seed crops, represent a modest 1.5 EJ (about 1.5%) of transport fuel use worldwide. Global interest in transport biofuels is growing, particularly in Europe, Brazil, North America, and Asia (most notably Japan, China and India) [WEA, 2000/2004; IEA, 2006b]. Global ethanol production has more than doubled since 2000, while production of biodiesel, starting from a much smaller base, has expanded nearly threefold. In contrast, crude oil production has increased by only 7% since 2000 [WorldWatch Institute, 2007].

## Bioenergy policies and market prospects

Due to rising prices for fossil fuels (especially oil, but also natural gas and to a lesser extent coal) the competitiveness of biomass use has improved considerably over time. In addition, the development of $CO_2$ markets (emission trading), as well as ongoing learning and subsequent cost reductions for biomass and bioenergy systems, have strengthened the economic drivers for increasing biomass production, use, and trade [Schlamadinger et al., 2006]. Biomass and bioenergy are now a key option in energy policies. Security of supply, an alternative for mineral oil and reduced carbon emissions are key reasons. Targets and expectations for bioenergy in many national policies are ambitious, reaching 20-30% of total energy demand in various countries. Similarly, long-term energy scenarios also contain challenging targets.

Sufficient biomass resources and a well-functioning biomass market that can assure reliable, sustainable, and lasting biomass supplies are crucial preconditions to realise such ambitions. To date, various countries have considerable experience with building biomass markets and linking available resources with market demand. Examples are found in Brazil, Sweden, Finland, Canada, and the Netherlands. Relatively recently, international trade in biomass resources has become part of the portfolio of market dealers and volumes traded worldwide have increased at a very rapid pace with an estimated doubling of volumes in several markets over the past few years [Faaij et al., 2005].

## GLOBAL BIOMASS RESOURCES

Various biomass resource categories can be considered: residues from forestry and agriculture, various organic waste streams and, most importantly, the possibilities for dedicated biomass production on land of different categories, e.g., grass production on pasture land, wood plantations and sugar cane on arable land, and low productivity afforestation schemes for marginal and degraded lands.

The potential for energy crops depends largely on land availability considering that worldwide a growing demand for food has to be met, combined with environmental protection, sustainable management of soils and water reserves, and a variety of other sustainability requirements. Given that a major part of the future biomass resource availability for energy and materials depends on these complex and related factors, it is not possible to present the future biomass potential in one simple figure.

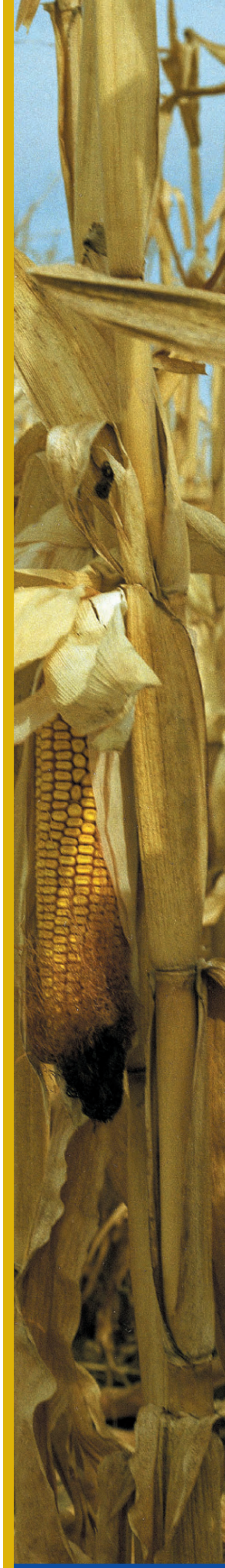
Table 1 provides a synthesis of analyses of the longer term potential of biomass resource availability on a global scale. Also, a number of uncertainties are highlighted that can affect biomass availability. These estimates are sensitive to assumptions about crop yields and the amount of land that could be made available for the production of biomass for energy uses, including biofuels. Critical issues include:

- *Competition for water resources*: Although the estimates presented in Table 1 generally exclude irrigation for biomass production, it may be necessary in some countries where water is already scarce.
- *Use of fertilisers and pest control techniques*: Improved farm management and higher productivity depend on the availability of fertilisers and pest control. The environmental effects of heavy use of fertiliser and pesticides could be serious.
- *Land-use*: More intensive farming to produce energy crops on a large-scale may result in losses of biodiversity. Perennial crops are expected to be less harmful than conventional crops such as cereals and seeds, or even able to achieve positive effects. More intensive cattle-raising would also be necessary to free up grassland currently used for grazing.
- *Competition with food and feed production*: Increased biomass production for biofuels out of balance with required productivity increases in agriculture could drive up land and food prices.

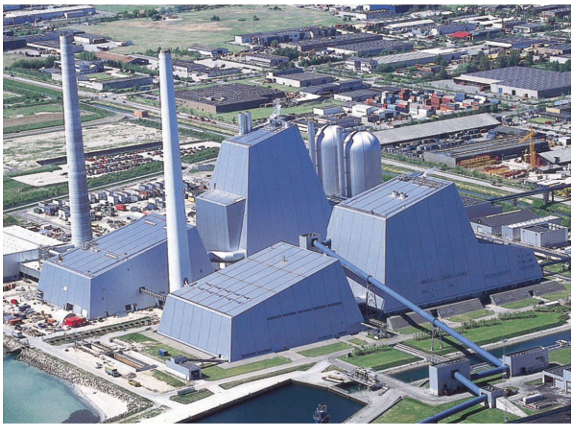
**Table 1:** Overview of the global potential of biomass for energy (EJ per year) to 2050 for a number of categories and the main preconditions and assumptions that determine these potentials [Sources: Berndes et al., 2003; Smeets et al., 2007; Hoogwijk et al., 2005a].

| Biomass category | Main assumptions and remarks | Energy potential in biomass up to 2050 |
|---|---|---|
| Energy farming on current agricultural land | Potential land surplus: 0-4 Gha (average: 1-2 Gha). A large surplus requires structural adaptation towards more efficient agricultural production systems. When this is not feasible, the bioenergy potential could be reduced to zero. On average higher yields are likely because of better soil quality: 8-12 dry tonne/ha/yr* is assumed. | 0 – 700 EJ (more average development: 100 – 300 EJ) |
| Biomass production on marginal lands. | On a global scale a maximum land surface of 1.7 Gha could be involved. Low productivity of 2-5 dry tonne/ha/yr.* The net supplies could be low due to poor economics or competition with food production. | <60 – 110 EJ |
| Residues from agriculture | Potential depends on yield/product ratios and the total agricultural land area as well as type of production system. Extensive production systems require re-use of residues for maintaining soil fertility. Intensive systems allow for higher utilisation rates of residues. | 15 – 70 EJ |
| Forest residues | The sustainable energy potential of the world's forests is unclear – some natural forests are protected. Low value: includes limitations with respect to logistics and strict standards for removal of forest material. High value: technical potential. Figures include processing residues | 30 - 150 EJ |
| Dung | Use of dried dung. Low estimate based on global current use. High estimate: technical potential. Utilisation (collection) in the longer term is uncertain | 5 – 55 EJ |
| Organic wastes | Estimate on basis of literature values. Strongly dependent on economic development, consumption and the use of bio-materials. Figures include the organic fraction of MSW and waste wood. Higher values possible by more intensive use of bio-materials. | 5 – 50 EJ |
| Combined potential | Most pessimistic scenario: no land available for energy farming; only utilisation of residues.<br>Most optimistic scenario: intensive agriculture concentrated on the better quality soils.<br>In parentheses: average potential in a world aiming for large-scale deployment of bioenergy. | 40 – 1100 EJ<br>(200 - 400 EJ) |

* Heating value: 19 GJ/tonne dry matter.



