Unclassified **TAD/CA/APM/WP(2009)18/FINAL**

Organisation de Coopération et de Développement Économiques
Organisation for Economic Co-operation and Development **19-Mar-2010**

English - Or. English

TRADE AND AGRICULTURE DIRECTORATE
COMMITTEE FOR AGRICULTURE

Working Party on Agricultural Policies and Markets

BIOHEAT, BIOPOWER AND BIOGAS: DEVELOPMENTS AND IMPLICATIONS FOR AGRICULTURE

Contact person: Martin von Lampe (e-mail: martin.vonlampe@oecd.org)

JT03280425

Note

The APM discussed the draft of this report in its October 2009 meeting [TAD/CA/APM/WP(2009)18]. Based on numerous comments made by Delegations during and after the meeting, the report, output of the PWB 2007-08 activity “Market and Policy Based Approaches to Bioenergy”, has been revised. As agreed during the meeting, the report now is made available as an unclassified document.

TABLE OF CONTENTS

Boxes

EXECUTIVE SUMMARY

Bioenergy – or energy produced from biomass – receives a lot of attention both at the policy level and from the public. Past OECD analysis on policies supporting the production and use of liquid biofuels for transport (OECD, 2008) has shown that other forms of bioenergy, such as bioheat, biopower and biogas, could represent economically more viable and environmentally more efficient ways to reduce GHG emissions and fossil fuel use, two of the high-ranking objectives behind most bioenergy support policies. The present report aims to complement this first study in explicitly looking at those forms of bioenergy and the policies supporting them.

Bioenergy represents a rather heterogenous portfolio of different biomass feedstocks and conversion technologies. While particularly first-generation liquid biofuels are dominated by feedstocks originating from agricultural products, such as grains, sugar crops and oilseeds, non-agricultural feedstocks (such as forest products and residues, industrial and municipal wastes) and, to a lesser extent, agricultural residues and wastes, dominate in the generation of bioheat and biopower, resulting in substantially less competition with the production of food and animal feed. Commercialised biomass crops, which could compete with land use for food production, are being developed, but today only play a minor role. Main technologies to convert biomass to heat and/or electrical power include the direct combustion (partly as co-firing with fossil fuels), the gasification and the anaerobic digestion producing biogas. Combined heat and power generation plants allow improving the energy efficiency with the use of the remaining heat after power generation for space heating or in industrial applications.

Being part of the renewable energy portfolio, heat and power generation from biomass benefits from public support measures in many countries. The objectives of such support are many fold and in particular include the security of energy supply, environmental improvements, rural development, and the generation of supplementary outlets for agricultural products. While a number of countries have established national or regional targets for renewable energy, only a few have defined specific targets for bioheat and/or biopower, including Germany, Ireland, Japan, New Zealand, Norway, Romania and the US. The policy measures applied most commonly include guaranteed prices for renewable electricity or gas fed into the grid, and investment subsidies. The application of these measures differs across countries, however, and is complemented by a large set of other support measures.

To what degree does the environmental performance of the different bioenergy chains meet the objectives behind the political support? While many other factors are relevant in this context, the present study focuses on two major variables: greenhouse gas (GHG) savings and energy balances.

A large number of studies providing life-cycle analyses (LCAs) for bioheat, biopower and biogas chains were evaluated for this study, and the results indicate that while there is substantial variation in the GHG and energy balances, indeed most of these chains show important savings of GHG emissions when compared to the main fossil alternatives. This is particularly true for electricity production chains, where GHG savings generally range between 63% and 99% when compared to the use of coal, and between 37% and 98% when compared to the use of natural gas. While still significant, savings were found to be smaller for heat applications, though this may reflect on the lower efficiency associated with smaller district, space heating and domestic heating systems. In either case, GHG savings for most chains seem to be significantly higher than for liquid biofuel chains.

While the average energy efficiency for most biopower chains ranges between 0.3 and 0.8 MJ_{in} per MJ_{out}, with a few studies indicating values above 1 MJ_{in} per MJ_{out}, this represents significant fossil energy savings when compared to efficiencies of 2.1 MJ_{in} per MJ_{out} for natural gas, and 2.8 MJ_{in} per MJ_{out} for coal fired power plants. Similar savings in fossil energy use are found for a range of bioheat chains when compared to natural gas and fuel oil as feedstocks.

Data on the production of bioheat, biopower and biogas, and particularly on biomass use, is scarce, but available data provide a couple of general trends. First, on a global level, some 10% of total primary energy demand is met by energy from biomass, but almost two-thirds of this come from non-agricultural solid biomass outside the OECD area. While detailed data are lacking it can be assumed that much of this is traditional biomass, such as firewood used in developing countries for cooking and heating. Within the OECD, too, the vast majority of bioenergy is based on forest products and residues. Agricultural biomass – crops, residues and wastes – only plays a relatively small role, particularly after deduction of first generation liquid biofuels.

Second, modern bioenergy has been gaining importance over the past two decades, and particularly since the beginning of the century. This is mainly driven by the rapid development of liquid biofuels for transport, but biogas – mainly landfill and sludge gases, to a lesser extent gas from other (mainly agricultural) biomass – shows a clear upward trend as well. Shares of agricultural biogas in total primary energy supply of at least 0.1% are largely limited to a few countries today, including Germany, Denmark, Luxembourg and The Netherlands as well as, outside the OECD, China.

Third, on an aggregate level, implications of increased production and use of bioheat, biopower and biogas for agricultural markets are likely to be small for the time being. Exceptions at a local or national level could include the increasing area used for biogas substrate production in Germany, potentially competing with the production of food and feed, and a few other countries where the use of sugar cane bagasse or straw as bioenergy feedstock might have the opposite effect of raising incentives for commodity production. A stronger focus on agricultural biomass crops in the development of bioheat and biopower could, however, result in potentially more significant implications. It has been shown in earlier OECD studies that increased production of first-generation liquid biofuels results in higher crop prices. The impact of growing bioheat and biopower markets may have a similar – though probably less pronounced – effect through increased competition for agricultural land and other resources, although this could not be analyzed quantitatively in the present study due to data limitations. Policies supporting bioenergy chains should therefore ensure that they do not compromise the ability of the agricultural sector to provide food and feed commodities in a sustainable manner.

BIOHEAT, BIOPOWER AND BIOGAS – DEVELOPMENTS AND IMPLICATIONS FOR AGRICULTURE

Introduction

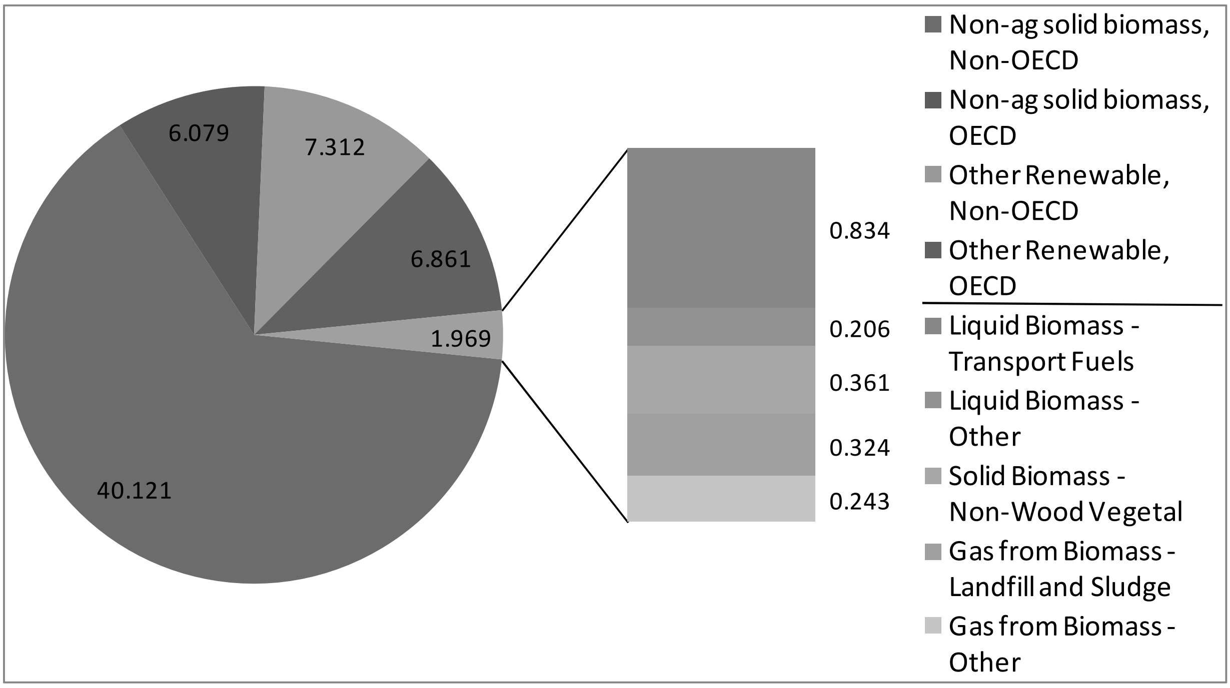
Bioenergy – or energy produced from biomass – has been enjoying a high degree of attention in recent years, both at a policy level and from the public. An extensive analysis on policies supporting the production and use of liquid biofuels was published in 2008 (OECD, 2008) concluding, among others, that other forms of bioenergy may represent an economically more viable and environmentally more efficient way to reduce GHG emissions and fossil fuel use – two of the high-ranking objectives behind most bioenergy support policies – without, however, providing any analysis on bioheat, biopower or biogas. The present report aims to complement the first study in explicitly looking at those forms of bioenergy as well as the policies that support them.

Bioenergy comprises a fairly heterogeneous portfolio of different energy forms produced from a large range of biomass feedstocks. In 2006, about 10% of global primary energy demand were met by energy from biomass (data from IEA, 2008), amounting to some 48 exajoule (EJ), while another 14 EJ (slightly less than 3% of global primary energy demand) are provided by other renewable sources (such as hydro, solar and wind energy). The vast majority of the biomass used for energy is so-called traditional bioenergy such as firewood which is used in developing countries for cooking and heating – IEA data suggest that some 40 EJ worth of solid biomass were used in the middle of this decade outside the OECD.[1] Solid biomass also represents the majority of the OECD's biomass used for energy production: 6 EJ out of a total biomass supply of 7.6 EJ were estimated to come from non-agricultural solid biomass in 2006.

---

[1] IEA data does not allow distinguishing between traditional and modern biomass use – it is assumed that all energy use of solid biomass in non-member economies is traditional biomass. The Global Bioenergy Partnership (GBEP, 2007) confirms that currently more than 85% of world biomass energy is traditional biomass, "as solid fuels for cooking, heating and lighting, often with low efficiency", providing for substantial shares of primary energy consumption in developing countries (p. 1).

Figure 1. Global primary energy supplies from renewable sources, 2006 (EJ)



Notes: Non-ag solid biomass refers to solid biomass other than non-wood vegetal according to IEA data. Given to data availability problems, it does contain non-wood vegetal biomass for some countries, however. Numbers for the OECD include non-OECD EU Member States.

Source: IEA (2008a)

“Modern” bioenergy still remains comparatively limited. Apart from non-agricultural solid biomass commercialised in OECD countries (in particular charcoal and firewood/wood pellets) which can be considered to primarily pass “modern” channels, this also refers to liquid (biofuels) and gaseous (biogas) biomass-based energy carriers, both of which require the biomass to be transformed in a chemical and/or biological conversion process.

Box 1 provides some definitions of key terms used in this document.

Box 1. Definitions of key terms used in the work on bioenergy[2]

Bioenergy: renewable energy produced from *biomass*. Bioenergy includes ***biofuels***, ***biopower*** and ***bioheat*** (and ***biogas*** which, as mentioned below, can also go to the end use directly). In addition, ***rural (off-grid) energy from biomass*** (also referred to as ***traditional bioenergy***, mainly in developing countries' rural areas, e.g. firewood, dung) could be added as a type of bioenergy but in general is not considered in this work.

Biomass: any organic material of plant and animal origin, derived from agricultural and forestry production and resulting by-products, and from industrial and urban wastes, used as feedstock for producing *bioenergy* and other non-food applications. In the present work only biomass originating from agriculture or forestry, used as feedstock for producing bioenergy, will be considered.

Biofuels: fluid or (less frequently) gaseous fuels used to power engines in private or public transport. In particular, biofuels include:

- Bioethanol (in the following just called ethanol), ethylic alcohol produced from starch and sugar crops (first-generation ethanol) or from cellulose and lingo-cellulose biomass (second-generation ethanol) and used in transport vehicles with spark ignition engines;
- Biodiesel, generally produced by transesterification of vegetable oils and used in transport vehicles with compression ignition engines;
- Vegetable oils to be used without modification in compression ignition engines;
- Synthetic biofuels, also called Biomass-To-Liquid (BTL) fuels, synthesised fuels produced from almost any form of biomass (via a gasification process) with the possibility of tailoring the fuel to either spark ignition or compression ignition engines;
- Biogas and hydrogen, gaseous fuels produced from almost any form of biomass that require dedicated engines for gaseous fuels or fuel cells; biogas can also be used to generate electrical power or heat.

Biopower: electricity produced from *biomass*, generally via combustion of the feedstock or a derived product (e.g. *biogas*) driving power generating turbines. Biopower is often, though not always, co-generated with *bioheat*.

Bioheat: thermal energy produced from *biomass*, used either for space heating or in production processes requiring process heat such as steam, generally *via* combustion of the feedstock or a derived product (e.g. *biogas*). Bioheat is often, though not always, co-generated with *biopower*.

Biogas: methane or similar gas from anaerobe digestion of biomass. Biogas can be used as a transport fuel in engines for gaseous fuels, as an input for the heat and/or power generation, or can directly be used by the end user for heating or warm water generation.

The heterogeneity of the bioenergy portfolio is indicated in Table 1 below. Biofuels for transport have been analysed extensively in OECD (2008), but biopower, bioheat and biogas, too, can be – and are – produced from a large range of feedstocks, including agricultural food and feed commodities as well as, more commonly, residues and wastes from agriculture and forestry, wood and wood chips, non-food crops and industry and municipal wastes. The potential implications for agricultural differ significantly, ranging from the direct competition for food and feed crops to area competition in the case of non-food crops, to virtually no link in the case of industrial and municipal wastes to complementarities with food production when agricultural residues and wastes are used as bioenergy feedstocks. In consequence, any assessment of likely impacts from expanding bioenergy supplies on agricultural markets has to take these differences into account.

