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COMMENTS ON TEXT BY TSU TO REVIEWER:

Government and expert reviewers are kindly asked to note that, due to time constraints, this chapter has been formatted but has – unlike the other chapters - not gone through a preliminary screening by the TSU.

This chapter has been allocated 102 template pages, currently it counts 116pages (excluding this page and the bibliography), so it is 14pages over target. Government and expert reviewers are kindly asked to indicate where the chapter could be shortened.

Chapter 2: Bioenergy

CONTENTS

EXECUTIVE SUMMARY

Bioenergy today. Chapter 2 discusses biomass, a primary source of fiber, food, fodder and energy. It is the most important renewable energy source, providing about 10% (46 EJ) of annual global primary energy demand. A major part of biomass use (37 EJ) is the use of charcoal, wood, and manure for cooking, space heating, and lighting generally by poorer populations in developing countries called traditional. Modern bioenergy use (for industry, power generation, or transport fuels) is making a significant 9 EJ contribution and its share is growing rapidly.

Modern bioenergy chains involve a range of feedstocks, conversion processes and end-uses. Feedstock types include annual and perennial plants including food crops; residues from agriculture, forestry, and related transformation industries; and recurrent organic waste streams. Several bioenergy systems can be deployed competitively, most notably sugarcane ethanol and heat and power generation from wastes and residues. Other biofuels have also undergone cost and environmental impact reductions but still may require government subsidies. Deployed bioenergy usually provided economic development, including poverty elimination, energy security, environmental improvements, etc. Bioenergy system economics and yields vary across world regions and feedstock type/conversion processes, with costs from 5 to 80 US$/GJ for biofuels, from 5 to 20 US$/GJ for electricity, and from 1 to 5 US$/GJ for heat from solid fuels or waste.

Future potential. Between studies the expected medium to longer term deployment of bioenergy differs. Large scale deployment largely depends on: sustainable resource base development and governance of land use, development of infrastructure, and cost reduction of key technologies. Current analyses show the upper bound of resource potential by 2050 can amount to up to 400 EJ. This requires sophisticated land and water management, large worldwide plant productivity increases, land optimization, and other measures. Biomass potential is roughly in line with IPCC SRES A1 and B1 conditions and storylines, assuming sustainability and policy frameworks to secure good governance of land-use and improvements in agricultural and livestock management are secured.

If the right policy frameworks are *not* introduced, further biomass expansion can lead to significant regional conflicts for food supplies, water resources and biodiversity. Supply potential may be constrained to residues and organic waste use, cultivation of bioenergy crops on marginal/degraded and poorly utilized lands and regions where biomass is a cheaper energy supply option compared to reference options, which is the case for sugar cane ethanol production. Biomass supplies may then remain limited to ~100 EJ in 2050. The most likely biomass potential range is 100-300 EJ taking into account the literature available to date on environmental and social aspects of bioenergy.

Impacts. Bioenergy production has complex society and environmental interactions, such as climate change feedback, biomass production and land use. Bioenergy’s impact on social and environmental issues (e.g., health, poverty, biodiversity) may be positive or negative depending on local conditions and design/implementation of criteria for projects. Many conflicts can be avoided through synergies with better natural resources management and contributing to rural development. Policies need to take into account that optimal use and performance of biomass production is regional, incorporating the agricultural and livestock sector as part of good governance of land use and rural development interlinked with developing bioenergy.

Future options and cost trends. Further improvements in power generation technologies, supply systems of biomass and production of perennial cropping systems can bring the costs of power (and heat) generation from biomass down in many regions, especially compared to natural gas. If carbon taxes of 20-30 U$/tonne were deployed (or when CCS would be deployed), biomass can be competitive with coal-based power generation and contribute significantly to carbon sequestration.

There is clear evidence that technological learning and related cost reductions occur in biomass technologies with comparable progress ratios to other renewable energy technologies. This is true for cropping systems (following progress in agricultural management when annual crops are concerned), supply systems and logistics (as clearly observed in Scandinavia, as well as international logistics), and in conversion (ethanol production, power generation, biogas and biodiesel).

Recent analyses of lignocellulosic biofuels, indicate potential improvement to compete at 60-70 U$/barrel oil. Scenario analyses indicate that strong short term R&D and market support could allow for ~2020 commercialization depending on oil and carbon pricing. Multiple biofuels and bioenergy options could become available under these conditions. In addition to ethanol and biodiesel, a range of hydrocarbons identical to petroleum could substitute for gasoline, diesel, jet fuel, and other markets. Biomass is the only unique renewable resource to provide high energy density fuels. Biobased products can continue to develop with biorefineries making multiple products and energy. Some short term options that can deliver important long term synergies, are co-firing, CHP, heat production and sugarcane based ethanol production. Significant improvements in other bioenergy is possible. Development of working bioenergy markets and facilitation of international bioenergy trade is another important facilitating factor to achieve such synergies.

Biobased materials and Bio-CCS concepts have limited literature cost estimates, future projections and learning studies although industrial production and use occurs. Advanced biobased materials, cascaded use of biomass, and bio-CCS may become attractive medium term mitigation options. More experience and detailed analyses of these options is needed.

GHG & Climate change impacts. Bioenergy has a significant GHG mitigation potential, provided resources are developed sustainably and provided the right bioenergy systems are applied. Perennial cropping systems and biomass residues and wastes are in particular able to deliver good GHG performance in the range of 80-90% GHG reduction compared to the fossil energy baseline. Climate change impacts influence and interact with biomass potentials. This interaction is still poorly understood, but there will be strong regional differences. Climate change impacts on feedstock production exist but if temperature raise is limited to 2 ^{o}C do not pose serious constraints. Combining adaptation measures and biomass resource production offers opportunities for bioenergy and perennial cropping systems.

The recently and rapidly changed policy context in many countries drives bioenergy to more sustainable directions, in particular development of sustainability criteria and framework/support for advanced biorefinery and second generation biofuel options. There is consensus on the critical importance of biomass management in global carbon cycles, and on the need for reliable and detailed data and scientific approaches to facilitate more sustainable land use in all sectors.

2.1 Introduction Current Pattern of Bioenergy Use and Trends

Biomass is the source of food, fodder and fibre as well as a renewable resource for use as a source of energy products such as heat, electricity, liquid fuels and chemicals. Bioenergy sources include forest, agricultural and livestock residues, short-rotation forest plantations, dedicated herbaceous energy crops, the organic component of municipal solid waste (MSW), and other organic waste streams. These are used as feedstocks, which through a variety of biological, chemical and physical processes produce energy carriers in the form of solid fuels (such as fuelwood, charcoal, chips, pellets, briquettes, and logs), liquid fuels (e.g., methanol, ethanol, butanol, biodiesel, and hydrocarbon fuels), and gaseous fuels (synthesis gas, biomethane, and hydrogen). These fuels can then be used to produce mechanical power (which can be used for transportation or other applications), electricity and heat as shown in Figure 2.1.1.

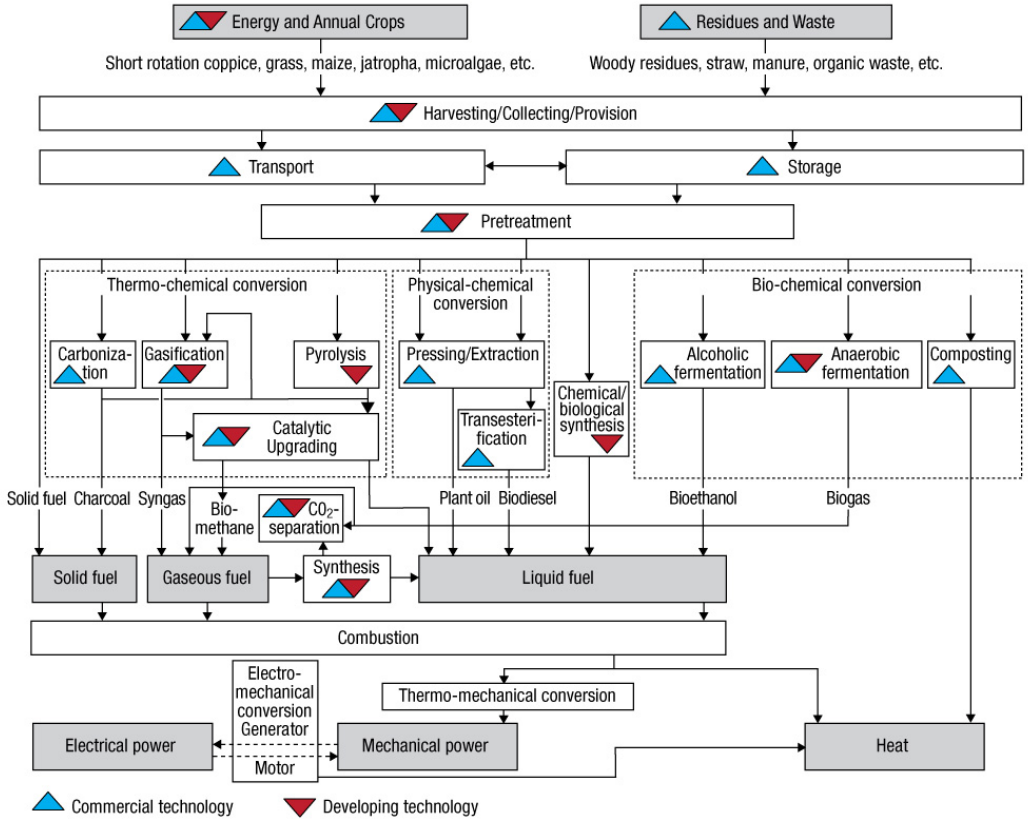


Figure 2.1.1. Pathways for producing energy products from biomass. Modified after Sterner 2009 and Karlschmitt and Hartmann 2001.

Sustainably produced and managed, bioenergy can provide a substantial contribution to climate change mitigation and at the same time provide large co-benefits in terms of local employment and regional economic development. Bioenergy options may help increase biospheric carbon stocks (for example through plantations on degraded lands), or reduce carbon emissions from unsustainable forest use (for instance through the dissemination of more efficient cookstoves). Additionally, bioenergy systems may reduce emissions from fossil fuel-based systems by replacing them in the generation of heat and power (for example by gasifying biomass in combined heat and power (CHP) systems, or in the provision of liquid biofuels such as ethanol instead of gasoline. Advanced bioenergy systems and end-use technologies, can also substantially reduce the emission of black carbon and other short-lived GHGs such as methane and carbon monoxide, which are related to the burning of biomass in traditional open fires and kilns. Not properly designed or implemented, the large-scale expansion of bioenergy systems is likely to also have negative consequences for climate and sustainability such as inducing direct and indirect land use changes that can alter surface albedo, release carbon from soils and vegetation, reducing biodiversity or negatively impacting local populations in terms of land tenure or reduced food security, among other effects.

Currently bioenergy is the most important renewable energy source (78% of all renewable energy produced) and provides about 10% (47 EJ) of the annual global primary energy demand. A full 97 percent of biofuels are made of solid biomass, 71 percent of which is used in the residential sector, as biomass provides fuel for the cooking needs of 2.4 billion people (Figure 2.1.2). Biomass is also used to generate gaseous and liquid fuels, and growth in demand for the latter has been significant over the last ten years (GBEP, 2008). Residues from industrialized farming, plantation forests, and food and fibre-processing operations that are currently collected worldwide and used in modern bioenergy conversion plants are difficult to quantify but probably supply approximately 6 EJ/yr. Current combustion of municipal solid waste (MSW) provides more than 1 EJ/yr though this includes plastics, etc. Landfill gas also contributes to biomass supply at over 0.2 EJ/yr (IPCC, 2007) (Figure 2.1.3)

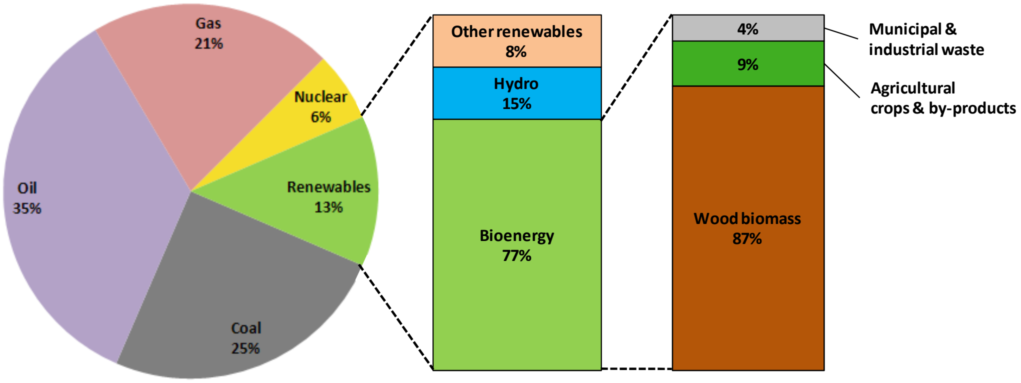


Figure 2.1.2. Share of bioenergy in the world primary energy mix. Source: based on IEA (2008) and IPCC (2007).

Global bioenergy use has been steadily growing worldwide in absolute terms in the last 40 years, with large differences among countries. Worldwide, China with its 9000 PJ/yr is the largest user of biomass as a source of energy, followed by India (6000 PJ/yr), USA 2300 PJ/yr, and Brazil (2000 PJ/yr).

Up to now biomass provides a relatively small amount of the total primary energy supply (TPES) of the largest industrialized countries (grouped as G8 countries: United States, Canada, Germany, France, Japan, Italy, United Kingdom, and Russia) (1-4 %), but this share is growing. The use of solid biomass for electricity production is important, especially from pulp and paper plants and sugar mills. Bioenergy's share in total energy consumption is increasing in the G8 Countries through the use of modern forms (e.g. co-combustion for electricity generation, buildings heating with pellets) especially Germany, Italy and the United Kingdom.

By contrast, bioenergy, mainly through the use of traditional forms (e.g. woodfuel and charcoal for cooking and heating) is a significant part of the energy supply in the largest developing countries representing from 5-27% of TPES (China, India, Mexico, Brazil, and South Africa) and more than 80% of TPES in the poorest countries. The bioenergy share in India, China and Mexico is decreasing, mostly as traditional biomass is substituted by kerosene and Liquified Petroleum Gas (LPG) within large cities, but consumption in absolute terms continues to grow. The latter is also true for most African countries, where demand has been driven by a steady increase in woodfuels, particularly in the use of charcoal in booming urban areas.

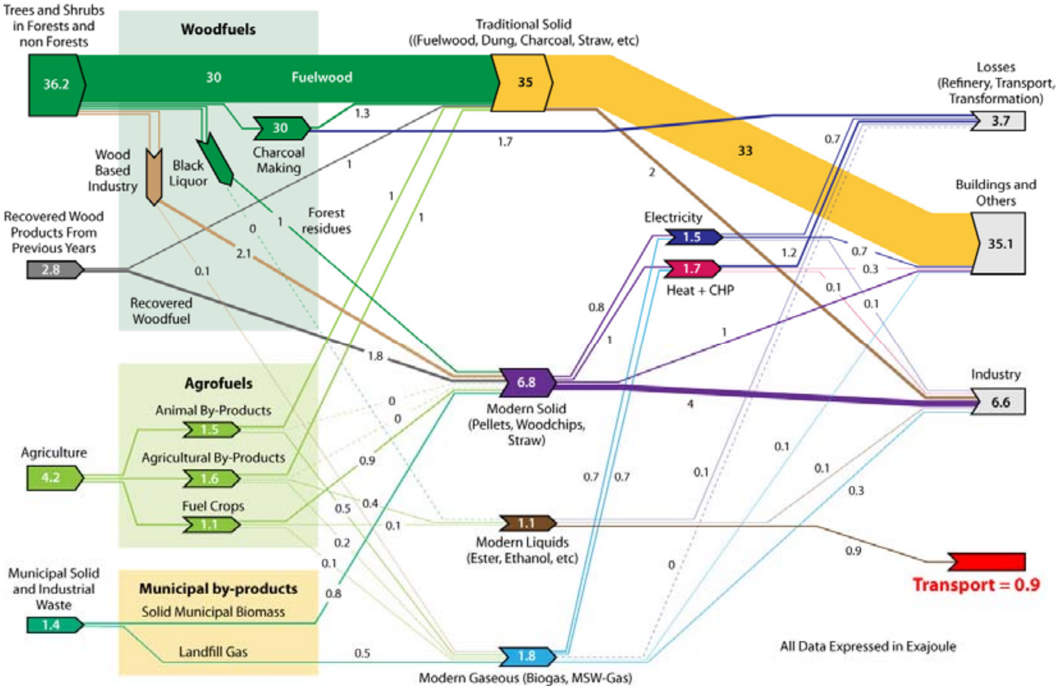


Figure 2.1.3. Global Biomass Energy Flows**.** Source: IPCC, 2007

While these statistics represent an essential reference, they tend to underestimate woodfuel consumption. Until recent years biomass fuels were regarded as marginal products in both energy and forestry sectors (FAO, 2005a). In addition to such historical disregard, production and trade of biomass fuels are largely informal, thus excluded from the conventional sources of energy and forestry data. International forestry and energy data are the main reference sources for policy analyses but they are often in contradiction, when it comes to estimate biomass consumption for energy. Moreover, detailed analyses indicate quite firmly that national statistics systematically underestimate the consumption of woody biomass for energy [Masera et al. 2005 (Mexico); Drigo and Veselič 2006 (Slovenia), Drigo et al. 2007 (Italy), and Drigo et al 2009 (Argentina)]

2.1.1 Previous IPCC Assessments

Bioenergy has not been examined in detail in previous IPCC reports. In the most recent assessment (4AR) the analysis of GHG mitigation from bioenergy was scattered among 7 chapters making it difficult to obtain an integrated and cohesive picture of its potential, challenges and opportunities. The main conclusions from the 4AR report (IPCC, 2007) are as follows:

i) <u>Biomass Energy Demand</u>: Demand projections for primary biomass for production of transportation fuel were largely based on IEA-WEO (2006) global projections, with a relatively wide range of about 14 to 40 EJ of primary biomass, or 8-25 EJ of fuel in 2030. However, higher estimates were also included, ranging between 45-85 EJ demand for primary biomass in 2030 (or roughly 30-50 EJ of fuel). Demand for biomass for heat and power was stated to be strongly influenced by (availability and introduction of) competing technologies such as CCS, nuclear power, wind energy, solar heating, etc). The projected demand in 2030 for biomass would be around 28-43 EJ according to the data used in AR4. These estimates focus on electricity generation. Heat is not explicitly modeled or estimated in the WEO, therefore underestimating total demand for biomass.

Also potential future demand for biomass in industry (especially new uses as biochemicals, but also expansion of charcoal use for steel production) and the built environment (heating as well as increased use of biomass as building material) was highlighted as important, but no quantitative projections were included in potential demand for biomass on medium and longer term.

ii) Biomass energy potentials (supplies). According to AR4, the largest contribution could come from energy crops on arable land, assuming that efficiency improvements in agriculture are fast enough to outpace food demand so as to avoid increased pressure on forests and nature areas. A range of 20-400 EJ is presented for 2050, with a best estimate of 250EJ/yr. Degraded lands for biomass production (e.g. in reforestation schemes: 8-110 EJ) can contribute significantly. Although such low yielding biomass production generally result in more expensive biomass supplies, competition with food production is almost absent and various co-benefits, such as regeneration of soils (and carbon storage), improved water retention, protection from (further) erosion may also off-set part of the establishment costs. An example of such biomass production schemes at the moment is establishment of Jathropa crops (oilseeds) on marginal lands.

The energy potentials in residues from forestry is estimated a 12-74 EJ/yr, from agriculture at 15-70 EJ/yr, and from waste at 13 EJ/yr. Those biomass resource categories are largely available before 2030, but also partly uncertain. The uncertainty comes from possible competing uses (e.g. increased use of biomaterials such as fibreboard production from forest residues and use of agro-residues for fodder and fertilizer) and differing assumptions on sustainability criteria deployed with respect to forest management and intensity of agriculture. The biogas fuel potentials from waste, landfill gas and digester gas, are much smaller.

iii) Carbon mitigation potential. The mitigation potential for electricity generation reaches 1,220 MtCO2eq for the year 2030, a substantial fraction of it at cost lower than 20 USD/tonne CO2. From a top-down assessment estimate the economic mitigation potential of biomass energy supplied from agriculture is estimated to range from 70–1260 MtCO2-eq/yr at up to 20 US$/tCO2-eq, and from 560–2320 MtCO2-eq/yr at up to 50 US$/tCO2-eq. The overall mitigation from the biomass energy coming from the forest sector is estimated to reach 400 MtCO2/yr up to 2030.

2.2 Resource Potential

2.2.1 Introduction

Bioenergy production interacts with food and forestry production in complex ways. It can compete for land, water and other production factors but can also strengthen conventional food and forestry production by offering new markets for biomass flows that earlier were considered as waste products. Bioenergy demand can provide opportunities for cultivating new types of crops and integrate bioenergy production with food and forestry production in ways that improves the overall resource management, but it can also lead to overexploitation and degradation of resources, e.g., too intensive biomass extraction from the lands leading to soil degradation, or water diversion to energy plantations that impacts downstream water uses including for terrestrial and aquatic ecosystem maintenance.

Thus, the biomass resource potential depends on the priority of bioenergy products vs. other products obtained from land – notably food and conventional forest products such as sawnwood and paper – and on how much biomass can be mobilized in total in agriculture and forestry. This in turn depends on natural conditions (climate, soils, topography) and on agronomic and forestry practices to produce the biomass, but also on how society understands and prioritizes nature conservation and soil/water/biodiversity protection and in turn how the production systems are shaped to reflect these priorities (Figure 2.2.1).

As a first view on biomass resource potentials, the total annual aboveground net primary production (NPP; the net amount of carbon assimilated in a given period by vegetation) on the earth's terrestrial surface is estimated at about 35 PgC, or 1260 EJ/year (assuming an average C content at 50% and 18 GJ/Mg average heating value) (PNAS, 2007), which can be compared with the world primary energy demand at about 500 EJ (WEO 2009). This comparison shows that terrestrial NPP is larger but not huge in relation to what is required to meet society's energy demand. Establishing bioenergy as a major future primary energy source requires that a significant part of global terrestrial NPP takes place within production systems that are shaped to provide bioenergy feedstocks. Possibly also that the total terrestrial NPP is increased from fertilizer, irrigation and other inputs on lands managed for food, fiber and bioenergy.

A comparison with the biomass production in agriculture and forestry can further give perspectives on prospective bioenergy supply in relation to what is presently harvested in land use. Today's global industrial roundwood production corresponds to 15-20 EJ/yr, and the global harvest of major crops (cereals, oil crops, sugar crops, roots & tubers and pulses) corresponds to about 60 EJ/yr (FAOstat, 2010). One immediate conclusion from this comparison is that the biomass extraction in agriculture and forestry will have to increase substantially in order to provide feedstock for a bioenergy sector large enough to make a significant contribution to the future energy supply.

At the same time, studies estimating the human appropriation of NPP (HANPP) suggest that society already today appropriate a substantial share of the aboveground NPP. Results of HANPP estimates vary depending on its definition as well as models and data used for the calculations. Haberl et al., (2007) estimated that aboveground HANPP amounted to almost 29% of the modelled aboveground NPP. Human biomass harvest alone was estimated to about 20% of aboveground NPP. Other HANPP estimates range from a similar level down to about half this level (Imhoff et al., 2004; Wright, 1990). The HANPP concept cannot be used to define a certain level of biomass use that would be "safe" or "sustainable" since the impacts of human land use depends on how agriculture and forestry systems are shaped (Bai et al. 2008). However, it can be used as a measure of the human domination of the biosphere and as such represent a complementary view on bioenergy potential assessments.

Besides biophysical factors, socioeconomic conditions also influence the biomass resource potential by defining how – and how much – biomass can be produced without causing unacceptable socioeconomic impacts. Socioeconomic restrictions vary around the world, change as society develops, and depends on how societies prioritize bioenergy in relation to specific more or less compatible socioeconomic objectives (see also Section 2.5 and Section 2.8).

This Section focuses on the longer term biomass resource potential and how this has been estimated based on considering the Earth's biophysical resources (ultimately NPP) and restrictions on their energetic use arising from competing requirements on these resources – including non-extractive requirements such as soil quality maintenance/improvement and biodiversity protection. First, approaches to assessing biomass resource potentials – and results from selected studies – are presented with an account of how the main determining factors have been taken into account. After that, these factors are treated explicitly including the constraints on their utilization. The Section ends by summarizing conclusions on biomass resource assessments including uncertainties and requirements for future research. The different bioenergy production systems are described in more detail in Section 2.3 and 2.6.

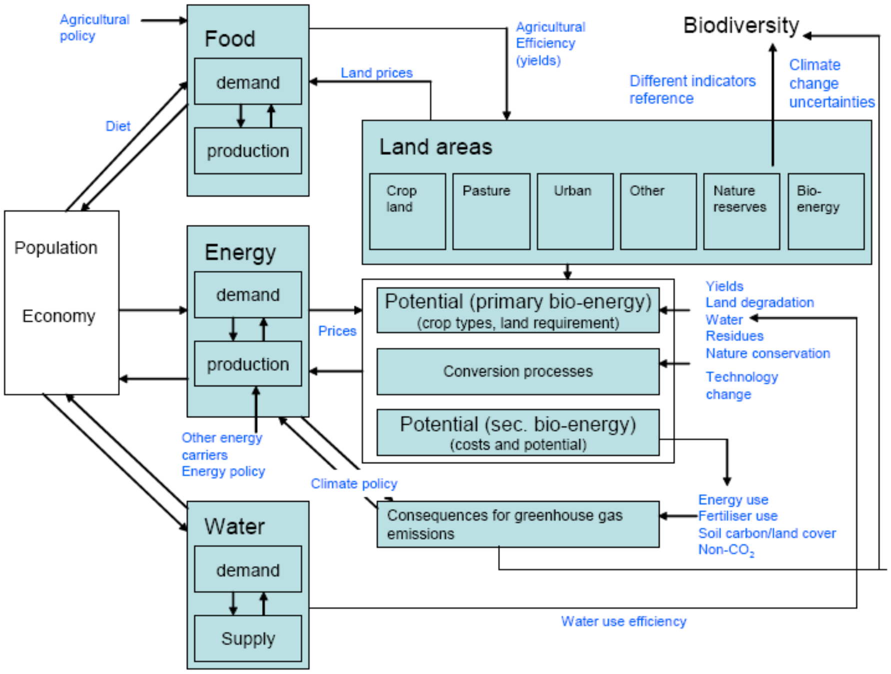


Figure 2.2.1. Overview of key relationships relevant to assessment of bioenergy potentials (Dornburg et al., 2008). Indirect land use issues and social issues are not displayed

2.2.2 Assessments of the biomass resource potential

Studies quantifying the biomass resource potential have in various ways assessed the resource base while to varying extent considering the influence of natural conditions (and how these can change in the future) and various types of limitations including socioeconomic factors, the character and development of agriculture and forestry, and restrictions connected to nature conservation and soil/water/biodiversity preservation (Berndes et al., 2003). The following types of potentials are commonly referred to:

- ***theoretical potential*** refers to the biomass supply as limited only by bio-physical conditions;
- ***technical potential*** considers limitations of the biomass production practices assumed to be employed, and also restrictions imposed by demand for food, feed and fiber, and area requirements for human infrastructure. Restrictions connected to nature conservation and soil/water/biodiversity preservation can be also considered. In such cases, the term ***sustainable potential*** is sometimes used;
- ***economic potential*** refers to the part of the technical potential that can be produced given a specified requirement for the level of economic profit in production. This depends not only on cost of production but also on the price of the biomass feedstock, which is determined by a range of factors such as characteristics of biomass conversion technologies, price on competing energy technologies, and prevailing policy regime. The term ***implementation potential*** is a variant of the economic potential that refers to a certain time frame and context taking into account institutional and social constraints on the pace of expansion.