Focussing on the more average estimates of biomass resource potentials, energy farming on current agricultural (arable and pasture) land could, with projected technological progress, contribute 100 - 300 EJ annually, without jeopardising the world's future food supply. A significant part of this potential (around 200 EJ in 2050) for biomass production may be developed at low production costs in the range of €2/GJ assuming this land is used for perennial crops [Hoogwijk et al., 2005b; WEA, 2000]. Another 100 EJ could be produced with lower productivity and higher costs, from biomass on marginal and degraded lands. Regenerating such lands requires more upfront investment, but competition with other land-uses is less of an issue and other benefits (such as soil restoration, improved water retention functions) may be obtained, which could partly compensate for biomass production costs.



*The Avedore Powerstation, near Copenhagen shows prize winning architecture (Courtesy Thomas Scottt Lund, Energi E2, Denmark)*

Combined and using the more average potential estimates, organic wastes and residues could possibly supply another 40-170 EJ, with uncertain contributions from forest residues and potentially a significant role for organic waste, especially when biomaterials are used on a larger scale. In total, the bioenergy potential could amount to 400 EJ per year during this century. This is comparable to the total *current* fossil energy use of 388 EJ.

Key to the introduction of biomass production in the suggested orders of magnitude is the rationalisation of agriculture, especially in developing countries. There is room for considerably higher land-use efficiencies that can more than compensate for the growing demand for food [Smeets et al., 2007].

The development and deployment of perennial crops (in particular in developing countries) is of key importance for bioenergy in the long run. Regional efforts are needed to deploy biomass production and supply systems adapted to local conditions, e.g., for specific agricultural, climatic, and socio-economic conditions.

## CONVERSION OPTIONS AND OUTLOOK

Conversion routes for producing energy carriers from biomass are plentiful. Figure 1 illustrates the main conversion routes that are used or under development for production of heat, power and transport fuels. Key conversion technologies for production of power and heat are combustion and gasification of solid biomass, and digestion of organic material for production of biogas. Main technologies available or developed to produce transportation fuels are fermentation of sugar and starch crops to produce ethanol, gasification of solid biomass to produce syngas and synthetic fuels (like methanol and high quality diesel), and extraction of vegetal oils from oilseed crops, which can be esterified to produce biodiesel.

The various technological options are in different stages of deployment and development. Tables 2 and 3 provide a compact overview of the main technology categories and their performance with respect to energy efficiency and energy production costs. The 'End-use Applications' section discusses the likely deployment of various technologies for key markets in the short- and the long-term.

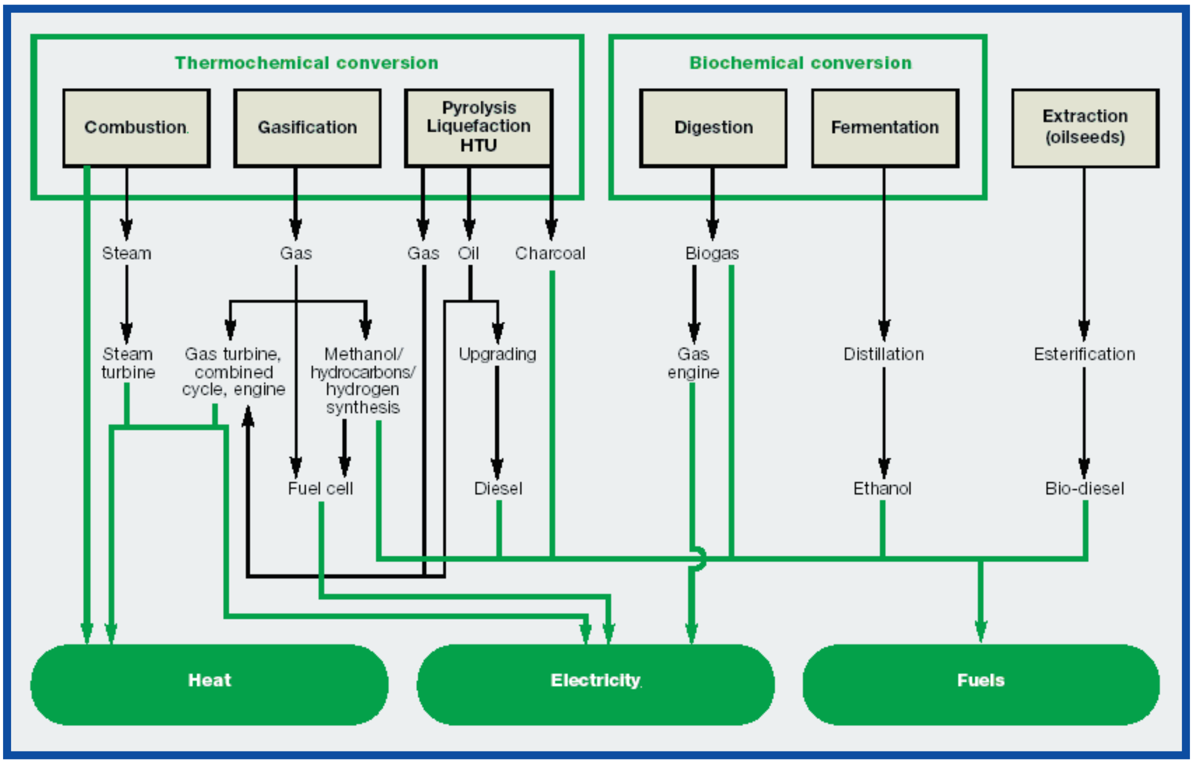


**Figure 1:** Main conversion options for biomass to secondary energy carriers [WEA, 2000]. Some categories represent a wide range of technological concepts as well as capacity ranges at which they are deployed, and these are dealt with further in the text.

**Table 2:** **Overview of current and projected performance data for the main conversion routes of biomass to power and heat and summary of technology status and deployment.** Due to the variability of technological designs and conditions assumed, all costs are indicative [van Loo and Koppejan, 2002; Knoef, 2005; USDOE, 1998; Dornburg and Faaij, 2001].