---

[2] Modified from OECD (2004) p. 17

Table 1. Sources and forms of bioenergy

Bioenergy form / Bioenergy source	Transport energy ("Biofuels")	Electricity ("Biopower")	Heat ("Bioheat")	Gas ("Biogas")	Link to agricultural markets
Agricultural commodities	*Ethanol* (grains, sugar crops, edible part of other starchy commodities) *Biodiesel* (vegetable oils) *Biogas* (grains)	*Biogas* (grains) *Combustion* (grains)	*Biogas* (grains) *Combustion* (grains)	*Biogas* (grains)	Direct competition with other uses
Residues and wastes from agriculture and food industry	*Biodiesel* (used cooking oil, animal fats) *Second-generation ethanol* (straw, non-edible part of starchy commodities) *Biogas* (manure, crop residues etc.)	*Biogas* (manure, crop residues etc.) *Combustion* (straw)	*Biogas* (manure, crop residues etc.) *Combustion* (straw)	*Biogas* (manure, crop residues etc.)	Co-production with agricultural or food products; potential competition with other uses
Forest products	Second generation ethanol (wood)	Direct combustion (wood)	Direct combustion (wood)		Potential competition with agricultural land use
Forest residues	Second generation ethanol (wood chips)	Direct combustion (wood chips)	Direct combustion (wood chips)		Little
Dedicated biomass crops	*Second generation ethanol* (grasses, poplar trees etc.) *BTL* (any biomass) *Biogas* (any biomass)	*Biogas* (any biomass) *Direct combustion* (wood, wood chips)	*Biogas* (any biomass) *Direct combustion* (wood, wood chips)	*Biogas* (any biomass)	Competition with land use for agricultural commodity production
Industrial wastes	Biogas	Biogas	Biogas	Biogas	Little
Municipal wastes	Biogas	Biogas	Biogas	Biogas	Little

Source: OECD Secretariat.

Overview on commercialised biomass crops and conversion technologies[3]

Key attributes of commercialised biomass crops

Currently a large number of plant species are or could potentially be cultivated for the purposes of energy generation. Due to the large number of potential species detailed descriptions of the full list of these species would go beyond the scope of this report. Discussions in this section shall therefore highlight three non-food crop systems that have already been extensively cultivated and evaluated for biomass production, and for which reliable and published data on life-cycle GHG emissions and/or net energy yields are

---

[3] The contribution of this section by a group of consultants, D. B. Turley, H. Parry and R. Laybourn (Central Science Laboratory, UK) is gratefully acknowledged.

available. These three crop systems are miscanthus, switchgrass and short rotation coppice, based on both willow and poplar trees.

Miscanthus (*Miscanthus sinensis, M.giganteus, M. sacchariflorus*): Originating from Asia, miscanthus is a woody, C4 perennial[4], rhizomatous species of grass, typically established from rhizome fragments. Sterile hybrid forms are mostly used in field production. Once established the 3 metres tall crop can be harvested annually for 15-20 years. The crop dies back in the autumn/winter and the dry canes are then harvested during the winter or in early spring after leaf senescence and natural drying. Yields of 12-14 dry tonne of plant material per hectare are typical in temperate climates for commercial operations on good quality land, in some case up to 16 t/ha can be achieved for older stands. The crop requires little input in terms of nutrients and pesticides. Miscanthus can be used in the form of bales, briquettes, pellets or ground for use in combustion and fossil-fuel co-firing systems.

Switchgrass (*Panicum virgatum*): A perennial sod-forming C4 grass, originating from North America. It grows up to 2.5 metres tall with rhizomes spreading below ground. It can produce to 18 dry tonne per hectare in temperate climates when harvested in winter (Price *et al.,* 2004). Once established, switch grass requires few inputs, apart from the first few years when it requires weed management. A well-established crop can remain productive for 10-15 years.

Short rotation coppice (SRC) (*Salix spp and Populus spp*)*:* Willow and poplar for SRC production is planted in spring from cuttings. After one year's growth it is cut back to ground level to encourage the growth of multiple stems. The crop re-grows rapidly, reaching up to 8 metres in height. The first commercial harvest usually occurs three years after cut back and subsequently every three years, though harvest frequencies may vary dependent on growth rates. The harvested crop is usually chipped and dried then stored until needed. In northern temperate climates, yields from the first harvest tend to be around 25-30 dry tonnes per hectare, and 30-35 dry tonnes per hectare in subsequent harvests, giving an annualised yield of 10-12 dry tonnes per hectare. Once established the crop can remain viable for 25-30 years.

In all the above cases, the yields represent typical field yields obtained from crops grown on reasonable /medium quality soils (it is unlikely that perennial energy crops would ever be grown on the best quality land reserved for high output, high quality food production). Such figures are typically used in LCA's to evaluate the potential of biomass supply chains. However, production on low quality land (to avoid land use conflicts) is likely to result in lower yields, particularly if water or other nutrients are constrained. This will tend to lower the GHG savings that are achievable.

Conversion technologies

The main thermal processes by which dry biomass can be converted to more useful energy forms in the power and heat sector are combustion and gasification. However, within these two broad categories a range of systems and technologies has been developed to convert biomass to useful energy with relevance at different scales of energy generation. In contrast wet biomass materials, such as fresh crop material or animal manures can be utilised by biological anaerobic digestion systems to produce energy, where otherwise the costs of drying would outweigh the benefits.

Combustion

The most common form of electricity generation from solid fuels from both fossil and biomass sources is through combustion in a furnace to heat steam to drive turbines (using Rankine cycle

---

[4] C4 carbon fixation is a more efficient metabolism to bind the gaseous CO_2 for the production of plant sugar, compared to the C3 carbon fixation operating in most plants. C4 carbon fixation is used by many grasses, including (besides miscanthus) maize, sugar cane, and many other tropical grasses.

technology), where surplus heat may be either captured or lost (see combined heat and power generation below). Theoretical energy efficiency (useful energy out *v* primary energy in) is high, though in practice rarely achieved. Older plants utilising such technology for generation of electricity typically have energy conversion efficiencies of around 30%. However, in newer dedicated biomass facilities efficiencies of >40% are reported (pers. comm. Swedish Ministry of Agriculture). There are a number of process modifications, varying in how solid fuels are handled. Fuels may be simply piled in furnaces with air blown through (pile burners), or fitted with sloping or vibrating grates to improve material combustion through provision of a more even flow of material into the furnace. Fluidised bed systems blast hot air through the fuel material to aerate and mix the fuel and improve combustion, which is useful in co-firing mixed fuel materials such as biomass and coal mixtures. Fuels can also be ground and fired into furnaces using air (suspension fired), a method often used in co-firing of coal and biomass mixtures. Pulverising fuels can increase energy conversion efficiency (Broek *et al.,* 1995) and efficiencies of up to 42% are reported (Swedish Ministry of Agriculture).

Large quantities of biomass are co-fired with fossil fuels, as this is the simplest and cheapest means of utilising biomass without the expense of developing dedicated biomass facilities, though this tends to mean biomass is utilised in less efficient and less modern plants. Biomass materials do cause combustion problems, both in terms of production of corrosive gasses that need to be scrubbed from the flue gas and in the different combustion characteristics of biomass and fossil fuels that can lead to additional ash problems (including slagging and fouling problems) and incomplete combustion, reducing the overall efficiency. Dedicated biomass plants can reduce such problems and optimise systems to deal with such issues. However, the ability to supply biomass from the locality, affected by the high bulk density and relatively low calorific value of biomass materials compared to fossil fuels, typically limits the scale of biomass dedicated heat and power plants to between 1 and 35 MW_e which can reduce efficiencies associated with scale of generation. However in areas with a large forest industry, larger plants can be contemplated, for example there are plans for a 150MW_e plant in Stockholm, Sweden.

Gasification

Advanced natural gas technologies use so-called ‘combined cycle technologies’, whereby combustion of gas is used to drive a turbine to produce electricity and the waste heat is re-used to generate steam and additional electricity via a steam-driven turbine. In this case, high energy efficiencies of around 60% are possible in theory, though in current practice are more typically around 50%. Through the process of gasification, biomass can be converted to gas to utilise the same technology.

In contrast to combustion, gasification takes place in a low oxygen atmosphere, where heating of the biomass leads to charring of the biomass and, through volatilisation, generation of hot fuel gases that can be cleaned and fed directly into a gas turbine or a gas engine to generate electricity directly or to heat boilers. The technology for biomass gasification is not as well developed as traditional combustion technologies. There have been few large-scale commercial examples of biomass gasification.

In the gasification process, dry biomass is first pyrolised in the absence of air to produce gasses, tars and a solid char product. The ratio of these depends on the fuel and combustion conditions. The gases are then allowed to react with oxygen or air to give mainly CO, CO_2, H_2 and smaller quantities of hydrocarbon gases, with composition and heating value again affected by feedstock and reaction conditions (Bridgewater, 2006). Production of tars is a significant problem for turbines and engines. Other contaminants also need to be removed from the gas (alkali metals, particulates, nitrogen, sulphur and chlorine). Energy efficiencies of up to 50% are predicted for the largest installations, but these are likely to fall to 35% for smaller installations (Bridgewater, 2006). A 2MW_e gasification pilot plant using a gas engine has been running successfully in Gűssing, Austria, this represents the most advanced biomass gasification plant to date, but efficiency is currently well below 50%.

Conversion efficiencies for thermal processes

The main advantage of gasification technologies over direct combustion is the increased efficiency of these systems. The steam cycle used to generate electricity in direct combustion systems operates at an efficiency of typically around 36%. The fuel gases formed by gasification enable use of gas turbine cycle technologies, with the most advanced gasification systems estimated to have an overall energy efficiency in excess of 40%. Gasification and pyrolysis technologies are still at a very early stage of development, while direct combustion is a proven technology, it is cheap by comparison and requires less technical knowledge to operate, and large scales of operation can lead to high efficiency. Scale of operation is a key factor affecting overall efficiency. Large co-firing plants may have outputs of 600 MW_e compared to the typical much smaller biomass dedicated plants.

It should be clear from the above that when talking about biomass and its use in combustion, gasification and even anaerobic digestion conversion systems, this reflects a very generic use of terms. There are a wide range of technology combinations and scale of operations within each of the generic energy conversion systems that will have a significant impact on overall energy efficiency.

Van den Broek *et al.,* (1996), reviewed the efficiencies of a range of existing and demonstration biomass combustion plants. It was concluded that current biomass combustion technologies should deliver energy conversion efficiencies above 30%, (ranging from 22 to 39%) with lowest efficiencies associated with travelling grate systems, while fluidized bed and vibrating grate technologies reached 33%. In large-scale co-firing plants efficiencies of 37-40% can be achieved. Data for biomass gasification systems with combined cycle technologies identified efficiencies of 40-42% for basic atmospheric systems, rising to 45-46% for pressurized systems, which compares well with figures for biomass gasification efficiencies presented above by Bridgewater for larger systems (2006).

In this report reference to energy efficiency and conversion efficiency relate to energy conversion efficiencies, *i.e.* the efficiency with the energy delivered in the feedstock is delivered as useful power or heat.

Combined heat and power (CHP) generation (cogeneration)

Conventional electricity generation plants dissipate waste heat via cooling towers. Energy efficiency can be significantly improved where the heat from combustion of fuels can also be captured and utilized through combined heat and power generation, where the heat can be used for space heating or in industrial applications. Large scale CHP technologies (>2 MW_e) generally utilize steam or gas turbine generating technologies, but smaller scale developments, where heat output is typically the primary driving requisite, utilize a range of technologies in the drive to maintain energy conversion efficiency. Overall, energy conversion efficiencies of around 85% are possible with CHP operations.

Anaerobic digestion (AD)

AD is the most efficient means of generating energy from wastes with dry matter contents below 30% (ideally in range 5-12.5%) such as manures, sewage sludge, food and other organic wet wastes. The basic technology of AD involves anaerobic fermentation of wet organic waste feedstocks to produce methane and carbon dioxide, with the methane being used for heating, electricity generation or as a transport fuel. 'Dry' AD methods for biomass dry matter contents of around 30% or more, are currently being commercialised in Germany using biomass crops as part of the feedstock mix.

Digestion takes place in a warmed, sealed container (the digester) where bacteria ferment the organic material in oxygen-free conditions. Heating for the digester is derived from a methane-fuelled boiler or recovered heat from the gas engine system. The temperature of the digester tank may be increased to the mesophilic range (30 - 35°C) where the feedstock remains in the digester typically for 15-30 days, or into the thermophilic range (55-65°C) where the residence time is typically 12-15 days. Thermophilic digestion systems offer higher methane production, but require more expensive technology, greater energy input and a higher degree of operation and monitoring. Typically around 30-60% of the mass of the feedstock biomass solids are converted into biogas (methane and carbon dioxide), higher conversion rates rely on longer residence times.

The first stage of decomposition is enzymic hydrolysis, whereby carbohydrates are broken down to sugars, proteins to amino acids and lipids to fatty acids. The products of hydrolysis are then further degraded by acetogenic bacteria to volatile fatty acids, CO_2 and hydrogen. Methanogenic bacteria utilise the volatile fatty acids, hydrogen and CO_2 to produce methane, which is the main useful energetic output of AD.

In animal wastes, the highest proportion of AD biodegradable organic matter is found in poultry waste (65%) with less in pig waste (50%) and cattle waste (25-40%). Cattle manures have already undergone some methanogenesis in the ruminant stomach, so, even though the organic matter content of different manures can be similar, methane yields per unit of feedstock, and rate of methane emission can be very different.

The output of methane is very dependent on the materials fed into the system, how effectively the biological systems involved are optimised, operating temperature and stability of temperature all of which can lead to significant variation in efficiencies between systems.

The by-product of fermentation is termed ‘digestate’, and consists of fibre and liquid. More than 90% of nutrients entering anaerobic digesters are retained within the digestate, which can therefore be used as a soil conditioner and low-grade fertiliser.

Material preparation

Appropriate preparation of biomass materials can help improve utilization. Ensuring biomass is as dry as possible (to increase its calorific value) means that additional drying heat may be required. Pelleting biomass provides advantages in aiding mixing with other materials, improving compatibility with existing handling systems and reduces transport costs (and transport emissions per tonne transported). However, there is a significant energy input into the pelleting operation itself. There is commonly little information available on energy inputs to pelleting operations, that which is available is often conflicting and may not include inputs associated with drying prior to materials preparation. In other work, the authors have found GHG emission values for pelleting ranging from 38 to 469 $kgCO_{2eq}$/tonne.

Bioenergy support policy developments – objectives, targets and policy measures

As outlined in OECD (2008), a number of objectives are mentioned in the policy debate on support to bioenergy production and use. In particular, these include the security of energy supply; environmental improvements, including particularly the reduction of greenhouse gas emissions and climate change; rural development, employment and economic growth; and, to the degree the bioenergy is based on agricultural feedstocks, the creation of new outlets and demand for agricultural products to raise farm incomes. A (non-representative) survey with OECD and several non-OECD governments between October 2007 and April 2008 showed that the avoidance of GHG emissions and the reduction of energy imports ranked high in their policy priorities, even though it should be stressed that a ranking of policy objectives not only differs by countries, but may also change in time and across Ministries.

Besides mandates and non-obligatory targets for the use of biofuels in the transport sector (defined either as shares of biofuels in the total transport fuel mix, or as absolute consumption quantities), a number of countries have also defined targets for the use of renewable energy sources (RES) and their shares in total primary energy supplies. As Pons (2007) has shown, a number of EU Member States have defined minimum targets for renewable energy, ranging from 4% to 14% of total primary energy supplies for different target years. With the Renewable Energy Directive of December 2008 (published on 23 April 2009), an EU-wide mandatory target of 20% has been defined, applicable with individual targets to all Member States ranging from 10% (Malta) to 49% (Sweden), with intermediate objectives set to achieve these targets. Other countries, both within the OECD and beyond, have established or announced such targets as well, including New Zealand (targeting 90% of total electricity to be renewable by 2025), the US (5% to 20% of renewable electricity in 20 states), China (16% of renewable energy in the total energy mix by 2020), Russia (16% of bioenergy by 2020) and others.