Most assessments of the biomass resource potential considered in this Section are variants of technical/economic potentials employing a “food/fiber first principle” intending to ensure that the biomass resource potentials are quantified under the condition that global requirements of food and conventional forest products such as sawnwood and paper can be met (see e.g. WBGU, 2009 and Smeets and Faaij, 2007).

Studies that start out from such principles should not be understood as providing guarantees that a certain level of biomass can be supplied for energy purposes without competing with food or fibre production. They quantify how much bioenergy could be produced at a certain future year based on using resources not required for meeting food/fibre demands, given a specified development in the world or in a region. But they do not analyse how bioenergy expansion towards such a future level of production would – or should – interact with food and fibre production.

Studies using integrated energy/industry/land use cover models (see, e.g., Leemans et al, 1996; Strengers et al, 2004; Johansson and Azar, 2007; Müller et al, 2007; Van Vuuren et al, 2007; Wise et al, 2009; Melillo et al, 2009) can give insights into how an expanding bioenergy sector interacts with other sectors in society including land use and management of biospheric carbon stocks. Sector-focusing studies can contain more detailed information on interactions with other biomass uses. Restricted scope (only selected biofuel/land uses and/or regions covered) or lack of sufficiently detailed empirical data can limit the confidence of results – especially in prospective studies. This is further discussed in Section 2.5 and Section 2.8.
Three principal categories are – more or less comprehensively – considered in assessments of biomass resource potentials (see also Section 2.3.1.1):

- Primary residues from conventional food and fibre production in agriculture and forestry, such as cereal straw and logging residues;
- Secondary and tertiary residues in the form of organic food/ forest industry by-products and retail/ post consumer waste;
- Various plants produced for energy purposes including conventional food/feed/industrial crops, surplus roundwood forestry, and new types of agricultural, forestry or aquatic plants grown under varying rotation length.

Given that resource potential assessments quantify the availability of residue flows in the food and forest sectors – and as a rule are based on a food/fibre first principle – the definition of how these sectors develop is central for the outcome. Discussed further below, consideration of various types of restrictions connected to environmental and socioeconomic factors as a rule limits the assessed potential to lower levels.

Table 2.2.1 shows ranges in the assessed resource potential year 2050, explicit for various biomass categories. The ranges are obtained based on IEA Bioenergy (2009) and Lysen and van Egmond (2008), which reviewed a number of studies assessing the global and regional potential, and on selected additional studies not included in these reviews (Field et al, 2008; Smeets and Faaij, 2007; Fischer and Schrattenholzer, 2001; Hakala et al., 2009; Metzger and Huttermann, 2009; Van Vuuren et al, 2009; Wirsenius et al, 2009).

The wide ranges in Table 2.2.1 is due to that the studies differ in their approach to considering different determining factors, which are in themselves uncertain: population, economic, and technology development can go in different directions and pace; biodiversity and nature conservation requirements set limitations that are difficult to assess; and climate change as well as land use in itself can strongly influence the biophysical capacity of land. Biomass potentials can also not be determined exactly as long as uncertainty remains about agreed tradeoffs with respect to additional biodiversity loss or intensification pressure in food production as well as potential synergies in land use.

Table 2.2.1. Overview of the assessed global biomass resource potential of land-based biomass supply over the long term for a number of categories (primary energy, rounded numbers). The total assessed potential can be lower than the present biomass use at about 50 EJ/yr in instances of high future food and fiber demand in combination with slow productivity development in land use leading to strong restrictions on biomass availability.

Biomass category	**Comment**	**Global biomass resource potential year 2050 (EJ/yr)**
Category 1. Dedicated biomass production on surplus agricultural land	Includes both conventional agriculture crops and dedicated bioenergy plants including oil crops, lignocellulosic grasses, short rotation coppice and tree plantations. The potential biomass supply from agricultural land is usually assessed based on a “food first paradigm”: only land not required for food, fodder or other agricultural commodities production is assumed to be available for bioenergy. However, surplus – or abandoned – agriculture land need not imply that development is such that less total land is needed for agriculture: the lands may become excluded from agriculture use in modeling runs due to land degradation processes or climate change (see also “marginal lands” below). Large potential requires global development towards high-yielding agricultural production. Zero potential reflects that studies report that food sector development can be such that no surplus agricultural land will be available.	0 – 700
Category 2. Dedicated biomass production on marginal lands	Refers to biomass production on deforested or otherwise degraded or marginal land that is judged unsuitable for conventional agriculture but suitable for some bioenergy schemes, e.g., via reforestation. There is no globally established definition of degraded/marginal land and not all studies make a distinction between such land and other land judged as suitable for bioenergy. Adding category 1 and 2 can therefore lead to double counting if numbers come from different studies. Zero potential reflects that studies report low potential for this category due to land requirements for e.g., extensive grazing management and/or subsistence agriculture, or poor economic performance of using the marginal lands for bioenergy.	0 – 110
Category 3. Residues from agriculture	By-products associated with food production and processing, both primary (e.g. cereal straw from harvesting) and secondary residues (e.g. rice husks from rice milling)	15 – 70
Category 4. Forest biomass	By-products associated with forest wood production and processing, both primary (e.g. branches and twigs from logging) and secondary residues (sawdust and bark from the wood processing industry). Biomass growth in natural/semi-natural forests that is not required for industrial roundwood production to meet projected biomaterials demand (e.g., sawnwood, paper and board) represents an additional resource. By-products provide up to about 20 EJ/yr implying that high potential numbers correspond to a much larger forest biomass extraction for energy than what is presently achieved in industrial wood production. Zero potential indicates that studies report that demand from other sectors than the energy sector can become larger than the estimated forest supply capacity.	0 – 110
Category 5. Dung	Animal manure. Population development, diets, and character of animal production systems are critical determinants.	5 – 50
Category 6. Organic wastes	Biomass associated with materials use, e.g. organic waste from households and restaurants, discarded wood products including paper, construction and demolition wood	5 – >50
Total		**<50 – >1000**

Although assessments employing improved data and modeling capacity have not succeeded in providing narrow distinct estimates of the biomass resource potential, they do indicate what the most influential parameters are that affect this potential. This is further discussed below, where approaches used in the assessments are treated in more detail.

2.2.2.1 The contribution from residues, dung, processing by-products and waste

Retail/post consumer waste, dung and primary residues/processing by-products in the agriculture and forestry sectors are judged to be important for near term bioenergy supplies since they can be extracted for energy uses as part of existing waste management and agriculture and forestry operations. As can be seen in Table 2.2.1 biomass resource assessments indicate that these biomass categories also have prospects for providing a substantial share of the total global biomass supply also on the longer term. Yet, the sizes of these biomass resources are ultimately determined by the demand for conventional agriculture and forestry products as well as the sustainability of the land resources.
Assessments of the potential contribution from these sources to the future biomass supply combines data on future production of agriculture and forestry products obtained from food/forest sector scenarios with so-called residue factors that account for the amount of residues generated per unit of primary product produced. For example, harvest residue generation in agricultural crops cultivation is estimated based on harvest index data, i.e., ratio of harvested product to total aboveground biomass (see, e.g., Wirsenius 2003; Lal, 2005; Hakala et al., 2009). The generation of logging residues in forestry, and of additional biomass flows such as thinning wood and process by-products, are estimated using similar residue factors.

The shares of the generated biomass flows that are available for energy – recoverability fractions – are then estimated based on considering competing uses, which can be related to soil conservation requirements or other extractive uses such as animal feeding and bedding in agriculture or fibre board production in the forest sector.

2.2.2.2 The contribution from unutilized forest growth

In addition to the forest biomass flows that are linked to industrial roundwood production and processing into conventional forest products, currently not used forest growth is considered in some studies. This biomass resource is quantified based on estimates of the biomass increment in forests assessed as being available for wood supply that is above the estimated level of forest biomass extraction for conventional industrial roundwood production – and sometimes for traditional bioenergy, notably heating and cooking. Smeets and Faaij (2007) provide illustrative quantifications showing how this "surplus forest growth" can vary from being a potentially major source of bioenergy to being practically zero as a consequence of competing demand as well as economic and ecological considerations. A comparison with the present industrial roundwood production at about 15-20 EJ/year shows that a drastic increase in forest biomass output is required for reaching the higher end potential assessed for the forest biomass category in Table 2.2.1.

2.2.2.3 The contribution from energy plantations

From Table 2.2.1 it is clear that substantial supplies from biomass plantations are required for reaching the very high levels of bioenergy supply. Land availability (and suitability) for dedicated biomass plantation, and the biomass yields that can be obtained on the available lands, are consequently two critical determinants of the biomass resource potential. Thus, food sector development is a critical aspect to consider when estimating biomass resource potentials. Determining land availability and suitability has to consider maintaining the economic, natural and social value of ecosystems by preventing ecosystem degradation and habitat fragmentation.

Most earlier assessments of biomass resource potentials used rather simplistic approaches to estimating the potential of biomass plantations (Berndes et al. 2003), but the continuous development of modeling tools that combine databases containing biophysical information (soil, topography, climate) with analytical representations of relevant crops and agronomic systems has resulted in improvements over time (see, e.g., Fischer et al, 2008; Van Vuuren et al, 2007; Wise et al, 2009; Melillo et al, 2009; Lotze-Campen et al., 2009).

Figure 2.2.2 – representing one example (Fischer et al. 2009) – shows the modeled global land suitability for selected first generation biofuel feedstocks and for lignocellulosic plants (see Caption to Figure 2.2.2 for information about included plants). In this case a suitability index has been used in order to represent both yield potentials and suitability extent (see Caption to Figure 2.2.2). The map shows the case of rain-fed cultivation; including the possibility of irrigation would result in another picture. Land suitability also depends on which agronomic system is assumed to be in use (e.g., degree of mechanization, application of nutrients and chemical pest, disease and weed control) and this assumption also influence the biomass yield levels on the lands assessed as available for bioenergy plantations.

Based on overlaying information about the present global land cover – agricultural land, cities, roads and other human infrastructure, and distribution of forests and other natural/semi natural ecosystems – including protected areas – it is possible to quantify how much suitable land there is on different land cover types. For instance, almost 700 Mha, or about 20%, of currently unprotected grass- and woodlands was in (Fischer et al., 2009) assessed as suitable for soybean while less than 50 Mha was assessed suitable for oil palm (note that these land suitability numbers cannot be added since areas overlap). Considering instead unprotected forest land, roughly ten times larger area (almost 500 Mha) is assessed as suitable for oil palm. However, converting large areas of forests into biomass plantations would negatively impact biodiversity and might – depending on C density of converted forests – also lead to large CO2 emissions that can drastically reduce the climate benefit of substituting fossil fuels with the bioenergy derived from such plantations. Converting grass- and woodlands with high soil C content to intensively cultivated annual crops can similarly lead to large CO2 emissions. Conversely, if degraded and C depleted pastures are cultivated with herbaceous and woody lignocellulosic plants soil C may instead accumulate, enhancing the climate benefit. This is further discussed in Section 2.5.

Supply potentials for biomass plantations can be calculated based on assessed land availability and corresponding yield levels. Fischer et al. (2009) estimated the land availability for rain-fed lignocellulosic plants under a “food and environment first” paradigm excluding forests and land currently used for food and feed as unavailable. Lands with low productivity and steep sloping conditions were also excluded and a rough land balance was made based on subtracting land estimated to be required for livestock feeding. The results, shown in Table 2.2.2, represent just one example corresponding to a specific set of assumptions regarding for example nature protection requirements, crop choice and agronomic practice determining attainable yield levels, and livestock production systems determining grazing requirements. Furthermore, it corresponds to the present situation concerning agriculture practice and productivity, population, diets, climate, etc. and quantifications of future biomass resource potentials need to consider how such parameters change over time.

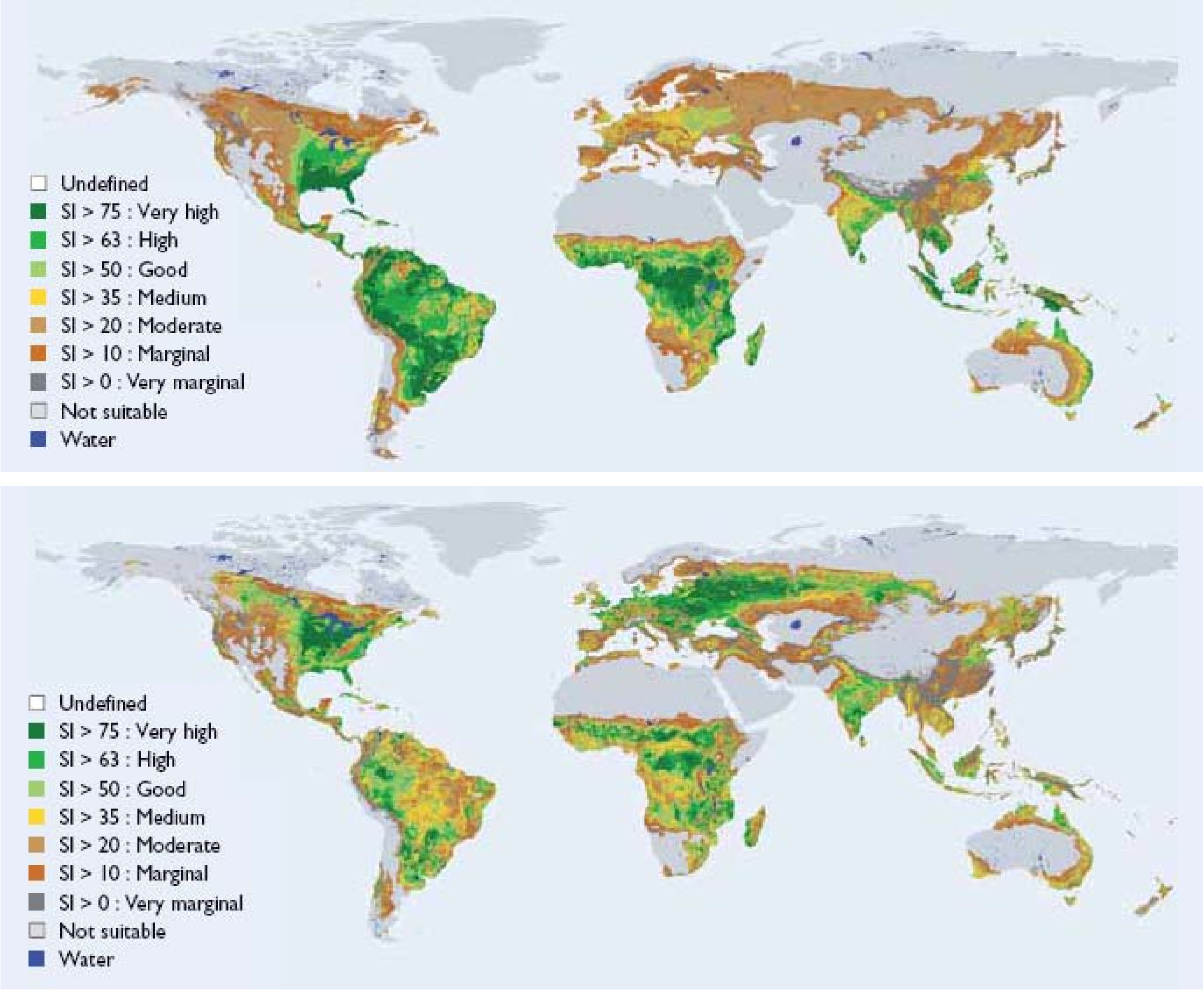


Figure 2.2.2. Global land suitability for bioenergy plantations. The upper map shows suitability for herbaceous and woody lignocellulosic plants (miscanthus, switchgrass, reed canary grass, poplar, willow, eucalypt) and the lower map shows suitability for 1st generation biofuel feedstocks (sugarcane, maize, cassava, rapeseed, soybean, palm oil, jatropha). The suitability index SI used reflects the spatial suitability of each pixel and is calculated as $SI=VS*0.9+S*0.7+MS*0.5+mS*0.3$, where VS, S, MS, and mS correspond to yield levels at 80-100%, 60-80%, 40-60% and 20-40% of modelled maximum, respectively (Fischer et al. 2009).

In a similar analysis (WBGU, 2009) reserved current and near-future agricultural land for food and fibre production and also excluded unmanaged land from being available for bioenergy if its conversion to biomass plantations would lead to large net CO2 emissions to the atmosphere, or if the land was degraded, a wetland, environmentally protected, or rich in biodiversity. If dedicated biomass plantations were established in the available lands an estimated 34-120 EJ/year could be produced.

Water constraints can in several regions limit the potential to lower levels than what is assessed based on approaches that do not involve geo-explicit hydrological modeling. The use of areas with sparse vegetation for establishment of high-yielding bioenergy plantations may lead to substantial reductions in downstream water availability. This can become an unwelcome effect requiring management of trade-offs between upstream benefits and downstream costs.

Illustrative of this, Zomer et al. (2006) report that large areas deemed suitable for forestation within the Clean Development Mechanism would exhibit evapotranspiration increases and/or decreases in runoff in case they become forested, i.e. a decrease in water potentially available off-site for other uses. This was particularly evident in drier areas, the semi-arid tropics, and in conversion from grasslands and subsistence agriculture. Similarly, based on a global analysis of 504 annual catchment observations, Jackson et al. (2005) report that afforestation dramatically decreased stream flow within a few years of planting. Across all plantation ages in the database, afforestation of grasslands, shrublands or croplands decreased stream flow by, on average, 38%. Average losses for 10- to 20-year-old plantations were even greater, reaching 52% of stream flow (see also Section 2.2.5.3)

Table 2.2.2. Potential biomass supply from rain-fed lignocellulosic plants on unprotected grassland and woodland (i.e., forests excluded) where land requirements for food production including grazing have been considered. Calculated based on Fischer et al. (2009). Areas given in million hectares.

	Total grass- & woodland (Mha)	**Of which (Mha)**		**Balance available for bioenergy (Mha)**	**Biomass potential**	
Regions		Protected areas	Unproductive or very low productive areas	Rough balance where areas req. for grazing has been excluded	Average yield[1] (GJ/ha)	Total bioenergy (EJ)
North America	659	103	391	110	165	18
Europe & Russia	902	76	618	110	140	15
Pacific OECD	515	7	332	110	175	19
Africa	1086	146	386	275	250	69
S&E Asia	556	92	335	14	235	3
Latin America	765	54	211	160	280	45
M East & N Afr.	107	2	93	1	125	0.2
World	**4605**	**481**	**2371**	**780**	**225**	**176**

[1] Calculated based on average yields for total grass- & woodland area given in Fischer (2009) and assuming energy content at 18 GJ/Mg dry matter(rounded numbers).

Studies by Hoogwijk et al (2003), Wolf et al. (2003), Smeets et al. (2007), and van Minnen et al. (2008) are also illustrative of the importance of biomass plantations for reaching higher global biomass resource potentials, and also of how different determining parameters are highly influential on the resource potential. For instance, in a scenario having rapid population growth and slow technology progress, where agriculture productivity does not increase from its present level and little biomass is traded, Smeets et al. (2007) found that no land would be available for bioenergy plantations. In a contrasting scenario where all critical parameters were instead set to be very favorable, up to 3.5 billion hectares of former agricultural land – mainly pastures and with large areas in Latin America and sub-Saharan Africa – was assessed as not required for food in 2050. A substantial part of this area was assessed as technically suitable for bioenergy plantations.

2.2.3 Economic considerations in biomass resource assessments

Some studies exclude areas where attainable yields are below a certain minimum level. Other studies, exclude biomass resources judged as being too expensive to mobilize, given a certain biomass price level. The potential of bioenergy plants can also be quantified based on combining land availability, yield levels and production costs to obtain plant- and region-specific cost-supply curves (Walsh 2000). These are based on projections or scenarios for the development of cost factors, including opportunity cost of land, and can be produced for different context and scale –

including feasibility studies of supplying individual bioenergy plants to describing the future global cost-supply curve (Figure 2.2.5). Studies using this approach at different scales include (Dornburg et al. 2007, Hoogwijk et al. 2008, de Wit et al. 2009, van Vuuren et al. 2009). (Gallagher et al. 2003) exemplify the production of cost-supply curves for the case of crop harvest residues and (Gerasimov and Karjalainen, 2009) for the case of forest wood.

The biomass production costs can be combined with techno-economic data for related logistic systems and conversion technologies to derive economic potentials on the level of secondary energy carriers such as bioelectricity and biofuels for transport (see, e.g., Gan, 2007, Hoogwijk et al. 2008, van Dam et al. 2009). Using biomass cost and availability data as exogenously defined input parameters in scenario-based energy system modeling can provide information about implementation potentials in relation to a specific energy system context and possible climate and energy policy targets. Cost trends are discussed further in more detail in Section 2.7.

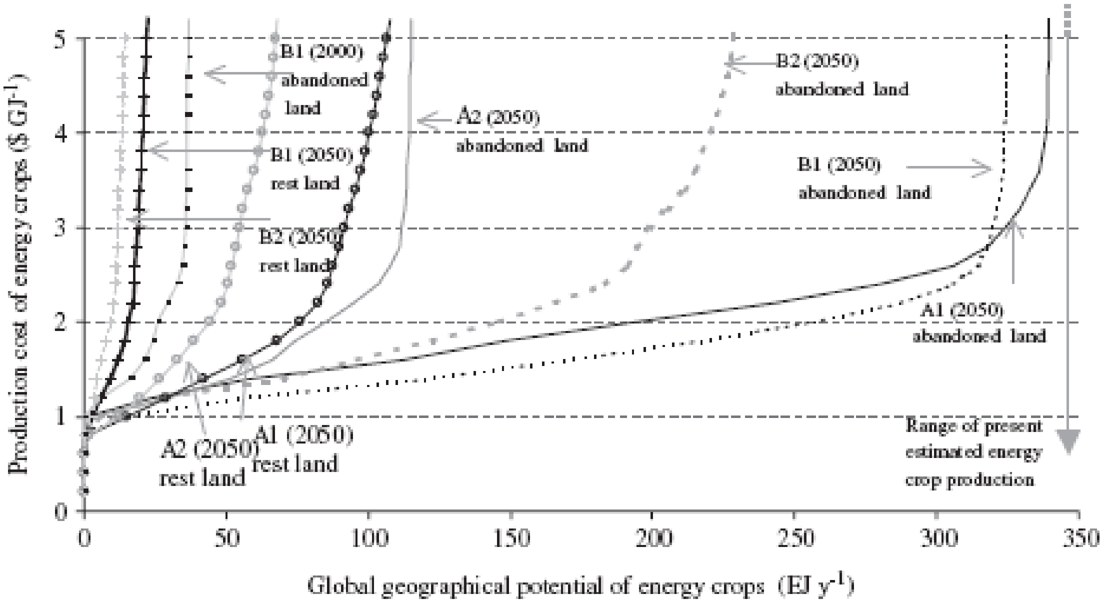


Figure 2.2.5. Global average cost-supply curve for the production of bioenergy plants on the two land categories “abandoned land” (agriculture land not required for food) and “rest land” (), year 2050. The curves are generated based on IMAGE 2.2 modeling of four SRES scenarios (IMAGETeam 2001). The cost-supply curve at abandoned agriculture land year 2000 (SRES B1 scenario) is also shown. Source: Hoogwijk et al. 2008. The scenarios A1, A2, B1, B2 correspond to the storylines developed for the IPCC Special Report on Emission Scenarios.

As examples of region/country scale assessments, biomass potentials for selected countries are illustrated in Figure 2.2.5. Using data from Europe, a scenario was constructed based on the land area needed in 2030 to meet food demand under specific population growth and economic assumptions (Fischer et. al. 2009). Then, by introducing restrictions on land availability focused on nature protection requirements and infrastructure development the study identified land with capacity to support cultivation of selected energy crops. The estimated biomass supply potential of this area, added to the potential of agriculture harvest residues, resulted in the total potential for Europe in 2030 shown in Figure 2.2.5(a). A high growth scenario with limited pasture conversion was estimated to reach about 27 EJ by 2030. Key factor determining the size of the potential was the development of agricultural productivity per ha, including animal production. Figure 2.2.5(b) displays the resulting cost-supply curves showing production costs for different crops using the part of total assessed surplus agricultural land that is suitable for their production (de Wit and Faaij 2009).