| Conversion option | Typical capacity | Net efficiency (LHV basis) | Investment cost ranges (€/kW) | Status and deployment |
|---|---|---|---|---|
| Biogas production via anaerobic digestion | Up to several MWe | 10-15% electrical (assuming on-site production of electricity) | | Well established technology. Widely applied for homogeneous wet organic waste streams and waste water. To a lesser extent used for heterogeneous wet wastes such as organic domestic wastes. |
| Landfill gas production | Generally several hundred kWe | As above. | | Very attractive GHG mitigation option. Widely applied and, in general, part of waste treatment policies of many countries. |
| Combustion for heat | Residential:<br>5-50 kWth<br>Industrial:<br>1-5 MWth | Low for classic fireplaces, up to 70-90% for modern furnaces. | ∼100/kWth for logwood stoves,<br>300-800/kWth for automatic furnaces,<br>300-700/kWth for larger furnaces | Classic firewood use still widely deployed, but not growing. Replacement by modern heating systems (i.e., automated, flue gas cleaning, pellet firing) in e.g., Austria, Sweden, Germany ongoing for years. |
| Combined heat and power | 0.1-1 MWe<br>1-20 MWe | 60-90% (overall)<br>80-100% (overall) | 3500 (Stirling)<br>2700 (ORC)<br>2500-3000 (Steam turbine) | Stirling engines, steam screw type engines, steam engines, and organic rankine cycle (ORC) processes are in demonstration for small-scale applications between 10 kW and 1 MWe. Steam turbine based systems 1-10 MWe are widely deployed throughout the world. |
| Combustion for power generation | 20->100 MWe | 20-40% (electrical) | 2.500 –1600 | Well established technology, especially deployed in Scandinavia and North America; various advanced concepts using fluid bed technology giving high efficiency, low costs and high flexibility. Commercially deployed waste to energy (incineration) has higher capital costs and lower (average) efficiency. |
| Co-combustion of biomass with coal | Typically 5-100 MWe at existing coal-fired stations. Higher for new multifuel power plants. | 30-40% (electrical) | 100-1000 + costs of existing power station (depending on biomass fuel + co-firing configuration) | Widely deployed in various countries, now mainly using direct combustion in combination with biomass fuels that are relatively clean. Biomass that is more contaminated and/or difficult to grind can be indirectly co-fired, e.g., using gasification processes. Interest in larger biomass co-firing shares and utilisation of more advanced options is increasing. |
| Gasification for heat production | Typically hundreds kWth | 80-90% (overall) | Several hundred/ kWth, depending on capacity | Commercially available and deployed; but total contribution to energy production to date limited. |
| Gasification/ CHP using gas engines | 0.1 – 1 MWe | 15-30% (electrical)<br>60-80% (overall) | 1.000-3.000 (depends on configuration) | Various systems on the market. Deployment limited due to relatively high costs, critical operational demands, and fuel quality. |
| Gasification using combined cycles for electricity (BIG/CC) | 30-200 MWe | 40-50% (or higher; electrical) | 5.000 – 3.500 (demos)<br>2.000 – 1.000 (longer term, larger scale) | Demonstration phase at 5-10 MWe range obtained. Rapid development in the nineties has stalled in recent years. First generation concepts prove capital intensive. |
| Pyrolysis for production of bio-oil | 10 tonnes/hr in the shorter term up to 100 tonnes/hr in the longer term. | 60-70% bio-oil/feedstock and 85% for oil + char. | Scale and biomass supply dependent; Approx 700/kWth input for a 10 MWth input unit | Commercial technology available. Bio-oil is used for power production in gas turbines, gas engines, for chemicals and precursors, direct production of transport fuels, as well as for transporting energy over longer distances. |

**Table 3:** Overview of current and projected performance data for the main conversion routes of biomass to transport fuels. Due to the variability of data in the various references and conditions assumed, all cost figures should be considered as indicative [Hamelinck and Faaij, 2006; IEA, 2006b; Ogden et al., 1999; IEA, 2004; Lynd, 1996].

| Concept | Energy efficiency (HHV) + energy inputs | | Estimated production costs (€/GJ fuel) | |
|---|---|---|---|---|
| | Short-term | Long-term | Short-term | Long-term |
| **Hydrogen:** via biomass gasification and subsequent syngas processing. Combined fuel and power production possible; for production of liquid hydrogen additional electricity use should be taken into account. | 60% (fuel only)<br>(+ energy input of 0.19 GJe/GJ $H_2$ for liquid hydrogen) | 55% (fuel)<br>6% (power)<br>(+ 0.19 GJe/GJ $H_2$ for liquid hydrogen) | 9-12 | 5-8 |
| **Methanol:** via biomass gasification and subsequent syngas processing. Combined fuel and power production possible | 55% (fuel only) | 48% (fuel)<br>12% (power) | 10-15 | 6-8 |
| **Fischer-Tropsch liquids:** via biomass gasification and subsequent syngas processing. Combined fuel and power production possible | 45% (fuel only) | 45% (fuel)<br>10% (power | 12-17 | 7-9 |
| **Ethanol from wood:** production takes place via hydrolysis techniques and subsequent fermentation and includes integrated electricity production of unprocessed components. | 46% (fuel)<br>4% (power) | 53% (fuel)<br>8% (power) | 12-17 | 5-7 |
| **Ethanol from sugar beet:** production via fermentation; some additional energy inputs are needed for distillation. | 43% (fuel only)<br>0.065 GJe + 0.24 GJth/GJ EtOH | 25-35 | 20-30 | 20-30 |
| **Ethanol from sugar cane:** production via cane crushing and fermentation and power generation from the bagasse. Mill size, advanced power generation and optimised energy efficiency and distillation can reduce costs further in the longer term. | 85 litre EtOH per tonne of wet cane, generally energy neutral with respect to power and heat | 95 litre EtOH per tonne of wet cane. Electricity surpluses depend on plant lay-out and power generation technology. | 8-12 | 7-8 |
| **Biodiesel RME:** takes place via extraction (pressing) and subsequent esterification. Methanol is an energy input. For the total system it is assumed that surpluses of straw are used for power production. | 88%; 0.01 GJe + 0.04 GJ MeOH per GJ output. Efficiency of power generation in the shorter term, 45%; in the longer term, 55% | | 25-40 | 20-30 |

- Assumed biomass price of clean wood: €2/GJ. RME cost figures varied from €20/GJ (short-term) to €12/GJ (longer term), for sugar beet a range of €8 to €12/GJ is assumed. All figures exclude distribution of the fuels to fuelling stations.
- For equipment costs, an interest rate of 10%, economic lifetime of 15 years is assumed. Capacities of conversion unit are normalised on 400 MWth input in the shorter term and >1000 MWth input using advanced technologies and optimised systems in the longer term.
- Diesel and gasoline production costs vary strongly depending on the oil prices, but for indication: recent cost ranges (end 90s till 2006 are between €4 and €9/GJ. Longer term projections give estimates of roughly €6 to €10/GJ. Note that the transportation fuel retail prices are usually dominated by taxation and can vary between €$_{ct}$50 and €$_{ct}$130 /litre depending on the country in question.

Short-term represents best available technology or the currently non-commercial systems which could be built around 2010. Long-term represents technology with considerable improvement, large-scale deployment, and incorporation of process innovations that could be realised around 2040. This is also the case for the biomass supplies, assuming biomass production and supply costs around €2/GJ for plants which are close to the biomass production areas

## END-USE APPLICATIONS

Biomass-based energy carriers are competitive alternatives in situations where cheap, or even 'negative-cost', biomass residues or wastes are available. In order to make large-scale bioenergy use competitive with fossil fuels, the conversion technologies, biomass production (especially from dedicated biomass crops), and total bioenergy systems require further development and optimisation.

Table 4 gives an overview of the perspectives for bioenergy processes combined with main biomass resources.

### Heat and power from biomass

Production of heat and electricity dominate current bioenergy use. At present, the main growth markets for bioenergy are the European Union, North America, Central and Eastern Europe, and South-east Asia (Thailand, Malaysia, Indonesia), especially with respect to efficient power generation from biomass wastes and residues and for biofuels. Two key industrial sectors for application of state-of-the-art biomass combustion (and potentially gasification) technology for power generation are the paper and pulp sector and cane-based sugar industry.