While in most cases, targets are unspecific with respect to the type of renewable energy and hence cover other forms such as wind, solar or hydro as well, energy from biomass is widely seen to provide an important contribution in the future. Specific targets for bioheat and biopower have been defined, however, only by a limited number of countries, as indicated in Table 2.

Table 2. Specific targets for bioheat and biopower

Country	Targets for bioheat and biopower
New Zealand	19 PJ of bioheat and biopower by 2025
Norway	Irrespective of end use (power, heat or transport fuel), the Government has proposed development of bioenergy up to 14 TWh witihin 2020. The proposal has yet to be discussed by Parliament.
Japan	Bioheat and biopower (including waste) supply: 2,580 Mil litres and 5.860 Mil litres of oil equivalent by 2010, respectively[5]
USA	5% to 30% of bio-electricity in 20 states (including DC).
Germany	12% bioheat, 27% biopower by 2020
Ireland	5% and 12% bioheat by 2010 and 2020, respectively. 30% biomass co-firing in Peat Power Stations (combined capacity: 360 MW) by 2015
Romania	33% of gross electricity consumption by 2010

Source: Data from questionnaires provided to the OECD Secretariat between October 2007 and April 2008.

Support for the production and use of bioenergy is provided at all levels of the chain, beginning with the production of biomass and ranging over infrastructure, the conversion of biomass to usable energy forms and the distribution of bioenergy to support to final consumers of bioenergy. Similarly, programs supporting bioenergy supply and use are often run by a range of government departments and ministries at both national and sub national levels, and may apply to all forms of renewable or bioenergy or may focus on certain production chains such as biomass-powered CHP plants or biogas. A number of examples for support at various levels of the production chains are listed by OECD (2008), based on Pons (2007).

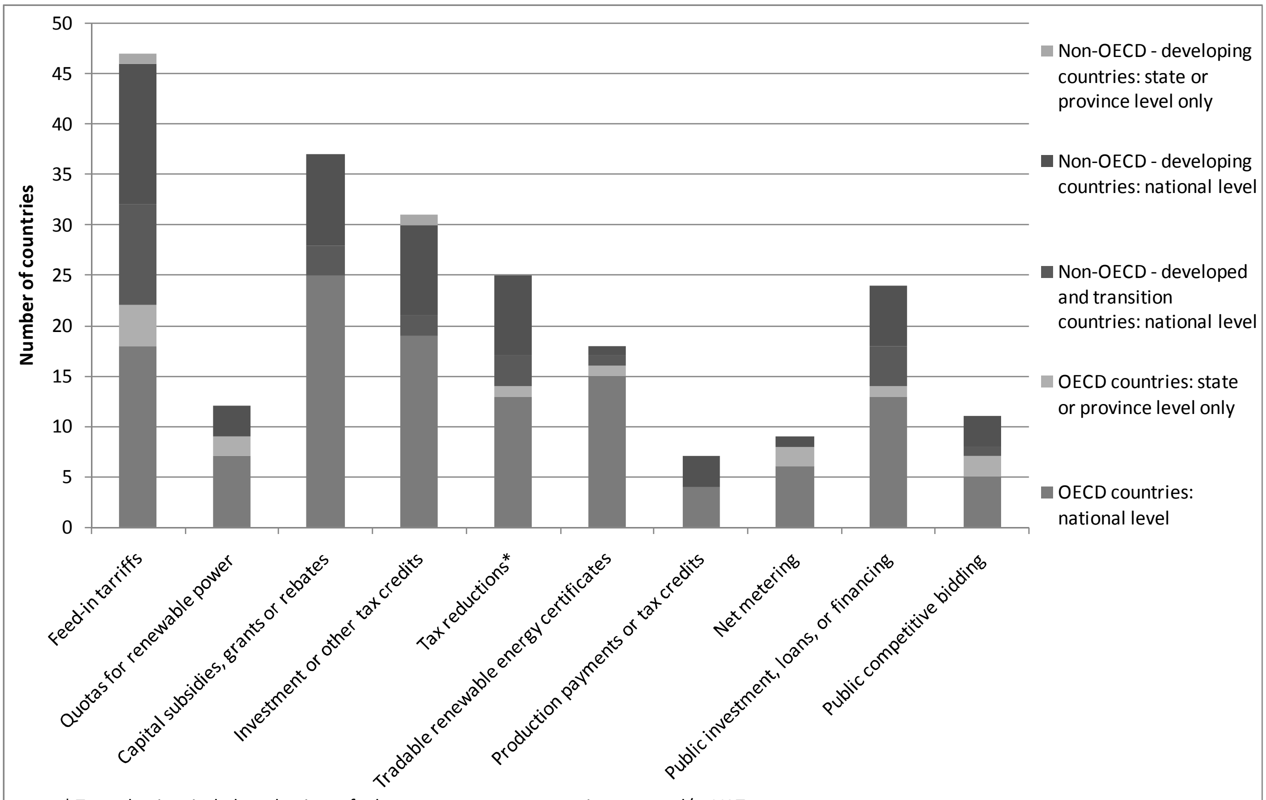
Among the many different support measures, capital grants or loan guarantees for bioenergy production plants, and feed-in tariffs for renewable electricity, are among the most common ones, provided by a large number of countries both within the OECD and elsewhere (Figure 2). Capital grants or loan guarantees allow reducing the start-up costs for the bioenergy industry, thus both reducing bioenergy production costs and the failure risk faced by the industry. As shown in the figure, capital subsidies, grants

---

[5] Japan has two target quantities in the “Kyoto Protocol Target Achievement Plan”, denoting maximum and minimum amounts
(see Appendix 1, http://www.kantei.go.jp/foreign/policy/ondanka/KP_Achievement_Plan_Appendix.pdf). Figures given here correspond to the maximum introduction case.

or rebates are applied in 25 of the 30 OECD countries as well as in 12 non-member economies including large ones such as China, India and Russia. While these numbers refer to grants given for any type of renewable electricity – as is the case for many other support policies in this area – producers of biomass-based power (and in many cases heat as well) can benefit from these programmes in some form or another.

Figure 2. Frequency of policy measures to promote renewable power generation



* Tax reductions include reductions of sales taxes, energy taxes, excise taxes and/or VAT

Note: Non-OECD developed and transition countries covered here include Croatia, Cyprus[6,7], Estonia, Israel, Latvia, Lithuania, Malta, Romania, Russia, Slovenia; non-OECD developing countries covered here include Algeria, Argentina, Brazil, Cambodia, Chile, China, Costa Rica, Ecuador, Guatemala, Honduras, India, Indonesia, Morocco, Nicaragua, Panama, Philippines, South Africa, Sri Lanka, Thailand, Tunisia, Uganda.

Source: Based on REN21 (2007, 2009).

Guaranteed feed-in tariffs (minimum prices producers receive when feeding their renewable energy into the grid, set by governments above the market price of the energy type) provide producers of renewable electricity including biopower (or, in similar ways, biogas) with stable and plannable returns if they sell their energy to the grid. Feed-in tariffs are often differentiated relative to a number of factors,

---

[6] Footnote by Turkey.
The information in this document with reference to « Cyprus » relates to the southern part of the Island. There is no single authority representing both Turkish and Greek Cypriot people on the Island. Turkey recognizes the Turkish Republic of Northern Cyprus (TRNC). Until a lasting and equitable solution is found within the context of United Nations, Turkey shall preserve its position concerning the "Cyprus issue".

[7] Footnote by all the European Union Member States of the OECD and the European Commission.
The Republic of Cyprus is recognized by all members of the United Nations with the exception of Turkey. The information in this document relates to the area under the effective control of the Government of the Republic of Cyprus."

including plant capacity, technology (often related to production costs), location and/or environmental and energy performance, and may be defined directly as feed-in price per kWh or as premiums above the grid price. Furthermore they may be degressive over time.

Feed-in tariffs are common support measures in many countries. Apart from a number of OECD countries – in some of which it is applied on a provincial or state level rather than the national level, this policy is applied frequently in Central Europe as well as in a number of developing countries. Furthermore, a number of other countries are discussing the introduction of such feed-in policies.[8]

A number of OECD countries as well as several non-member economies have provided detailed information on support policies for bioenergy in their countries.[9] These data confirm the large range of applied policy measures found by REN21 (2007, 2009) and provide information on the aims and volumes of various support programmes particularly on capital grants. While it is not possible to estimate the overall spending for measures supporting bioheat, biopower and biogas, the data would suggest that the various support measures represent an important driver for the development of these chains.

Many of the existing policies supporting the production and use of renewable energy in general, and of bioenergy in particular, have been in place for a number of years. For instance, the United States Energy Tax Act of 1978, superseded by the Energy Policy Act 1992, first constituted tax credits for households and business investing in renewable energy, as well as an excise tax exemption for fuel use of ethanol and methanol (IEA online, 2010). The Brazilian ProAlcool program promoting the use of sugar-cane based ethanol even dates back to 1975 (see e.g. REN21, 2005, p. 25). However, the number of support measures has significantly increased over the past several years, and targets for renewable energy were enacted or revised. For instance, within the 63 countries or subnational units having had enacted feed-in policies by early 2009, 50 were added after 2000 (REN21, 2009, p. 26),

The environmental performance of alternative bioenergy chains[10,11]

GHG savings

While there is considerable variability in the effects between scenarios it is clear that there is a general consensus that all of the biomass conversion systems studied delivered very positive average GHG savings, ranging from 63-99% when compared to use of coal for electricity generation (Figure 3), and from 37-98% when compared to use of natural gas for electricity generation (Figure 4). However, as highlighted earlier, there are significant levels of uncertainty associated with such estimates and such results should be used cautiously when using such data to determine policy actions.

---

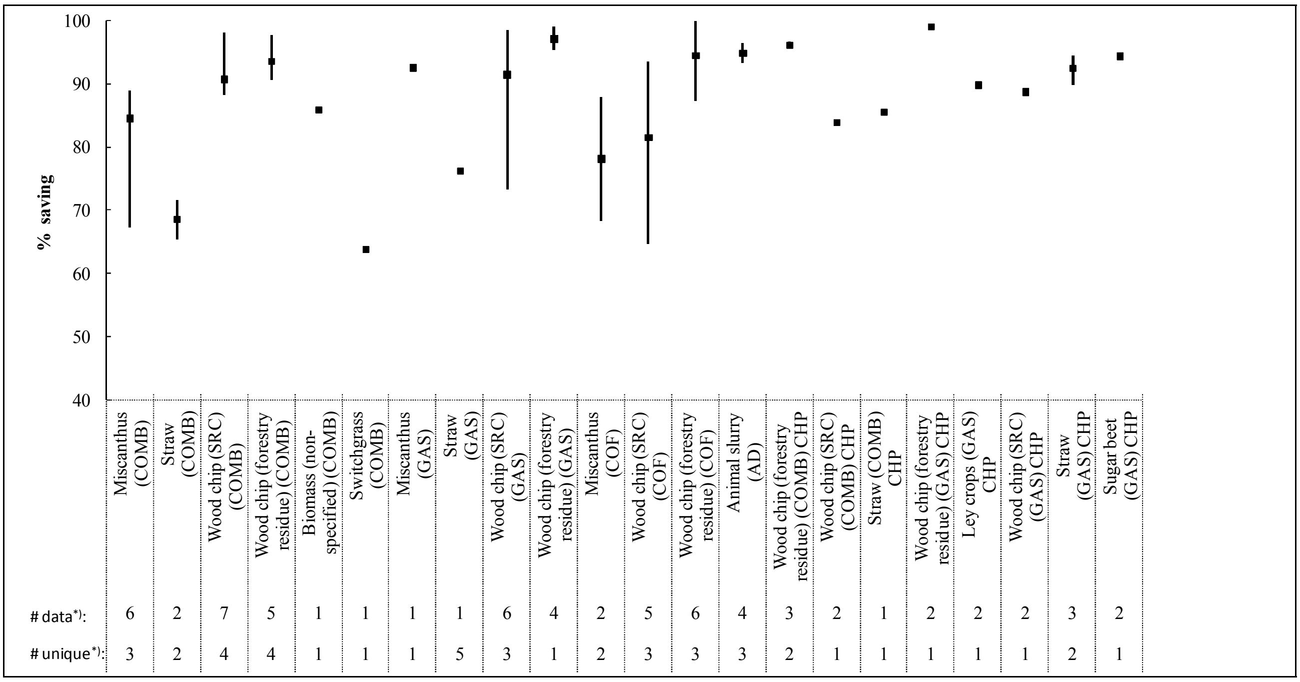
[8] REN21 (2009)

[9] The compiled dataset can be made available upon request.

[10] This section provides an overview on results from various life-cycle analyses (LCAs) about the GHG and energy balances of different bioenergy chains, mainly focusing on biopower and bioheat. Some technical remarks on LCAs can be found in Annex 1. It should be noted that the environmental performance of these chains is also determined by numerous other factors, such as the emission of fine particles and other harmful substances, biodiversity issues etc., not covered here.

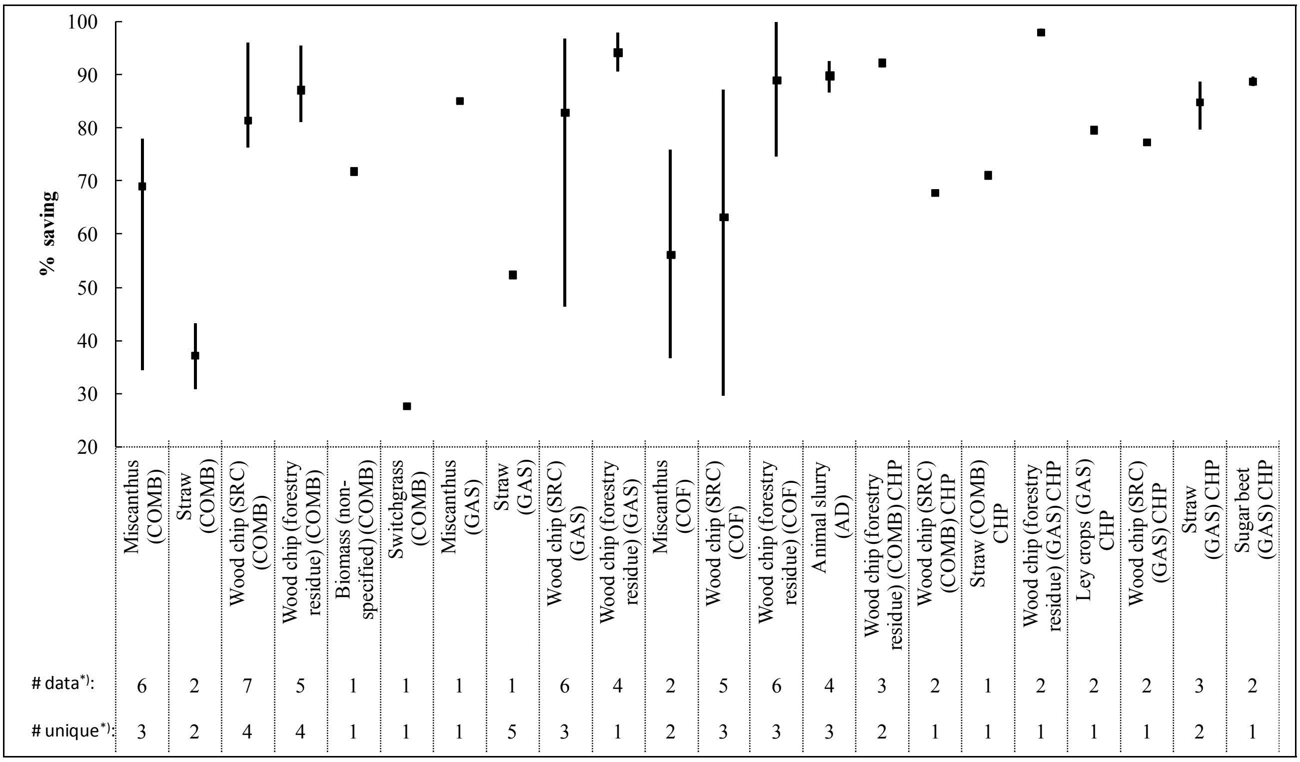
[11] The contribution of this section by a group of consultants, D. B. Turley, H. Parry and R. Laybourn (Central Science Laboratory, UK) is gratefully acknowledged.