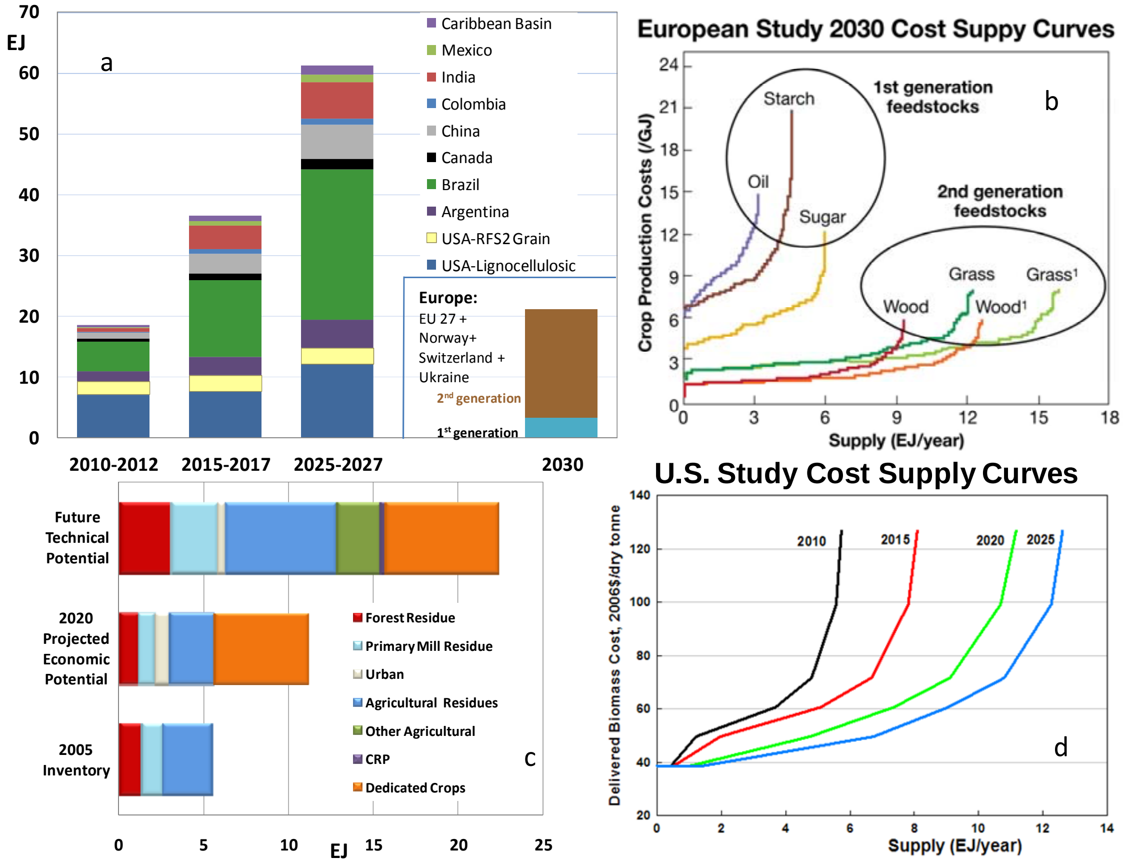


Figure 2.2.5. Regional/country-level potentials as assessed in recent studies. See text for further information about countries and biomass systems assessed.

The other estimate shown in Figure 2.2.5 was based on historic production trends and the structure of average production costs at the state/province level for selected feedstock/country combinations. Feedstocks included were sugarcane, corn, soybeans, wheat, palm oil, recoverable agricultural residues, a percentage of wastes and biomass associated with current forestry activities and fuelwood supplies, and potential perennial biomass crops. Biomass potentials were estimated as a function of arable land availability for energy use considering environmental restrictions and infrastructure. Figure 2.2.5(a) shows the estimated high-growth economic resource potential (Kline et al. 2007) for the years of 2012, 2017, and 2027. In the baseline case, roughly half the potential was estimated for 2027, but the baseline and high-growth estimates for 2017 were similar. The U.S. potentials come from similar but more detailed county-level analysis for cellulosic materials in 2010, 2015 and 2025 (Walsh 2008). Biofuel contributions from grain feedstocks are added with data of the same spatial resolution (EPA 2010). Individual data for the U.S. Figure 2.2.5(c) further illustrate the U.S. inventory for biomass resources (Milbrandt 2005); projected economic potential including considerations of restrictions relative to soil sustainability of agriculture residues and dedicated crops for 2020 (NRC 2009 b); and a higher future technical potential that could be achieved with successful research and development in energy crops and considering some sustainability factors (Perlack et al. 2005). Example of supply curves for the U.S. are given in

Figure 2.2.5(d) for multiple years that are shown used in Figure 2.2.5(a) (Walsh 2008 at $17/dry Mg delivery cost).

2.2.4 Analysis of factors influencing the biomass resource potentials

As described briefly above, many studies that quantify the biomass resource potential consider a range of factors that restrict the potential to lower levels than those corresponding to unconstrained technical potentials. These constraints are connected to various impacts arising from the exploitation of the biomass resources, which are further discussed in Section 2.5. Below, important factors are presented and analyzed in relation to how they influence the future biomass resource potential

2.2.4.1 Constraints on residue supply in agriculture and forestry

Soil conservation and biodiversity requirements set constraints on residue potentials for both agriculture and forestry. Organic matter at different stages of decay has an important ecological role to play in conserving soil quality as well as biodiversity in soils and above-ground.

In forests, wood ash application can recycle nutrients taken from the forest and mitigate negative effects of intensive harvesting. Yet, dying and dead trees, either standing or fallen and at different stages of decay, are valuable habitats (providing food, shelter and breeding conditions, etc.) for a large number of rare and threatened species (Grove and Hanula 2006). Thresholds for desirable amounts of dead wood at the forest stands are difficult to set and the most demanding species require amounts of dead wood that are difficult to reach in managed forests (Ranius and Fahrig 2006).

In agriculture, overexploitation of harvest residues is one important cause to soil degradation in many places of the world (Lal 2008, Ball 2005, Blanco-Canqui 2006, Wilhelm 2004). Fertilizer inputs can compensate for nutrient removals connected to harvest and residue extraction, but maintenance or improvement of soil fertility, structural stability and water holding capacity requires recirculation of organic matter to the soil (Lal and Pimentel 2007, Wilhelm et al. 2007, Blanco-Canqui and Lal 2009). Residue recirculation leading to nutrient replenishment and storage of carbon in soils and dead biomass not only contributes positively to climate change mitigation by withdrawing carbon from the atmosphere but also by reducing soil degradation and improving the soil productivity since this leads to higher yields and consequently less need to convert land to croplands for meeting future food/fibre/bioenergy demand (often leading to GHG emissions when vegetation is removed and soils are cultivated). Residue removal can, ceteris paribus, be increased when total biomass production per hectare becomes higher and if ‘waste’ from processing of crop residues that is rich in refractory compounds such as lignin is returned to the field (Johnson et al 2004; Reijnders 2007; Lal 2008).

Overexploitation of harvest residues is one important cause to soil degradation in many places of the world (Lal 2008, Ball 2005, Blanco-Canqui 2006, Wilhelm 2004). Residue recirculation leading to nutrient replenishment and storage of carbon in soils and dead biomass not only contributes positively to climate change mitigation by withdrawing carbon from the atmosphere but also by reducing soil degradation and improving the soil productivity since this leads to higher yields and consequently less need to convert more land to croplands (often leading to GHG emissions when vegetation is removed and soils are cultivated) for meeting future food/fibre/bioenergy demand.

Besides the difficulties in establishing sustainable residue extraction rates, there are also large uncertainties linked to the possible future development of several factors determining the residues generation rates. Population growth, economic development and dietary changes influence the demand for products from agriculture and forestry products and materials management strategies (including recycling and cascading use of material) influence how this demand translates into demand for basic food commodities and industrial roundwood.

Furthermore, changes in food and forestry sectors influences the residue/waste generation per unit product output which can go in both directions: crop breeding leads to improved harvest index (less residues); implementation of no-till/conservation agriculture requires that harvest residues are left on the fields to maintain soil cover and increase organic matter in soils (Lal, 2004); shift in livestock production to more confined and intensive systems can increase recoverability of dung but reduce overall dung production at a given level of livestock product output; increased occurrence of silvicultural treatments such as early thinning to improve stand growth will lead to increased availability of small roundwood suitable for energy uses and development of technologies for stump removal after felling increases the generation of residues during logging (Näslund-Eriksson and Gustafson, 2008)

Consequently, the longer term biomass resource potentials connected to residue/waste flows will continue to be uncertain even if more comprehensive assessment approaches are used. It should be noted that it is not obvious that more comprehensive assessments of restrictions will lead to lower residue potentials; earlier studies may have used conservative residue recovery rates as a precaution in the face of uncertainties (see, e.g., Kim and Dale 2004).

2.2.4.2 Constraints on dedicated plant production in agriculture and forestry

The prospects for intensifying conventional long-rotation forestry to increase forest growth and total biomass output – for instance by fertilizing selected stands, introducing alien forest species and using shorter rotations – are not thoroughly investigated in the assessed studies of biomass resource potentials. Intensification in forestry is instead related to shifts to higher reliance on fast-growing wood plantations that are in many instances similar to the bioenergy plantation systems assumed to become established on surplus agricultural land.

Intensification in agriculture is on the other hand a key aspect in essentially all of the assessed studies since it influences both land availability for biomass plantations (indirectly by determining the land requirements in the food sector) and the biomass yield levels obtained. High assessed potentials for energy plantations rely on high-yielding agricultural systems and international bioenergy trade leading to that biomass plantations are established globally where the production conditions are most favorable. Increasing yields in existing agricultural land is also in general proposed a key component for agriculture development (Ausubel, 2000; Tilman et al., 2002; Fischer et al 2002, Cassman et al., 2003; Evans, 2003; Balmford et al., 2005; Green et al., 2005; Lee et al., 2006; Bruinsma, 2009). Van Vuuren et al. (2009) show that yield increases for food crops in general have a more substantial impact on bioenergy potentials than yield increase for bioenergy plants specifically. Studies also point to the importance of diets and the food sector's biomass use efficiency in determining land requirements for food (Gerbens-Leenes and Nonhebel 2002; Smil 2002; Carlsson-Kanyama et al. 2003; de Boer et al. 2006; Elferink and Nonhebel 2007; Stehfest et al. 2010; Wirsenius et al. 2010).

Studies of agriculture development (see, e.g., Koning 2008, IAASTF 2009, Alexandratos 2009) show lower expected yield growth than studies of the biomass resource potential that report very high potentials for biomass plantations. Some observations indicate that it can be a challenge to maintain yield growth in several main producer countries and that much cropland and grazing land undergo degradation and productivity loss as a consequence of improper land use (Cassman, 1999; Pingali and Heisey, 1999; Fischer et al. 2002). The possible consequences of climate change for agriculture are not firmly established but indicate net global negative impact, where damages will be concentrated in developing countries that will lose in agriculture production potential while developed countries might gain (Fischer et al. 2002, Cline 2007, Schneider et al 2007, Lobell et al 2008, Fischer 2009). Water scarcity can limit both intensification possibilities and the prospects for expansion of bioenergy plantations (Berndes 2008, De Fraiture et al. 2008, De Fraiture and Berndes 2009, Rost et al. 2009, Van Vuren 2009). Biomass potential studies that use biophysical datasets and modelling can consider water limitations in land productivity modelling. However, assumptions about productivity growth in land use may implicitly presume irrigation development that could lead to challenges in relation to regional water availability and use. There is a need of empirical data for use in hydrological process models to better understand and predict the hydrological effects of various land use options on the landscape level (Malmer et al 2009). Water related aspects are further discussed in Section 2.5.

Conversely, some observations indicate that rates of gain obtained from breeding have increased in recent years and that yields might increase faster again as newer hybrids are adopted more widely (Edgerton 2009). Theoretical limits also appear to leave scope for further increasing the genetic yield potential (Fischer et al. 2009). It should be noted that studies reaching high potentials for bioenergy plantations points primarily to tropical developing countries as major contributors. In these countries there are still substantial yield gaps to exploit and large opportunities for productivity growth – not the least in livestock production (Wirsenius et al. 2010, Edgerton 2009, Fischer et al 2002). There is also a large yield growth potential for dedicated bioenergy plants that have not been subject to the same breeding efforts as the major food crops, as is the case for sugar cane. Selection of suitable plant species and genotypes for given locations to match specific soil types and climate is possible, but is at an early stage of understanding for some energy plants, and traditional plant breeding, selection and hybridization techniques are slow, particularly in woody plants but also in grasses. New biotechnological routes to produce both non-genetically modified (non-GM) and GM plants are possible. GM energy plant species may be more acceptable to the public than GM food crops, but there are concerns about the potential environmental impacts of such plants, including gene flow from non-native to native plant relatives.

There can be limitations and negative aspects of further intensification aiming at farm yield increases; high crop yields depending on large inputs of nutrients, fresh water, and pesticides, can contribute to negative ecosystem effects, such as changes in species composition in the surrounding ecosystems , groundwater contamination and eutrophication with harmful algal bloom, oxygen depletion and anoxic "dead" zones in oceans being examples of resulting negative impacts (Donner and Kucharik 2008, Simpson et al. 2009. See also Section 2.5). However, intensification is not necessarily equivalent to an industrialization of agriculture, as agricultural productivity can be increased in many regions and systems with conventional or organic farming methods (Badgley et al. 2007). Potential to increase the currently low productivity of rainfed agriculture exists in large parts of the world through improved soil and water conservation (Lal 2003, Rockström et al 2007, 2010), fertilizer use and crop selection (Cassmann 1999; Keys and McConnell, 2005). Available best practices are not at present applied in many world regions (Godfray et al. 2010), e.g. mulching, low tillage, contour ploughing, bounds, terraces, rainwater harvesting and supplementary irrigation, drought adapted crops, crop rotation and fallow time reduction, due to a lack of dissemination, capacity building, availability of resources and access to markets, with distinct regional differences (Neumann et al. 2010).

Conservation agriculture and mixed production systems (double-cropping, crop with livestock and/or crop with forestry) hold potential to sustainably increase land and water productivity as well as carbon sequestration and to improve food security and efficiency in the use of limited resources such as phosphorous (Kumar 2006, Heggenstaller 2008, Herrero et al 2010). Integration can also be based on integrating feedstock production with conversion – typically producing animal feed that can replace cultivated feed such as soy and corn (Dale 2008) and also reduce grazing requirement (Sparovek et al, 2007).

Investment in agricultural research, development and deployment could produce a considerable increase in land and water productivity (Rost et al. 2009, Sulser et al 2010, Herrero et al 2010) as well as improve robustness of plant varieties (Ahrens et al. 2010, Reynolds and Borlaug, 2006). Multi-functional systems (IAASTD 2009) providing multiple ecosystem services (Berndes et al 2004, 2008; Folke et al 2004, 2009,) represent alternative options for the production of bioenergy on agricultural lands that could contribute to development of farming systems and landscape structures that are beneficial for the conservation of biodiversity (Vandermeer and Perfecto 2006).

Biomass potential studies also point to that marginal/degraded lands – where productive capacity has declined temporarily or permanently – can be used for biomass production. Advances in plant breeding and genetic modification of plants not only raise the genetic yield potential but also adapts plants for more challenging conditions (Fischer et al. 2009). Improved drought tolerance can improve average yields in drier areas and in rain-fed systems in general by reducing the effects of sporadic drought (Nelson et al., 2007; Castiglioni et al., 2008) and can also reduce water requirements in irrigated systems. Thus, besides reducing land requirements for meeting food and materials demand by increasing yields, plant breeding and genetic modification can make lands earlier considered as unsuitable become available for rainfed or irrigated production.

Some studies show a significant technical potential of marginal/degraded land, but it is uncertain how much of this technical potential that can be realized. Main challenges in relation to the use of marginal/degraded land for bioenergy include (i) the large efforts and long time period required for the reclamation of more degraded land; (ii) the low productivity levels of these soils; and (iii) ensuring that the needs of local populations that use degraded lands for their subsistence are carefully addressed. Studies point to benefits of local stakeholder participation in appraising and selecting appropriate measures (Schwilch et al 2009) and suggest that land degradation control could benefit from addressing also aspects of biodiversity and climate change and that this could pave the way for funding via international financing mechanisms and the major donors (Knowler 2004, Gisladottir and Stocking 2005). In this context, the production of properly selected plant species for bioenergy can be an opportunity, where additional benefits involve C sequestration in soils and aboveground biomass and improved soil quality over time.

Besides that biodiversity consideration can limit residue extraction and intensification, it can limit agriculture land expansion. WBGU (2009) shows that the way biodiversity is considered can have a larger impact on bioenergy potential than either irrigation or climate change. The common way of considering biodiversity requirements as a constraint is by including requirements on land reservation for biodiversity protection. Biomass potential assessments commonly exclude nature conservation areas from being available for biomass production, but the focus is as a rule on forest ecosystems and takes the present level of protection as a basis. Other natural ecosystem also needs protection – not the least grassland ecosystems – and the present status of nature protection may not be sufficient for a certain target of biodiversity preservation. While many highly productive lands have low natural biodiversity, the opposite is true for some marginal lands and, consequently, the largest impacts on biodiversity could occur with widespread use of marginal lands.

Some studies indirectly consider biodiversity constraints on productivity implicitly by assuming a certain expansion of alternative agriculture production (to promote biodiversity) that yields lower than conventional agriculture and therefore requires more land for food production (Fischer et al. 2009, EEA, 2007). However, for multi-crop systems a general assumption of lower yields in alternative cropping systems is not consistent. Biodiversity loss may also occur indirectly, such as when productive land use displaced by energy crops is re-established by converting natural ecosystems into croplands or pastures elsewhere. Integrated energy system - land use/vegetation cover modeling have better prospects for analyzing these risks. They are further discussed in Section 2.2.6 below.

2.2.5 Summary conclusions

As shown above, narrowing down the biomass resource potential to distinct numbers is not possible. But it is clear that several hundred EJ per year can be provided for energy in the future, given favourable developments. It can also be concluded that:

- The size of the future biomass supply potential is dependent on a number of factors that are inherently uncertain and will continue to make long term biomass supply potentials unclear. Important factors are population and economic/technology development and how these translate into fibre and food demand (especially share and type of animal food products in diets) and development in agriculture and forestry.
- Additional important factors include (i) climate change impacts on future land use including its adaptation capability; (ii) restrictions set by biodiversity and nature conservation requirements; and (iii) consequences of land degradation and water scarcity.
- Studies point to residue flows in agriculture and forestry and unused (or extensively used) agriculture land as an important basis for expansion of biomass production for energy, both on the near term and on the longer term.
- Grasslands and marginal/degraded lands are also considered to have potential for supporting substantial bioenergy production, but biodiversity considerations may limit this potential. The possibility that conversion of such lands to biomass plantations reduces downstream water availability also needs to be considered
- Biodiversity-induced limitations and the need to ensure maintenance of healthy ecosystems and avoid soil degradation also set limits on residue extraction in agriculture and forestry.
- Yet, several hundred EJ per year of biomass could be provided for energy in the future, given favourable developments. This can be compared with the present biomass use for energy at about 50 EJ per year
- The cultivation of suitable plants crops can allow for higher potentials by making it possible to produce bioenergy on lands where conventional food crops are less suited – also due to that the cultivation of conventional crops would lead to large soil carbon emissions (further discussed in Section 2.5.2).
- Landscape approaches integrating bioenergy production into agriculture and forestry systems to produce multi-functional land use systems could contribute to development of farming systems and landscape structures that are beneficial for the conservation of biodiversity and helps restore/maintain soil productivity and healthy ecosystems
- Water constraints may limit production in regions experiencing water scarcity. But the use of suitable energy crops that are drought tolerant can also help adaptation in water scarce situations. Assessments of biomass resource potentials need to more carefully consider constrains and opportunities in relation to water availability and competing use.

While recent assessments employing improved data and modeling capacity have not succeeded in providing narrow distinct estimates of the biomass resource potential, they have advanced the understanding of how influential various factors are on the potential. The insights from the resource assessments can improve the prospects for bioenergy by pointing out the areas where development is most crucial and where research is needed. A summary is given in Section 2.8.

2.3 Technology

Bioenergy chains involve a wide range of feedstocks, conversion processes and end-uses (Figure 2.1.1). This section covers the existing commercial technologies used in the various steps of these chains worldwide, and details some of the major systems which are deployed. Developing technologies which are in various stages of the research and development phases are presented in detail in section 2.6 and summarized in Figure 2.3.1.

2.3.1 Feedstock

2.3.1.1 Feedstock production and harvest

Tables 2.3.1 and 2.3.2 summarize performance criteria of major biomass production systems across the world regions, whether using dedicated plants and primary residues (Table 2.3.1) or secondary residues (Table 2.3.2). The management of energy plants includes the provision of seeds or seedlings, stand establishment and harvest, soil tillage, and various rates of irrigation, fertilizer and pesticide inputs, which depend on crop requirements, target yields, and local pedo-climatic conditions, and may vary across world regions for a similar species (Table 2.3.1). Strategies such as integrated pest management or organic farming may alleviate the need of synthetic inputs for a given output of biomass.

Wood for energy is obtained as fuelwood from the logging of natural or planted forests, and from trees and shrubs from agriculture fields surrounding villages and towns. While natural forests are not managed toward production per se, problems arise if fuelwood extraction exceeds the regeneration capacity of the forests, which is the case in many parts of the world. The management of planted forests involves silvicultural techniques similarly to those of cropping systems, from stand establishment to tree fallings (Nabuurs et al., 2007).

Biomass may be harvested several times a year (for forage-type feedstocks such as hay or alfalfa), once a year (for annual species such as wheat, or perennial grasses), or every 2 to 50 years or more (for short-rotation coppice and conventional forestry, respectively). Biomass is typically transported to a collection point on the farm or at the edge of the road before transport to the bioenergy unit or an intermediate storage. It may be preconditioned and densified to make storage, transport and handling easier (see section 2.3.2.).

Table 2.3.1. Typical characteristics of the production technologies for dedicated species and their primary residues. Management inputs symbols: +: low; ++: moderate; +++: high requirements.

Feedstock type (Status: C=commercial D=developing)	**Region**	**Yield (GJ/ha/yr)**	**Management**			**Co-products**	**Costs USD$_{2005}$/GJ**	**Refs.**
			N/P/K use	**Water needs**	**Pesticides**			
OIL CROPS		As oil						
Oilseed rape (C)	Europe	40-70	+++	+	+++	Rape cake, straw	7.2	1,2,3
Soybean (C)	N America Brazil	16-19 18-21	++ ++	+ +	+++ +++	Soy cake, straw	11.7	3,12
Palm oil (C)	Asia Brazil	135-200 169	++ ++	+ +	+++ +++	Fruit bunches, press fibers	12.6	3
Jatropha (D)	World	17-88	+/ ++	+ +	- -	Seed cake (toxic), wood, shells	2.9	3,4,5,10, 11
STARCH CROPS		As ethanol						
Wheat (C)	Europe	54-58	+++	++	+++	Straw, DDGS	5.2	3
Maize (C)	N America	72-79	+++	+++	+++	Corn stover, DDGS	10.9	3
Cassava (D fuel)	World	43	++	+	++	DDGS		3
SUGAR CROPS		As ethanol						
Sugar cane (C)	Brazil India	116-149 95-112	++	+	+++	Bagasse, straw	1.0-2.0	3,20 3
Sugar beet (C)	Europe	116-158	++	++	+++	Molasses, pulp	5.2	3,13
Sorghum (sweet) (D)	Africa China	105-160	+++	+	++	Bagasse	4.4	3, 24
LIGNOCELLULOSIC CROPS								
Miscanthus (D)	Europe	190-280	+/++	++	+		4.8-16	6,8
Switchgrass (D)	Europe N America	120-225 103-150	++ ++	+ +	+ +		2.4-3.2 4.4	10,14
Short rotation Eucalyptus (C for materials; D energy)	S Europe S America	90-225 150-415	+ +/++	++ +	+ +	Tree bark	2.9-4 2.7	2,2219,2 2
S.rotation Willow (D)	Europe	140					4.4	3,7
Fuelwood (chopped) (C)	Europe	110				Forest residues	3.4-13.6	17
Fuelwood (from native forests, renewable)	C America	80-150				Forest residues	2-4	
PRIMARY RESIDUES								
Wheat straw (D for fuels)	Europe USA	60 7-75	+				1.9	2 14, 23

Sugar cane straw	Brazil	90-126	+					21
Corn stover (D for fuels)	N America India	15-155 22-30	+ +				 0.9	9,14 21
Sorghum stover (D)	World	85	+					9
Forest residues (C)	Europe World	2-15					1-7.7	17

References: 1: EEA, 2006; 2: JRC, 2007; 3: Bessou et al., 2009; 4: Jongschaap et al., 2007; 5: Openshaw, 2000; 6: Clifton-Brown et al., 2004: 7: Ericsson et al., 2009; 8: Fargernäs et al., 2006; 9: Lal, 2005; 10: WWI, 2006; 11: Maes et al., 2009; 12: Gerbens-Leenes et al., 2009; 13: Berndes, 2008; 14: Perlack et al., 2005; 15: Yokoyama and Matsumura, 2008; 16: Kärhä,et al., 2009; 17: Karjalainen et al., 2004; 18: Nabuurs et al., 2007; 19: Scolforo, 2008; 20: Folha, 2005; 21: Guille, 2007; 22: Diaz-Balteiro & Rodriguez, 2006; 23: Lal, 2005; 24: Grassi, 2005.

The species listed in Table 2.3.1 are not equivalent in terms of possible energy end-uses. Starch, oil and sugar crops are grown as feedstock first-generation liquid biofuels (ethanol and bio-diesel – see 2.3.3.), which only use a fraction of their total above-ground biomass, the rest being processed in the form of animal feed or lignocellulosic residues. Sugar cane bagasse and even sugar cane straw are being used as a source of process heat and power in many sugar and ethanol producing countries (Dantas et al, 2009). On the other hand, lignocellulosic crops (such perennial grasses or short-rotation coppice) may be entirely converted to energy, and feature 2 to 5 times higher yields per ha than most of the other feedstock types, requiring far less synthetic inputs when managed carefully (Hill, 2007). However, their plantation and harvest is more resource intensive than annual species, and their impact on soil organic matter after the removal of stands is poorly known (Anderson-Texeira et al., 2009; Wilhelm et al., 2007). In addition, with the current technology lignocellulose can only provide heat and power (and products) whereas the harvest products of oil, sugar and starch crops may be readily converted to liquid biofuels. Costs for dedicated plants vary widely according to the prices of inputs and machinery, labor and land-related costs (Ericsson et al., 2009). If energy plantations are to compete with land dedicated to food production, the opportunity cost of land (the price a farmer should be paid to switch to an energy crop) may become dominant and scales with the demand for energy feedstock (Bureau et al., 2009). Cost-supply curves are needed to account for these effects in the economics of large-scale deployment scenarios. See examples of cost supply curves in Figure 2.2.5.

2.3.1.2 Synergies with the agriculture, food & forest sectors

As underlined in section 2.2.1., bioenegy feedstock production competes with other usages for resources, chief of which land, with possible negative effects on biodiversity, water availability, soil quality, and climate. However, synergistic effects may also emerge through the design of integrated production systems, which might also provide additional environmental services. Intercropping and mixed cropping are interesting options to maximize the output of biomass per unit area farmed (WWI, 2006). Mixed cropping systems result in increased yields compared to single crops, and may provide both food/feed and energy feedstock from the same field (Tilman et al., 2006; Jensen, 1996). Double-cropping systems have the potential to generate additional feedstocks for bioenergy and livestock utilization and potentially higher yields of biofuel from two crops in the same area in a year (Heggenstaller, 2008).