Power generation from biomass by advanced combustion technology and co-firing schemes is a growth market worldwide. Mature, efficient, and reliable technology is available to turn biomass into power. In various markets the average scale of biomass combustion schemes rapidly increases due to improved availability of biomass resources and economies of scale of conversion technology. Competitive performance compared to fossil fuels is possible where lower cost residues are available particularly in co-firing schemes, where investment costs can be minimal. Specific (national) policies such as carbon taxes or renewable energy support can accelerate this development. Gasification technology (integrated with gas turbines/ combined cycles) offers even better perspectives for power generation from biomass in the medium term and can make power generation from energy crops competitive in many areas in the world once this technology has been proven on a commercial scale. Gasification, in particular larger scale circulating fluidised bed (CFB) concepts, also offers excellent possibilities for co-firing schemes.

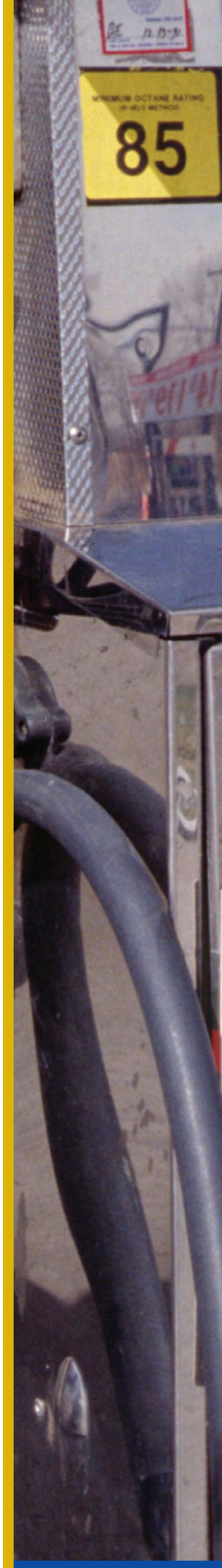
With biomass prices of about €2/GJ, state-of-the-art combustion technology at a scale of 40-60 MWe can result in electricity costs of around €$_{ct}$4 to 6/kWh produced. Co-combustion, particularly at efficient coal-fired power plants, can result in similar or lower cost figures, largely depending on the feedstock costs. When Biomass Integrated Gasification/Combined Cycle technology becomes available commercially, electricity costs could drop further to about €$_{ct}$3 to 4/kWh, especially with higher electrical efficiencies. For larger scales (i.e., over 100 MWe) cultivated biomass will be able to compete with fossil fuels in many situations [Knoef, 2005; Williams and Larson, 1996] The benefits of lower specific capital costs and increased efficiency may in many cases outweigh the increase in costs and energy use for transport for considerable distances once a reasonably well-developed infrastructure is in place.
Decentralised power (and heat) production is generally more expensive due to higher capital costs and lower efficiencies than large-scale systems, but could be economical for off-grid applications. The costs that could ultimately be obtained with e.g., gasifier/diesel systems are still unclear and depend strongly on what emissions and fuel quality are considered acceptable. CHP generation is generally attractive when heat is required with high load factors.

Traditional use of biomass, in particular, is for production of heat for cooking and space heating. It is not expected that this traditional use will diminish in coming decades. Nevertheless, modernising bioenergy use for poorer populations is an essential component of sustainable development schemes in many countries. This creates opportunities and major markets - for example, for improved stoves, and production of high quality fuels for cooking (e.g., biofuel-based such as ethanol and Fischer-Tropsch liquids) - with considerable efficiency and health advantages. Furthermore, digesters producing biogas on a village level, can prove very effective in various countries (such as China and India) in solving waste treatment problems and supplying high-quality energy carriers (clean gas and power when used in gas engines) along with hygienic bio-fertilisers.

For commercial heat production, reliable technology (e.g., boilers, advanced stoves, etc.) is commercially available for many industrial, district and domestic heating applications. Also, combined heat and power generation seems attractive to various markets. The production of heat and process steam from biomass for specific industrial applications is an economically attractive option, as is evident in the paper and pulp and sugar industries worldwide.

**Table 4:** **Generic overview of performance projections for different biomass resource – technology combinations and energy markets on shorter (~5 years) and longer (>20 years) timeframes.** [WEA, 2004; IEA, 2006b; Faaij, 2006; IPCC, 2007; Knoef, 2005; van Loo and Koppejan, 2002]

| Biomass resource | Heat | | Electricity | | Transport fuels | |
|---|---|---|---|---|---|---|
| | *Short-term; stabilising market* | *Longer term* | *Short-term; strong growth market worldwide* | *Longer term; growth may stabilise due to competition of alternative options* | *Short-term; growing market, but highly policy driven* | *Longer term; potential key market for cultivated biomass.* |
| Organic wastes (i.e., MSW etc.) | Undesirable for domestic purposes (emissions); industrial use attractive; in general competitive. | Especially attractive in industrial setting and CHP. (advanced combustion and gasification for fuel gas) | <€$_{ct}$3-5/kWh for state-of-the-art waste incineration and co-combustion. Economics strongly affected by tipping fees and emission standards.<br>Landfill gas recovery and utilisation is generally a competitive utilisation scheme. | Similar range; improvements in efficiency and environmental performance, in particular through IG/CC technology at large-scale. | N.A. | In particular possible via gasification routes (see below) |
| Residues:<br>● Forestry<br>● Agriculture | Major market in developing countries (<€$_{ct}$1-5/kWhth); stabilising market in industrialised countries. | Especially attractive in industrial setting and CHP. Advanced heating systems (residential) possible but not on global scale. | €$_{ct}$4-12/kWh (see below; major variable is supply costs of biomass); lower costs also in CHP operation and industrial setting depending on heat demand. | €$_{ct}$2-8/kWh (see below; major variable is supply costs of biomass) | N.A. | €5-10/GJ; low costs obtainable with lignocellulosic biomass (<US$2 /GJ) advanced hydrolysis techniques and large-scale gasification (i.e., <1000 MWth) for MeOH/H$_2$/FT, as well as improved sugar cane production and subsequent ethanol production in optimised distilleries. |
| Energy crops:<br>● oil seeds<br>● sugar/starch<br>● sugar cane<br>● perennial crops (i.e., short rotation cropping trees and grasses) | N.A. | Unlikely market due to high costs of feedstock for lower value energy carrier; possible niches for pellet or charcoal production in specific contexts. | €$_{ct}$5-15/kWh High costs for small-scale power generation with high-quality feedstock. Lower costs for large-scale (i.e., >100 MWth) state-of-the-art combustion (wood, grasses) and co-combustion. | €$_{ct}$3-8/kWh Low costs especially possible with advanced co-firing schemes and BIG/CC technology over 100-200 MWe. | €8-25/GJ; lower figures for ethanol from sugar cane; higher for biodiesel (RME) and sugar and starch crops in Europe and North America. | |



*The Barra Grande alcohol and sugar production plant in Brazil produces ethanol from sugar cane on a commercial scale*

## Production of liquid and gaseous fuels from biomass

Table 3 provides a summary of estimates for costs of various fuels that can be produced from biomass. A distinction is made between performance levels in the short and in the longer term. Generally, the economics of 'traditional' fuels like rapeseed methyl esther and ethanol from starch and sugar crops in moderate climate zones are unlikely to reach truly competitive price levels, although trade barriers such as tariffs and quotas can be used to increase the economic performance of these fuels [IEA, 2004]. Also, the environmental impacts of growing annual crops are not as good as perennials because per unit of product considerably higher inputs of fertilisers and agrochemicals are needed. In addition, annual crops on average need better quality land than perennials to achieve good productivities. Perennial crops can also be grown on marginal lands, thereby achieving other potential benefits such as soil quality improvement.