Figure 3. GHG savings for biomass energy chains relative to the use of coal for power generation



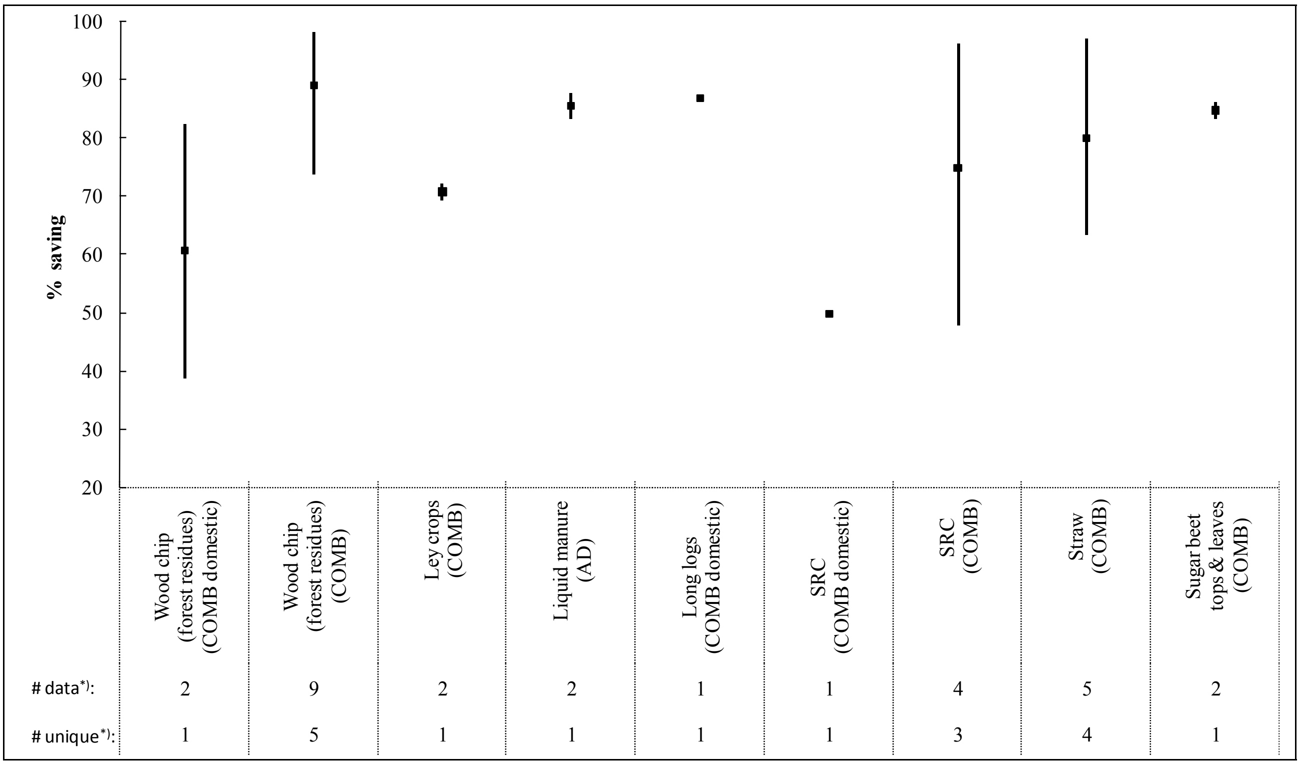
Notes: *) "# data" refers to the number of data points collated within each scenario while "# unique" refers to the number of unique reverences providing data for each scenario, to provide an indication of the reliability of the results.
COMB = direct combustion, GAS = gasification, COF = co-fired with fossil fuels, AD = anaerobic digestion, CHP = combined heat and power.
Source: Compiled from various studies providing results of life-cycle analyses. See Annex 1 for more details.

Figure 4. GHG savings for biomass energy chains relative to the use of natural gas for power generation



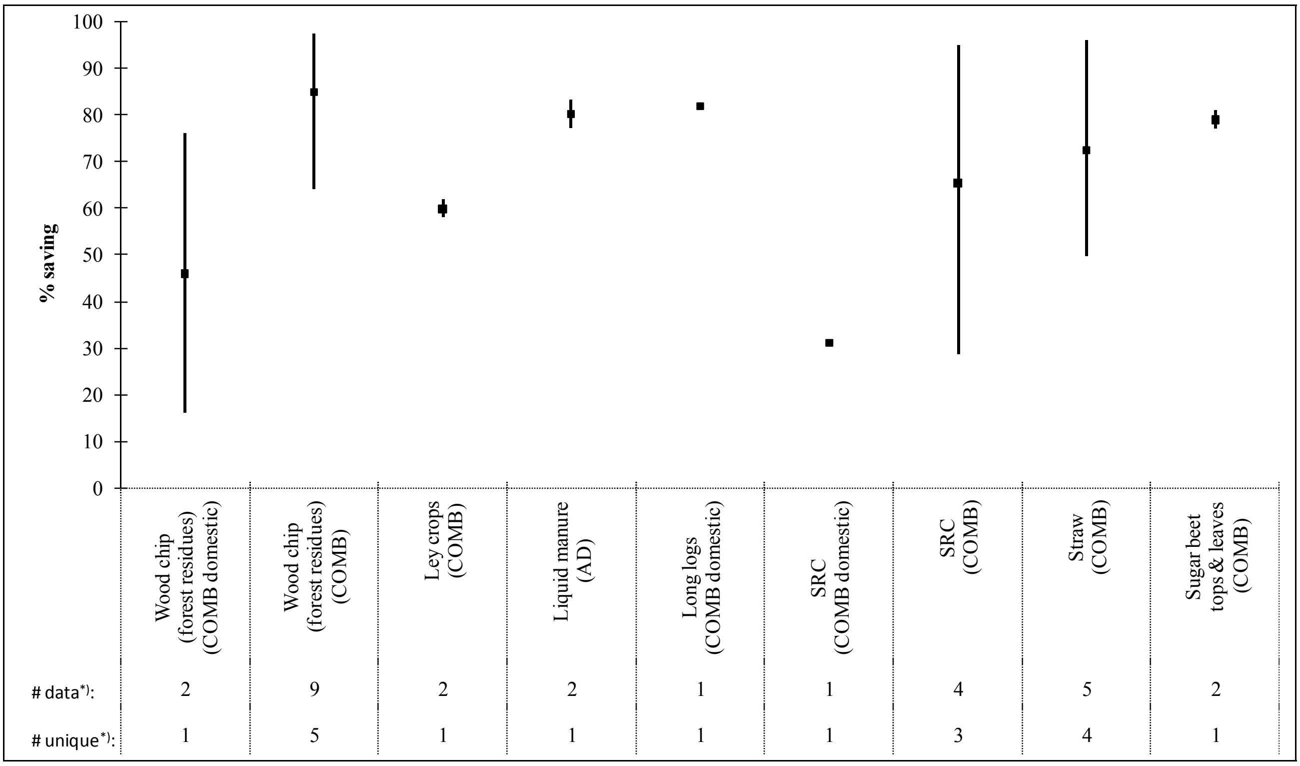
Notes and sources: See notes and sources to Figure 3 above.

Figure 5. GHG savings for biomass heat supply chains relative to the use of fuel oil for heat applications



Notes and sources: See notes and sources to Figure 3 above.

Figure 6. GHG savings for biomass heat supply chains relative to the use of natural gas for heat applications



Notes and sources: See notes and sources to Figure 3 above.

Surprisingly, the savings were lower for heat applications, though this may reflect on the lower efficiency associated with smaller district, space heating and domestic heating systems. Use of biomass resulted in average GHG savings ranging from 50-89% when compared to use of fuel oil for heating (Figure 5), and ranging from 31-84% compared with use of gas for heating (Figure 6). Again this is an area where studies are limited and would benefit from further work to clarify impacts.

Ranges of GHG savings tended to be greatest where larger numbers of data points were derived from more than one reference source, indicating that LCA methodologies and approaches had a significant impact on the results and this makes it very difficult to compare differences in detail between studies. From first principles one might expect that:

1. For the same energy conversion system, high yielding low input and perennial biomass sources should deliver better GHG savings than annually harvested crops.
2. ‘Waste’ materials from agriculture or the food industry (*e.g.* straw) and forest residues should perform particularly well as only a proportion of the agricultural and forestry inputs should be allocated to energy feedstock production and no land use change element is involved.
3. Coppiced wood should perform as an intermediate to 1) and 2) above.
4. Based on energy conversion factors for different technologies GHG saving performance in the sequence combustion ≤ co-firing < gasification < CHP is anticipated.

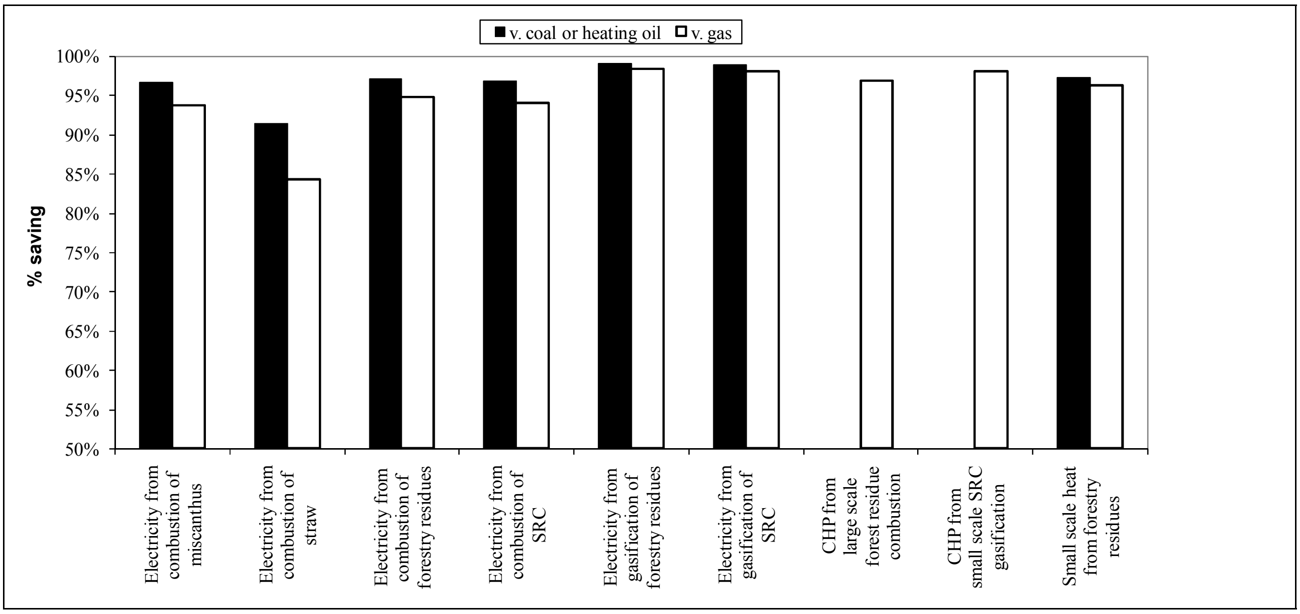
It is difficult to see any such clear trends in the data collated, however CHP systems perform consistently well across a range of scenarios returning GHG savings ranging from 84-99% compared to use of coal and 68-97% compared to use of natural gas for electricity generation. There was little evidence that gasification is likely to perform better than combustion technologies. However, this may reflect on the lack of significant numbers of gasification examples in practice on which to draw data, such that many LCAs covering gasification are indicative only and include assumptions on energy conversion efficiency. In some cases, as shown earlier, this may not be significantly greater than the efficiencies obtained through large-scale combustion operations. Co-firing operations also show a wide range of GHG savings and this reflects the wide range of technologies involved as well as the greater study of such systems.

Biomass utilized for heat applications shows a wide range of GHG savings, with much overlap between feedstock types, though smaller domestic applications fare less well than large scale applications, though all perform particularly well.

Although the data sets are limited, AD systems (utilizing animal slurry) perform well against both electricity and heat only applications, providing average GHG savings ranging from 90-95% against fossil-fuelled electricity production and 80-85% against fossil-fuelled heating systems. The analyses studied also did not take account of the mitigation of emissions that would have otherwise arisen if the manure had been stored and spread to land, taking these into account would boost the overall GHG savings further.

To try to overcome some of the problems associated with drawing comparisons across different studies, where assumptions and approaches differ, data was drawn from one comprehensive open study (Elsayed *et al,* 2003) to compare the GHG savings for different biomass sources and conversion chains (Figure 7). Across all scenarios, GHG savings from use of biomass ranged from 92-99% compared to use of coal for electricity generation and from 84-98% compared to use of natural gas for electricity generation. Combustion of straw was the lowest performing, while figures for GHG savings arising from combustion of miscanthus, forestry residues and short rotation coppice (SRC) for electricity were very similar (94% v gas and 97% v coal). In this study gasification performed slightly better than combustion, with GHG savings ranging from 98% v natural gas, to 99% v coal. GHG savings form CHP applications were also high (97-98%) as well as for small scale heat applications (96-97%).