Agroforestry systems make it possible to use land for both food and energy purposes with mutual benefits for the associated species (Bradley et al., 2008). The associated land equivalent ratios may reach up to 1.5 (Dupraz and Liagre, 2008), meaning a 50% saving in land area when combining trees with arable crops respective to mono-cultures. Another option would consist in growing an understory food crop and coppicing the ligneous specie (to produce residual biomass for energy (similarly to short-rotation coppice). (Dupraz and Liagre, 2008). Integration may also occur with the by-products of bioenergy conversion processes. Typically, animal feed by-products can replace cultivated feed such as soy and corn (Dale 2008) and also reduce grazing requirement (Sparovek et al, 2007).

Perennial species create positive externalities such as erosion control, improved fertilizer use efficiency, reduction in nitrate-N leaching relative to annual plants. Lastly, the revenues generated from growing bioenergy feedstock may provide access to technologies or inputs enhancing the yields of food crops, provided the benefits are distributed to local communities (Practical Action Consulting, 2009).

Table 2.3.2: Typical characteristics of the production technologies for selected secondary residues and waste stream.

Feedstock type	Region	Energy content	Cost USD$_{2005}$/GJ	Ref.
Sugar cane bagasse	Brazil	15.5 GJ/odt	1.6-5.3	10,2
Rice husk	India	15 GJ/odt	2	21
Waste wood	Europe	18 GJ/odt	2.2	2
Wood pellets and briquettes	N Europe US/Canada	18 GJ/odt	8.8 5-5.3	16
MSW	USA	3.4 GJ/inhab.(organic)	May be negative for a while	10
Cattle slurry	Asia N America	14-17/cattle head 14-32/cattle head		15
Black liquor	Europe	12 GJ/odt		
Waste cooking oil	Global	40 GJ/t		3

Same references as Table 2.3.1; odt = oven dry tons

2.3.2 Logistics and supply chains

Since biomass is mostly available in low density form, it demands more storage space, transport and handling than fossile equivalents, with consequent cost implications. It often needs to be processed (pre-treated) to improve handling. For most bioenergy systems and chains, handling and transport of biomass from the source location or area to conversion plant is an important contributor to the overall costs of energy production. Including e.g. harvest of crops, storage, transport, pre-treatment and delivery can amount 20 to up to 50% of total costs of energy production (Allen et al, 1998.

Use of a single agricultural biomass feedstock for year-round energy generation necessitates relatively large storage since this is available for a short time following harvest. Among the characteristics that complicate the biomass supply chain and that are to be taken into account when organizing biomass supplies for conversion capacity over time are (Rentizelas et al, 2008; Junginger et al., 2001):

- Multiple feedstocks with their own complex supply chains.
- Storage challenges including space constraints, fire hazards, moisture control, and health risks from fungi and spores.
- Seasonal variation in supply.

Over time (i.e. starting in the eighties) several stages may be observed in biomass utilization and market developments in biomass supplies. Different countries seem to follow these stages over time, but clearly differ in the stage of development (Faaij, 2006).

1. Waste treatment (e.g. MSW and use of process residues (paper industry, food industry) 'on site' of production facilities is generally the starting phase of a developing bio-energy system. Resources are available and often have a negative value, making utilization profitable and simultaneously solving waste management problems.
2. Local utilization of resources from forest management and agriculture. Such resources are more expensive to collect and transport, but usually still economically attractive. Infrastructure development is needed.
3. Biomass market development on regional scale; larger scale conversion units with increasing fuel flexibility are deployed; increasing average transport distances further improved economies of scale. Increasing costs of biomass supplies make more energy efficient conversion facilities necessary as well as feasible. Policy support measures such as feed-in tariffs are usually already needed to develop into this stage.
4. Development of national markets with increasing number of suppliers and buyers; creation of a market place; increasingly complex logistics. Often increased availability due to improved supply systems and access to markets. Price levels may therefore even decrease (see e.g. Junginger et al., 2005).
5. Increasing scale of markets and transport distances, including cross border transport of biofuels; international trade of biomass resources (and energy carriers derived from biomass). Biomass is increasingly becoming a globally traded energy commodity (see e.g. Junginger et al., 2008). Bio-ethanol trade has come closest to that situation (see e.g Walter et al., 2008)
6. Growing role for dedicated fuel supply systems (biomass production largely or only for energy purposes). So far, dedicated crops are mainly grown because of agricultural interests and support (subsidies for farmers, use of set-aside subsidies), which concentrates on oil seeds (like rapeseed) and surplus food crops (cereals and sugar beet).

Countries that have gained large commercial experience with biomass supplies and biomass markets were generally also able to obtain substantial cost reductions in biomass supply chains over time. In Finland and Sweden cost of delivery went down from some 12 US$/GJ delivered halfway the 70-ies to less than 5 US$/GJ at present. This was due to many factors - scale increase, technological innovations, increased competition, etc. Similar trends are observed in logistics around the corn ethanol industry in the US and cane ethanol in Brazil (see also section 2.7 on cost trends).

Analyses of regional and international biomass supply chains show that road transport of untreated and bulky biomass becomes uncompetitive, as well as a significant factor in energy use when crossing distances of 50-150 km (see e.g. (Dornburg & Faaij, 2001) and (Hamelinck et al., 2005a)). It is also obvious that when long distance transport is required, early pre-treatment and densification in the supply chain (see 2.3.2.1 and 2.6) pays off to minimize longer distance transport costs. Taking into account energy use and related GHG emissions, well organized logistic chains can require less than 10% of the initial energy content of the biomass (Hamelinck et al., 2005b; Damen & Faaij, 2006), but this requires substantial scale in transport, efficient pre-treatment and minimization of road transport of untreated biomass.

Such organization is observed in rapidly developing international wood pellet markets (see also section 2.4 and below). Furthermore, (long distance) transport costs of liquid fuels such as ethanol and vegetal oils contributes only in a minor way to overall costs and energy use of bioenergy chains (Hamelinck et al., 2005b).

2.3.2.1 Wood pellet logistics and supplies

Wood pellets are one of the most successful bioenergy-based commodities traded internationally. Wood pellets offer a number of advantages compared with other solid biomass fuels: they generally have a low moisture content and a relatively high heating value (about 17 MJ/kg), which allows long-distance transport by ship without affecting the energy balance (Junginger et al, 2008). Local transportation is carried out by trucks, which sets a feasible upper limit for transportation (assuming 150 km transportation for raw biomass, 50 km for pellets) and necessary storage usually represent more than 50% of the final cost. Bulk delivery of pellets is very similar to a delivery of home heating oil and is carried out by the lorry driver blowing the pellets into the storage space, while a suction pump takes away any dust. Storage solutions include underground tanks, container units, silos or storage within the boiler room. Design of more efficient pellet storage, charging and combustion systems for domestic users is on-goings (Peksa-Blanchard et al, 2007). International trade is done by ships and ports suitability for handling the product is one of the major logistic barriers. In most potential exportation countries ports are not yet equipped with storage and modern handling equipments or are poorly managed, which implies in high shipping cost. Another barrier is freight costs, which are very sensitive to international trade demand (Junginger et al, 2008).

2.3.2.2 Biomass and charcoal supplies in developing countries

Developing countries have some specific issues. Charcoal in Africa is predominantly produced in inefficient traditional kilns by the informal sector, often illegally. Current production, packaging and transportation of charcoal is characterised by low efficiencies and poor handling, leading to losses. To introduce change to this industry requires that it be recognised and legalised, where it is found to be sustainable and not in contradiction with environmental protection goals. Once legalised it would be possible to regulate it and introduce standards including fuel quality, packaging standards, production kiln standards and what tree species could be used to produce charcoal (Kituyi, 2004).

The majority of households in the developing world depend on solid biomass fuels such as charcoal for cooking, and millions of small-industries (such as brick and pottery kilns) generate process heat from these fuels. Despite this pivotal role of biomass, the sector remains largely unregulated, poorly understood, and the supply chains are predominantly in the hands of the informal sector (GTZ, 2008).

When fuelwood is marketed, trees are usually felled and cut into large pieces and transported to local storage facilities from where they are collected by merchants to wholesale and retail facilities, mainly in rural areas. Some of the wood is converted to charcoal in kilns and packed into large bags and transported by hand, animal drawn carts and small trucks to roadside sites from where they are collected by trucks to urban wholesale and retail sites. Thus charcoal making is an enterprise for rural populations to supply urban markets. Crop residues and dung are normally used by the owners as a seasonal supplement to fuelwood.

2.3.2.3 Preconditioning of biomass

Shredded biomass residues may be densified by briquetting or pelletizing, typically in screw or piston presses that compress and extrude the biomass (FAO, 2009c). Briquettes and pellets can be good substitutes for coal, lignite and fuelwood as they are renewable, have consistent quality, size, better thermal efficiency, and higher density than loose biomass.

There are briquetting plants in operation in India and Thailand, using a range of secondary residues and with different capacities, but none as yet in other Asian countries. There have been numerous, mostly development agency-funded briquetting projects in Africa, and most have failed technically and/or commercially. The reasons for failure include deployment of new test units that are not proven, selection of very expensive machines that do not make economic sense, low local capacity to fabricate components and provide maintenance, and lack of markets for the briquettes due to uncompetitive cost and low acceptance (Erikson and Prior, 1990).

Wood pellets are made of wood waste such as sawdust and grinding dust. Pelletization produces somewhat lighter and smaller pellets of biomass compared to briquetting. Pelletization machines are based on fodder making technology. Wood pellet are easy to handle and burn since their shape and characteristics are uniform; transportation efficiency is high; energy density is high. Wood pellets are used as fuel in many countries for cooking and heating application (EREC, 2009).

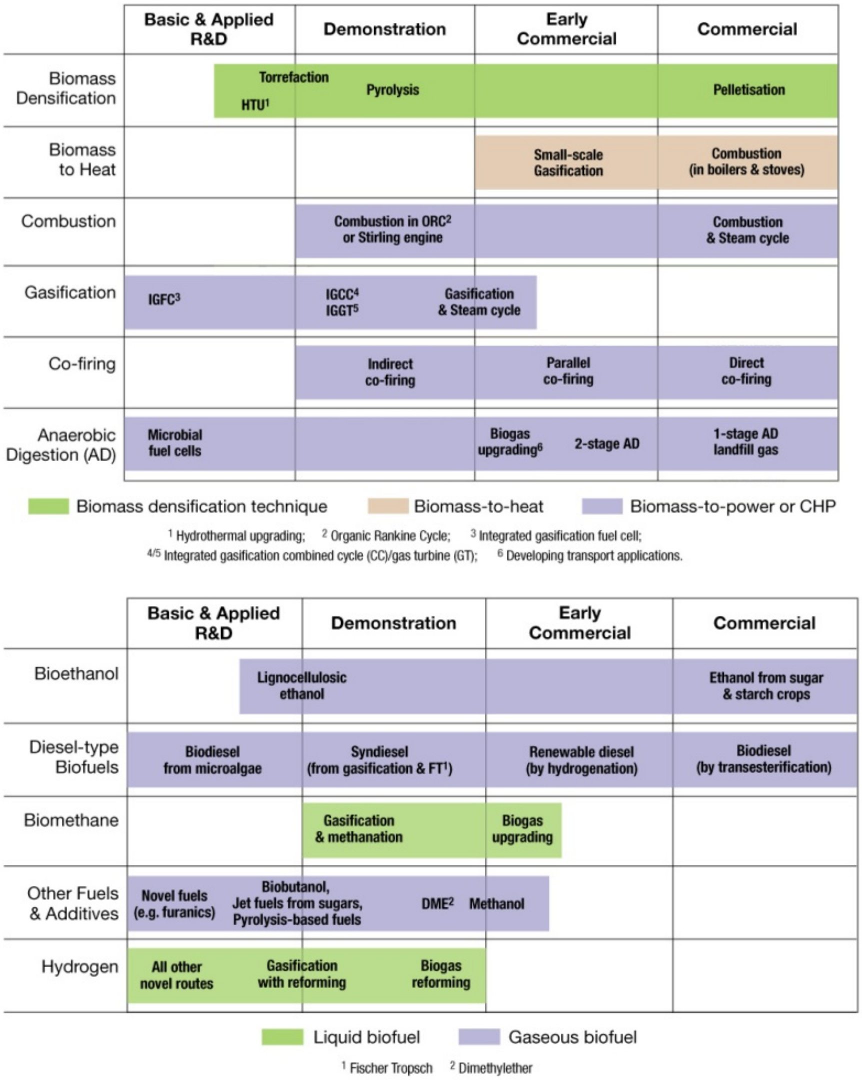
Chips are mainly produced from plantations waste wood and wood residues (branches and nowadays even spruce stumps) as a by-product of conventional forestry. They require less processing and are cheaper than pellets. Depending on end use, chips may be produced on-site, or the wood may be transported to the chipper. Chips are commonly used in automated heating systems, and can be used directly in coal fired power stations or for combined heat and power production (Fargernäs et al., 2006).

Charcoal is a product obtained by heating woody biomass to high temperatures in the absence of oxygen, with a twice higher calorific value than the original feedstock. It burns without smoke and has a low bulk density which reduces transport costs. In many African countries charcoal is produced in traditional kilns in rural areas with efficiencies as low as 10% (Adam, 2009), and typically sold to urban households while rural households use fuelwood. Hardwoods are the most suitable raw material for charcoal, since softwoods incur possibly high losses during handling/transport. Charcoal from granular materials like coffee shells, sawdust, and straw is in powder form and needs to be briquetted with or without binder. Charcoal is also used in large-scale industries as iron reducer, particularly in Brazil, and in many cases, in conjunction with sustainably produced wood, and also increasingly as co-firing in oil-based electric power plants. Charcoal is produced in large-scale efficient kilns and fuelwood comes from high-yielding eucalyptus plantations (Scolforo, 2008).

2.3.3 Conversion technologies

Different end-use applications require that biomass be processed through a variety of conversion steps depending on the feedstock and its chemical composition. Sugar-rich feedstocks like sugarcane and beets require the least amount of processing because simple sugars are present in the juice after pressing that can be fermented into liquid fuels such as ethanol or butanol or a variety of other products. Grains and tubers contain starches that are complex polymeric carbohydrates that break down by enzymes into simpler fermentable sugars. However, as one moves to biomass present in short rotation wood, stalks of annual plants, and herbaceous plants, the presence of the more intractable carbohydrates, cellulose and hemicelluloses and additional phenolic polymers has to be overcome by mechanical, chemical, thermal or combined processes to generate the desired final energy product.

Combustion with excess oxygen at high temperatures requires the least amount of prior processing. To obtain stable chemical intermediates, compatible with the chemical and petroleum industry of today, intermediate severity processes need to be used. For instance, through a partial oxidation of biomass, gasification, intermediates that resemble synthesis gas usually derived from natural gas – hydrogen and carbon monoxide mixture - are obtained. From synthesis gas, a variety of catalytic processes have been developed by the chemical industry to make hydrocarbons in the diesel range or methanol, ethanol, other alcohols, or ethers such as dimethylether, and other fuels. Today these oils provide specialty chemicals, or can be burned to generate electricity in diesel engines, or if the pyrolysis process is done slowly, charcoal becomes the main product (e.g., Huber et al.2006).



	Basic & Applied R&D	Demonstration	Early Commercial	Commercial
Biomass Densification	Torrefaction HTU[1]	Pyrolysis		Pelletisation
Biomass to Heat			Small-scale Gasification	Combustion (in boilers & stoves)
Combustion		Combustion in ORC[2] or Stirling engine		Combustion & Steam cycle
Gasification	IGFC[3]	IGCC[4] IGGT[5]	Gasification & Steam cycle	
Co-firing		Indirect co-firing	Parallel co-firing	Direct co-firing
Anaerobic Digestion (AD)	Microbial fuel cells		Biogas upgrading[6] 2-stage AD	1-stage AD landfill gas

🟩 Biomass densification technique 🟧 Biomass-to-heat 🟪 Biomass-to-power or CHP

[1] Hydrothermal upgrading; [2] Organic Rankine Cycle; [3] Integrated gasification fuel cell;
[4/5] Integrated gasification combined cycle (CC)/gas turbine (GT); [6] Developing transport applications.

	Basic & Applied R&D	Demonstration	Early Commercial	Commercial
Bioethanol		Lignocellulosic ethanol		Ethanol from sugar & starch crops
Diesel-type Biofuels	Biodiesel from microalgae	Syndiesel (from gasification & FT[1])	Renewable diesel (by hydrogenation)	Biodiesel (by transesterification)
Biomethane		Gasification & methanation	Biogas upgrading	
Other Fuels & Additives	Novel fuels (e.g. furanics)	Biobutanol, Jet fuels from sugars, Pyrolysis-based fuels DME[2]	Methanol	
Hydrogen	All other novel routes	Gasification with reforming Biogas reforming		

🟩 Liquid biofuel 🟪 Gaseous biofuel

[1] Fischer Tropsch [2] Dimethylether

Figure 2.3.1 Development status of the main technologies to produce from biomass energy products such as heat, power, or its combination (CHP), and fuels in the solid, liquid, or gaseous state. Liquid and gaseous fuels are used for transport (modified from E4tech 2008).

To use fermentation processes, the cellulosic and hemicellulosic fractions have to be converted into mixtures of simple six and five carbon sugars with glucose and xylose being dominant. Sugars are the other stable intermediates from which fuels, chemicals, and materials identical to those made by the petrochemical industry or new ones can be made. For these reasons lignocellulosic biomass thermal processes, principally combustion, are commercial while other thermal, chemical, biochemical, or hybrid of those, or biological synthesis routes are developing technologies. So, simpler sources of sugars than lignocellulosic biomass, such as sugarcane, beet, and starch from grains, are the prime sources of liquid fuels from fermentation today.

Figure 2.3.1 shows the snapshot of the stage of development of multi-step conversion processes to transform biomass into energy products for both small and large scale applications. Commercial technologies are presented in Table 2.3.3 with specific characteristics such as energy efficiency, estimated production costs, and anticipated technological advances and anticipated potential costs, and an indication of their potential to mitigate climate change through the relationship between the direct emissions of the life cycle of the biofuels compared to the fossil fuel being replaced. Developing technologies, many of which are already at demonstration or even design and construction of first commercial plants, are discussed in Section 2.6 and are listed on Tables 2.6.2 and 2.6.3. Industrial activities in these areas have been discussed in reports such as IEA Task 39 (2008)[1], and E4Tech (2009) for aviation fuels.

2.3.3.1 Thermo-chemical Processes

Biomass combustion is a process where carbon and hydrogen in the fuel react with oxygen to form carbon dioxide and water with a release of heat. Direct burning of biomass is popular in rural areas for cooking. Wood and charcoal is also being used as a fuel in industry. Combustion of biomass for generating electricity through fluidised bed technology has the advantages of more flexibility for fuels, and lower emissions of sulphur, nitrogen oxides and unburned components (Fargernäs et al., 2006).

Pyrolysis is the thermal decomposition of the biomass into gaseous, liquid, and solid products without oxygen or steam. Depending on the residence times, temperature, and heating rate the process can be optimized to produce one or the other product. At high heating rates and moderate temperature range (450-550°C) the oxygenated oils are the major product (70%-80%), with the remainder split into char and gases.

Cogeneration is the process of using a single fuel to produce more than one form of energy in sequence. In cogeneration mode, the heat generated as steam is not wasted but used to meet process heating requirement, with an overall efficiency of 60% or even higher (over 90%) in some cases (Williams et al., 2009). Technologies available for high-temperature/high pressure steam generation using bagasse as a fuel make it possible for sugar mills to operate at higher level of energy efficiency and generate more electricity than what they require. Similarly black liquor, an organic pulping product containing the pulping chemicals is produced in paper and pulp industry is being burnt efficiently in boilers for producing energy that is used back as process heat and recovers the expensive chemicals (Faaij, 2006). District heating Scandinavian is very popular through cogeneration mode for meeting commercial and residential space heating and water heating.

Biomass Gasification occurs through a partial combustion as it converts the biomass to a syngas (mixture of mostly CO and H2, with other components such as H2O, CO2, CH4, and tars). The end-use product determines the desired syngas composition, and thus the gasifier reactor's design and operating conditions. After gasification, the syngas must be cleaned of particulates, tars, and gaseous components such as sulfur compounds that can inhibit the activity of the catalyst the biofuel desired. The equipment downstream of the gasifier for conversion to H2, methanol, methane, or Fischer Tropsch (FT) diesel is the same as that used to make these products from natural gas. A gas turbine or boiler, and a steam turbine optionally employ the unconverted gas fractions for electricity co-production. Synthesis gas can be used as a fuel in place of diesel in suitably designed/adapted internal combustion (IC) engines coupled with generators for electricity generation. Most commonly available gasifiers use wood/woody biomass; some can use rice husk as well. Many other non-woody biomass materials can also be gasified, specially designed gasifiers to suit these materials (Yokoyama and Matsumura, 2008).

Biomass gasifier stoves are also being used in many rural industries for heating and drying (Yokoyama and Matsumura, 2008; Mukunda et al., 2009).

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[1] **http://biofuels.abc-energy.at/demoplants/projects/mapindex**

2.3.3.2 Chemical Processes

Transesterification is the process where the alcohols (often methanol) react with triglycerides oils contained in vegetable oils or animal fats to form an alkyl ester of fatty acids, in the presence of a catalyst (acid or base with byproducts of glycerin and oil cake/meal ; WWI, 2006). The production of this fuel referred to as biodiesel thus involves extraction of vegetable oils from the seeds, usually with mechanical crushing or chemical solvents. The protein-rich by-product of oil (cake) is sold as animal feed or fertilizers, but may also be used to synthesize higher-value chemicals.

A diesel analog is obtained by hydrogenolysis of the vegetable oils, usually coupled to a refinery. Many companies throughout the world have patents, demonstrations, and have tested this technology at commercial scale for diesel and also jet fuel applications (IEA Bioenergy, 2009). Hydrogenated biofuels have higher cetane number, low sulphur content, high viscosity with 97% biodegradable content. The high cost of the vegetable oil in many locations makes the process less cost-effective.

2.3.3.3 Biochemical Processes

Fermentation is the process to breakdown sugars by yeasts to produce a variety of end products such as ethanol. The major feedstocks are sugarcane, sweet sorghum, sugar-beet and starch crops (such as corn, wheat or cassava). Ethanol from sugarcane or sugar-beets is generally available as a by-product of sugar mills, but it can also be directly produced from extraction juices and molasses. The fermentation either takes place in single-batch or fed batch, or continuous processes, the latter becoming widespread and being much more efficient since yeasts can be recycled. The ethanol content in the fermented liquor is about 10%, and is subsequently distilled to increase purity to about 95%. As the ethanol required for blending with gasoline should be anhydrous, the mixture has to be further dehydrated to reach a grade of 99.8%-99.9% (WWI, 2006).

Anaerobic digestion involves the breakdown of organic matter in agricultural feedstock such as animal dung, human excreta, leafy plant materials, and urban solid and liquid wastes by a consortium of micro-organisms in the absence of oxygen to produce biogas, a mixture of methane (60-70%) and carbon dioxide. In this process, the organic fraction of the waste is segregated and fed into a closed container (biogas digester). In the digester, the segregated waste undergoes biodegradation in presence of methanogenic bacteria under anaerobic conditions, producing methane-rich biogas and effluent. The biogas can be used either for cooking/heating applications or for generating motive power or electricity through dual-fuel or gas engines, low-pressure gas turbines, or steam turbines; it can also be upgraded to a higher heat content biomethane gas mixed with the natural gas grid (IEA Bioenergy, 2009; IEA, 2005). The sludge from anaerobic digestion, after stabilization, can be used as an organic amendment. It can even be sold as manure depending upon its composition, which is determined mainly by the composition of the input waste. Many developing countries like India and China are making use of this technology extensively in rural areas. Many German and Swedish companies are market leaders in large size biogas plants (Faaij, 2006). In Sweden multiple wastes and manures are also used.

2.3.4 Bioenergy Systems and Chains: Description of existing state of the art systems

Table 2.3.3 shows the most relevant commercial bioenergy systems that operate presently in the world. The table lists by end use sector and biomass energy product(s) the feedstock used along with processes used in specific countries. Processes are briefly described with their current efficiency and estimated current production costs (or as close to current based on literature available) along with 2030 (or 2020) estimated production costs. Since the costs are obtained from the literature, no special effort was made to bring all these costs into comparable basis (a major undertaking). Process costs provided by the same reference are usually done under the same conditions and thus enable a firmer comparison. That is why we provided several references for these estimated production costs. Information on the current markets and potential is provided in Section 2.4 for bioenergy products along with examples of specific countries are provided. Another characteristic provided was the measure of the ability of the current chain to reduce GHG emissions compared to the fossil fuel it replaces. A more detailed discussion of this metric of the biofuels is provided in Section 2.5.

Liquid biofuels are mainly used in the transport sector, although in some developing countries they are also used to generate household or village electricity. Ethanol costs are usually lower than biodiesel for the systems which are already in commercial use (the ones based in rapeseed, soya and oil palm), although in Asian countries like Thailand the production costs are close to each other for the two biofuels. The conversion efficiency (from feedstock to end-use product) is modest, from a little over 50% to around 10%, but the low conversion cases are those in which the fuel is a byproduct of a grain to food/feed production process (soya, for instance). Space for better use of the feedstock and, mainly the total biomass produced, is remarkable.

Solid biomass, mostly used for heat, power and combined heat and power (CHP) has usually lower estimated production costs than liquid biofuels. Unprocessed solid biomass is less costly than pre-processed type (via densification), but for the final consumer the transportation and other logistic costs have to be added, which justify the existence of a market for both types of solid biomass. Some of the bioenergy systems are under demonstration for small scale application due cost barriers imposed by economies of scale and consequently it is necessary to identify a different technology than the one used successfully for large scale applications (such as combustion for electricity generation).

From the data in table 2.3.3, the lowest cost liquid biofuels is ethanol from sugarcane as produced in Brazil, followed by ethanol from corn in the United States (including coproduct revenues), molasses in Thailand, sugar beet in Europe (including coproduct revenues), and cassava in Thailand, although the differences in these costs can be within the uncertainties of the various estimates. The higher cost production including coproducts is from wheat in the U.K. Significant projected cost reductions are shown for sugarcane and corn, and there is room for increased efficiency of all other routes.