A key exception under 'conventional' biofuels is production of ethanol from sugar cane in tropical regions where good soils are available. For countries where sugar cane production is feasible, commercially available technology allows for production of relatively low-cost ethanol. Brazilian experience shows that ethanol production is competitive with gasoline at oil prices over US$60/barrel [Goldemberg et al., 2004]. Ethanol production capacity based on sugar cane is increasing substantially in African, Latin American, and Asian (e.g., India, Thailand, and China) countries. Furthermore, better use of cane residues (e.g., for power generation or use via hydrolysis processes) can further improve the performance of cane-based ethanol production.

The production of methanol (and di-methyl esters or DME), hydrogen, Fischer-Tropsch liquids, and ethanol produced from lignocellulosic biomass offers much better perspectives and competitive fuel prices in the longer term, i.e., between 2010 and 2020. Partly, this is because of the inherently lower feedstock prices and versatility of producing lignocellulosic biomass under varying circumstances. Furthermore, the (advanced) gasification and hydrolysis technologies under development have the potential for efficient and competitive production of fuels, sometimes combined with co-production of electricity [Hamelinck and Faaij, 2006]. Comprehensive research and development strategies for such technologies are required, though. Such strategies should focus not only on development of technologies but also on long-term deployment and building the infrastructure and markets required for those technologies.

## Market development and international trade

Biofuel and biomass trade flows are modest compared to total bioenergy production but are growing rapidly. Trade takes place between neighbouring regions or countries, but increasingly trading is occurring over long distances.

The possibilities for exporting biomass-derived commodities to the world's energy markets can provide a stable and reliable demand for rural regions in many developing countries, thus creating an important incentive and market access that is much needed. For many rural communities in developing countries such a situation would offer good opportunities for socio-economic development.

Sustainable biomass production may also contribute to the sustainable management of natural resources. Importing countries on the other hand may be able to fulfil cost-effectively their GHG emission reduction targets and diversify their fuel mix.

Given that several regions of the world have inherent advantages for producing biomass (including lignocellulosic resources) and biofuels in terms of land availability and production costs, they may gradually develop into net exporters of biomass and biofuels. International transport of biomass (or energy carriers from biomass) is feasible from both the energy and the cost points of view. The import of densified or pre-treated lignocellulosic biomass from various world regions may be preferred, especially for second generation biofuels, where lignocellulosic biomass is the feedstock and large-scale capital-intensive conversion capacity is required to achieve sound economics. This is a situation comparable to that of current oil refineries in major ports which use oil supplies from around the globe.

Very important is the development of a *sustainable*, international biomass market and trade. Proper standardisation and certification procedures are to be developed and implemented to secure sustainable biomass production, preferably on the global level. Currently, this is a priority for various governments, market players, and international bodies. In particular, competition between production of food, preservation of forests and nature and use of land for biomass production should be avoided. As argued, this is possible by using lignocellulosic biomass resources that can come from residues and wastes, which are grown on non-arable (e.g., degraded) lands, and in

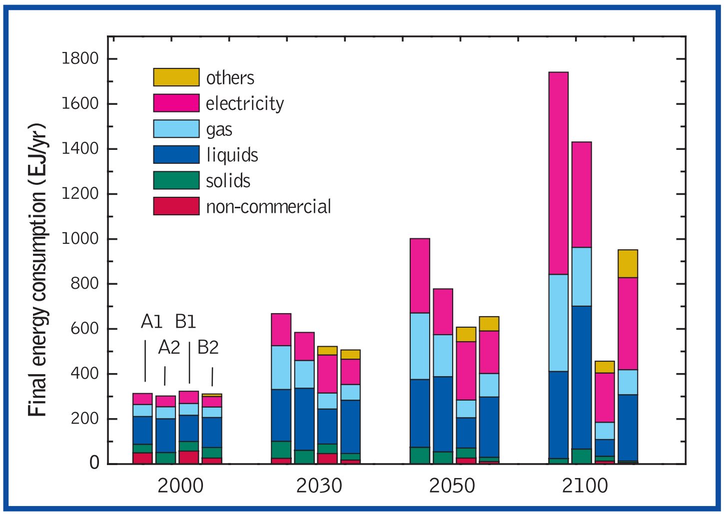
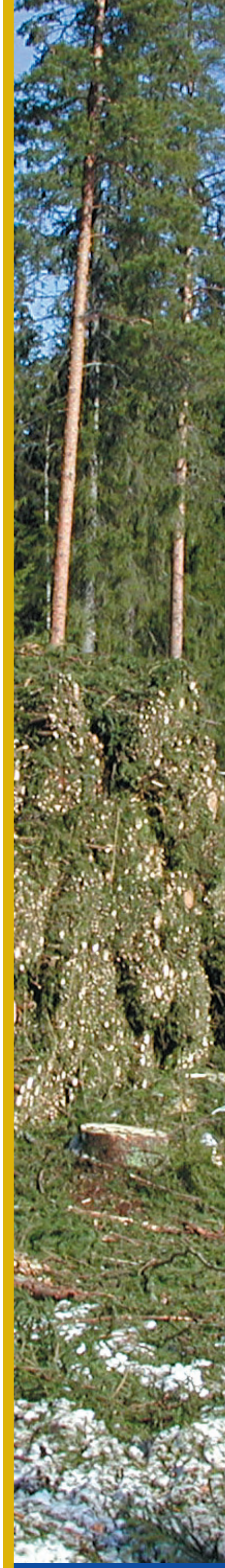


**Figure 2:** Projections for global final energy demand for the four IPCC SRES scenarios (A1, A2, B1, B2). [IPCC, 2000]



particular by increased productivity in agricultural and livestock production. Demonstration of such combined development where sustainable biomass production is developed in conjunction with more efficient agricultural management is a challenge. However, this is how bioenergy could contribute not only to renewable energy supplies and reducing GHG emissions, but also to rural development [Faaij and Domac, 2006].

## BIOMASS AND BIOENERGY IN THE WORLD'S FUTURE ENERGY SUPPLY

What contribution can biomass make to future global energy (and bio-products) demand? A wide diversity of projections of potential future energy demand and supply exist [IPCC, 2007]. Typically, scenarios are used to depict uncertainties in future developments and possible development pathways. The 'Special Report on Emission Scenarios' (SRES) developed in the context of the Intergovernmental Panel on Climate Change (IPCC) is based on four storylines that describe how the world could develop over time. Differences between the scenarios concern economic, demographic, and technological development and the orientation towards economic, social, and ecological values. The storylines denoted A1 and A2 are considered societies with a strong focus towards economic development. In contrast, the B1 and B2 storylines are more focused on welfare issues and are ecologically orientated. While the A1 and B1 storylines are globally oriented, with a strong focus towards trade and global markets, the A2 and B2 storylines are more regionally oriented. Figure 2 shows the total energy demand for secondary energy carriers (such as transport fuels, electricity, gas, etc.) in four distinct years of the four scenarios. Clearly, the various scenarios show large differences in demand and energy mix, as a result of variations in population dynamics, and economic and technological development. Total *primary* (the presumed mix of fossil fuels, renewables and nuclear) energy demand in 2050 varies between about 800 EJ and 1,400 EJ.