Figure 7. Comparison of GHG savings of bioheat and biopower chains relative to fossil fuel chains

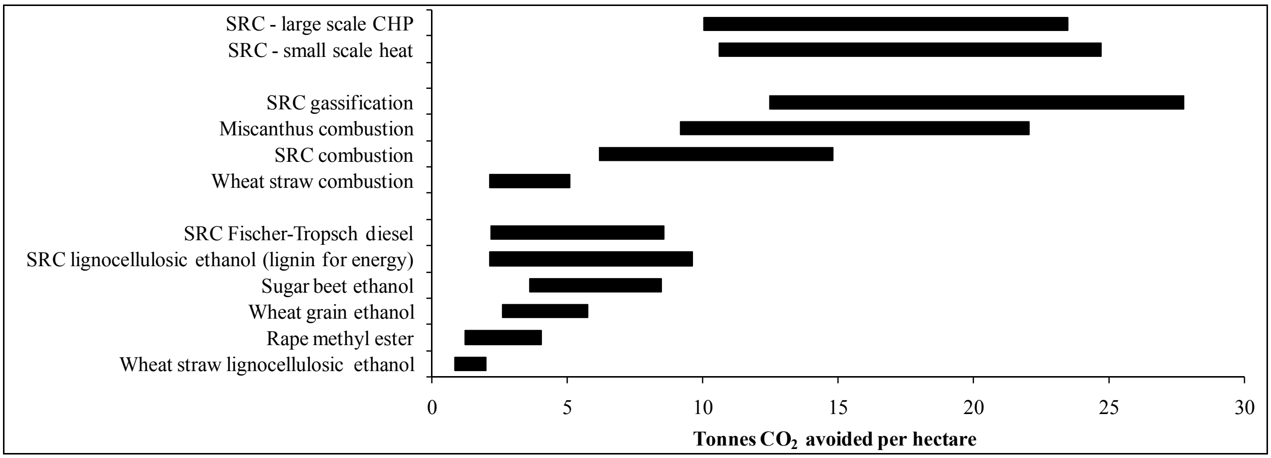


Notes: Black bars compare to coal power or oil heating applications; white bars compare to natural gas power and heating applications.

Source: Elsayed *et al.,* (2003).

In terms of actual carbon abatement potential, the potential abatement savings possible are higher than those that would be achieved by use of the same feedstocks for liquid biofuel production for use in transport, even when considering the developing second-generation technologies (Fischer Tropsch diesel (biomass to liquid) and lignocellulosic fermentation technologies) (see Figure 8). However, the number of alternative viable options for renewable alternatives in the transport sector is much more limited. Initial construction and ongoing cost of advanced biomass energy technologies will also have a significant impact on the marginal cost of carbon abatement. New technologies are likely to be significantly higher than those of current technologies.

Figure 8. GHG savings per hectare of biomass crop production for different bioenergy chains



Note: SRC = short rotation willow or polar coppice

Source: Data derived from Woods and Bauen, 2003 and Elsayed *et al,* 2003.

The GHG savings quoted are based on the assumption that there is no impact of land use change, which can have a significant impact on the GHG balance. The Intergovernmental Panel on Climate Change (IPCC) has published a methodology for accounting for land use change and the following default values for emissions from land use change (Table 3) are used in climate change agreements. It should be noted, however, that the estimation of GHG effects related particularly to indirect land use changes – changes induced by, but geographically seperated from, the production of biomass for energy – is subject to substantial methodological problems and topic of numerous research projects. Such estimates consequently carry significantly lower levels of precision than those for direct land use changes (where the use of land is changed from high-carbon covers such as forest of grassland to planted biomass crops).

Table 3. Range of IPCC default values for annual CO2 emissions associated with land use changes

Original land use	**Forest land**		**Grassland**	
New land use	Annual cropland	Perennial cropland	Annual cropland	Perennial cropland
Annualised CO2 emissions	15-37 t CO_{2eq}/ha	14-31 t CO_{2eq}/ha	2-10 t CO_{2eq}/ha	1-18 t CO_{2eq}/ha

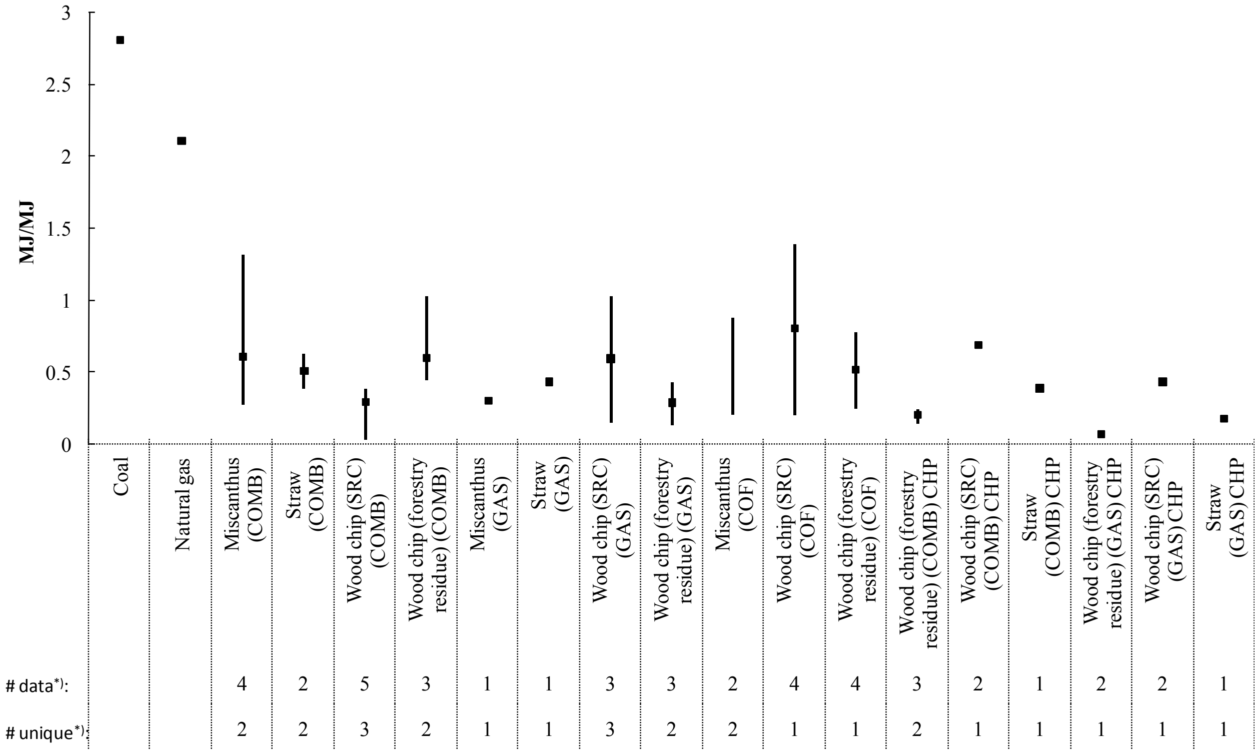
Note: Default year of 2005, all soil carbon change figures amortised to 20 year time period. Ranges reflect differences reported across countries and continents.

Comparing the above figures with data presented in Figure 8 shows that in the medium-long term (20 years or less) conversion of land with high carbon stocks to inappropriate energy cropping can negate any carbon savings achieved by displacement of fossil fuel heat and power technologies. The IPCC does calculate country-specific defaults. However, the actual impacts will depend on locality, soil carbon content associated with current land use and impacts of the new land use. It is therefore important to identify land areas where bioenergy production is likely to occur and whether this involves any change in land use. Avoiding unsuitable land will ensure positive GHG savings can be achieved within a reasonable timescale.

Energy balance

All biomass electricity and CHP supply chains show improvements in energy balances over fossil-fuelled electricity production (Figure 9), with a great deal of overlap between different biomass conversion chains. All show a mean energy balance of less than 1 (MJ in per MJ out) compared to a figure of 2-3 for fossil-fuel derived chains, though there are a few examples where the range of data within some biomass conversion combination exceed 1 MJ in/MJ out.

Figure 9. Energy efficiency (MJin/MJout) of electricity and CHP supply chains for coal power, natural gas power, biomass power and CHP chains

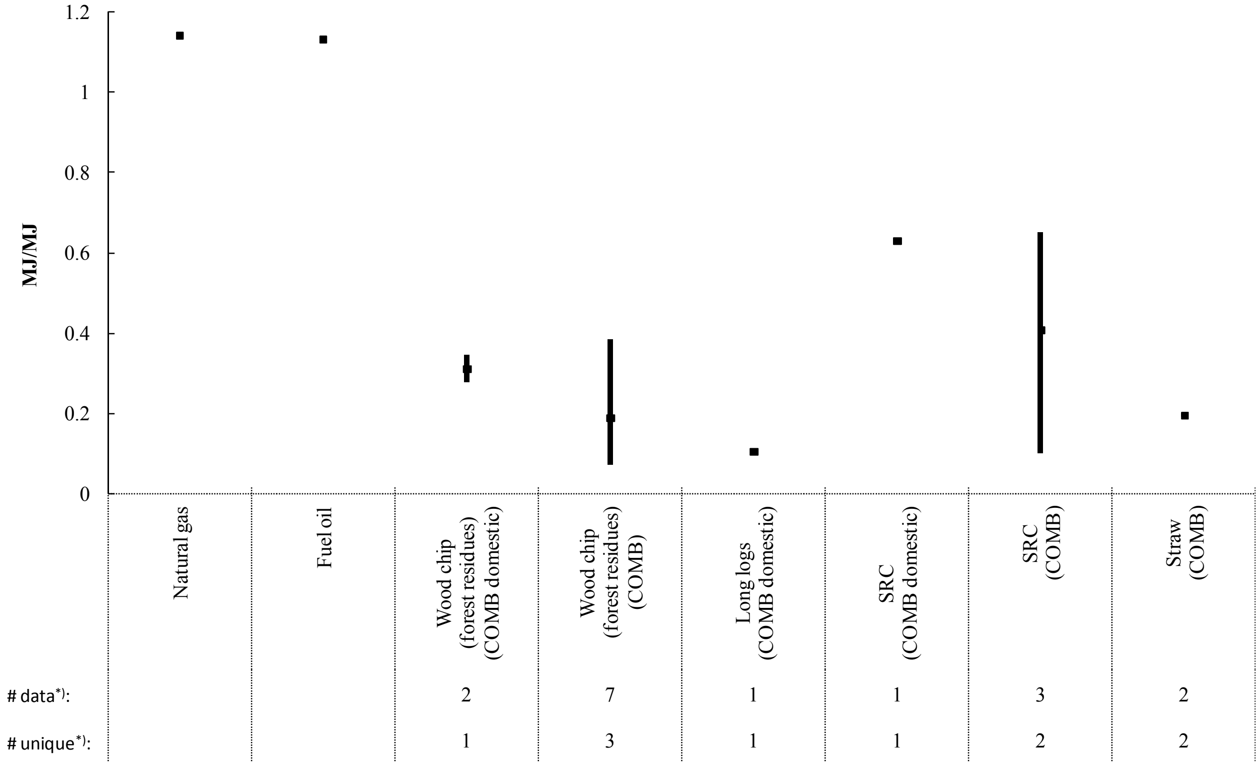


Notes and sources: See notes and sources to Figure 3 above.

CHP chains perform particularly well, with mean energy balances ranging from 0.07-0.68 MJ/MJ. However, it is difficult to discern other trends within the data sets available.

Mean energy balances for biomass heat applications are also very positive compared to fossil fuel chains, ranging from 0.1 to 0.63 MJ/MJ compared to >1 for fossil fuel chains. Again there is considerable overlap between studies which makes it difficult to discern any key trends.

Figure 10. Energy efficiency (MJin/MJout) of heat production supply chains using natural gas, fuel oil and biomass

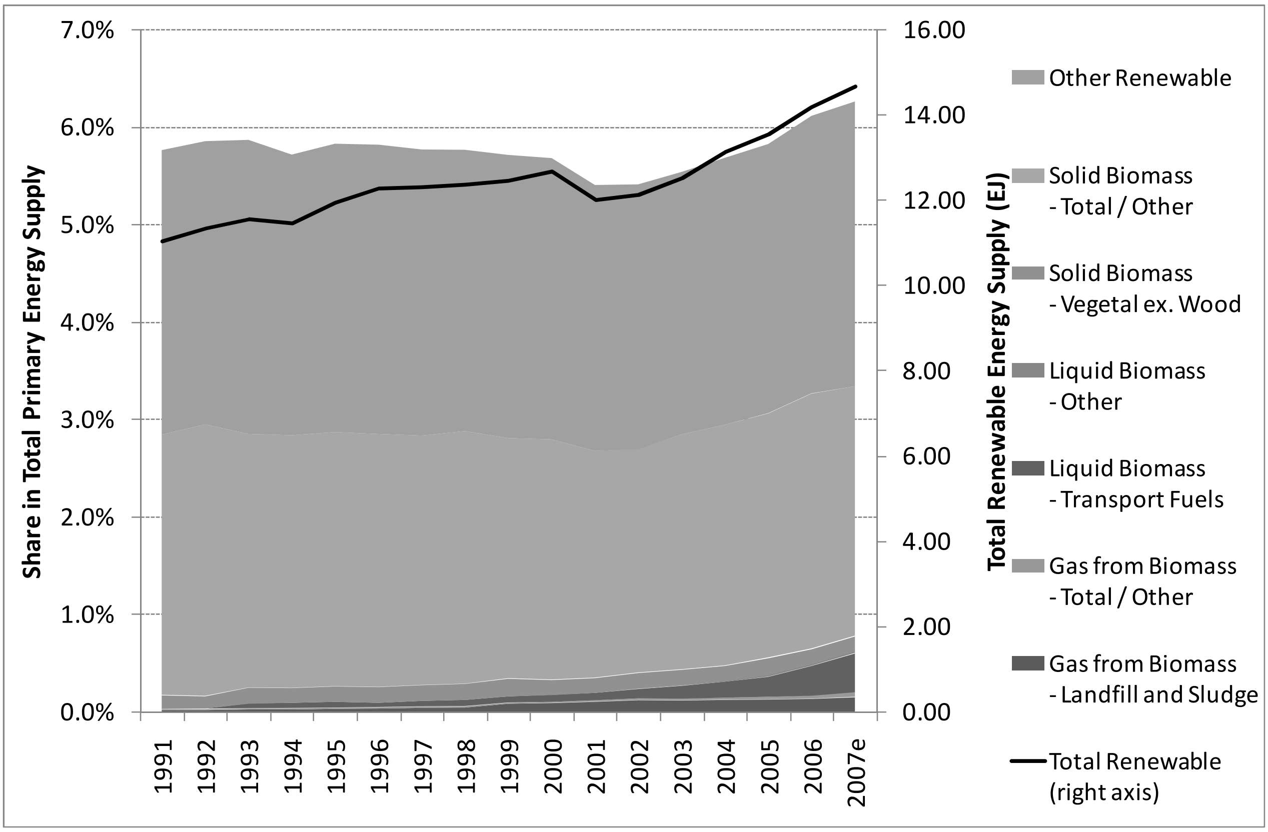


Notes and sources: See notes and sources to Figure 3 above.