Biodiesel production costs reach those of ethanol range for countries with higher productivity plants or lower cost base such as Indonesia/Malaysia and Brazil/Argentina. Next come the European countries and the United States. The projected 2022 EPA’s projected costs based on the use of the model FASOM to projected grain costs evolution are significantly lower than current and even corn oil from dry mill expansion into fractionation processes could lead to biodiesel. Similarly, 2030 costs for the OECD project cost reductions for rapeseed biodiesel.

A significant number of electricity generation routes are available and co-combustion (cofiring) is a relatively high efficiency process for use of solid biomass fuel products compared to direct combustion at medium to large sizes. Small plants provide usually heat and electricity at a higher production cost than the larger systems although that varies somewhat with location (see India’s example for small scale application of gasifier/engines) compared to a higher efficiency Japanese case. Heat and power systems are available in a variety of sizes and with high efficiency. The reductions of GHG emissions from these systems is usually very high – in the high 90% (see Section 2.5) compared to the fossil fuel replaced.

Small systems have been improving in efficiency from cooking stoves to small gasifier systems and also in anaerobic digestion systems. Several European countries are advancing mixed solid biomass, food, and manures digestion systems and are obtaining high quality methane from upgrading. Many applications, including transportation systems, are developing and have the potential to further increase their effectiveness. Similarly, at the low scale, the primary use is for lighting and heating of cleaner stoves. These applications too have significant room to improve.

Technologies for the use of biomass for the existing commercial applications are mature but many have room for significant improvement. They provide direct climate change benefits as shown by the GHG emissions reductions compared to the fossil baseline for that particular application principally with a lower fossil carbon source as primary energy.

To illustrate the technological progress ethanol production in Brazil and North America over time, Table 2.3.4 shows the chains' performance including feedstocks, conversion processes, and fuel use in terms of GHG emissions for the full lifecycles. Major variables are feedstock mass, overall fossil energy consumed, produced (heat and power) in the case of Brazil, energy delivered per unit of land used or volume of fuel delivered. Also shown are impacts of bagasse to ethanol as a source of additional ethanol while maintaining the ability of the mills to generate electricity as well, as more field residues are collected through mechanical harvesting. Finally, the table also illustrates the evolution of other routes such as carbon sequestration coupled with these chains (see Section 2.5 for additional details).

North American corn ethanol emissions relative to gasoline (2005) reached the GHG emissions savings per unit biofuel energy is 37% for an individual plant; the average North American natural gas industry is at 34-35% (Plevin, 2009) having evolved from about 18% (Farrell et al., 2006). Sugarcane, a perennial plant harvested every 5-6 years, has a higher GHG performance relative to gasoline, of 86% in 2005/2006. The emissions savings increases by a factor of nearly four per hectare of land going from the annual to the perennial (5-6 year rotation). Technology improvements increased use of field residues from mechanical harvest for electricity or for additional fuel production could increase emissions savings in both cases by factors of two to three. However, the amount of fuel per hectare is half for the annual crop compared to the perennial plant in 2005 and also in the projections shown where biomass productivity increases in both cases.

Table 2.3.3. Biomass-derived Energy Products used in the Global Economy

Transport Fuels: Ethanol

Feedstock	Major Process	Country	Efficiency and process economics Eff. = Energy Product energy/Biomass Energy	Estimated Production Cost 2005 US$/GJ	% GHG reduction from fossil reference	2030 Efficiency and Economics Potential Technical Advances
Sugarcane	Pressed, washed, and separated into a syrup and solid residue, bagasse, combusted in boilers for process heat and power (CHP). Sugar solution (sucrose) fermented by yeasts to ethanol recovered by distillation. The hydrous fraction sold as neat ethanol (6 wt% water). Further drying with molecular sieves or cyclohexane azeotropic distillation makes anhydrous ethanol for blending with gasoline. Excess electricity is already sold to the grid.	Brazil	Eff. = 0.38[1]; 0.41[2] (only ethanol production). Mill size (170 million),[2] advanced power generation and optimised energy efficiency and distillation can reduce costs further in the longer term/surplus electricity, 50kWh/t sugar cane	10 to 15[1] 14[2] w/ coproduct revenue (CR)	86 [24]	Projected 2030 US$ 9 to 10/GJ[1]. Projected 2020 Eff. = 0.50.[3] Biological Carbon Capture and Storage (BCCS) from sugar fermentation. Efficient use of sugar cane straw and leaves as an extra source of heat & power through mechanized harvest.[5] Widespread use of GMO. Evolution of the biorefinery approach with multiple products.[6] Improved yeasts.
			250 Mi l/yr plant, feedstock costs at $7.7/GJ, conversion costs (including capex + opex) at $7/GJ without co-products revenue.	14.7[4] no CR		
Corn grain	Grain soaked in dilute sulfurous acid; resulting slurry ground to separate the germ (for corn oil food or biodiesel) from the fiber (for food/feed), gluten (protein), and starch components which are further separated and upgraded into various products such as high fructose corn syrup. Starch solution is hydrolyzed to glucose and fermented by yeasts to ethanol.	USA	Eff. = 0.56[7,8] wet milling; 11 plants, 11% production; Average size: 600 million l (up to 1000 million l).[3]	20[9] 2005/2006 net production cost; 15.9[9] 2006/2007	15 [23]	Projected Eff.=0.62[3] BCCS from sugar fermentation Membrane separation for ethanol separation. Incorporation of CHP including sales of power to the grid . Widespread use of GMO for increased yields with lower inputs.[3]
	Whole grain hammer milled into course flour and cooked to form a slurry hydrolyzed with alpha amylase enzymes forming dextrins, followed by cooking with gluco-amylase to sugars and fermentation by yeasts. Last two processes can be combined. 35.4d w/o coproduct revenue		Dry Mill only Eff. = 0.62 (150 plants; 88% production). Production cost estimated used 170 million l/yr.[2,11] Dry milling technical progress leading to more co-products. 30% coproduct feed DDGS sold wet.[3] 250 Mi l/y plant, feedstock costs at $29.4/GJ, conversion costs (including capex + opex) at $6/GJ without co-products revenue.[4]	20[2]-21[11] w/ CR 17.5 [3] w/CR 35.4 [4] no CR	35-56 Depending on co-product credit method[25]	2020 Projected US$ 18/GJ[12] with $6/GJ capex/opex. 2020 Eff. = 0.64 [4]; industry Eff.=0.65-0.68[4] with projected 2020 $16/GJ; FASOM modeled cost used.[3] BCCS. Low temperature starch enzyme hydrolysis and fermentation. Corn dry fractionation and corn oil to biodiesel production in 90% mills. Membrane separation and CHP. Increase % wet feed sold.[4]
	Only three corn ethanol plants continue to operate with corn. Operated for years with distressed corn unfit for animal consumption	China	Estimated cost (60% is feedstock cost) includes subsidy which is 8.9% of gasoline price[12]	26-30[13]	-42 [26]	Process and energy efficiency improvements

Transportation Fuels: Ethanol Continued

Feedstock	**Major Process**	**Country**	**Efficiency and process economics** Eff. = Energy Product energy/Biomass Energy	**Estimated Production Cost 2005 US$/GJ**	**% GHG reduction from fossil reference**	**2030 Efficiency and Economics** **Potential Technical Advances**
Sugar beet	Sugar beet is crushed and then soluble sugars are extracted by washing through with water. Yeast is added and fermentation and ethanol recovered by distillation.	EU	Eff. = 0.12.[1] 250 Mi l/y plant, feedstock costs at $21.6/GJ, conversion costs (including capex + opex) at $11/GJ with co-products revenue $8.2/GJ (UK costs).[4]	24.4[4] w/ CR	32-65 Alternate co-product use[27]	2020 Eff. = 0.15[1]
Wheat	Process similar to that described for corn dry milling starting with the malting. Either enzyme or acid hydrolysis can lead to sugars for fermentation	EU	Eff. = 0.53 to 0.59[14, 15, 6] IEA, 2002 NDDC 2002. 250 Mi l/y plant, feedstock costs at $36.2/GJ, conversion costs (including capex + opex) at $10.5/GJ and $6/GJ co-products revenue for UK.[4]	40.7[4] w/ CR (UK)	40% DDGS to energy[27]	2020 Eff.=0.64[4]
Cassava	High starch content tuber mashed, cooked and fermented in a simultaneous saccharification and fermentation, followed by ethanol distillation.	Thailand, China	China plant of 200 thousand tonnes of ethanol which is operating at partial capacity.[13] Thailand's process described by Nguyen[15] produces about 10 Mi Gal,[17 ,18] productivity 20-25 tonnes/ha, highest in world.	26[4] Thailand estimate	45 [28]	Production expected to continue to increase in Thailand and become more important than molasses
Molasses	By product of sugar separation from the cooking liquor. Contains glucose and fructose from sucrose decomposition	India, Colombia, Thailand	By product utilization; about 3 % molasses could be used for ethanol in Thailand leading.	22[18] Thailand estimate	27-59 Depending on co-product credit method[29].	

Transport Fuels: Biodiesel

Feedstock	Major Process	Country	**Efficiency and process economics** Eff. = Energy Product energy/Biomass Energy	Estimated Production Cost 2005 US$/GJ	% GHG reduction from fossil reference	2030 Efficiency and Economics Potential Technical Advances
Rape seed	Vegetable oil extracted from seed is reacted with alcohol (usually methanol) to produce fatty acid methyl esters (FAME) in a base-catalyzed process, the most common process with high yields (>98%). Called biodiesel when it meets user country specifications. Alternative processes are direct acid catalyzed esterification of the oil with the alcohol or conversion of the oil to fatty acids, and then to alkyl esters with acid catalysis.	Germany	Eff. = 29%. For the total system it is assumed that surpluses of straw are used for power production[19]	31 to 50[1]	31 [30]	2030 Projected US $25 to $37/GJ[1] for OECD. US Projected 2020 soya biodiesel cost $20/GJ based on FASOM modeled feedstock cost.[3] US Projected 2020 waste oil cost $18/GJ.[3] New methods using bio-catalysts; Supercritical alcohol processing.[20] Heterogeneous catalysts or bicatalysts. New uses for glycerin.[21] Improved feedstock yields.
		France	55 GJ/ha/yr (EU). 220 Mi l/y plant, feedstock costs at $40.5/GJ, conversion costs (including capex + opex) at $2.7/GJ and $1.7/GJ co-products revenue.	41.4[4] w/ CR	75 [31]	
		UK	Same size plant, $35.2/GJ, conversion costs at $4.2/GJ and $11.3/GJ coproduct revenue	28.5[4] w/ CR	39-49 Alternate co-product use[27].	
Soya		USA	20 GJ/ha/yr. Same size plant, $100.6/GJ, conversion costs at $4.2/GJ and $55.6/GJ coproduct revenue	49.2[4] w/ CR	67-100 Depending on co-product credit method[32].	
		Brazil/ Argentina	Same size plant, $22.6/GJ, conversion costs at $2.7/GJ and $1.7/GJ coproduct revenue. Agrolink 2009 reports that ranges of production cost are $24-$34/GJ	23.5[4] w/ CR	NA	
Oil palm		Indonesia Malaysia	163 GJ/ha/yr. Same size plant, $25.1/GJ, conversion costs at $2.7/GJ and $1.7/GJ coproduct revenue	26.1[4] w/ CR	35-66 Alternate co-product use[33].	
Vegetable oils	Starting from the oils	109 countries	Based on total lipids exported costs. Neglects few countries with high production costs.[22] Oil at $0.48/l.[11]	7 to 30[22] 15.9[11] US 10.5[2]US trap grease	NA	

Abbreviations: capex=capital expenses; opex=operating expenses; CR = Coproduct Revenue; References

[1]IEA Bioenergy: ExCo,2007; [2]Tao, Aden 2009; [3]EPA 2010; [4]IEA Bioenergy: ExCo, 2009; [5]Seabra et al., 2008; [6]Seabra et al., 2010; [7]UK DFT 2009; [8]Hamelinck 2004; [9]F.O. Licht 2007; [10]Rendleman and Shapouri 2007; [11]Bain 2007; [12]Hettinga et al. 2009; [13]Qiu et al. 2010; [14]Reith, 2002;[15]IEA 2002; [16]Nguyen et al. 2008; [17]Koizumi 2008; [18]Milbrandt, Overend 2008; [19]CSIRO, 2000 [20]Egsgaard et al., 2009; [21]Bhojvaidad 2008 [22]Johnston, Holloway 2007; [23]Wang et al, 1999; [24]Macedo et al, 2008; [25]Wang et al., 2010; [26]Ou et al., 2009; [27]Edwards et al., 2008; [28]Nguyen et al., 2008; [29]Beer et al., 2001; [30]Reinhardt et al., 2006; [31]Ecobilan,2002: [32]Hou et al., 2009; [33]Wiche et al, 2008

Table 2.3.3. Biomass-derived Energy Products used in the Global Economy Continued

Power from Solid Biomass Fuels

Feedstock	Major Process	Country	Efficiency and process economics Eff. = Energy Product energy/Biomass Energy	Estimated Production Cost 2005 US$/GJ	% GHG reduction from fossil reference	2030 Efficiency and Economics Potential Technical Advances
Wood residue	Co-combustion with coal	Worldwide	Eff. ~ 0.35-0.4[1]. Production cost assumes biomass cost $3/GJ, discount rate of 10%. More than 50 power plants operated or carried experimental operation, from which 16 are operational using coal. More than 20 pulverised coal plants in operation.[2] Usually the operation requires subsidies[3]	4.2/GJ (0.05/kWh)[1]	10[14]	Reduce the cost of fuel, by improved pre-treatment, better characterisation and measurement methods.[10] Promising technology is torrefaction. The treatment yields a solid uniform product with lower moisture content and higher energy content compared to those in the biomass feedstock and make biomass very suitable for pulverized coal plants[3]
MSW			Eff. ~ 0.22, due low temperature steam to avoid corrosion[9]. Few coal-based plants cofire MSW, but at least 2 are in commercial operation[2,3].		NA	New CHP plant designs using MSW are expected to reach 28%-30% electrical efficiency, and above 85%-90% overall efficiency in CHP[9.] Working environment problems, caused by dust and micro-organisms, need further attention [10]
Wood log/Wood residue	Direct combustion	Worldwide	Plant size: 1–20 MWe[5]	4.2-10/GJ (0.05-12/kWh)[5]	96[15]	
			Plant size: 20-100 MWe. Eff.= 20 to 40%[1,13]. Investment cost = 3.000 –1900 US$/kW[1]. Well established technology, especially deployed[1.] According to most energy scenarios, global electricity production from biomass is projected to increase from its current 1.3% share (231 TWh/year) to 3%-5% by 2050 (~1400-1800 TWh/year).[7] Major variable is supply costs of biomass[1] in Scandinavia and North America; various advanced concepts using fluid bed technology giving high efficiency, low costs and high flexibility. Commercially deployed waste to energy (incineration) has higher capital costs and lower (average) efficiency. Overall energy delivered: 0.57 -0.74 EJ[5,4,12]	Worldwide: 4.2-10/GJ (0.05-12/kWh)[1,13] U.S.:[15] 7.5/GJ (0.09/kWh) Stoker: 7.5/GJ (0.09/kWh) 50 MW Fluidized Bed: 8.3/GJ (0.1/kWh)	97[16]	Worldwide: 2.1 - 6.7/GJ (US$0.021 - 0.096/kWh)[6] U.S. 2020 projections:[15] 6.3-7.8/GJ (0.076-0.092/kWh) Stoker: 7.5-8.1/GJ (0.091-0.096/kWh
Wood residues/Agricultural residues	Gasification for small scale application/gas engine	Worldwide	eff., 17%, India	4.5-6.3/GJ (0.054-0.076/kWh	NA	Reduce feedstock production price[10]
			eff., 20%, Japan; Assumptions: 1) Biomass cost $3/GJ; Discount rate 10%; 2) Heat value $5/GJ[9].	7.5/GJ (0.09/kWh)[9]	95[17]	

Briquettes	Drying /Mechanical compression	EU	Large and continuously increasing co-combustion market[10]		NA	Improve feedstock supply[10]
Wood pellets			Used in 2 operating power plants in cofiring with coal[2]		NA	http://www.pelletsatlas.info (EU price)

Power from Solid Biomass Fuels continued

Feedstock	Major Process	Country	Efficiency and process economics Eff. = Energy Product energy/Biomass Energy	Estimated Production Cost 2005 US$/GJ	% GHG reduction from fossil reference	2030 Efficiency and Economics Potential Technical Advances
Wood chips	Co-combustion with coal/ Direct combustion	EU	Used in at least 5 operating power plants in cofiring with coal.[2] Used in large scale direct combustion plants (150-300 MWe)[13]		9[18]	CAPEX 2000-3000 US$/kW[13]
Ag residues		EU	Straw used in at least 10 operating power plants in cofiring with coal[2.] Long-term storage of willow chips is very difficult due moisture content (55-58 %).[10]	$4.7/GJ[11]	9[19]	Concentration of chloride and potassium salts. Straw contains a lot of these salts, which can cause corrosion and slagging problems. The need to make power plants from corrosion-resistant materials has increased the cost of energy from straw, at least in Denmark[8]

[1]IEA Energy, 2007; [2]IEA Task 32, 2010; [3]IEA Bioenergy Task 32, 2009; [4]WEO, 2009; [5]REN21, 2007; [6]IEA BIOENERGY: EXCO: 2007:02; Helynen et al., 2002; [7]COMPETE, 2010; [8]Egsgaard et al, 2009; [9]IEA EnergyTechnology Essentials, 2007; [10]Econ Pöyry, 2008; [11]Hoogwijk, 2004; [12]IEA Balances, 2009; [13]IEA Task 32, 2009; [14]Pehnt, 2006; [15]Elsayed et al., 2003; [16]Forsberg, 2000; [17]Searcy and Flynn, 2008; [18]Styles and Jones, 2007; [19]Hartmann and Kaltschmitt, 1999; [20]NRC Electricity, 2009.

Table 2.3.3. Biomass-derived Energy Products used in the Global Economy Continued

Heat from Solid Biomass Fuels

Feed-stock	Major Process	Country	Efficiency and process economics Eff. = Energy Product energy/Biomass Energy	Estimated Production Cost 2005 US$/GJ	% GHG reduction from fossil reference	2030 Efficiency and Economics Potential Technical Advances
Fuelwood	Combustion for residential use (cooking and 5-50 kWhth heating)[z]	Mostly in Developing countries	Eff.= 10-20%[1]. Of the 45 EJ of biomass supplied to the global primary energy mix in 2006, an estimated 39 EJ (i.e. 87%) is burnt in traditional stoves for domestic heating and cooking primarily in developing countries[4,5.] Traditional devices are inefficient and generate indoor pollution. Improved	Costs are extremely variable (from 0 monetary costs when fuelwood is collected to 8 GJ or more when fuelwood is scarce)	1-2 tCO2e/yr for the simplest improved stoves 3-9 tCO2e/yr for the advanced systems (see section	Improved cookstoves are presently available/reduce fuel use (up to 60%)/cut 70% indoor pollution. Optimized design of cookstoves and new materials, gasifier stoves for household use. Combined heat/electric. Production already in demonstration. New stoves with 35-50% efficiency.[15] Indoor air pollution reduced more than 90%. Replacement by modern heating systems (i.e., automated, flue gas cleaning, pellet firing) in e.g., Austria, Sweden, Germany

			cookstoves are available that reduce fuel use (up to 60%) and cut 70% indoor pollution. About 2.5 EJ usable energy generated.		2.5)	ongoing for years[1].

Heat from Solid Biomass Fuels Continued

Feed-stock	Major Process	Country	Efficiency and process economics Eff. = Energy Product energy/Biomass Energy	Estimated Production Cost 2005 US$/GJ	% GHG reduction from fossil reference	2030 Efficiency and Economics Potential Technical Advances
Fuelwood	Combustion for small scale industries and few large scale industries (1-20 MWth)[2]	Mostly in Developing countries	Eff.= Up to 70-90% for modern furnaces[1]. Existing industries have low efficiency kilns that are also high polluting. Improved kilns are available that cut consumption in 50-60%. Total 1 to 6 EJ generated[2]	Costs are extremely variable (from 0 monetary costs when fuelwood is collected to $8/ GJ or more when fuelwood is scarce)	NA	1.2 to 5.9 US$/GJ[1] Improved kilns cut consumption in 50-60%. There are very large cobenefits of improved technologies in terms of public health and environment.
Fuelwood	Pyrolysis for charcoal production mainly in small-scale industrial activities	Mostly in Developing countries	Wood in smaller pieces is easier to dry in the air and hence the yield in carbonising is higher and is also required for the mechanised feeding systems used in most industrial type carbonising processes. Generally any industrial system adopted must face quite large wood preparation costs[10]	Ranges from US$6.3/GJ for brick kiln to US$7.6/GJ for continuous retort assuming US$23/t wood; US$ 9.6/GJ using continuous retort and forestry residues at US$7.0/tonne[10]	NA	One of the most important steps forward in the production of charcoal is the use of continuous carbonisers[10]. By causing the raw material wood to pass in sequence through a series of zones were carbonisation are carried out it is possible to introduce economies in use of labour and heat[10]. Recovery of the heat from the top of the carboniser is achieved by burning the gas and vapours under controlled conditions in hot blast stoves[10]. Use of liquids and gases from carbonization can yield valuable coproducts[10]. All these technologies available but poorly used in Developing Countries.
Wood residues/Agric. Wastes	Gasification	Mostly in Developing countries	Eff. 80-90%. Typically hundreds kWth[3]. Commercially available and deployed; but total contribution to energy production to date limited[3]. Investment: several hundred/ kWth, depending on capacityf. Example: $300-$800/kWhth	$0.009-0.048/kWh fuel[3]	NA	
Wood	Combustion	Worldwide	Processes are in demonstration for small-scale applications between 10 kW and 1 MWe using Stirling engines (SE), with Eff. = 11-20%[8] or Organic Rankine Cycle (ORC), with Eff.=10-14%[12]. Steam turbine based systems 1-10 MWe are widely deployed throughout the	$0.021-0.15/kWh electricity. High costs for small scale power gen. with high-quality feedstock. [9]Value of heat $03/kWh, value of electricity $0.10/kWh (2006) Low costs for large-	NA	Stirling engines with future Eff.=15 to 30%[12], steam screw type engines, steam engines, and organic rankine cycle (ORC) processes for small-scale applications between 10 kW and 1 MWe[6]. Mass production will reduce investment costs[12]
Wood residues	Combustion	Worldwide				

Briquettes	Combustion	Worldwide	world. Efficiency of conversion to electricity in the range of 30-35%[1]	scale (i.e., >100 MWth) state-of-art.[1,7,8,]		
Wood residues/Agric. Wastes	Gasification and gas engines	Worldwide	Effi. 15-30%(electrical); 60-80% (overall).[1] Various systems on the market[1]. Deployment limited due to relatively high costs, critical operational demands, and fuel quality[1]. Size 0.1 - 1.0 MWe[1]	Investment 1,180-3,550 US$/kW[1]	NA	

Heat from Solid Biomass Fuels Continued

Feed-stock	Major Process	Country	Efficiency and process economics Eff. = Energy Product energy/Biomass Energy	Estimated Production Cost 2005 US$/GJ	% GHG reduction from fossil reference	2030 Efficiency and Economics Potential Technical Advances
Sugar cane bagasse&waste	Combustion	Worldwide	limited use due to relatively abundance. Critical operational demand and fuel quality	About $0.058/kWh[11]	NA	Large potential availability either using high-pressure steam boilers or gasification. Concentration of chloride and potassium salts. Straw contains a lot of these salts, which can cause corrosion and slagging problems. The need to make power plants from corrosion-resistant materials has increased the cost of energy from straw, at least in Denmark[7]
Wood residues/Agric. Wastes	Pyrolysis for production of bio-oil	USA	Eff. 60-70% bio oil/feedstock and 85% for oil+char[1]. Commercial technology available. Bio-oil is used for power production in gas turbines, gas engines, for chemicals and precursors, direct production of transport fuels, as well as for transporting energy over longer distances[1].	$4-6/GJ of bio-oil[13,14] Scale and biomass supply dependent; capital cost $690 for 10 MWth[1]	NA	Cost: 10% – 100% more than fossil fuel. Availability: limited supplies for testing; Standards: lack of standards and inconsistent quality inhibits wider usage. Incompatibility with conventional fuels. Unfamiliarity of users. Dedicated fuel handling needed. Poor image[13]

[1]IEA Energy 2007 [2]REN21,2007 [3]IEA BIOENERGY: EXCO: 2007:02 [4]Third Periodic Activity Report, 2010 [5]IEA BIOENERGY ANNUAL REPORT 2009; [6]IEA Bioenergy: ExCo,2007 [7]Egsgaard et al, 2009 [8]IEA Energy Technology Essentials, 2007 [9]Hoogwijk, 2004 [10]FAO, 1985 [11]EPE, 2008l [12]Ragossnig, 2008 [13]Bain, 2004 [14]Bridgewater, 2003; [15]Mukunda et al, 2010; [16]NRC electricity, 2009

Table 2.3.3. Biomass-derived Energy Products used in the Global Economy Continued
Solid Biomass Fuel Products for Energy

Feedstock	Major Process	Country	Comments Eff. = literature energy product energy/biomass energy	Estimated Production Cost 2005 US$/GJ	% GHG reduction from fossil reference	2030 Efficiency and Economics Potential Technical Advances

Pellets	Combustion for heating houses and combustion under co-firing for electricity	EU	Lower prices are for wholesale to industrial and power plant use as cofiring. Higher price for bagged or packet used in residential market[1]. The production capacity in all EU 27 states is estimated at about 9 million tonnes (2007). Globally it might be as much as 12–14 million tonnes capacity[3]	FOB Brazil 0.6-1.4; FOB Brazil 2.2;FOB Canada 3.2; Netherland 6.2; Norway 12.3; UK 6.1[2]	NA	1. Removal of indirect trade barriers for import in certain areas of Europe. 2. Establish common standard for pellets. Some countries in Europe have pellet standards, some have none, and even those that have are different. 3. Freight costs reduction due market increase[2]

[1]E4Tech,2010 [2]Junginger et al, 2008 [3]Renewable Energy World, 2010

Table 2.3.3. Biomass-derived Energy Products used in the Global Economy Continued

Heat, Power or Transport Fuel from Animal Manures (AM), Organic Wastes (OW - includes municipal), Agricultural or Wood Residues (AR, WR)