As discussed previously, the total primary biomass supplies in 2050 could amount to 200-400 EJ. This is conservative relative to the increased availability of primary biomass for the different SRES scenarios, shown in Figure 3. The circled lines depict the total primary energy demand per scenario, corresponding with the projected energy consumption data in Figure 2. All scenarios project a gradual development of biomass resource availability, largely corresponding to the (potentially) gradually increased availability of land over time.

Assuming conversion to transport fuels with an expected average conversion efficiency of 65%, this would result in 130-260 $EJ_{fuel}$. This is up to double the current demand and a similar range to the expected demand in the SRES scenarios discussed above.

Conversion to power with an assumed average efficiency of 50% logically results in 100-200 $EJ_e$, also a similar range to the expected future demand.

Additional future demand for (new) biomaterials such as bio-plastics could add up to 50 EJ halfway through this century [Hoogwijk et al., 2003]. It is clear, therefore, that biomass can make a very large contribution to the world's future energy supply. This contribution could range from 20% to 50%. The higher value is possible when growth in energy demand is limited; for example, by strongly increased energy efficiency.

## Competing markets for biomass?

Biomass cannot realistically cover the whole world's future energy demand. On the other hand, the versatility of biomass with the diverse portfolio of conversion options, makes it possible to meet the demand for secondary energy carriers, as well as biomaterials. Currently, production of heat and electricity still dominate biomass use for energy. The question is therefore what the most relevant future market for biomass may be.

For avoiding $CO_2$ emissions, replacing coal is at present a very effective way of using biomass. For example, co-firing biomass in coal-fired power stations has a higher avoided emission per unit of biomass than when displacing diesel or gasoline with ethanol or biodiesel. However, replacing natural gas for power generation by biomass, results in levels of $CO_2$ mitigation similar to second-generation biofuels. Net avoided GHG emissions therefore depend on the reference system and the efficiency of the biomass production and utilisation chain. In the future, using biomass for transport fuels will gradually become more attractive from a $CO_2$ mitigation perspective because of the lower GHG emissions for producing second-generation biofuels and because electricity production on average is expected to become less carbon-intensive due to increased use of wind energy, PV and other solar-based power generation, carbon capture and storage technology, nuclear energy, and fuel shift from coal to natural gas. In the shorter term, however, careful strategies and policies are needed to avoid brisk allocation of biomass resources away from efficient and effective utilisation in power and heat production or in other markets, e.g., food. How this is to be done optimally will differ from country to country.

The use of biomass for biomaterials will increase, both in well-established markets (such as paper, construction) and for possibly large new markets (such as bio-chemicals and plastics) as well as in the use of charcoal for steel making. This adds to the competition for biomass resources, in particular forest biomass, as well as land for producing woody biomass and other crops. The additional demand for bio-materials could surpass the current global biomass use (which is some 10% of the global energy use) [Hoogwijk et al., 2003]. However, increased use of bio-materials does not prohibit the production of biofuels (and electricity and heat) per se. Construction wood ends up as waste wood, paper (after recycling) as waste paper, and bio-plastics in municipal solid waste [Dornburg and Faaij, 2005]. Such waste streams still qualify as biomass feedstock and are available, often at low or even negative costs.

Cascading biomass over time in fact provides an essential strategy to optimise the $CO_2$ mitigation effect of biomass resources. The IPCC (2007) reports that the largest sustained mitigation benefit

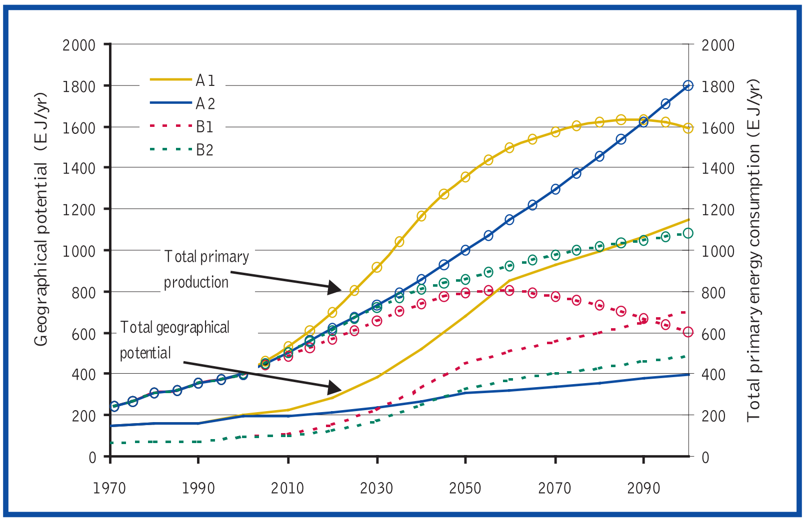


**Figure 3:** Technical potential of woody biomass energy crops (lower lines without circles) as assessed for the four SRES scenarios over time, as well as the simulated total primary energy consumption (lines with circles) [Hoogwijk et al., 2005b].

will result from a sustainable forest management strategy aimed at maintaining or increasing forest carbon stocks, while producing an annual sustained yield of timber, fibre, or energy from the forest. This could for example involve conventional forests producing material cascades (e.g., solid wood products, reconstituted particle/fibre products, paper products) with wood or fibre that cannot be reused/recycled being used for energy.

## Comparison with other energy supply options

Table 5 provides a general overview of the current use, and the technical and theoretical energy potentials of various renewables: biomass, wind energy, solar energy, hydropower, and geothermal energy. Current and potential future energy production costs of electricity, heat, and fuels are given in Table 6.

State-of-the-art scenario studies on energy supply and mitigation of climate change agree that all climate-friendly energy options are needed to meet the future world's energy needs and simultaneously drastically reduce GHG emissions. Intermittent sources such as wind and solar energy have good potential, but their deployment is also constrained by their integration into electricity grids. In addition, electricity production from solar energy is still expensive. Hydropower has a limited potential [IPCC, 2007] and commercial deployment of geothermal and ocean energy, despite their large theoretical potentials, has proved to be complex. Biomass in particular can play a major and vital role in production of carbon-neutral transport fuels of high quality as well as providing feedstocks for various industries (including chemical). This is a unique property of biomass compared to other renewables and which makes biomass a prime alternative to the use of mineral oil. Given that oil is the most constrained of the fossil fuel supplies, this implies that biomass is particularly important for improving security of energy supply on the global as well on a national level. In addition, competitive performance is already achieved in many situations using commercial technologies especially for producing heat and power. It is therefore expected that biomass will remain the most important renewable energy carrier for many decades to come.