Market developments of bioheat, biopower and biogas in the overall bioenergy context

The importance of modern bioenergy is increasing in a large number of countries. Within the OECD, biomass based energy supply amounted to some 7.8 Exajoule (EJ) in 2006, up from 5.5 EJ 16 years earlier. Since 2003, the share of bioenergy in total energy supplies exceeded that of other renewable energy sources, with total renewable energy representing 6.3% of total OECD energy supplies in 2007 (Figure 11). Within the OECD, the share of renewable energy varies significantly, ranging from less than 1% in South Korea to more than 75% in Iceland (see Figure 12), where virtually all of the domestically produced primary energy comes from renewable sources, particularly the hot springs in the country.

Figure 11. Renewable energy supplies in the OECD, 1991-2007



Source: IEA (2008a)

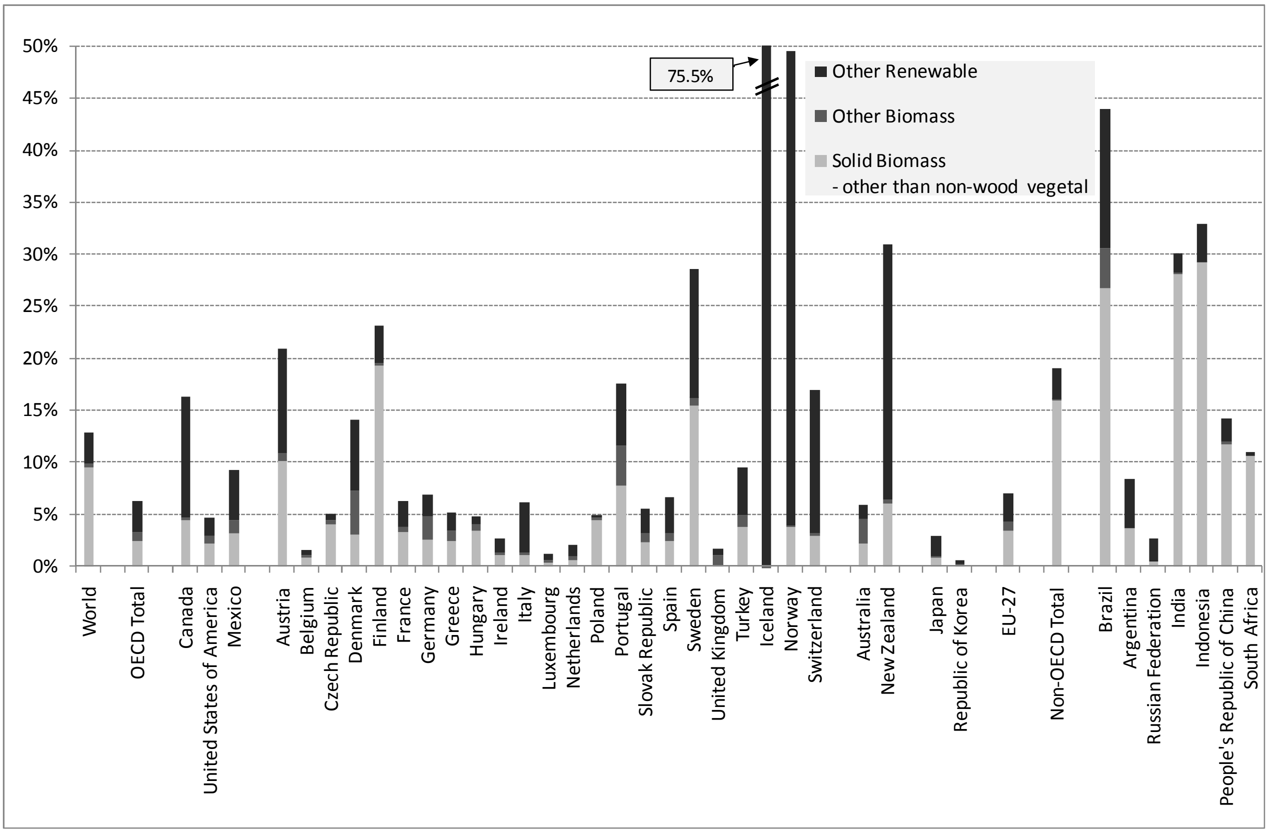
Agricultural biomass only plays a relatively small role in total bioenergy supplies, which are dominated by forest products[12]. Much of the growth in recent years comes, however, from increased use of liquid biofuels in transport, showing a strongly increasing trend. As discussed in OECD (2008), the production and use of biofuels in the OECD transport sectors, most notably in the US and the EU, are rapidly increasing, driven particularly by strong public policy support and increasing crude oil prices. For the OECD as a whole, liquid biofuels represented 0.42% of total primary energy supply (0.4% of which were used in the transport sector) – in the US and the EU, these shares were 0.6% and 0.5%, respectively. Given that the transport sector accounted for about 23.5% of the OECD's total primary energy demand (2006 data), the share of biofuels in the transport energy mix was 1.7%-2.1% in both the US and the EU.[13] All these shares have increased further, and while the IEA (2008b) estimates the biofuel shares in the US and EU to reach 5% and 5.5% by 2020, respectively, OECD and FAO (2009) expect these shares to grow to 5.8% and 7.1% by 2018, respectively.

---

[12] Note that some countries explicitly aim to increase the use of agricultural biomass. Poland, for instance, has legislated the obligation to increase the share of agricultural biomass (energy crops, residues or wastes both from agricultural production and the processing industry) in the process of biomass combusion to at least 20-25% in 2010, and 60-100% in 2017, depending on the size of the power generation unit (Ordonance of the Polish Ministry of Economy, 14.08.2008).

[13] According to the database of OECD-FAO (2009), the shares of biofuels in total transport energy use in the USA and the EU were even higher in 2007 at 2.8% and 2.2%, respectively. This latter source only considers gasoline, ethanol, diesel and biodiesel fuels, however.

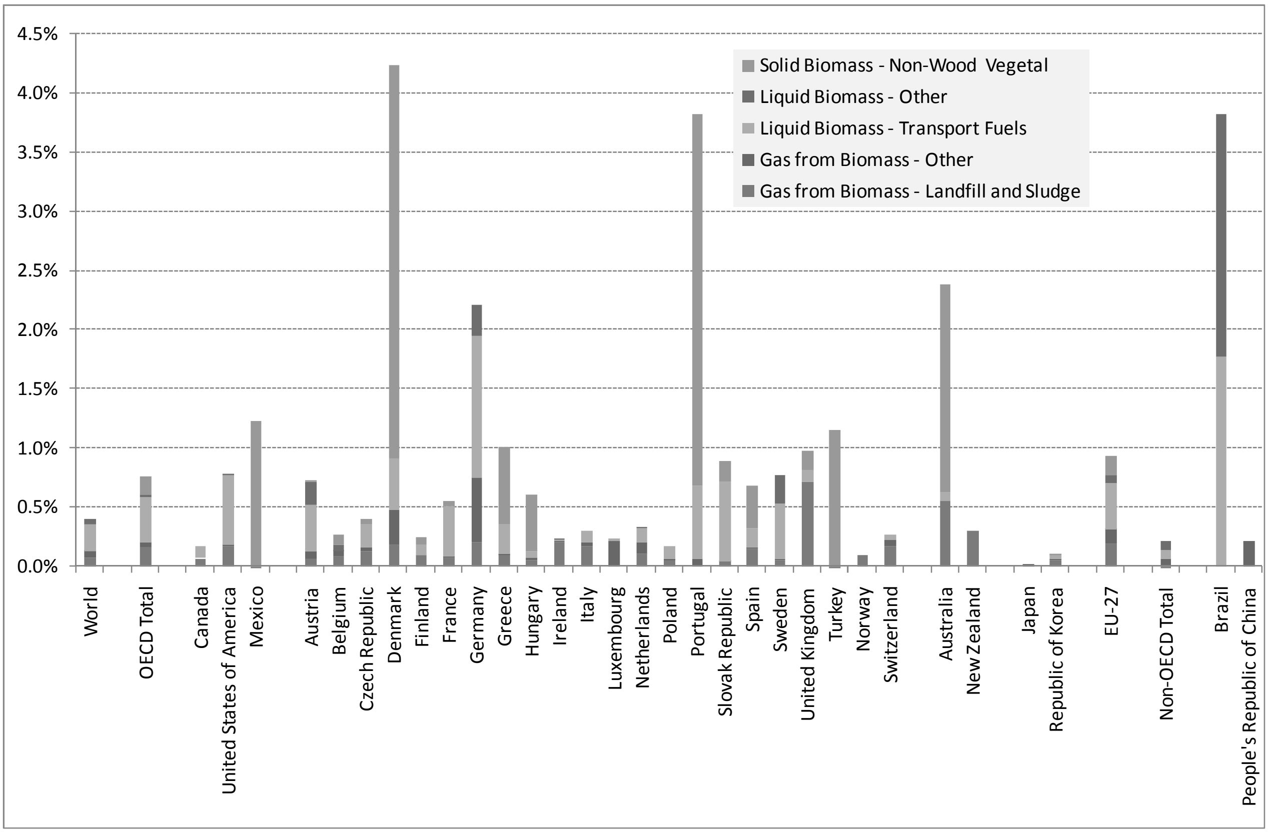
Figure 12. Renewable Energy Shares in Total Primary Energy Supply, 2007 (2006 where more recent data is missing)



Source: IEA (2008a)

Biogas represents another form of increasing energy supply. Mostly from landfill and sludge, it is also derived from agricultural biomass. For the OECD as a whole, biogas only represented about 0.17% of total primary energy supply (of which 0.14% are from landfill and sludge gases), but this share varies significantly across countries, with Germany and the UK heading the list with biogas shares in total primary energy supplies exceeding 0.7% in both countries (Figure 13).

Figure 13. Shares of biogas, biofuels and non-wood vegetal solid biomass in Total Primary Energy Supply, 2007 (2006 where more recent data is missing)



Source: IEA (2008a)

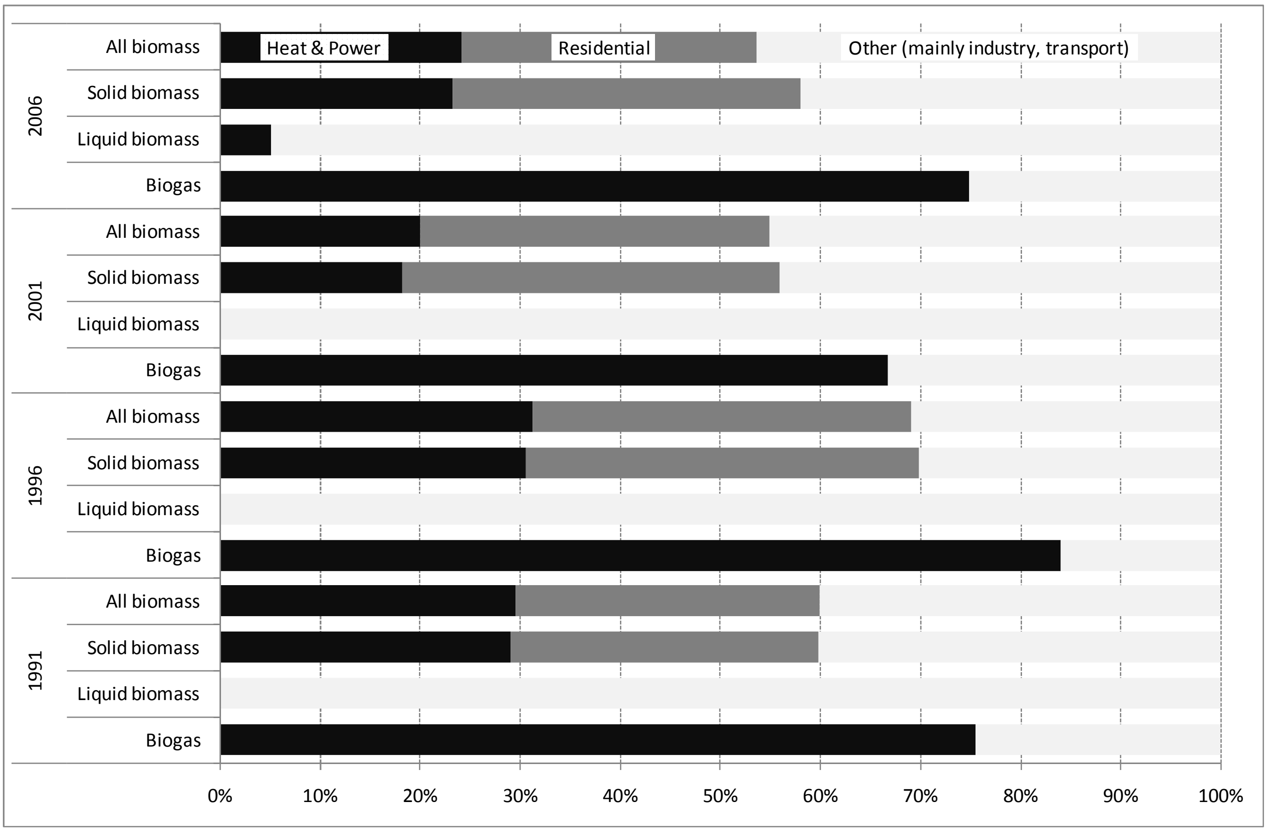
Looking at the question where the biomass for energy purposes is used, available data suggest that the different forms of biomass are distributed quite differently across the sectors in the OECD. While on average, biomass use in heat and power generation represents about a quarter of total biomass use for energy, with residential and other sectors representing some 30% and 46%, respectively, liquid biomass is essentially used in the transport sector (Figure 14). In contrast, biogas use is largely concentrated (75% in 2006) in the generation of heat and power. Residential use of biomass is focused on solid biomass.

Within the 15 years covered by available data, few clear trends can be detected. While overall biogas use remains concentrated in the heat and power generation, data suggests that this sector is particularly increasing importance for biogas made from agricultural biomass, whereas the share of landfill and sludge gases used by other sectors, notably the industry, is much higher today than a decade ago. Similarly, the use of bio liquids is no longer restricted to the transport sector, as increasingly liquid biomass is used to generate heat and power.

Looking beyond the OECD, biomass use in non-OECD economies is, as mentioned above, largely focused at solid biomass, roughly three quarters of which are used at the residential level, thus confirming the hypothesis that this concerns mainly traditional biomass used for cooking, heating and light at the household level. Though not very strong, however, there can be seen a slowly declining trend since the beginning of this decade in the share of solid and overall biomass used at the residential level, while slightly larger shares are used by other sectors, notably the industry. Small but increasing shares (about 1.2% in 2006) are also used in the generation of heat and power for delivery to the grid.

From these data it can be concluded that while the majority of biomass is used at the residential level in non-OECD economies, the energy use of biomass more or less related to agricultural production is, for the time being, largely an OECD topic. Bioheat and biopower – heat and electricity generation on the basis of biomass – represent a major outlet for biomass both in liquid form and as biogas, and the role of agricultural biomass, though still small relative to woody and other non-agricultural biomass sources, is gaining in importance. This is particularly true for the use of biogas, three quarters of which are used for heat and power generation. A similar share of all biogas other than landfill and sludge gases in the OECD is used in CHP plants, highlighting the strong links between agricultural biomass and heat and power generation – even though heat and power generation represents only one fourth of overall biomass use for energy.