Feedstock	Major Process	Country	Comments Eff. = literature energy product energy/biomass energy	Estimated Production Cost 2005 US$/GJ	% GHG reduction from fossil reference	2030 Efficiency and Economics Potential Technical Advances
OW/MSW	Landfill with methane recovery	Worldwide	Eff. 10-15%[1].Widely applied for electricity generation and, in general, part of waste treatment policies of many countries[1]		89[6]	Large expectation for further use. In some European countries the biogas technology developed in the last years very impressive (Germany, Austria, Sweden). In Europe it increased by 35% between 2004 and 2006[2].
OW/AR/AM	Anaerobic co-digestion, gas clean up, compression, and distribution	EU	In the city of Linkoping, Sweden, since 1999, a multiple waste streams plant produces methane upgraded to high quality to fuel in a local grid the rail commuter train and buses (slow fill).	13[4]	108[7] Heat & Power	Trend to large scale biogas installations, where the biogas is upgraded to bio-methane and injected into gas pipelines, as well as biogas as transport fuel[2].
		USA	By product credit not considered for fertilizer[3]	14[3]	NA	State of California study showing the potential for utilization of these residues and augmenting the natural gas distribution.
Manures	Household digestion	Worldwide	Cooking, heating and electricity applications. Use also human wastes. By product- liquid fertilizer.	1 to 2 years payback time	NA	Large reductions in costs by using geomembranes; improved designs and reduction in digestion times. Use of waste food and leafy material as input
Manures	Farms	Finland	Biogas from farms etc. 18-50kWe; Investment: 400-720 k$(2009)[5]	$0.28-0.29/kWh[5]	NA	Improved designs and reduction in digestion times. Improvements in the understanding of anaerobic digestion, metagenomics of complex consortia of microorganisms
Manures and food processing residues			Biogas from combined farm animal residues and food processing residues at 145-290kWe; Investment: 2200-3600k$ (2009) [5]	$0.25-0.32/kWh[5]	NA	

[1]IEA Energy, 2007; [2]Ragossnig, 2008; [3]Krich et al., 2005; [4]Sustainable Transportation Solutions, 2006; [5]Kuuva et al., 2009; [6]Norstrom et al., 2001; [7]Chevalier and Meunier, 2005

Table 2.3.4 Ethanol from Corn and Sugarcane Ethanol – Past and projected carbon mitigation potential

Indicators/	**Corn Ethanol - North America, Natural Gas**	**Sugarcane Ethanol - Brazil**
Biomass type kg GHG savings per tonne of biomass feedstock or waste (absolute values)	Company Data 1995 **330** 2005 **440** 2015 Projection (a) CHP **560** (b) CHP + CCS **930** CHP = combined heat and power CCS = carbon capture and storage from fermentation	Industry Data Cases based on dry cane stalk (70% wet) 2002 (specific mill) **735** 2005/2006(44 mills) **530** 2020 Mechanical Harvest Scenarios (a) w/8x 2005/6 electricity proj. **775; +CCS 1050** (b) w/3x 2005/6 electricity and 40% more than 2005/6 ethanol (from bagasse) proj. **860; + CCS 1210**
Bioenergy output and fossil energy use in processing expressed in kg GHG per unit output (GJ - LHV basis) and (Primary fossil energy - renewable credit/ biofuel energy output)	1995 **64 (0.9)** 2005 **54 (0.7)** 2015 (a) proj **0.1 (0.5)** 2015 (b) proj **12 (0.6)**	2002 115 (0.04) 2005/2006 80 (-0.02) 2020(a) proj. 115 (-0.4) 2020(b) proj. 90 (-0.04)
Biomass and process productivity -- land use in kg GHG savings by biomass production per ha of available land and (thousand liters/ha)	1995 **2600 (3.0)** 2005 **3900 (3.5)** 2015 (a) proj **6400 (4.5)** 2015 (b) proj **10600 (4.5)**	Calculated per harvested ha 2002 **18000 (7.1)** 2005/2006 **14000 (7.5)** 2020 (a)proj. **22000 (8.8)** 2020(b)proj. **25000 (12)**
	(S&T)2 Consultants Inc., 2009	Macedo et al., 2004; Macedo, Seabra, 2008; Molersten et al., 2003

2.4 Global and Regional Status of Market and Industry Development

2.4.1 Current bioenergy production and outlook[2]

Biomass is the most important renewable energy source, providing about 10% (48 EJ) of the annual global primary energy demand. A major part of this biomass (38 EJ) is used locally in rural areas and relates to charcoal, wood, agricultural residues, and manure used for cooking, lighting, and space heating, generally by the poorer part of the population in developing countries. Modern bioenergy use (for industry, power generation, or transport fuels) is making already a significant contribution of 10 EJ and this share is growing. Today, biomass (mainly wood) contributes some 10% to the world primary energy mix, and is still by far the most widely used renewable energy source (Figure 2.4.1).

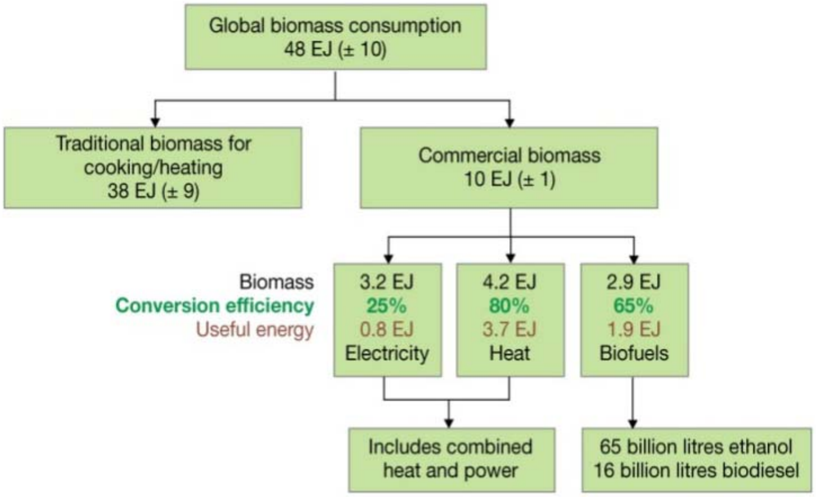

Figure 2.4.1. Global biomass consumption for bioenergy and biofuels in 2008. Source: based on IEA 2009 update of 2007

One of the fastest-growing applications of biomass is the production of biofuels based on agricultural crops – current global biofuels preliminary supply estimates at 1.9 EJ (2008) or about 2% of transportation fuel, a significant growth from 1.43 EJ in 2007. Most of the increase in the use of biofuels in 2007 and 2008 occurred in the OECD, mainly in North America and Europe. There is currently an excess of installed capacity and underutilization of facilities, more in biodiesel than in ethanol, but Asia Pacific and Latin American markets are growing, primarily in developing countries for economic development. The recent surge in biofuels production is not expected to continue in the near term. This depends largely on the continuation of blending mandates in OECD countries, oil prices, and the overall global economy.

Despite this anticipated short term downturn, world use of biofuels is projected to recover from 2015 and in the longer term. According to the 2009 World Energy Outlook scenarios, biofuels may contribute 5.7 to 11.6 EJ to the global transport fuel demand, thus meet about 5% to 11% of total world road-transport energy demand, up from about 2% today (IEA, 2009). In the 450

Scenario, biomass consumption also increases and in 2030 is 14.7 EJ higher than in the Reference Scenario. The use of biomass in CHP and in electricity-only power plants increases by 67% by 2030, to 7.2 EJ above the level in the Reference Scenario. Major increases in global biofuels production are seen in the 450 Scenario (to meet the CO2 intensity standards set by international

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[2] This section is largely based on the World Energy Outlook 2009 (IEA, 2009) and Global Biofuels Center Assessments (GBC 2010).

sectoral agreements), with consumption in 2030 reaching 11.6 EJ, more than double that in the Reference Scenario. The last decade of the projection period sees a strong increase in the production of lignocellulosic biofuels. Regions that currently have strong policy support for biofuels take the largest share of the eight-fold increase over the Outlook period, led by the United States (where one third of the increase occurs) and followed by the European Union, Brazil and China. To highlight the scale of the challenge, the 7 EJ of biofuels required in 2030 in the 450 Scenario is greater than India's current oil consumption and is derived from the advanced technologies discussed in Section 2.6 which are at various stages of development. To achieve this would require accelerated research and development efforts, operational demonstration plants in the next few years, and significant public and private investment.

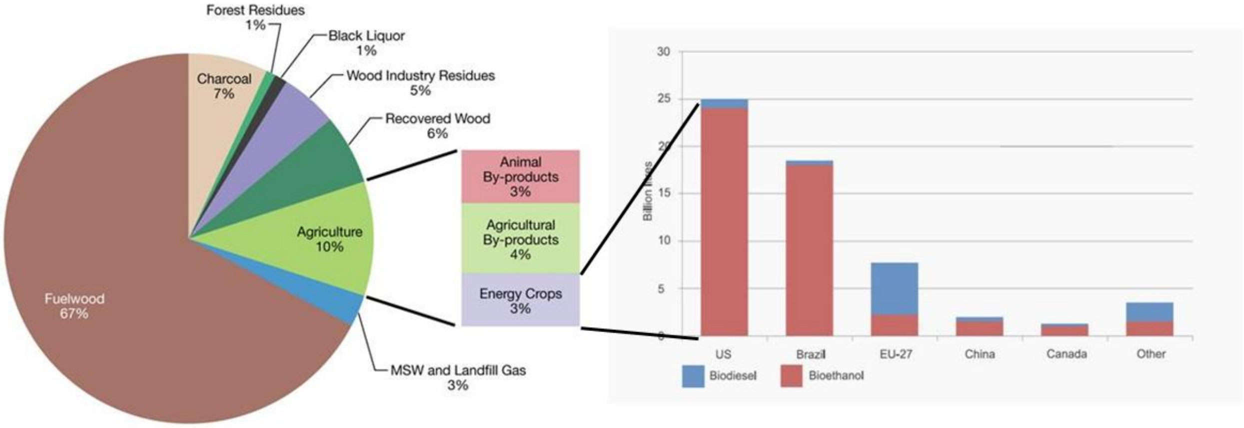


Figure 2.4.2. Share of the biomass sources in the primary bioenergy mix. Source: Bauen et al. (2009c), based on data from IPCC, 2007 and end-use energy built in major biofuel producers in 2007 (in billion litres). Actually, energy crops provide, on top of the biofuels shown, electricity and heat not properly quantified. Source: Prepared by authors based in Bauen et al. (2009c), Lichts, 2007 and national sources.

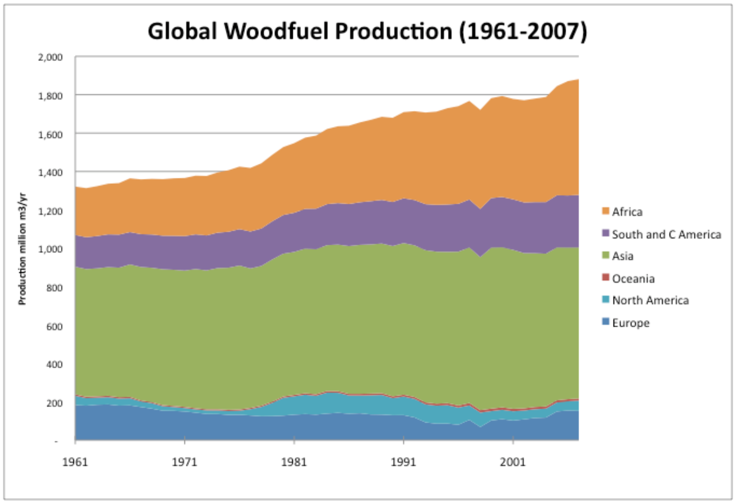


Figure 2.4.3 The evolution of global fuelwood production in the period 1961-2007 Source: FAOSTAT 2009

Figure 2.4.2 provides an overview of the biomass sources in the primary bioenergy mix, illustrating the importance of fuelwood. The WEO-2009 scenarios foresee that the transition towards modern fuels for cooking and heating and technologies drives down demand for traditional biomass in developing countries, but it is still possible that the absolute amount consumed may still grow with increasing world population. However, there is significant scope to improve efficiency and environmental performance, which will reduce biomass consumption and related impacts (Bauen et al. 2009c).

The use of solid biomass for electricity production is important, especially from pulp and paper plants and sugar mills. Bioenergy's share in total energy consumption is increasing in the G8 Countries (e.g. co-combustion for electricity generation, buildings heating with pellets), especially in Germany, Italy and the United Kingdom.

2.4.2 Traditional Biomass, Improved Technologies and Practices, and Barriers

While bioenergy represents a mere 3% of primary energy in industrialised countries, it accounts for 22% of the energy mix in developing countries, where it contributes largely to domestic heating and cooking, mostly in low efficiency cooking stoves. An estimated 2.5 billion people depend on biomass primary energy for cooking (IEA WEO 2009). Most developing countries initiated some type of improved cooking stove (ICS) since the 1980s and many are in operation as shown in Figure 2.4.3, sponsored by development agencies, governments, NGOs, and the private sector. China had the major initial success with 250 million improved cookstoves installed. Other countries were not as successful, but programmes of the past 10 years led to a new generation of advanced biomass-based cookstoves, dissemination approaches, and innovation. An estimated 820 million people in the world are currently using some type of improved cookstove for cooking (WHO, 2009). The new generation of cookstoves shows clear reductions in biomass fuel use, indoor air pollution, and also mitigation of GHG emissions with regards to open fires (see Section 2.5). Technologies used include direct combustion, small scale gasification, and small scale anaerobic digestion, or direct use of a liquid fuel (ethanol) discussed in Section 2.3 or combinations of technologies.

In general, successful stoves programs are those that included: a) a proper diagnose of people´s needs, traditional cooking practices and devices, as well as the institutional setting; the undertaking of regional market surveys and studies on people´s preferences has been key in this area; b) technology innovation, many times with critical input from local users and artisans. Two main lines of technology development have been followed, mass-scale approaches that rely on centralized production of stoves or critical components, with distribution channels that can even include different countries (e.g., Stovetec and Envirofit); a second approach relies more on strengthening regional capabilites, giving more emphasis to local employment creation, sometimes the stoves are built on site rather than sold on markets, such as the Patsari Stove in Mexico, GERES in Cambodia; c) the use of financial mechanisms and incentives to facilitate the dissemination of the stoves. The incentives given are very diverse and can be directed to stove's producers to lower production costs, to end-users in the form of microfinance schemes or subsidies, and other forms. Carbon offset projects are increasingly entering as a major source of stove financing in particular regions; d) an enabling institutional environment, largely facilitated by Governments (as in the case of the Chinese cookstove program); and e) the accurate monitoring and evaluation (M&E) of impacts from the new stoves. Programs with good M&E activities have been able to detect problems early on in the dissemination phase and make changes accordingly.

Drivers for increased adoption of improved cookstoves have included cooking environments where smoke caused health problems and annoyance; a short consumer payback (few months) donor or government support extended over at least five years and designed to build local institutions and develop local expertise. Government assistance has been more effective in technical advice, and quality control.

Convenient cooking and lighting are also provided by biogas production with household scale biodigestors, which reach today 25 million households, the majority in China and India (REN21

2009, REN/GTZ/BMZ 2008). China and India, for example, are promoting biogas on a large scale, and there is significant experience of commercial biogas use in Nepal (Hu, 2006; Rai, 2006; India, 2006). Early stage results have been mixed because of quality control and management problems, which have resulted in a large number of failures. Smaller scale biogas experience in Africa has been often disappointing at the household level as the capital cost, maintenance, and management support required have been higher than expected. Under subsistence agriculture, access to cattle dung and to water that must be mixed together with slurry has been more of an obstacle than expected. More actively managed livestock and where dung supply is abundant, as in rearing feedlot-based livestock, would facilitate technology adoption. (Hedon Household Network, 2006)

Experience of NGOs that are members of the Integrated Sustainable Energy and Ecological Development Association (INSEDA) for the last two decades in the transfer, capacity building, extension and adoption of household biogas plants in rural India has shown that for successful implementations of biogas and other RET programmes in the developing countries, the important role of NGOs networks/associations needs to be recognized. These may provide funding and support under the Clean Development Mechanism (CDM) in the implementation of household biogas programmes in target regions through north-south partnerships in which both groups gain.

Legal barriers to increased biogas adoption include: lack of proper legal standards; insufficient economic mechanisms to achieve desired profits related to the investment costs, installations and equipments; relatively high costs of technologies and of labour (e.g. geological investigations to site installations). Many information barriers related to projects feasible for technical applications, installations producers, suppliers and contractors, and reliability and performance of the designs and construction of scale anaerobic digestion systems. Also there is limited application of knowledge gained from the operation of existing plants in the design of new plants.

2.4.2.1 Small-Scale Bioenergy Initiatives

Linkages between livelihoods and small-scale bioenergy initiatives were studied based on a series of 15 international case studies conducted between September and November 2008 in Latin America, Africa and Asia (Energy Research Programme Consortium, 2009). The cases were selected to highlight the use of a range of bioenergy resources (residues from existing agricultural, forestry or industrial activities; both liquid and solid energy crops) for cooking, mobility, productive uses and electricity. The approach taken also considers the non-energy by-products of production processes where these form, or could form, a significant added benefit in terms of livelihoods, revenues and efficiency. A summary of preliminary lessons and conclusions that are drawn from these case studies are summarised as follows (Practical Action Consulting, 2009):

- Natural resource efficiency is possible in small-scale bioenergy initiatives
- Local and productive energy end-uses develop virtuous circles
- Where fossil energy prices dominate, partial substitution is an option (i.e., hybrid systems)
- Longer term planning and regulation plays a crucial role for the success of small-scale bioenergy

At the project level, important lessons include:

- Flexibility and diversity can reduce producer risk
- Collaboration in the market chain is key at start up
- Long local market chains spread out the benefits
- Adding value to feedstocks by processing them into modern fuels increases project viability

- Any new activity raising demand will raise prices, even those for wastes
- Cases do not appear to show local staple food security to be affected
- Small-scale bioenergy initiatives offer new choices in rural communities

In summary, if improved cooking stoves (ICS) and other advanced biomass systems for cooking that are currently entering the market energy and climate-change benefits could be significant. About 600 million households cook with solid biofuels worldwide. Assuming fuel savings from 30-60% (Jetter and Kariher, 2009; Berrueta et al 2008) and average energy use of 40 GJ/HH/yr for cooking with open fires, the technical energy mitigation potential ranges from 10-17 EJ/yr (GEA, 2010). The reduction in fuelwood and charcoal use from the adoption of ICS will help reduce the pressure on forest and agriculture areas, with major benefits in terms of increasing aboveground biomass stocks, soil and biodiversity conservation (Ravindranath et al, 2006; Röther et al., 2010).

2.4.3 Global Trade in Biomass and Bioenergy

Global trade in biomass feedstocks (e.g. wood chips, vegetable oils and agricultural residues) and especially of processed bioenergy carriers (e.g. ethanol, biodiesel, wood pellets) is growing rapidly. Present estimates indicate that bioenergy trade is modest – around 1 EJ (about 2% of current bioenergy use) (Junginger et al. 2009). In the longer term, much larger quantities of these products might be traded internationally, with Latin America and Sub-Saharan Africa as potential net exporters and North America, Europe and Asia foreseen as net importers (Heinimö and Junginger, 2009). Trade will be an important component of the sustained growth of the bioenergy sector.

Table 2.4.1: Overview of global production and trade of the major biomass commodities in 2008. Source: Junginger et al. (2010 forthcoming)

	Bioethanol [b]	Biodiesel [c]	Wood pellets [d]
Global production in 2008 (million tonnes)	52.9	10.6	11.5
Global net trade in 2008 (million tonnes)[a]	3.72	2.92	Approx. 4
Main exporters	Brazil	USA, Argentina, Indonesia, Malaysia	Canada, USA, Baltic Countries, Finland, Russia
Main importers	USA, Japan, European Union	European Union	Belgium, Netherlands, Sweden, Italy

a. While biodiesel and wood pellets are almost exclusively traded as an energy carrier, bioethanol may also be used of in other end-uses. Approximately 75% of the traded bioethanol is used as transport fuel.
b. Based on FAPRI (2009), EurObserv'ER (2009) and Martinot and Sawin (2009)
c. Based on FAPRI (2009), Martinot and Sawin (2009), CARD (2008) and EurObserv'ER (2009)
d. Based on Sikkema et al. (2009), Bradley et al. (2009) and Spelter and Toth (2009).

In 2008, the two leading *ethanol* producers were the United States (26.8 million tonnes) and Brazil (21.3 million tonnes), accounting for 91% of the world production (FAPRI, 2009). The US is the largest bioethanol consumer: about 28.4 million tonnes in 2008, of which about 4.6% was imported. Brazilian consumption amounted to approximately 16.5 million tonnes. In the EU, total consumption for transportation was 2.6 million tonnes, the largest users being France, Germany, Sweden and The Netherlands (EurObserv'ER, 2009). Data related to fuel bioethanol trade are imprecise on account of the various potential end-uses of ethanol (i.e. fuel, industrial, and beverage use) and also because of the lack of proper codes for biofuels in the Harmonized System.

World *biodiesel* production increased six-fold from about 1.8 million tonnes in 2004 to about 10.6 million tonnes in 2008 (Martinot and Sawin, 2009). The EU produces about two-thirds of this, with

Germany, France, Italy and Spain being the top EU producers. European biodiesel production rose to 7.8 million tonnes in 2008, equivalent to a 35.7% increase compared to 2007 and 2008. However, EU production declined 7% in 2009 because of strong competition from abroad (FAPRI, 2009). Other main biodiesel producers include the United States, Argentina, and Brazil. Biodiesel consumption in the EU amounted to about 9.2 million tonnes (EurObserv'ER, 2009), with Germany alone consuming 2.9 million tonnes. International b*iodiesel trade h*as been increasing strongly since 2005 (EBB 2009c compared to net export about 1.175 million tonnes, FAPRI, 2009, EBB, 2009b).

Production, consumption and trade of *wood pellets* have grown strongly within the last decade. *Production* mainly takes place in Europe and North America. As a rough estimate, in 2008, about 8 million tonnes of pellets were produced in 30 European countries, compared to 1.8 million tonnes in the US and 1.4 million tonnes in Canada. *Consumption* is high in many EU countries and the US. The largest EU consumers are Sweden (1.8 million tonnes), Denmark, the Netherlands, Belgium, Germany and Italy (all roughly one million tonnes). The first intercontinental wood pellet *trade* has been reported in 1998, for a shipment from British Columbia (Canada) to Sweden. Since then, Canada has been a major exporter to Europe (especially Sweden, the Netherlands and Belgium) and to the US. In 2008, the US started to export wood pellets to Europe, while Canadian producers started to export to Japan. Total imports of wood pellets by European countries in 2009 were estimated to be about 3.4 million tonnes, of which about half of it can be assumed to be intra-EU trade. Total export is estimated at 2.7 million tonnes, predominantly intra –EU trade.

2.4.4 Overview of support policies for biomass and bioenergy

Typical examples of support policies for *liquid biofuels* include the Brazilian Proálcool program, the Common Agricultural Policy (CAP) in the EU, and several farm bills and state and federal incentives for ethanol production in the US (WWI, 2006). The majority of successful policies in biomass for *heat* in recent decades have focused on more centralised applications for heat or combined heat and power, in district heating, and industry (Bauen et al., 2009c). For these sectors, a combination of direct support schemes with indirect incentives has been successful in several countries, such as Sweden (Junginger, 2007). In the *power sector*, feed-in tariffs have gradually become the most popular incentive for bioenergy and for renewables in general. In contrast, quota systems have so far been less successful in getting renewables (and bioenergy) off the ground (van der Linden et al., 2005). Next to feed-in tariffs or quotas, almost all countries that have successfully stimulated bioenergy development have applied additional incentives relating to investment support, such as fiscal measures or soft loans (GBEP, 2007). Additionally, grid access for renewable power is an important issue that needs to be addressed. This can be a particular bottleneck for distributed, medium-scale technologies such as biogas-to-power. Priority grid access for renewables is applied in most countries where bioenergy technologies have been successfully deployed (Sawin, 2004).

The main drivers behind government support for the sector have been concerns over climate change and energy security as well as the desire to support the farm sector through increased demand for agricultural products (FAO, 2008). According to the REN21 global interactive map, a total of 69 countries had one or several biomass support policies in place in 2009 (REN21, 2010). These include Canada and the US, most Latin American countries, all EU countries, China, India, many South-East Asian countries, and Australia. On the other hand, in the Near- and Middle East and many African countries, no biomass support policies are currently implemented. The most dominant support policies are feed-in tariffs for electricity (in 41 countries) followed by biofuels blending mandates (29) as shown in Figures 2.4.5. Other instruments included hot water/heating policies (21), public investments, loans or financing (17), tradable renewable energy certificates (17), sales tax, energy excise tax or VAT exemption (16), capital subsidies, grants or rebates (13), investment tax credits (11), energy production payments / production tax credits (9) and public competitive bidding (7). In Table 2.4.2 an overview of current policies is listed for electricity, heat and transport fuels.

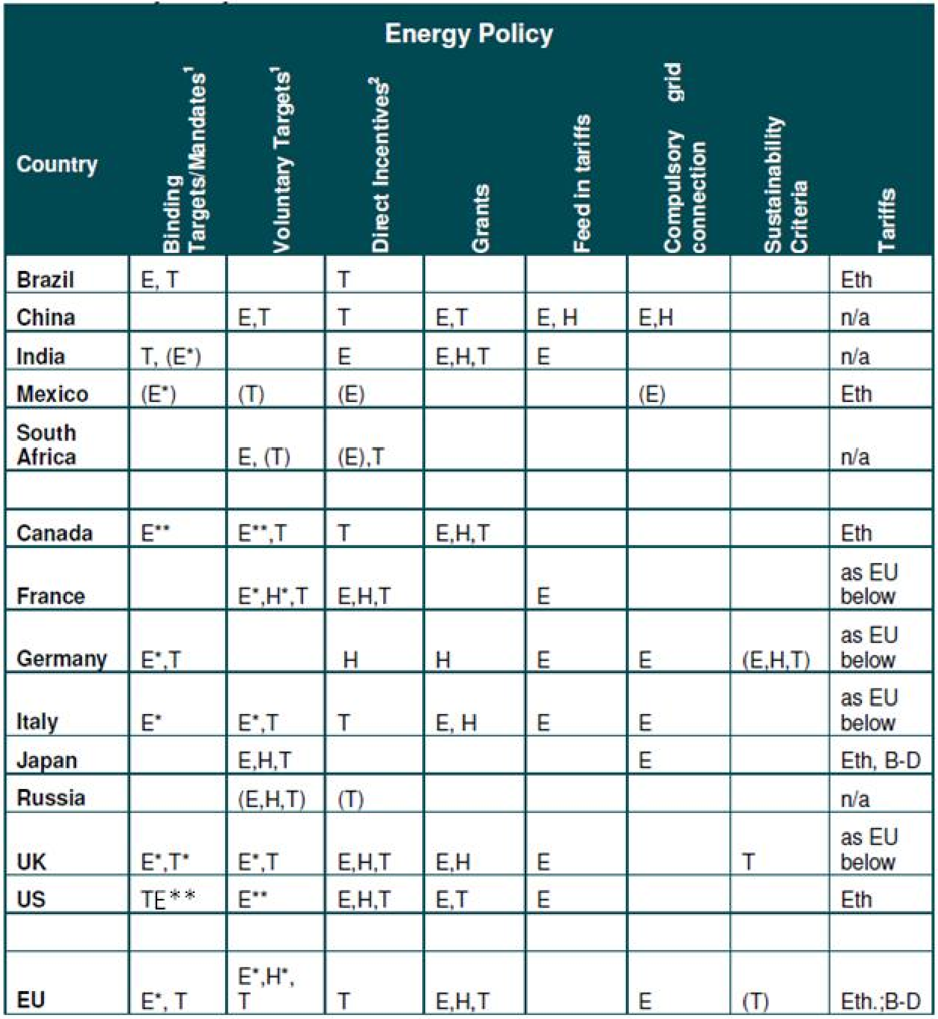
Feed-in tariffs¶

Biofuels blending mandates¶

Figure 2.4.6: Global overview of feed-in tariffs for electricity from biomass and biofuels blending mandates in place in 2009. Source: Ren21 (2010).