## OPPORTUNITIES FOR BIOENERGY

Biomass is a versatile energy source that can be used for production of heat, power, and transport fuels, as well as biomaterials and, when produced and used on a sustainable basis, can make a large contribution to reducing GHG emissions. Biomass is the most important renewable energy option at present and is expected to maintain that position during the first half of this century and likely beyond that [IPCC, 2007; IEA, 2006a]. Currently, combined heat and power (CHP), co-firing and various combustion concepts provide reliable, efficient, and clean conversion routes for converting solid biomass to power and heat. Production and use of biofuels are growing at a very rapid pace.

Although the future role of bioenergy will depend on its competitiveness with fossil fuels and on agricultural policies worldwide, it seems realistic to expect that the current contribution of bioenergy of 40-55 EJ per year will increase considerably. A range from 200 to 400 EJ may be expected during this century, making biomass a more important energy supply option than mineral oil today – large enough to supply one-third of the world's total energy needs.

Bioenergy markets provide major business opportunities, environmental benefits, and rural development on a global scale. If indeed the global bioenergy market is to develop to a size of 300 EJ over this century (which is quite possible given the findings of recent global potential assessments) the value of that market at €4-8/GJ (considering pre-treated biomass such as pellets up to liquid fuels such as ethanol or synfuels) amounts to some €1.2-2.4 trillion per year.

Feedstocks can be provided from residues from agriculture, forestry, and the wood industry, from biomass produced from degraded and marginal lands, and from biomass produced on good quality agricultural and pasture lands without jeopardising the world's food and feed supply, forests, and biodiversity. The pre-condition to achieve such a situation is that agricultural land-use efficiency is increased, especially in developing regions.

**Table 5:** Overview of current use, and the technical and theoretical potentials of different renewable energy options [WEA, 2000].

| Resource | Current use (EJ) | Technical Potential (EJ) | Theoretical potential (EJ) |
|---|---|---|---|
| Biomass energy | ~50 | 200-400 (+) | 2,900 |
| Hydropower | 9 | 50 | 147 |
| Solar energy | 0.1 | >1,500 | 3,900,000 |
| Wind energy | 0.12 | 640 | 6,000 |
| Geothermal energy | 0.6 | 5,000 | 140,000,000 |
| Ocean energy | NA | NA | >140,000,000 |
| Total | 56 | >7,600 | >144,000,000 |

**Table 6:** Cost ranges (Euro-cents per unit) for production of electricity, heat, and fuel from various renewable energy options at present and longer term [WEA, 2004].

| Technology | Current energy cost | Potential long-term future energy cost (2050) |
|---|---|---|
| Biomass energy (based on energy crops as feedstock) | | |
| ● electricity | €$_{ct}$5-15/kWh electricity | €$_{ct}$4-10/kWh electricity |
| ● heat | €$_{ct}$1-5/kWh$_{fuel}$ | €$_{ct}$1-5/kWh |
| ● biofuels | €8-25/GJ$_{fuel}$ | €6-10/GJ |
| Wind electricity | €$_{ct}$5-13/kWh | €$_{ct}$3-10/kWh |
| Solar PV electricity | €$_{ct}$25-125$_{t}$/kWh | €$_{ct}$5-25/kWh |
| Solar thermal electricity | €$_{ct}$12-18/kWh | €$_{ct}$4-10/kWh |
| Low temperature solar heat | €$_{ct}$3-20/kWh | €$_{ct}$2-20/kWh |
| Hydroelectricity | €$_{ct}$2-10/kWh | €$_{ct}$2-10/kWh |
| Geothermal energy | | |
| ● electricity | €$_{ct}$2-10/kWh | €$_{ct}$1-10/kWh |
| ● heat | €$_{ct}$0.5-5/kWh | €$_{ct}$0.5-5/kWh |

Considering that about one-third of the above-mentioned 300 EJ could be supplied from residues and wastes, one-quarter by regeneration of degraded and marginal lands, and the remainder from current agricultural and pasture lands, almost 1,000 million hectares worldwide may be involved in biomass production, including some 400 million hectares of arable and pasture land and a larger area of marginal/degraded land. This is some 7% of the global land surface and less than 20% of the land currently in use for agricultural production.

There are rapid developments in biofuel markets: increasing production capacity, increasing international trade flows, increased competition with conventional agriculture, increased competition with forest industries, and strong international debate about the sustainability of biofuels production. Biomass is developing into a globalised energy source with advantages (opportunities for producers and exporters, more stability in the market) and concerns (competing land use options, sustainability).

Biomass trading and the potential revenues from biomass and biomass-derived products could provide a key lever for rural development and enhanced agricultural production methods, given the market size for biomass and biofuels. However, safeguards (for example, well-established certification schemes) need to be installed internationally to secure sustainable production of biomass and biofuels. In the period before 2020 substantial experience should be obtained with sustainable biomass production under different conditions as well as with deploying effective and credible certification procedures.

Especially promising are the production of electricity via advanced conversion concepts (i.e., gasification, combustion, and co-firing) and biomass-derived fuels such as methanol, hydrogen, and ethanol from lignocellulosic biomass. Ethanol produced from sugar cane is already a competitive biofuel in tropical regions and further improvements are possible. Both hydrolysis-based ethanol production and production of synfuels via advanced gasification from biomass of around €2/GJ can deliver high quality fuels at a competitive price with oil down to US$45/ barrel. Net energy yields per unit of land surface are high and GHG emission reductions of around 90% can be achieved, compared with fossil fuel systems. Flexible energy systems, in which biomass and fossil fuels can be used in combination, could be the backbone for a low risk, low-cost, and low carbon emission energy supply system for large-scale supply of fuels and power, providing a framework for the evolution of large-scale biomass raw material supply systems.

## REFERENCES

**Berndes, G., Hoogwijk, M. and van den Broek, R.** 2003. The contribution of biomass in the future global energy supply: a review of 17 studies, Biomass and Bioenergy, Volume 25, Issue 1, July, Pp 1-28.

**Dornburg, V. and Faaij, A.** 2001. Efficiency and economy of wood-fired biomass energy systems in relation to scale regarding heat and power generation using combustion and gasification technologies. Biomass & Bioenergy, Vol. 21. No. 2, Pp. 91-108.

**Dornburg, V. and Faaij, A.** 2005. Cost and $CO_2$-Emission Reduction of Biomass Cascading: Methodological Aspects and Case Study of SRF Poplar. Climatic Change, Vol. 71, No. 3, August, Pp. 373-408.

**Faaij, A.** 2006. Modern biomass conversion technologies. Mitigation and Adaptation Strategies for Global Change, Volume 11, No. 2, March, Pages 335-367.

**Faaij, A.P.C. and Domac, J.** 2006. Emerging international bio-energy markets and opportunities for socio-economic development. Energy for Sustainable Development (Special Issue on Emerging International Bio-energy markets and opportunities for socio-economic development), Vol. X. No. 1, March. Pp. 7-19.

**Faaij, A., Wagener, M., Junginger, M., Best, G., Bradley, D., Fritsche, U., Grassi,A., Hektor, B., Heinimö, J., Klokk, S., Kwant, K., Ling, E., Ranta, T., Risnes, H., Peksa, M., Rosillo-Calle, F., Ryckmanns, Y., Utria, B., Walter, A. and Woods. J.** 2005. Opportunities and barriers for Sustainable International bio-energy Trade; Strategic advice of IEA Bioenergy Task 40. 14th European Biomass Conference and Exhibition, October, Paris, France.