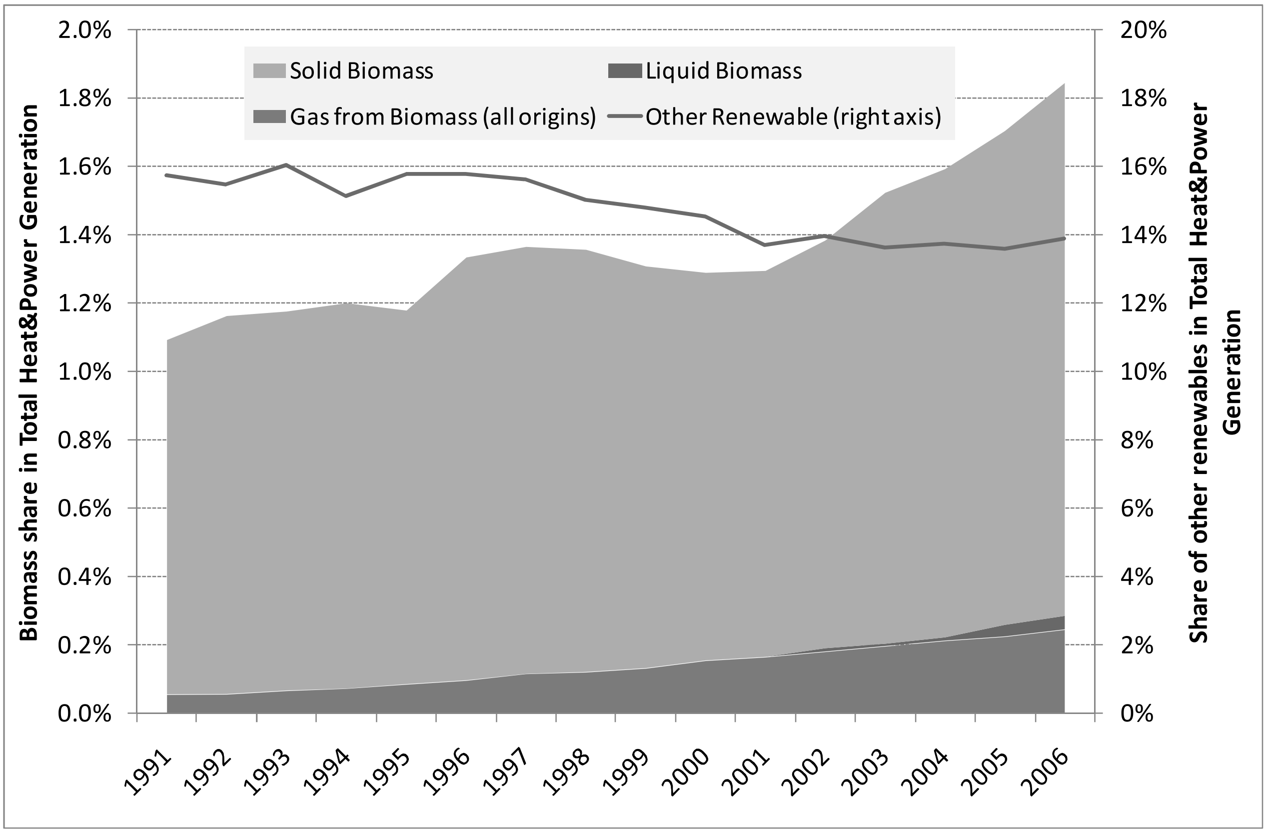
Figure14. Distribution of the biomass use for heat and power generation, residential use and other sectors, 1991-2006



Source: IEA (2008a)

While a significant share of biomass in general, and of biogas in particular, is used in heat and power applications, the share of heat and power produced from biomass is still much more modest. Despite substantial increases over the past 15 years, in 2006 bioheat and biopower still represented less than 2% of the heat and power generation on average in OECD countries (Figure 15). While the bulk of this biomass used in the heat and power generation is solid, increasingly biogas as well as, more recently, liquid biomass, is used as well increasing their share in the total bioheat and biopower generation from 5.3% in 1991 to 18.3% in 2006. Contrary to the trends in total primary energy supplies overall, the share of other renewables (such as hydro, solar and wind) in the OECD's heat and power generation has fallen between 1995 and 2001 and remained largely unchanged thereafter. Nevertheless, the use of these resources has increased strongly in absolute terms.

Figure15. Renewable energy use in OECD heat and power generation, 1991-2006



Source: IEA (2008a)

While projections for biomass-based energy production are scarce, IEA estimates in their Reference Scenario[14] total world energy use from biomass and waste to reach 1604 Mtoe by 2030, equivalent to roughly 67 EJ or about 36% above the corresponding 2007 figures. Potentially, the use of biomass for energy might grow much higher, however. Collecting the results of various biomass potential scenarios, IEA Bioenergy (2007) shows that, as an "average potential", global bioenergy production could reach 200-400 EJ per year by 2050, while in a "most optimistic scenario" the global potential could be as high as 1100 EJ – more than twice the world's current total primary energy demand. It should be noted, however, that these estimates rest on a number of crucial assumptions and are significantly affected by economic and environmental factors, as these high potentials would involve significant competition with other economic activities (food production, biodiversity etc.) for land, water and other production factors (IEA Bioenergy, 2007, p. 3). The Dutch National Institute for Public Health and the Environment (RIVM) estimates the biomass supply potential for 2050 realistically ranges 200-500 EJ per year, of which some 40-170 EJ per year could come from forest and agricultural residues and other organic waste (RIVM 2008, p. 25). Total biomass used for energy purposes is, however, estimated to reach only levels between 50 and 250 EJ per year by 2050 (ibid.). Regional estimates differ significantly, too. For Europe (EU-27 plus Norway, Switzerland and Ukraine), Smeets *et al.* (2007, quoted in BEE, 2008, p. 116) estimate a total bioenergy potential for 2050 to be between 18 and 59 EJ per year, with the higher value found for a scenario with high energy crop yields and the land use for food production reduced by 50% compared to today.

---

[14] IEA (2009) p. 622.

Costs of bioheat, biopower and biogas production

Data on the production costs for bioheat, biopower and biogas are scarce. Indicative values for typical energy costs (reflecting best conditions including system design, siting and resource availability) are given in REN21 (2007, p. 14) and shown in the Table 4 below.

Table 4. Typical costs of biomass-based power and heat production

Technology	Typical Characteristics	Typical Energy Costs (U.S. cents per kilowatt-hour)
Biomass power	Plant size: 1-20 MW	5-12
Biomass heat	Plant size: 1-20 MW	1-6
Biomass gasifier (rural, off-grid)	Size: 20-5,000 kW	8-12

Source: REN21 (2007) p. 14.

Actual production costs can be lower for particularly favourable conditions, but substantially higher, depending on a range of factors including the system size, location etc. The values shown in Table 4 can be compared to typical wholesale power generation costs from conventional fuels, ranging between 4-8 U.S. cents per kilowatt-hour for base-load power, but higher values for off-grid power. Particularly for off-grid biomass gasification, however, there could be a significant potential for future cost reductions with further technology development (REN21, 2005, p. 13)

Implications for agriculture

As demonstrated above, bioenergy contributes an increasing share to total primary energy supplies of both OECD and non-OECD countries, although overall shares tend to remain relatively small in most countries, particularly when it comes to energy based on agricultural biomass. The implications of growing production and use of bioenergy for agricultural production systems are, however, of great interest, both considering historical developments and future changes. It has been shown in the context of liquid biofuels that this growing industry and the policy support measures behind this growth can result in increased use of agricultural produce for non-food purposes, higher agricultural commodity prices at regional and international levels, and – in a regionally differentiated manner – expanded land use for agricultural production with potentially negative effects for the environment.[15]

Data on agricultural feedstock use for biopower, bioheat and biogas are scarce, particularly when it comes to aggregated information for countries and larger regions. While numerous studies provide estimates on biomass *potentials*[16], information on *actual* use of agricultural biomass remains sketchy and largely anectodical.

As indicated above, the bulk of the biopower and bioheat output is directly or indirectly based on forest products. Wood, pellets, wood waste, and saw dust represent important sources of raw materials for bioenergy. Unsurprisingly, therefore, this form of bioenergy is particularly important in countries with relatively large forest areas, including Brazil, Finland, Sweden, China and Austria, each of which producing between 10% and 27% of Total Primary Energy Supply (TPES) by non-agricultural solid biomass. While short-rotation coppice with fast-growing tree species are an option for agriculture to participate in this markets (see section on commercialized biomass crops above), data on actual planting area are not available.

---

[15] OECD (2008).

[16] See, e.g., IEA Task 41 (2007).

Data on energy supplies from "non-wood vegetal solid biomass" suggest that the use of straw and other crop or food industry residues for energy production plays a significant role (more than 1% of national TPES) only in a limited number of countries, including Denmark, Portugal, Australia, Mexico and Turkey. Sugar cane bagasse is the dominant feedstock for biopower generation in Australia[17], and the co-generation of electricity and heat in cane-based ethanol plants provides important additional revenues (as well as other benefits).

In Germany (which produced some 1.8 million tonnes of oil equivalent or 42 PJ worth of agriculture-based biogas in 2007), an estimated 500,000 ha were cultivated to produce plants used for the generation of biogas in 2008, up from 400,000 ha in 2007.[18] In 2008, this represented about 29% of the total area used for energy crops – with the bulk of the remainder being used for ethanol and biodiesel (including vegetable oils for fuel use) production, 7.1% of total land under cereals[19], or 4.2% of total arable land. Germany is by far the largest biogas producer in the OECD and second in the world after China.

According to IEA statistics, China had produced 4 million tonnes of oil equivalent or 171 PJ worth of biogas in 2006. While the available data does not allow distinguishing between landfill, sludge and other forms of biogas, an estimated 26.5 million households were equipped with biogas digesters in late 2007, producing some 400 PJ worth of biogas. Another 26,576 small and large biogas plants were installed on husbandry farms.[20] Detailed data about feedstock use are not available, but it seems likely that the plants will be fuelled largely with manure and other agricultural and (organic) household wastes. In contrast, the area specifically used to produce biogas substrates instead of food or feed crops is probably fairly limited.

In the UK and Ireland, a total of 11 large-scale anaerobic digestion plants were listed to produce biogas or to be at some stage of the planning and construction process.[21] Eight of them are (to be) fuelled entirely or mainly with animal manure and slurry, with the remaining three (to be) using biodegradable municipal waste as feedstock. None of the listed plants is supposed to use crop products or other plant matter.

Overall, the implications of increased production and use of biopower, bioheat and biogas for agricultural markets are likely to be minimal to date. A few exceptions at a local and national level could include the increasing area used for biogas substrate production in Germany which may compete with the production of food and feed, and countries such as Australia and Brazil (cane) or Denmark, Mexico and Turkey (grains), where the use of bagasse and straw as bioenergy feedstock might have the opposite effect of raising incentives for commodity production. A stronger focus on agricultural biomass crops in the development of bioheat and biopower could, however, result in potentially more significant implications for agricultural markets and, eventually, food supplies, as this has been discussed with greater emphasis for the production of liquid biofuels particularly of the first generation. Policies supporting bioenergy chains should therefore ensure that they do not compromise the ability of the agricultural sector to provide food and feed commodities in a sustainable manner.

---

[17] Schuck (2006).

[18] FNR (2009). Note that renewable raw materials represent only 26% of all substrates used in German biogas plants, with 48% from animal excrements and 26% from other organic wastes and residues. At the same time, biogas yields per tonne of fresh mass are generally higher, but methane contents (and hence energy density) in the final biogas lower for plant substrates than for manure. See http://www.fnr-server.de/cms35/index.php?id=399 for more information.

[19] Plant matter for biogas is mainly constituted from green maize and other cereals harvested as whole plants. Gras silage represents an alternative source for biogas plant matter.

[20] Methane to Markets (no date): Country profile of China.

[21] Methane to Markets (no date): UK Response.

ANNEX 1: SOME TECHNICAL REMARKS ON LIVE-CYCLE ANALYSES[22]

Total GHG emissions and primary energy inputs are calculated by life cycle assessment (LCA) methods. This is an established approach, specified by International Standard ISO 14040 series to provide a consistent framework for evaluating the environmental impacts of the complete life cycle of any given product or supply chain. The definition of the boundary for an individual LCA study is critically important in defining the impacts that will be covered in the assessment.

LCA studies do not provide definitive, universal results, but results specific to the system studied and the particular assumptions made in the assessment. Factors affecting the LCAs of biomass energy technologies include many site-specific factors such as fertiliser application rates, crop yields and distance to processing plants that will affect outputs. In recent years choice of appropriate reference system has become increasingly important to take account of any impacts on GHG emissions arising from land use change. However, many studies identified in this review took little or no account of such change and its implications for the LCA in terms of any GHG trade-offs.

Similarly, in defining the impacts of fossil fuel reference systems there are further considerations. There are very few truly transparent LCA studies published for conventional energy technologies. This is perhaps because it is known that their GHG and energy balances are considerably less attractive than those for most new energy technologies. Also in some cases, *e.g.* for nuclear electricity they are contentious (Scottish Government Research, 2006). As a result, fossil fuel reference values depend on agreed emission values for primary delivered energy, or for electricity derived from primary energy sources after accounting for losses along the supply chain (see section on fossil fuel reference chains).

It is important to ensure commonality in LCA approaches to treatment of soil carbon sources and sinks in relation to land use change, and also in accounting for nitrous oxide (N_2O) emissions from soil. These are currently areas of contention and debate in biomass LCA circles. Both N_2O and methane (CH_4, the third major greenhouse gas) have different global warming effects as well as different atmospheric lifetimes, so any aggregation over different greenhouse gases requires the use of standard multiplier values that average the warming potential of each gas over a set period of time. This study uses values taken from the Second Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 1995), suggesting that 1 kg of N_2O and 1 kg of CH_4 can be expressed as 21 and 310 kg of $CO_{2(eq)}$.[23]

As an LCA does not provide universal answers relevant to all circumstances, it is often necessary to interrogate the basic parameters and assumptions in an existing LCA, and it may also be necessary to modify data and inputs to examine impacts under a different set of circumstances, scenarios or situations. How any co-products are dealt with can also have a significant impact; by-products should attract an allocated proportion of the burdens incurred in producing the main product, but may also deliver credits where they displace use of fossil fuels or avoid emission of GHG's. The way such credits are apportioned should also be clear. LCAs need to be as open and detailed as possible; transparent in the parameters, inputs and units used and any assumptions should be clearly defined. Unfortunately very few meet these criteria and this causes problems in trying to interpret the breadth of coverage and level of inclusion of

---

[22] The contribution of this Annex by a group of consultants, D. B. Turley, H. Parry and R. Laybourn (Central Science Laboratory, UK) is gratefully acknowledged.

[23] Subsequent Assessment Reports of the IPCC provide slightly different multiplier values, with a somewhat lower multiplier for N_2O at 298 as indicated in the Fourth Assessment Report of the IPCC (2007, see OECD, 2008, p. 47). Given that many LCAs evaluated here do not provide individual data for the different greenhouse gases, a recalculation was not possible, but would yield only slightly different overall results.

individual LCAs, this affects the ability and confidence with which comparisons can be drawn across a range of different studies.