Support policies have strongly contributed in past decades to the growth of bioenergy for electricity, heat and transport fuels. However, several reports also point out the costs and risks associated with support policies for biofuels. As an estimate in 2006, about 11.3 billion US$ were spent on subsidies for liquid biofuels in OECD countries, of which the vast majority in the US (6.33 billion US$ driven by energy security and import fossil fuel reduction) and the EU (4.7 billion US$) (FAO, 2008). Concerns about food prices, greenhouse-gas emissions, and environmental impacts have also seen many countries rethinking biofuels blending targets. For example, Germany revised downwards its blending target for 2009 from 6.25% to 5.25% (IEA, 2009). Although seemingly effective in supporting domestic farmers, the effectiveness of biofuel policies in reaching the climate-change and energy security objectives is coming under increasing scrutiny. In most cases, these policies have been costly and have tended to introduce new distortions to already severely distorted and protected agricultural markets – at the domestic and global levels. This has not tended to favour an efficient international production pattern for biofuels and their feedstocks (FAO, 2008). On the other hand, energy and fossil fuels contribute to these distortions. These arguments are reiterated by a recent UNEP report (Bringezu et al., 2009), which warns that uncoordinated targets for renewables and biofuels without an overall biomass strategy may enhance competition for biomass. An overall biomass strategy would have to consider all types of use of food and non-food biomass (Bringezu et al., 2009).

Table 2.4.2 Key policy instruments in selected countries where E: electricity, H: heat, T: transport, Eth: ethanol, B-D: biodiesel (modified after GBEP 2007 and REN21 2010)



	Energy Policy							
Country	**Binding Targets/Mandates[1]**	**Voluntary Targets[1]**	**Direct Incentives[2]**	**Grants**	**Feed in tariffs**	**Compulsory grid connection**	**Sustainability Criteria**	**Tariffs**
Brazil	E, T		T					Eth
China		E,T	T	E,T	E, H	E,H		n/a
India	T, (E*)		E	E,H,T	E			n/a
Mexico	(E*)	(T)	(E)			(E)		Eth
South Africa		E, (T)	(E),T					n/a
Canada	E**	E**,T	T	E,H,T				Eth
France		E*,H*,T	E,H,T		E			as EU below
Germany	E*,T		H	H	E	E	(E,H,T)	as EU below
Italy	E*	E*,T	T	E, H	E	E		as EU below
Japan		E,H,T				E		Eth, B-D
Russia		(E,H,T)	(T)					n/a
UK	E*,T*	E*,T	E,H,T	E,H	E		T	as EU below
US	TE**	E**	E,H,T	E,T	E			Eth
EU	E*, T	E*,H*, T	T	E,H,T		E	(T)	Eth.;B-D

* target applies to all renewable energy sources

** target is set at a sub-national level

1. blending or market penetration

2. publicly financed incentives: tax reductions, subsidies, loan support/guarantees

2.4.4.1 Intergovernmental Platforms for Exchange on Bioenergy Policies and Standardization

Several multistakeholder initiatives exist in which policy makers can find advice, support, and the possibility to exchange experiences on policy making for bioenergy. Examples of such international organizations and fora supporting the further development of sustainability criteria and methodological frameworks for assessing GHG mitigation benefits of bioenergy include the Global Bioenergy Partnership (GBEP from the G8+5), the IEA Bioenergy, the International Bioenergy Platform at FAO (IBEP); the OECD Roundtable on Sustainable Development; and standardization organizations such as European Committee for Standardization (CEN) and the International Organization for Standardization (ISO) are active working toward the development of standards.

The Global Bioenergy Partnership (GBEP) provides a forum to inform the development of policy frameworks, promote sustainable biomass and bioenergy development, facilitate investments in bioenergy, promote project development and implementation, and foster R&D and commercial bioenergy activities. Membership includes individual countries, multilateral organizations, and associations (www.globalbioenergy.org).

The International Energy Agency (IEA) Bioenergy Agreement provides an umbrella organisation and structure for a collective effort in the field of bioenergy. It brings together policy makers, decision makers, and national experts from research, government and industry across the member countries. (www.ieabioenergy.com)

2.4.4.2 Sustainability frameworks and standards

Governments are stressing the importance of ensuring sufficient climate change mitigation and avoiding unacceptable negative effects of bioenergy as they implement regulating instruments. Examples include the new Directive on Renewable Energy in the EU (Directive 2009/28/EC); UK Renewable Transport Fuel Obligation; the German Biofuel Sustainability Ordinance; the U.S. Energy Independence and Security Act and the California Low Carbon Fuel Standard. The development of impact assessment frameworks and sustainability criteria involves significant challenges in relation to methodology and process development and harmonization.

As of a 2010 review, there are nearly 70 ongoing certification initiatives to safeguard the sustainability of bioenergy (van Dam et al., 2010 forthcoming). Most recent initiatives are focused on the sustainability of liquid biofuels including primarily environmental principles, although some of them such as the Council for Sustainable Biomass Production and the Better Sugarcane Initiative (BSI) include explicit socio-economic impacts of bioenergy production, and many others such as the Roundtable for Sustainable Biofuels (RSB) and the Roundtable for Responsible Soy, include social criteria as well. Principles such as those from the RSB have already led to a Biofuels Sustainability Scorecard used by the Interamerican Development Bank for the development of projects. The proliferation of standards that took place over the past three years, and continues, shows that certification has the potential to influence direct, local impacts related to environmental and social effects of direct bioenergy production. Many of the bodies involved conclude that for an efficient certification system there is a need for further harmonization, availability of reliable data, and linking indicators on a micro, meso and macro levels. Considering the multiple spatial scales, certification should be combined with additional measurements and tools on a regional, national and international level. The role of bioenergy production on indirect land use change (iLUC) is still very uncertain and current initiatives have rarely captured impacts from iLUC in their standards and the time scale becomes another important variable in assessing such changes (see Section 2.5). Addressing unwanted LUC requires first of all sustainable land use production and good governance, regardless of the end-use of the product or of the feedstocks.

2.4.5 Main opportunities and barriers for the market penetration and international trade of bioenergy

The main drivers behind the development of bioenergy in many OECD countries have been concerns over increasing and strongly fluctuating oil prices and consequent concerns regarding energy security and fuel diversification, climate change mitigation through a reduction in greenhouse gas emissions and a desire to support rural areas and promote rural development. To emphasize this point, global CPI deflated values of March 2008 compared to January of 1998, show an increase of nearly 500% for oil prices while food increased 36% and the non-food biomass raw materials (cotton, wool, timber, and leather) went down about 10% (Velasco, 2008). Additionally, the prospects for biofuels depend on developments in competing low-carbon and oil-reducing technologies for road transport (e.g., electric vehicles). Finally, biofuels may in the longer term be increasingly used within the aviation industry, for which high energy density carbon fuels are necessary (see Section 2.6).

However, major risks and barriers to deployment are found all along the bioenergy value chain and concern all final energy products (bioheat, biopower, and biofuel for transport)[3]. On the supply side, there are challenges in relation to securing quantity, quality, and price of biomass feedstock irrespective of the origin of the feedstock (energy crops, wastes, or residues). There are also technology challenges related to the varied physical properties and chemical composition of the biomass feedstock, and challenges associated with the poor economics of current power and biofuel technologies at small-scales. On the demand side, some of the key factors affecting bioenergy deployment are cost-competitiveness, stability and supportiveness of policy frameworks, and investors' confidence in the sector and its technologies, in particular to overcome financing challenges associated with demonstrating the reliable operation of new technologies at commercial scale. Some governments have jointly financed first-of-a-kind commercial technological development with the private sector in the past five years but the financial crisis is making it difficult to complete the private financing needed. In the power and heat sectors, competition with other renewable energy sources may also be an issue. Public acceptance and public perception are also critical factors in gaining support for energy crop production and bioenergy facilities.

As pointed out in section 2.4.3, international bioenergy trade is increasing rapidly. The development of truly international markets for bioenergy has become an essential driver to develop available biomass resources and bioenergy potentials, which are currently underutilised in many world regions. This is true for both (available) residues as well as possibilities for dedicated biomass production (through energy crops or multifunctional systems such as agro-forestry). The possibilities to export biomass-derived commodities for the world's energy market can provide a stable and reliable demand for rural communities in many (developing) countries, thus creating an important incentive and market access that is much needed in many areas in the world. The same is true for biomass users and importers that rely on a stable and reliable supply of biomass to enable (often very large) investments in infrastructure and conversion capacity. Fair trade concept and sustainability challenges need to be resolved before biomass reaches global markets as an energy commodity. Some of the issues have been listed below.

2.4.5.1 Opportunities and drivers for international bioenergy trade

1. Raw material/biomass push. These drivers are found in most countries with surplus of biomass resources. Ethanol export from Brazil and wood pellet export from Canada are examples of successful push strategies. These inexpensive resources may also become available due to (unexpected) economic events. For example, the recent decline of the US housing market led to low prices for wood products, which in turn triggered the establishment of very large pellet plants on the south-east coast of the US, using timbers as feedstock for pellet production dedicated for export to Europe.

2. Market pull. Import of wood pellets to countries such as the Netherlands and Belgium is facilitated by the very suitable structure of the leading large utility companies, making efficient transport and handling possible and low fuel costs.

3. Utilizing the established logistics of existing trade. Most of the bioenergy trade between countries in Northern Europe is conducted in integration with the trade in forest products. The most obvious example is bark, sawdust, and other residues from imported roundwood. However, other types of integration have also supported bio-energy trade, such as use of ports and storage facilities, organizational integration, and other factors that kept transaction costs low even in the initial

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[3] The remainder of this paragraph is taken from Bauen et al. (2009).

phases. Import of residues from food industries to the UK and the Netherlands are other examples in this field.

4. Effects of incentives and support institutions. The introduction of incentives based on political decisions is a driving force and triggered an expansion of bioenergy trade. However, the pattern has proved to be very different in the various cases, due partly to the nature of other factors, partly to the fact that the institutions related to the incentives are different. Institutions fostering general and free markets such as CO_2 taxes on fossil fuels appear to be more successful than specific and time-restricted support measures.

2.4.5.2 Barriers for international bioenergy trade

On the basis of literature review, a number of barriers for international bioenergy trade have been identified. Junginger et al. (2008, 2010) have listed the main barriers as follows:

1. Tariff barriers. Especially for ethanol and biodiesel, import tariffs apply in many countries. Tariffs are applied on bioethanol imports by both by EU (0.192 € per litre) and the US (0.1427 US$ per litre and an additional 2.5% ad valorem). In general, the most-favoured nation (MFN) tariffs range from roughly 6% to 50% on an ad valorem equivalent basis in the OECD, and up to 186% in the case of India (Steenblik, 2007). Biodiesel used to be subject to lower import tariffs than bioethanol, ranging from 0% in Switzerland to 6.5% in the EU and the USA. Tariffs applied by developing countries are generally between 14% (e.g., Brazil although Brazil lifted its tariff in 2010) and 50% (Steenblik, 2007). However, in July 2009, the European Commission confirmed a five-year temporary imposition of antidumping and anti-subsidy rights on American biodiesel imports, with fees standing between €213 and €409 per tonne (EurObserv'ER, 2009). These trade tariffs were a reaction to the so-called "splash-and –dash' practice, in which biodiesel blended with a 'splash' of fossil diesel was eligible for a $1/ gallon (equivalent to $300 per tonne).

2. Technical standards / Technical barriers to trade. Technical standards describe in detail the physical and chemical properties of fuels. Regulations pertaining to the technical characteristics of liquid transport fuels (including biofuels) exist in all countries. These have been established in large part to ensure the safety of the fuels and to protect consumers from buying fuels that could damage their vehicles' engines. Regulations include: maximum percentages of biofuels which can be blended with petroleum fuels; and regulations pertaining to the technical characteristics of the biofuels themselves. The latter may in the case of biodiesel depend on the vegetables oils used for the production, and thus might be used to favour biodiesel from domestic feedstocks over biodiesel from imported feedstocks. In practice, most market actors have indicated that they see technical standards as an opportunity enabling international trade rather than a barrier (Junginger et al., 2010; see also Section 2.4.7.8).

3. Sustainability criteria and certification systems for biomass and biofuels. In the past years, binding legislation on sustainability criteria for the production of biofuels was scarce. With the recent publication of sustainability criteria in the Renewable Energies Directive (RED) (European Commission, 2009) for liquid transport fuels, this situation has changed. The directive notably provides requirements for greenhouse gas emission reductions, the biofuels in question must not be produced from raw materials being derived from land of high value in terms of biological diversity or high carbon stocks. Also in the USA, the Renewable Fuel Standard (RFS) - included in the 2007 Energy Independence and Security Act (EISA) - provides provisions on the promotion of biofuels (especially cellulosic biofuels). EISA mandates minimum GHG reductions from renewable fuels, discourages use of food and feed crops as feedstock, permits use of cultivated land and discourages (indirect) land-use changes and sets thresholds for GHG reductions including major international land use change impact. Certification topics were discussed above. Regarding the development of sustainability criteria and certification systems, two major concerns in relation to international bioenergy trade may be distinguished:

1) Criteria, especially related to environmental and social issues, could be too stringent or inappropriate to local environmental and technological conditions in producing developing countries. The fear of many developing countries is that if the selected criteria are too strict or are based on the prevailing conditions in the countries setting up the certification schemes, only producers from those countries may be able to meet the criteria, thus these criteria may act as trade barriers. Recognizing this problem, the RSB is conducting pilot studies to assess the impact of such criteria for developing countries. Some view such criteria as a form of "green imperialism". As the criteria are extremely diverse, ranging from purely commercial aims to rainforest protection, there is a danger that a compromise could result in overly detailed rules that lead to compliance difficulties, or, on the other hand, in standards so general that they become meaningless. Implementing binding requirements is limited by WTO rules.

2) The second issue is the possible proliferation of different technical, environmental and social sustainability standards for biofuels production discussed above. With current developments by the European Commission, different European governments, several private sector initiatives, initiatives of round tables and NGO’s, there is a real risk that in the short term a multitude of different and partially incompatible systems will arise. If there are too many schemes in operation, each including a different set of requirements, then compliance, especially by small producers in developing countries, may become difficult. If they are not developed globally or with clear rules for mutual recognition, such a multitude of systems could potentially become a major barrier for international bioenergy trade instead of promoting the use of sustainable biofuels production. Additionally, lack of international systems may cause market distortions.

4. Logistical barriers. When setting up biomass fuel supply chains for large-scale biomass systems, logistics are a pivotal part of the system. Various studies have shown that long-distance international transport by ship is feasible in terms of energy use and transportation costs (e.g., Sikkema et al., 2010) but availability of suitable vessels and meteorological conditions (e.g., winter time in Scandinavia and Russia) need be considered. One of the problems of logistical barriers is a general lack of technically mature pre-treatment technologies in compacting biomass at low cost to facilitate transport, although technologies are developing (see Section 2.6).

5. Sanitary and phytosanitary (SPS) measures. Feedstocks for liquid biofuels may face sanitary and phytosanitary (SPS) measures or technical regulations applied at borders. SPS measures mainly affect feedstocks which, because of their biological origin, can carry pests or pathogens. One of the most common forms of SPS measure is a limit on pesticide residues. Meeting pesticide residue limits is usually not difficult, but on occasion has led to the rejection of imported shipments of crop products, especially from developing countries (Steenblik, 2007).

2.4.6 Final Remarks

The review of developments in biomass use, markets and policy shows that bioenergy has seen rapid developments over the past years. Bionergy use is growing, in particular biofuels (37% increase from 2006 to 2009). Projections from IEA, among others, but also many national targets count on biomass delivering substantially increase the share of renewable energy. International trade of biomass and biofuels has also become much more important over the recent years, with roughly 10% of all biofuels produced traded internationally and even a third of all pellet production for energy use (Junginger et al., 2010). The latter has proven to be an important facilitating factor in both increased utilisation of biomass in regions where supplies are constrained as well as mobilising resources from areas where demand is lacking. Nevertheless, many barriers remain in developing well working commodity trading of biomass and biofuels that at the same time meets sustainability criteria.

The policy context for bioenergy and in particular biofuels in many countries has changed rapidly and dramatically in recent years. The debate on food vs. fuel competition and the growing concerns about other conflicts haver resulted in a strong push for the development and implementation of sustainability criteria and frameworks as well as changes in temporization of targets for bioenergy and biofuels. Furthermore, the support for advanced biorefinery and second generation biofuel options does drive bioenergy to more sustainable directions.

Although this section did not evaluate the effectiveness of different policy strategies around bioenergy and biofuels, leading nations like Brazil, Sweden, Finland and the US, have shown that persistent policy and stable policy support is a key factor in building biomass production capacity and working markets, required infrastructure and conversion capacity that gets more competitive over time (see also section 2.7) and results in considerable economic activity.

Countries differ in their priorities, approaches, technology choices and support schemes for developing bioenergy further. Although on the one hand complex for the market, this is also a reflection of the many aspects that affect bioenergy deployment; agriculture and land-use, energy policy & security, rural development and environmental policies. Priorities, stage of development and physical potential and resource availability differ widely from country to country and for different settings.

One overall trend is though that policies surrounding bioenergy and biofuels become more holistic, taking sustainability demands as a starting point. This is true for the EU and the US, China, but also many developing countries such as Mozambique and Tanzania. This is a positive development, but by no means settled (see also section 2.5). The so far registered 70 initiatives worldwide to develop and implement sustainability frameworks and certification systems for bioenergy and biofuels lead to a fragmentation of efforts (van Dam et al., 2010). The need for harmonization and international collaboration and dialogue (e.g., via the Global Bioenergy Partnership) is widely stressed at present.

2.5 Environmental and Social Impacts[4]

Studies have recently highlighted environmental and socio-economic positive and negative effects associated with bioenergy. Land use changes related to agriculture and forestry play a major role in determining positive or negative outcomes (IPCC, 2000; MEA, 2005). Bioenergy can exacerbate negative impacts already of conventional agriculture and forestry systems, which include soil and vegetation degradation arising from overexploitation of forests, too intensive crop residue removal, water overexploitation, food commodity price volatility, and displacement of farmers lacking legal land ownership. But bioenergy can also lead to positive effects such as the environmental benefits derived from integrating different perennial grasses and woody crops into agricultural landscapes, including enhanced biodiversity (Baum et al., 2009; Schulz et al., 2009), soil carbon increase and improved soil productivity (Tilman, 2006; Baum et al., 2009b), reduced shallow landslides and local ‘flash floods’, reduced wind and water erosion and reduced volume of sediment and nutrients transported into river systems (Börjesson and Berndes, 2006). Forest residue harvesting improves forest site conditions for replanting, and thinning generally improves the growth and productivity of the remaining stand and can reduce wildfire risk. (Dymond et al., 2010).

Few universal conclusions of the socio-economic and environmental implications of bioenergy can currently be drawn, given the multitude of existing and rapidly evolving bioenergy sources,

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[4] As bioenergy is a part of the overall agriculture, forestry, and related systems, space restrictions prevent complete literature coverage of environmental and social aspects. Examples of key references may be applicable to many places in the text.

complexities of physical, chemical, and biological conversion processes to multiple energy products, and the variability in site specific environmental conditions. Factors determining merits and associated impacts are a function of the socio-economic and institutional context of biomass feedstocks and bioenergy production and utilization; types of lands used and feedstock types; the scale of bioenergy programs and production practices; conversion processes used including process energy; and the rate of implementation (see, for instance, The Royal Society, 2008; Firbank, 2008; Convention on Biodiversity, 2008; Gallagher, 2008; Howarth et al., 2009; Kartha, 2006; Purdon et al., 2009; Rowe et al., 2008; OECD, 2008; Pacca and Moreira, 2009).

Bioenergy system impact assessments (IAs) must be compared to the IAs of replaced systems – usually based on fossil fuels, but could be based on other primary energy sources (see Table 2.5.1). Methodologies for the assessments of environmental (Sections 2.5.2 and 2.5.3) and socio-economic (Section 2.5.4) effects differ. One particular challenge for socio-economic IAs is that their boundaries are difficult to quantify and are a complex composite of numerous, sometimes unknown, directly or indirectly interrelated factors, many of which are poorly understood. Social processes have feedbacks difficult to clearly recognize and project with an acceptable level of confidence. Environmental IAs manage many quantifiable impact categories but face lack of data and uncertainty in many areas. The outcome of environmental IAs depends on methodological choices – which are not yet standardized and uniformly applied throughout the world.

Table 2.5.1: Environmental and socio-economic impacts: example areas of concern with selected impact categories

Example areas of concern	Examples of Impact categories
Economic and occupational status	Displacement of population or relocation in response to employment opportunities; property values, distribution patterns of services
Social pattern or life style	Resettlement; rural depopulation; population density changes; food and material goods, housing; rural-urban; nomadic-settled
Social amenities and relationships including psychological features	Family life styles; schools; hospitals; transportation; participation-alienation; stability-disruption; freedom of choice; involvement; frustrations; commitment; local/national pride-regret
Physical amenities including. biodiversity and aesthetic features	Wildlife and national parks; aesthetic values of landscape; wilderness; vegetation and soil quality; local/regional air quality; water availability and quality; cultural buildings; sentimental values
Global/regional (off site) effects	Greenhouse gases; black carbon; albedo; acidification; eutrophication; hydrological changes
Health	Human Health changes; medical standard
Cultural, religion, traditional beliefs	Values and value changes; taboos; heritage; religious and traditional rites
Technology	Hazards; emissions; congestion; safety; genetically modified organisms, plants
Political and legal	Authority and structure of decision making; administrative management; level and degree of involvement; resource allocation; local/minority interests; priorities; public policy

2.5.1 Environmental effects

2.5.1.1 Methodologies for assessing environmental effects

Studies of environmental effects usually employ methodologies generally in line with the ISO 14040:2006 and 14044:2006 standards for Life Cycle Assessments (LCA) that underpin the principles, framework, requirements and guidelines for conducting an LCA study. LCA quantifies general environmental effects rather than for a specific bioenergy project, but LCAs can also be suitable for evaluating multiple technologies using the same feedstocks, for evaluating technology development (Wang, 2007), and for project impact statements (e.g., DOE, 2010). The conventional methodology for the assessment of the effects of bioenergy systems compared to their substitutes is attributional while consequential LCA requires auxiliary tools such as economic, biophysical, and land-use models to evaluate the consequences of bioenergy options. These model couplings involve higher uncertainties. Complementary insights into climate benefits can be obtained from energy system models – with or without linked land-use models – where the mitigation benefit is evaluated from a total energy system perspective considering a range of fossil as well as competing renewable energy options. In addition to comprehensive LCAs, there are studies with a bifurcated focus on energy balances and GHG emissions balances (e.g., Fleming et al., 2006; Larson, 2006, von Blottnitz and Curran, 2006; Zah, 2007; OECD, 2008; Rowe et al., 2008; Menichetti and Otto, 2009). A specific methodology for assessing GHG balances of biomass and bioenergy systems has also been developed since the late 90s (Schlamadinger et al., 1997).

Assessment results need to be analyzed in the context of specific locations considering natural conditions and industrial/institutional capacity. Water use is one such instance. In some locations with scarce water availability, production processes that consume large volumes of water can be problematic; other locations with plenty of water this is less of an issue; and often these results are compared with fossil energy production water consumption (Berndes, 2002; Wu et al., 2009; Fingerman et al., 2010, Rost et al., 2009). Technical solutions for effluent management are available but are under used because of lax environmental regulation or limited law enforcement capacity. Major reduction in sugarcane ethanol plants' effluent discharge into rivers in Brazil is illustrates the importance of institutions in determining impacts of bioenergy projects (Peres et al., 2007).

Most assumptions and data used in LCA studies are related to conditions in Europe or USA, but studies are becoming available for other countries such as Brazil and China (see Table 2.3.2 and 2.6.3). Most studies have concerned biofuels for transport from conventional food/feed crops. Prospective bioenergy options (e.g., biofuels derived from lignocellulosic biomass and biomass gasification routes, albeit less studied, and their assessment via the LCA process involves projections of performance of developing technologies that are at various stages of development and have greater uncertainties (see Figure 2.3.1). Despite following ISO standards, a wide range of results has been reported for the same fuel pathway, even holding temporal and spatial considerations constant (Fava, 2005). The variations may be attributed to actual differences in the systems being modeled but are also due to differences in method interpretation, assumptions, and data. Emissions performance technology is dated by the time of publication, and learning has occurred in process energy efficiency and feedstock productivity with rapid industry expansion, as illustrated in Table 2.5.2 for corn and sugarcane ethanol and in Table 2.3.5 for a variety of countries and systems and Table 2.6.3 for developing technologies, when available.

Key issues in bioenergy LCAs are system definition including spatial and dynamic system boundary, definition of functional unit, reference flows and indicators, and the selection of allocation methods for energy and material flows over the system boundary (Soimakallio et al., 2009a). Differences in co-products treatments has impacted LCA study results, although harmonized data have much less uncertainty. The handling of uncertainties and sensitivities related to data for parameter sets used may have significant impact on the results (see, e.g., Kim and Dale, 2002; Farrell et al., 2006; Larson, 2006; von Blottnitz and Curran, 2006; OECD, 2008; Rowe et al., 2008; Börjesson, 2009; Soimakallio et al., 2009b; Wang et al., 2010).