**Goldemberg, J., Teixeira Coelho, S., Mário Nastari, P. and Lucon, O.** 2004. Ethanol learning curve—the Brazilian experience, Biomass and Bioenergy, Volume 26, Issue 3, March, Pp. 301-304.

**Hamelinck, C., and Faaij, A.** 2006. Outlook for advanced biofuels. Energy Policy, Volume 34, Issue 17, November, Pp 3268-3283.

**Hoogwijk, M., Faaij, A., Eickhout, B., de Vries, B. and Turkenburg, W.** 2005a. Potential of biomass energy out to 2100, for four IPCC SRES land-use scenarios, Biomass & Bioenergy, Vol. 29, Issue 4, October, Pp. 225-257.

**Hoogwijk, M., Faaij, A., de Vries, B. and Turkenburg, W.** 2005b. Global potential of biomass for energy from energy crops under four GHG emission scenarios Part B: the economic potential. (submitted to: Biomass & Bioenergy).

**Hoogwijk, M., Faaij, A., van den Broek, R., Berndes, G., Gielen, D. and Turkenburg, W.** 2003. Exploration of the ranges of the global potential of biomass for energy. Biomass and Bioenergy, Vol. 25 No. 2, pp. 119-133.

**IEA.** 2004. Biofuels for Transport – an international perspective. Office of Energy Efficiency, Technology and R&D, OECD/IEA, Paris, France.

**IEA.** 2006a. World Energy Outlook, 2006. OECD/IEA, Paris, France.

**IEA.** 2006b. Energy Technology perspectives – Scenario's and strategies to 2050, OECD/IEA, Paris, France.

**IPCC.** 2000. Special report on emission scenarios. Cambridge: Intergovernmental Panel on Climate Change. Cambridge University Press.

**IPCC.** 2007. IPCC Fourth Assessment Report, Working Group III, Available from http://www.ipcc.ch.

**Knoef, H. (Ed.)** 2005. Handbook Biomass Gasification, Published by the Biomass Technology Group, European Commission, PyNe and GasNet, Enschede, the Netherlands. ISBN 90-810068-1-9, September.

**Lynd, L.R.** 1996. Overview and evaluation of fuel ethanol from lignocellulosic biomass: technology, economics, the environment and policy; Annual review Energy Environment, 21: 403-65.

**Ogden, J.M., Steinbugler, M.M. and Kreutz, T.G.** 1999. A comparison of hydrogen, methanol and gasoline as fuels for fuel cell vehicles: implications for vehicle design and infrastructure development. Journal of Power Sources 79 (1999) 143-168.

**Schlamadinger, B., Faaij, A., Junginger, M., Daugherty, E. and Woess-Gallasch, S.** 2006. Should we trade biomass, bio-electricity, green certificates or CO2 credits? In: IEA Bioenergy Agreement Annual Report 2005, IEA Bio-energy; ExCo:2006:01, January. Pp. 4-19.

**Smeets, E., Faaij, A., Lewandowski, I. and Turkenburg, W.** 2007. A quickscan of global bioenergy potentials to 2050. Progress in Energy and Combustion Science, Volume 33, Issue 1, February, Pp 56-106.

**USDOE. 1998.** Office of Utility Technologies, Renewable energy technology characterizations, Washington DC, USA, January.

**van Loo, S. and Koppejan, J. (Eds)** 2002. Handbook of Biomass Combustion and Co-firing, IEA Bioenergy Task 32, Twente University Press.

**Williams, R.H. and Larson, E.D.** 1996. Biomass gasifier gas turbine power generating technology, Biomass and Bioenergy, Vol. 10, Pp. 149-166.

**World Energy Assessment.** 2000. World Energy Assessment of the United Nations, UNDP, UNDESA/WEC, Published by: UNDP, New York, September.

**World Energy Assessment.** 2004. Overview: 2004 Update, UNDP, UNDESA and the World Energy Council.

**WorldWatch Institute.** 2007. Biofuels for Transport: Global Potential and Implications for Energy and Agriculture. ISBN: 1844074226, Published by EarthScan/James & James, April, Pp. 336.

## ACKNOWLEDGEMENTS

André Faaij, Associate Professor at the Copernicus Institute for Sustainable Development of the Utrecht University, the Netherlands was the lead author of this publication. André is also the Leader of Task 40: Sustainable International Bioenergy Trade - Securing Supply and Demand. He was assisted with contributions from the other Task Leaders of IEA Bioenergy. Josef Spitzer, Austria and Kees Kwant, the Netherlands comprised the editorial committee to review drafts of the text. In addition, Members of the Executive Committee provided discussion and comments on draft material. Judy Griffith and Justin Ford-Robertson provided valuable assistance in preparing the text for publication. The Secretary facilitated the editorial process and arranged final design and production. The assistance of Contracting Parties to IEA Bioenergy and the bioenergy industry in providing access to photographs is gratefully acknowledged.

## GLOSSARY

| | |
|---|---|
| BIG/CC | Biomass integration gasification using combined cycle |
| CFB | circulating fluidised bed |
| CHP | combined heat and power |
| $CO_2$ | carbon dioxide |
| DME | di-methyl esters |
| € | Euro |
| €$_{ct}$ | Euro cent |
| EJ | Exajoules ($10^{18}$ Joules; 1 EJ = 278 TWh; 1 Mtoe = 0.042 EJ) |
| EJ/yr | Exajoules per year |
| EtOH | ethanol |
| FT | Fischer-Tropsch |
| Gha | Gigahectares ($10^9$ hectares) |
| GHG | greenhouse gas |
| GJ | Gigajoule ($10^9$ Joules) |
| GJe | Gigajoule (electrical output) |
| GJth | Gigajoule (thermal output) |
| GW | Gigawatt ($10^9$ Watts) |
| $H_2$ | hydrogen |
| Ha | hectare |
| HHV | Higher heating value |
| IPCC | Intergovernmental Panel on Climate Change |
| kW | kilowatt ($10^3$ Watts) |
| kWe | kilowatt (electrical output) |
| kWh | kilowatt hour |
| kWth | kilowatt (thermal output) |
| LHV | Lower heating value |
| MeOH | Methanol |
| MSW | municipal solid waste |
| MW | Megawatt ($10^6$ Watts) |
| MWe | Megawatt (electrical output) |
| MWth | Megawatt (thermal output) |
| ORC | organic rankine cycle |
| PV | photovoltaic |
| RME | Rape methyl ester |
| SRES | Special Report on Emission Scenarios (IPCC report) |
| Tonne | Metric tonne (1 tonne = 1000 kg) |

IEA Bioenergy

## Further Information

**IEA Bioenergy Website:**
www.ieabioenergy.com

**IEA Bioenergy Secretariat**
John Tustin - Secretary
PO Box 6256
Whakarewarewa
ROTORUA
NEW ZEALAND
Phone: +67 7 3482563
Fax: +64 7 348 7503
Email: jrtustin@xtra.co.nz

Adam Brown – Technical Coordinator
Energy Insights Ltd
1, St Hilda's Close
Didcot
Oxfordshire, OX11 9UU
UNITED KINGDOM
Phone: +44 (0)7723 315441
Email: adam.brown@energyinsights.co.uk

This publication was produced by the Implementing Agreement on Bioenergy, which forms part of a programme of international energy technology collaboration undertaken under the auspices of the International Energy Agency.