As noted, nitrous oxide (N_2O) has a significant global warming impact, much greater than that of CO_2, such that small differences in N_2O can have very significant impact on GHG balance assessments. A significant source of N_2O is emissions from soils, where formation of N_2O occurs as part of the nitrogen cycle under low oxygen conditions (denitrification). Applying fertilizers significantly increases the risk of N_2O loss. The actual level of loss will depend on individual soil factors and soil conditions. In the absence of actual data, standard figures have been derived for N_2O loss associated with fertilizer use. Many studies use the standard values calculated for use in accounting methodologies developed by the Inter-Governmental Panel on Climate Change (IPCC). The IPCC default methodology proposes a value of 0.0196 kg N_2O per kg N applied, equivalent of a global warming potential of 6.1 kg CO_2-eq per kg N applied. However, these figures are subject to significant ongoing discussion. Use of different emission factors between studies can lead to discrepancies when allocating GHG impacts to production of biomass, particularly where nitrogen fertilizer inputs are high.

Importantly, the choice of fossil fuel chains used as a reference for comparison can have implications for findings on relative bioenergy performance with respect to GHG emission and energy balances. It is a common argument that support for biomass-based systems will actually result in displacement of the most expensive forms of fossil-fuelled energy generation, which tend to be the most advanced, energy efficient and cleanest systems such as combined cycle, natural gas-fuelled electricity generation. It may equally be argued that new efficient biomass plants will lead to the retirement of older inefficient plants. Therefore any energy or GHG savings from use of biomass should be compared and contrasted with the system replaced. To enable a meaningful comparison of fossil and biomass technologies, emission factors for coal-fired (large-scale, pulverized coal injection; 0.837 kg CO_2/kWh delivered) and natural gas-fired (large-scale combined-cycle gas turbine; 0.418 kg CO_2/kWh delivered) electricity generation were calculated separately in this study, to represent a high and low-emission fossil-fuelled energy system. This also reflects the lower energy efficiency for coal powered plants of 2.8 MJ_{in}/MJ_{out} compared to gas-fired systems (2.1 MJ_{in}/MJ_{out}[24]), accounting for direct and indirect energy losses associated to the production, transport and conversion of the feedstock and transmission to the end user. Similar emission values were calculated for heat delivery from natural gas or fuel oil, to represent typically encountered ‘low’ and ‘high’ emission comparators.

For Combined Heat and Power (CHP) technologies, reference is assumed to relate to outputs and efficiencies for large scale generation (>2 MWe) with 30% of output as electricity and 70% as useful heat. Such figures are typical for existing large-scale biomass-fired CHP plants operating in Denmark (Nikolaisen *et al,* 1998). For each KWh of energy output (KWhe or KWhh) an average CO_{2eq} GHG emission factor was calculated based on the above 30:70 split in output and associated GHG emissions/KWh for the electric and heat generation chains in CHP systems where these were identified separately.

For the review in this report, fourteen databases, spanning energy, agriculture, bioscience, engineering and environment fields were searched for data on the following key search terms: ‘biomass, energy crops’ + ‘electricity, power generation, combustion, pyrolysis, gasification’ + ‘energy balance, carbon balance, greenhouse gas’. The search was restricted to papers published after 2000, to identify those papers reflecting the latest research approaches and thinking in relation to energy and green house gas accounting methodologies. This identified 526 abstract items that were then individually assessed for relevance, and appropriate full references sought where deemed appropriate to the project. The individual references were examined to determine; whether the feedstock was specifically identified, how crop and machinery inputs

---

[24] Derived from BEAT 2 model ((BEAT 2, 2008).

were accounted for, how GHG losses from soils were treated, energy conversion methods used and efficiency assumptions used, inputs to building and processing, ability to separate bioenergy from fossil fuel components in co-firing examples and how transport was accounted for. There are few studies where transparency is apparent for all such factors.

After review, it was found that very few of the above studies covered the technologies or feedstocks of interest; were of sufficient detail or sufficiently open in terms of methodologies, assumptions or data used, or in terms of using common boundaries to the analysis (*i.e.* what was or what was not included in the analysis) to enable comparison and aggregation of studies. This has been a recurring problem for other reviews of bioenergy technologies (*e.g.* Scottish Government Research, 2006). In addition, very few appropriate and detailed studies were found covering AD technologies.

Where suited to analysis, data on total GHG emissions and energy balances (MJ energy in per MJ energy out) were derived from each selected reference. GHG emission data is presented as % saving in GHG emissions compared to the appropriate fossil fuel reference system (Table 3). Results are presented on GHG savings in Figures 3 and 4 for power applications and Figures 5 & 6 for heat applications. Energy balances are presented in Figure 9 for power and CHP applications and Figure 10 for heat-only applications.

Where more than one data point was sourced for a particular combination of biomass type and energy conversion system, the range (max and min value) and mean value for each data set is presented. As a single reference may cover more than one scenario, the header for each figure provides an indication of the number of unique references providing data, and the number of data points collated within each scenario, to provide an indication of the reliability of the results presented.

A wide range of biomass type and conversion methods (combustion (COMB), gasification (GAS), co-firing (COF), anaerobic digestion (AD) and combined heat and power (CHP)) systems were covered

REFERENCES

BEE (2008): *Status of biomass resource assessments, Version 1*. Biomass Energy Europe. (Accessed in January 2010 from http://www.eu-bee.info/default.asp?SivuID=24158).

Börjesson, P and Berglund, M. (2006), *Environmental systems analysis of biogas systems – part I: fuel-cycle emissions*. Biomass and bioenergy 30, pp. 469-485.

Bridgewater, T. (2006), *Biomass for energy*. Journal of the Science of Food and Agriculture, 86, pp. 1755-1768.

Broek, R. ven dan, Faaij, A. Wijk A. van. (1995), *Report on Biomass combustion power technologies*. Study funded by the EU JOULE-IIA programme – Energy from biomass: an assessment of two promising systems for energy production. Utrecht University, Netherlands (Accessed in Sept. 2009 from www.chem.uu.nl/nws/www/publica/95029.htm).

Elsayed M. A., Matthews R., Mortimer N. D. (2003), *Carbon and energy balances for a range of biofuel options*. Report prepared for UK DTI Sustainable Energy Programme.

FNR (2009), *Anbau nachwachsender Rohstoffe in Deutschland („production of renewable primary products in Germany“)*. Web information. Fachagentur Nachwachsende Rohstoffe. Accessed in July 2009 from http://www.bio-energie.de/daten-und-fakten/anbau.html.

GBEP (2007), *Bioenergy: Facts and Figures*. Global Bioenergy Partnership. Accessed in January 2010 at http://www.globalbioenergy.org/fileadmin/user_upload/gbep/docs/2007_events/press_G8/Bioenergy_Facts_and_Figures_01.pdf.

IEA (2008a), *Renewables Information*, 2008 Edition. Database accessed in October 2008.

IEA (2008b), *World Energy Outlook 2008*. International Energy Agency, Paris.

IEA (2009), *World Energy Outlook 2009*. International Energy Agency, Paris.

IEA Bioenergy (2007): *Potential Contribution of Bioenergy to the World's Future Energy Demand*. Paris. Accessed in January 2010 from http://www.ieabioenergy.com/LibItem.aspx?id=5584.

IEA online (2010): *Global Renewable Energy Policies and Measures*. Online database, accessed in January 2010 at http://www.iea.org/Textbase/pm/?mode=re

Matthews, R. W. (2001), *Modelling of energy and carbon budgets of wood fuel coppice systems.* Biomass and Bioenergy, vol. 21, pp. 1-19.

Methane to Markets (no date), *UK Response*. Accessed in July 2009 at http://www.methanetomarkets.org/resources/ag/docs/uk_response_final.pdf.

Methane to Market (no date), *Country Profile of China*. Accessed in July 2009 at http://www.methanetomarkets.org/resources/ag/docs/china_profile.pdf.

Nikolaisen, L. et al. (1998), *Straw for Energy Production, Technology-Environment-Economy*. The Centre for Biomass Technology, Denmark. Accessed in September 2009 at http://www.videncenter.dk/uk/engstraw.htm.

OECD (2004), *Biomass and Agriculture – Sustainability, Markets and Policies*. Proceedings of the OECD Workshop on Biomass and Agriculture, held on 10-13 June 2003 in Vienna. Paris: Organisation for Economic Co-operation and Development.

OECD (2008), *Biofuel Support Policies – An Economic Assessment*. Paris: Organisation for Economic Co-operation and Development.

OECD-FAO (2009), *OECD-FAO Agricultural Outlook 2009-2018*. Paris: Organisation for Economic Co-operation and Development.

Pons, E. (2007), *A review of policy measures supporting production and use of bioenergy*. Consultancy report [TAD/CA/APM/WP(2007)24/FINAL] provided to OECD Secretariat. Available online at http://www.oecd.org/dataoecd/37/43/41037609.pdf

Price, L. Bullard, M. Lyons, H. Anthony, S. and Nixon, P. (2004), *Identifying the yield potential of Miscanthus x giganteus: an assessment of the spatial and temporal variability of M. x giganteus biomass productivity across England and Wales*. Biomass and Bioenergy 26, No 1, pp. 3-13.

REN21 (2005), *Renewables 2005 – Global Status Report*. Renewable Energy Policy Network for the 21st Century. Accessed in January 2009 at http://www.ren21.net/pdf/RE2005_Global_Status_Report.pdf

REN21 (2007), *Renewables 2007 – Global Status Report*. Renewable Energy Policy Network for the 21st Century. Accessed in July 2009 at http://www.ren21.net/pdf/RE2007_Global_Status_Report.pdf

REN21 (2009), *Renewables – Global Status Report 2009 Update*. Renewable Energy Policy Network for the 21st Century. Accessed in July 2009 at http://www.ren21.net/pdf/RE_GSR_2009_Update.pdf

RIVM (2008): *Biomass Assessment – Assessment of global biomass potentials and their links to food, water, biodiversity, energy demand and economy, Main report*. National Institute for Public Health and the Environment (RIVM), Accessed in January 2010 at http://www.rivm.nl/bibliotheek/rapporten/500102012.pdf

Schuck, St. (2006), *Opportunities for Bioenergy in Australia*. Paper for the Australian Forest Growers Conference 2006. Accessed in July 2009 at http://www.planningplantations.com.au/assets/pdfs/sustainability/environment/bioenergy/OpportunitiesBioenergyIn%20Australia_SSchuck.pdf.

Scottish Government Research (2006), *Review of greenhouse gas life cycle emissions, air pollution impacts and economics of biomass production and consumption in Scotland*. Web-publication, available to view at: http://www.scotland.gov.uk/Publications/2006/09/22094104/0.

Smeets, E. M. W., Faaij, A. P. C., Lewandowski, I. M. and Turkenburg, W. C. (2007), *A bottom-up assessment and review of global bio-energy potentials to 2050*. Progress in Energy and Combustion Science 33(1): 56-106

Thrän, D., Seidenberger, Th. And Zeddies, J (2007), *Bioenergy – Competition and Synergies; Part B: Agricultural Sector*. IEA Task 41 Report. Accessed in July 2009 at http://www.ieabioenergy.com/LibItem.aspx?id=6103.

Van den Broek R., Faaij A. and van Wijk A. (1996). *Biomass combustion for power generation*. Biomass and bioenergy 11, p. 271-281.

Woods J., Bauen A. (2003). *Technology status review and carbon abatement potential of renewable transport fuels in the UK*. Report for the UK Department of Trade and Industry.

Additional References for Life Cycle Data

Björjesson, P. & Berglund, M. (2006), *Environmental systems analysis of biogas systems - Part I: Fuel-cycle emissions*. Biomass and Bioenergy, vol. 30, pp. 469-485.

BEAT2. (2008), *Biomass Environmental Assessment Tool* provided by DEFRA, the Biomass Energy Centre and the Environment Agency, Developed by AEA in association with North Energy Associates. Accessed in December 2008 at www.biomassenergycentre.org.uk.

Elsayed, M. A., Matthews, R., & Mortimer, N. D. (2003), *Carbon and energy balances for a range of biofuels options*. Report prepared for UK DTI Sustainable Energy Programme.

Gagnon, L., Bélanger, C., & Uchiyama, Y. (2002), *Life-cycle assessment of electricity generation options: The status of research in year 2001*. Energy Policy, vol. 30, pp. 1267-1278.

Grant, J., Hetherington, R., Horne, R., & Mortimer, N. 1995, *Energy and carbon analysis of straw as a fuel*. DTI, ETSU B/M4/00487/01/REP.

Hartman, D. & Kaltschmitt, M. (1999), *Electricity generation from solid biomass via co-combustion with coal. Energy and emission balances from a German case study*. Biomass and Bioenergy, vol. 16, pp. 397-406.

Klingler, B. (1998), *Environmental Aspects of Biogas Technology*. German Biogas Association.

Matthews, R. W. (2001), *Modelling of energy and carbon budgets of wood fuel coppice systems*. Biomass and Bioenergy, vol. 21, pp. 1-19.

Ney, R. & Schnoor, J. (2002), *Incremental life cycle analysis: using uncertainty analysis to frame greenhouse gas balances from bioenergy systems for emission trading*. Biomass and Bioenergy, vol. 22, pp. 257-269.

Paul, K., Booth, T., Elliot, A., Kirschbaum, M., Jovanovic, T., & Polglase, P. (2006), *Net carbon dioxide emissions from alternative firewood-production systems in Australia*. Biomass and Bioenergy, vol. 30, no. 7, pp. 638-647.

Pehnt, M. (2006), *Dynamic life cycle assessment (LCA) of renewable energy technologies*. Renewable Energy, vol. 31, pp. 55-71.

Rafaschieri, A., Rapaccini, M. & Manfrida, G. (1999), *Life Cycle Assessment of electricity production from poplar energy crops compared with conventional fossil fuels*. Energy Conservation & Management, vol. 40, pp. 1477-1493.

Rowe, R. L., Street, N. R., & Taylor, G. (2009), *Identifying potential environmental impacts of large-scale deployment of dedicated bioenergy crops in the UK*. Renewable and Sustainable Energy Reviews, vol. 13, no. 1, pp. 271-290.

Salter, A. (2005), *Energy balances*. Presentation given at the Jyväskylä Summer School, University of Jyväskylä, Finland, 15-18 August 2005.

Scottish Government Research (2006), *Review of greenhouse gas life cycle emissions, air pollution impacts and economics of biomass production and consumption in Scotland*. Web-publication, available to view at: http://www.scotland.gov.uk/Publications/2006/09/22094104/0.

White, D. (2004), *Reduction in carbon dioxide emissions: estimating the potential contribution from wind-power*. Renewable Energy Foundation.

Yoshioka, T., Aruga, K., Nitami, T., Kobayashi, H., & Sakai, H. (2005), *Energy and carbon dioxide (CO2) balance of logging residues as alternative energy resources: system analysis based on the method of a life cycle inventory (LCI) analysis*. Journal of Forest Research, vol. 10, no. 2, pp. 125-134.