Many biofuel production processes create multiple products. Bioenergy systems can be part of biomass cascading cycles in which co-products and biomaterial itself are used for energy after their useful life. This process introduces significant data and methodological challenges, including consideration of space and time aspects since environmental effects can be distributed over decades and different geographical locations (Mann and Spath, 1997; Cherubini and Jungmaier, 2009). Studies combining several LCA models and/or Monte Carlo analysis can provide quantification with information about confidence information on some bioenergy options or indicate what most important parameters are for minimization and optimization of developing processes (e.g., Soimakallio et al., 2009; Hsu et al., 2010).

2.5.1.2 Environmental effects related to climate change

Production and use of bioenergy influences global warming through (i) emissions from the bioenergy chain including non-CO2 GHG and fossil CO2 emissions from auxiliary energy use in the biofuel chain; (ii) GHG emissions related to changes in biospheric carbon stocks often – but not always – caused by associated LUC; (iii) other non-GHG related climatic forcers including changes in surface albedo; particulate and black carbon emissions from small-scale bioenergy use; and aerosol emissions associated with forests. The net effect is the difference between the influence of the bioenergy system and of the – often fossil based – energy system that is replaced. LUC and biospheric carbon stock changes are to a greater extent linked to bioenergy because of its close association with agriculture and forestry. However, current fossil energy chains and evolving non-conventional sources have land-use impacts detailed by Gorissen et al. (2010) including indirect impacts, such as for ensuring Middle Eastern petroleum flow (Liska and Perrin, 2009)

Different limiting resources may define the extent to which land management and biomass fuels can mitigate GHG emissions, making different indicators relevant in different contexts, two examples of which are shown in Figure 2.5.1 as GHG reductions per output bioenergy delivered either as heat or electricity, or in combined form. For transportation applications, the more appropriate metric is a distance driven per bioenergy delivered. Schlamadinger et al. (2005) proposed indicators to maximize GHG emission reductions when biomass, demand for bioenergy, and available land are the limiting factors. Useful indicators are the fossil Ceq emission displacement factor, which favors most efficient use of biomass and it allows external fossil inputs if they enhance biomass use efficiency. It can compare between outputs (electrity, heat, transport fuel, material substitution. The emission savings indicator favors biomass conversion processes with low GHG emissions but ignores the amount of biomass or land required. It cannot compare between different outputs (e.g., electricity and transport fuel). The emission savings per amount of land favors biomass yield and conversion efficiency. Greater GHG emissions from production may be acceptable if that increases biomass yield. It can compare different outputs. Another commonly used indicator is a function of how much primary fossil energy is used in the process per unit of biofuel energy output, but often, if the bioenergy chain coproduces electricity, the renewable credit is subtracted from the input. Indicators commonly lack consideration of the temporal dimension of biosphere carbon stocks changes: sustainable biomass production systems can temporarily involve substantial decreases in biosphere carbon stocks, long-rotation forestry being an illustrative example.

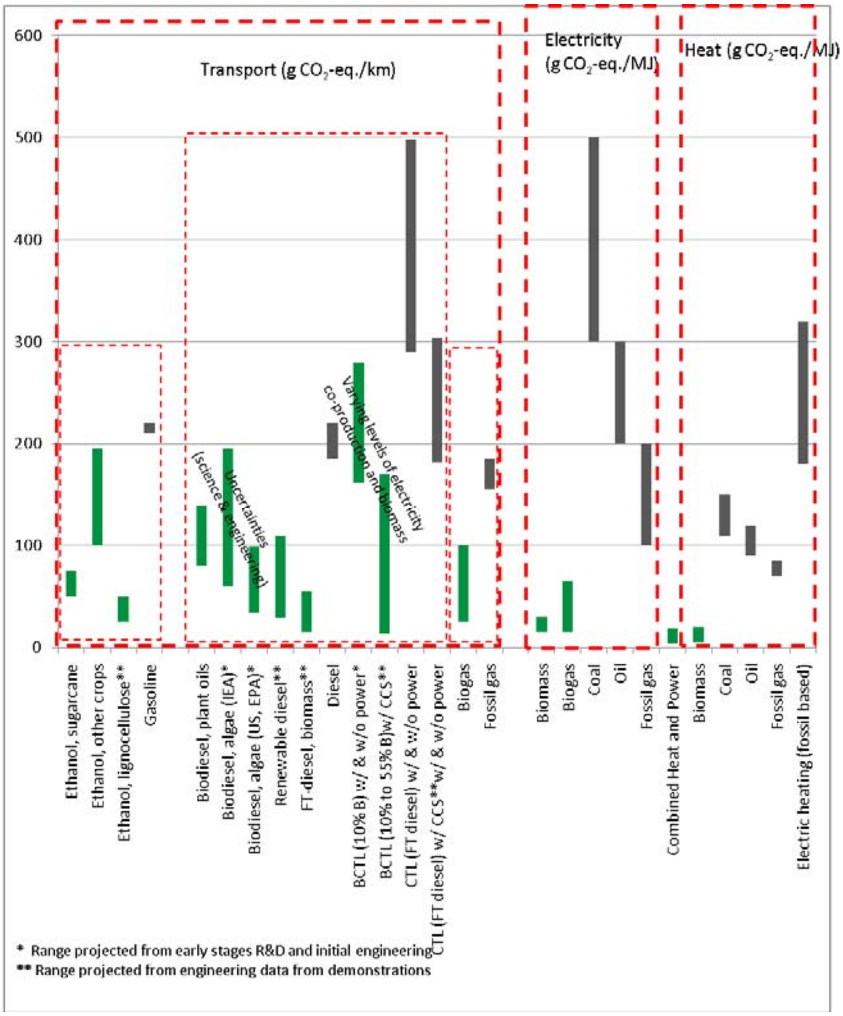
The above indicators are being used, for instance, to evaluate the individual technology options of two commercial ethanol cases production systems from sugarcane and from corn in Brazil and North America, showing substantial performance improvement ((S&T)2 Consultants Inc., 2009; Macedo et al., 2004, Macedo and Seabra, 2008; Seabra et al., 2010). These studies have provided substantive information on alternative functions for biorefinery development with time. Now it is necessary to complement the information with a more comprehensive analyses using integrated energy/industry/land use cover models for specific location studies (see, e.g., Leemans et al., 1996; Johansson and Azar, 2007; Van Vuuren, et al., 2007; Wise et al., 2009; Melillo et al., 2009). These can give insights into how an expanding bioenergy sector interacts with others in society, including land use and management of biospheric carbon stocks, and evaluate the importance of up-front emissions in the context of global climate targets and development pathways towards complying with such targets.

2.5.2 Climate change effects of modern bioenergy excluding the effects of land use change

Many studies have assessed the climate change effects of bioenergy and produce widely varying estimates of GHG emissions for biofuels (e.g., IEA, 2008; Menichetti and Otto, 2009) rapidly evolving bioenergy sources, complexities of physical, chemical, and biological conversion processes, feedstock diversity and variability in site specific environmental conditions – together with inconsistent use of methodology – complicate meta-analysis to produce valid quantification of the influence of bioenergy systems on climate. A recent meta-analysis explain some of the variability and compares a very wide range of production and utilization chains for many commercial and developing biofuels (Hoefnagels et al., 2010).

Efficient fertilizer strategies (minimizing N2O emissions) and the minimization of GHG emissions from the conversion process are essential for improving GHG savings. Process integration and the use of biomass fuels (e.g., bagasse, straw, wood chips), surplus heat from nearby energy or industrial plants can lead to low net GHG emissions from the conversion process. When evaluated using LCA, process fuel shifts from fossil fuels to using biomass or surplus heat can be attractive (Wang et al., 2007), but the marginal benefit of shifting depends on local economic circumstances and on how this surplus heat and biomass would otherwise have been used. Also, the GHG reduction per unit biomass used can be rather low when biomass is used as process fuel.

Crutzen et al (2007) proposed that N2O emissions from fresh anthropogenic N are considerably higher than what is obtained based on the IPCC’s recommended tier 1 methodology and that N2O emissions from biofuels consequently have been underestimated by a factor of two to three. However, differences between IPCC tier 1 and Crutzen et al (2007) arise due to use of different accounting approaches. It is estimated that about one-third of agricultural N2O emissions are due to newly-fixed N fertilizer (Mosier et al. 1998). About two-third takes place as N is recycled internally in animal production or by using plant residues as fertilizer. Using the emission factors proposed by Crutzen et al. (2007) to calculate N2O emissions from N fertilization of a specific bioenergy plantation makes this bioenergy production responsible for all N2O emissions taking place subsequently, for part of the applied N is recirculated into other agriculture systems where it substitutes for other N input. Nevertheless, N2O emissions can have an important impact on the overall GHG balance of biofuels (Smeets et al., 2008; Soimakallio et al., 2009), though there are large uncertainties.



* Range projected from early stages R&D and initial engineering
** Range projected from engineering data from demonstrations

Figure 2.5.1. Ranges of emissions from major modern bioenergy chains compared to conventional and selected advanced fossil fuel energy systems. Commercial and developing systems for biomass and fossil technologies are illustrated. Data sources: Cherubini 2010; EPA 2010; Kalnes et al. 2009; Kreutz et al. 2008; van Vliet et al., 2009; Daugherty 2001.

2.5.3 Climate change effects of modern bioenergy including the effects of land use change

Conversion of natural ecosystems to biomass production systems and changes in land use can lead to changes in biospheric carbon stocks. Examples are change in production, for instance, from food to biofuel crops, or in management practice, such as reduced forest rotation periods and increased forest residue extraction. Such changes can also arise indirectly, e.g., when conversion of pastures to biofuel plantations in one place leads to conversion of natural ecosystems to new pastures elsewhere to compensate for the lost meat/dairy production. An opposite example is when degraded pastureland is moved into biofuel production and pasture management is improved so that the same area can sustain a higher density of cattle. The use of agriculture/forest residues, post-consumer waste and agriculture/forest industry by-flows can avoid land-use change, although it can occur if earlier users of these biomass sources switch to using primary biomass. Also, if left untouched (e.g., as residues in the forest), some of these biomass sources would keep organic carbon away from the atmosphere for a longer time than if used for energy.

The dynamics of terrestrial carbon stocks in LUC and long-rotation forestry leads to GHG mitigation trade-offs between biomass extraction and use for energy and the alternative to leave the biomass as a carbon store that could further sequester more carbon over time (Marland and Schlamadinger, 1997). The cultivation of biofuel crops on previous cropland taken out of production can lead to foregone carbon sequestration if the alternative would be natural or assisted conversion to grasslands or forests. Forests that are in stages of net carbon accumulation naturally lose this sink capacity if it is converted to another land cover type. Observations indicate that also very old forests can be net carbon sinks (Luyssaert et al. 2008, Lewis et al. 2009). The CO2 fertilization effect – elevated CO2 levels in the ambient air stimulate plant growth – is one possible explanation. Climate-C cycle models indicate that the CO2 fertilization effect can become weaker in the future and that the terrestrial biosphere may even become a carbon source in the final decades of the 21st century if atmospheric CO2 levels increase radically (Sitch et al. 2008).

The relative merits of the principal options, extraction for bioenergy vs. carbon storage, depend on (i) efficiency with which bioenergy can substitute for fossil fuels described by the displacement factor this efficiency is high if biomass is produced and converted efficiently, the replaced fossil fuel would have been used with low efficiency, and a carbon intensive fossil fuel is replaced; (ii) time period of consideration – the longer the timeframe of the analysis the more attractive is the bioenergy option, for only limited amounts of carbon can be stored on land but bioenergy can be produced repeatedly; (iii) growth rate of the site – the higher the growth rate, the sooner the saturation constraints of carbon sequestration will be reached, and (iv) prior use of the land (and thus its current carbon content)

Ambitious climate targets such as the 2°C degree stabilization with global GHG emissions peak within one decade (IPCC 2007, p. 15, Table SPM5) suggest use of fossil alternatives can provide near-term net GHG reductions. Many studies (for instance, Leemans 1996, Pacca and Moreira 2009) have demonstrated the significance of LUC and the care needed in the selection of specific sites of bioenergy projects to obtain near-term carbon mitigation benefits while contributing effectively on the longer term. Upfront emissions arising from the conversion of land to bioenergy production has been attention with indicators such as Carbon Debt (Fargione et al., 2008) which estimate the number of years until a net GHG reduction is obtained from a bioenergy initiative under specific conditions. The Ecosystem Carbon Payback Time (Gibbs et al. 2008 illustrates this concept graphically on Figure 2.5.2 – in one case, the scenario reflected global yields typical of the year 2000 agricultural system. From the initial land conversion to plantation significantly higher amount of time is required to reach net GHG reduction than if the global agricultural productivity increased 10% major crops. The biggest effects are for maize and castor; sugarcane, soybeans and oil palm were already high yielding and show a smaller impact. The figure does not include GHG savings from fossil fuel replacement that can improve the situation further. Of particular importance is the starred points that represent oil palm conversion onto peatlands with payback times of nearly a thousand years that are halved with an increase in plant productivity of 10%.

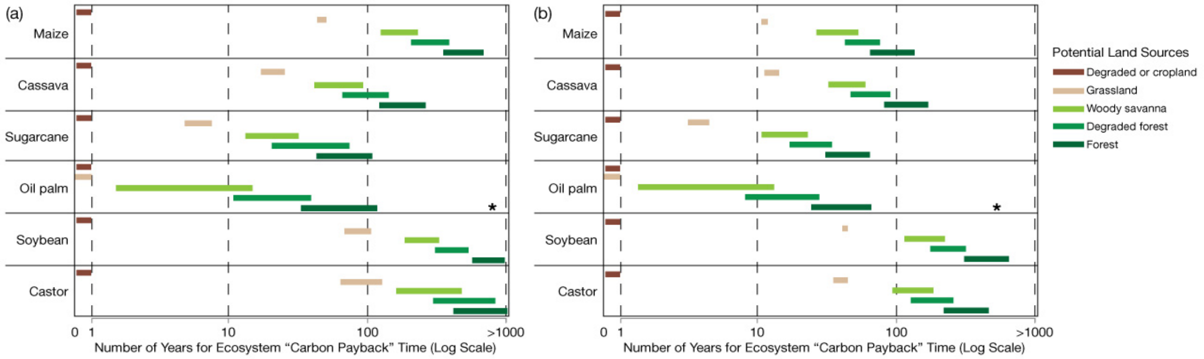


Figure 2.5.2. The ecosystem carbon payback time for potential biofuel crop expansion pathways across the tropics comparing the year 2000 agricultural system (a) with a scenario of 10% global crop increases (b).The "*" points represent oil palm crops grown in peatlands of more than 900-year payback time if oil palm expansion into peat forests of year 2000 productivity compared to 600 years for a 10% higher crop productivity (Gibbs et al., 2008)

The effects of LUC are complex and difficult to quantify with precision in relation to a specific bioenergy project because the causes of LUC are often multiple, complex, interlinked and time variable. The IPCC provides default values to consider effects of dLUC in LCA studies as well as a methodology to produce specific site estimates (IPCC 2006). However, it is preferable to use site specific data instead of general numbers for quantifying effects of dLUC in a specific case. Significant data need to be generated for such land conversions to obtain more precise dLUC values. The inclusion of iLUC in quantifications of LUC emissions adds an additional challenge. Hypotheses about indirect links between distant activities include: (i) deforestation in the Amazon region and sugarcane ethanol expansion far away in the SE of Brazil (Sparovek et al. 2009; Zuurbier and van de Vooren, 2008); (ii) increased biodiesel production from rape seed cultivated on the present cropland in Europe and increased deforestation for Palm oil in SE Asia (WWF 2007; RSPO, 2009, Reinhardt, 1991; BABCO, 2000); (iii) shift from soy to corn cultivation in USA and deforesting soy expansion in Brazil (Laurance, 2007); (iv) wheat based ethanol production in Europe reducing Amazonian deforestation by producing process by-products that substitutes imported soy feed (BABCO, 2000). Data obtained in the past three years have shed more light and did not substantiate all of the hypothesis above. The particulars of assumed scenarios need to be better founded on empirical evidence.

Presumably the faster the growth in the use of biomass for energy the higher the risk that bioenergy options will have high LUC emissions, unless mitigating measures becomes established or marginal lands are used. The extraction of temperate and boreal forest biomass can lead to near-term forest carbon stock reduction on stand level. Seen over larger areas and over longer time periods, the net carbon stock effects of increasing the use of forest bioenergy depends on how forest management evolves in response to increased bioenergy demand and other past and current pressures on forest conversion. Conclusions depend on systems definition and baseline assumptions in analyses – e.g., whether the temporal dimension includes a period before the actual biomass extraction to consider effects of different forest management regimes. A scenario involving increased forest bioenergy use and management regimes increasing forest stand growth (including growth of early thinning wood) can have higher net GHG benefit than a scenario where forest bioenergy demand is lower and management less.

The following summary of methodology and results illustrates strengths and weaknesses of assessment methodologies

2.5.3.1 Methodologies for Land Use Change Modeling

Methods used to estimate the global land use impacts of bioenergy utilization are under continuous development to address discovered weaknesses. Field measurements and model validation are needed to reduce uncertainties of analyses and models, and scenario development requires better documentation, analysis and inclusion of integrated production systems (Kline et al. 2009) (Dale et al. 2010). Existing methods for determining iLUC (often grouped with LUC) can be divided into two methods employing macro-economic/econometric and/or biophysical models and deterministic methods allocating global land-use change to respective fuels/feedstocks grown in a few specified land types (Fehrenbach et al., 2009). If specified land types were altered or key types absent, different carbon stock values (above and below ground) would be obtained over time (Amaral et al., 2009). Some recent research papers and reports that evaluate LUC or iLUC employing original methods (or significant variations) are listed in Tables 2.5.3

Results shown in first six rows of Table 2.5.3 use a combination of macro-economic/econometric models and/or biophysical models/data. Implementation of the use of these modelling systems generally proceeds in two phases. Global land use changes are calculated comparing results from scenarios with and without policy-induced increases in bioenergy. Then the impacts of iLUC are attributed to the appropriate fuel/feedstock as linked to via the economic system. Macroeconomic/econometric models combined with biophysical models/data are complex and resource intensive; they can be viewed as lacking transparency to non-modelers. Two studies utilizing these methodologies have conducted significant uncertainty analysis (EPA, 2010; Hertel et al., 2010).

Implementation of the use of these modelling systems generally proceeds in two phases. Global land use change estimates are derived from scenarios with and without policy-induced increases in bioenergy. Then the impacts of iLUC are attributed to the appropriate fuel/feedstock as linked to *via* the economic system. Macroeconomic/econometric models combined with biophysical models/data are complex and resource intensive; they can be viewed as lacking transparency to non-modelers. Two studies utilizing these methodologies have conducted significant uncertainty analysis (EPA, 2010; Hertel et al., 2010).

The recently released EPA results (2010) (see Table 2.5.3) resulted from a series of peer reviews and comments on initial modelling data (a similar review process is underway with CARB for ILUC determinations) (CARB 2010b). Among improvements EPA updated the Brazilian land use data, considering information provided by the Brazilian Land Use Model (BLUM, Nassar et al., 2009) combining remote sensing data, field data, and micro-regional modeling for inputs into a partial equilibrium model (FAPRI). With these inclusions changes in the elasticities of multiple crops across several land types were obtained for a series of larger regions for a more detailed picture of the dynamics of land use within Brazil. The major land-use change has been pasture intensification with use of degraded pastureland for biofuels derived from soya and sugarcane; also modelled are crop substitutions in the Cerrado and other regions (Nassar et al., 2009). Earlier modelling exploring the land-use consequences of increased use of U.S. corn for ethanol production used lower spatial resolution and did not include pastureland among land types covered, resulting in the conversion of forests to cropland for food and fuel production (Searchinger et al., 2008). As can be seen in Table 2.5.3, LUC estimates vary depending on model and scenario assumptions. Corn LUC results are converging with improvements in the models and their input data. Similarly, the high initial LUC values for sugarcane with low spatial resolution data (CARB) have decreased by factors of two to three (EPA and IFPRI) with improved land-use dynamics data in Brazil.

Some studies only proceed with the 1st portion of this analysis to focus on global or regional impacts and do not separate dLUC and iLUC (see, e.g., Fischer et al., 2009; Melillo et al., 2009; Wise et al., 2009)..

Papers and reports using the deterministic method for estimating iLUC are described in rows seven through nine of Table 2.5.2. This method assumes that additional biomass production will inherently lead to an increase in land use change, performs a calculation of total LUC impact using census/spatial data/measurements, and then allocates iLUC impacts among energy feedstocks/fuels. iLUC can be divided over a period of time and converted to various functional units to determine the impact of a feedstock or fuel on iLUC. Example approaches include Fritsche et al. (2009) and Tipper et al. (2009). The benefits of these deterministic methods are that they are simpler and more transparent to potential users. However, the simplified methodology might lead to the loss of important details of geographic scope and currently lack dynamic capabilities.

The models have the potential but have not been used, so far, to provide information about how much iLUC could decrease further as a result of (i) large increases in investments to enhance agriculture productivity growth and (ii) implementation of policies to protect C rich ecosystems.

Despite the differences between the method categories, specific methodologies, and remaining uncertainty surrounding estimates, there is a general convergence and trend towards lower estimates of LUC in more recent data, and an understanding of iLUC estimates from different models, although the extent of causal relationship biofuels and iLUC is still uncertain.

2.5.3.2 Climate change effects of traditional bioenergy

Traditional open fires and simple low efficiency stoves have a low combustion efficiency, producing large amounts of incomplete combustion products (CO, CH4, particle matter (PM), non-methane volatile organic compounds (NMVOCs), and others), with negative consequences for local air pollution and climate change (Smith et al. 2000). When biomass is harvested renewably— e.g., from standing tree stocks or agricultural residues - –most of the former CO2 emissions are sequestered as biomass re-growth. Worldwide, estimates are that household-fuel combustion causes approximately 30% of warming due to black carbon and carbon monoxide emissions from human sources, about a 15% of ozone-forming chemicals, and a few percent of methane and CO2 emissions (Wilkinson et al., 2009).

ICS GHG emissions are difficult to determine because of the wide range of fuel types, stove designs, cooking practices, and environmental conditions across the world but small-scale gasifier stoves and biogas stoves dramatically reduce short-lived GHG production up to 90% reletive to traditional stoves (Jetter and Kariher, 2009). Patsari improved stoves in rural Mexico saved between 3 and 9 tCO2-equivalent per stove-year relative to open fires, depending with or without renewable biomass harvesting conditions, respectively (Johnson et al., 2009). Wilkinson et al. (2009) estimated that advanced stove use, the dissemination of 150 million houses in a 10-yr program in India (a dissemination pace similar to that achieved in China in early 90s) may result in a mitigation of 0.5- 1 GtonCO2e, only from non-CO2 GHG.

Worldwide, using a unit GHG mitigation of 1-4 tonCO2e/stove/yr compared to the traditional open fires, the global mitigation potential of the advanced ICS was estimated at between 0.6-2.4 GtonCO2e/yr, without considering the effect of the potential reduction in black carbon emissions (GEA, 2010). Actual figures depend on biomass fuel renewability, stove and fuel characteristics, and the actual adoption and sustained used of the cookstoves.

Table 2.5.2. Summary of recent papers estimating iLUC by employing macroeconomic/ econometric and/or biophysical models/data for global and feedstock LUC estimates**.**

Reference	LUC (d+i) Source Models/Methodology	Scenario Description	Land Conversion Types	LUC (d+i) Geographic Resolution
U.S. Environmental Protection Agency (EPA) 2010 analysis of Renewable Fuel Standard 2 (RFS2) as required by the Energy Independence and Security Act (EISA) of 2007	**DAYCENT/CENTURY, FAPRI-CARD 2010, FASOM, GREET 1.8c, MODIS v5, and MOVES 2010** (Partial Equilibrium) FAPRI and GTAP v.6 models were compared with the same data (and sensitivity analysis). Results were consistent with the methodological differences between the models. FAPRI and FASOM provide higher resolution on crop expansion; GTAP total area. Projected impacts calculated for lignocellulosic biofuels technologies under development.	The "business as usual" volume of fuel is based on what would likely occur in 2022 without EISA. The control case assumed the EISA fuel mandate for 2022. For each individual biofuel, the incremental impact was analyzed while holding volumes of other fuels constant. Assumed levels of biofuels production of all countries at mandate levels at the time of analysis (2009). Studied US production and imports to meet legal requirements.	forest, grasslands, shrublands, savanna, natural and mixed, wetlands, barren	Algeria, Argentina, Australia, Bangladesh, Brazil: Amazon Biome, Brazil: Central-West Cerrados, Brazil: Northeast Coast, Brazil: North-Northeast Cerrados, Brazil: South, Brazil: Southeast, Canada, China, New Zealand, Colombia, Cuba, Egypt, EU, Guatemala, India, Indonesia, Iran, Iraq, Ivory Coast, Japan , Malaysia, Mexico, Morocco, Myanmar, Nigeria, Other Africa, Other Asia, Other CIS, Other Eastern Europe, Other Latin America, Other Middle East, Pakistan, Paraguay, Peru, Philippines, Rest of World, Russia, South Africa, South Korea, Taiwan, Thailand, Tunisia, Turkey, Ukraine, Uruguay, US, Uzbekistan, Venezuela, Vietnam, Western Africa
U.S. California Air Resources Board (CARB 2010) Analysis of Low Carbon Fuel Standard, LCFS regulation	**GTAP-SOY** (General Equilibrium) New sectors/commodities added to the model to represent production, consumption and trade of key commodities for biodiesel analyses	Two scenarios showing the change in biofuel production expected to occur in response to federal energy legislation and GHG emission regulations such as the LCFS over the time period from 2001 to 2040.	forest, grassland, crop	111 world regions
International Food Policy Institute (IFPRI 2010) study for EU Biofuels Mandate	**MIRAGE 2007, GTAP v.7 Database, Biophysical Data** (General Equilibrium)	A baseline scenario excluding EU biofuels. A scenario of first-generation land-using biofuels share of 5.6%. A final scenarios on a change in the EU biofuels trade policy regime, with an elimination of import tariffs	forest, grassland, crop	Brazil, Central America and Caribbean countries, China, East Europe, EU27, Indonesia and Malaysia, Other Latin American countries, Rest of the OECD, Rest of the World, US, Sub-Saharan Africa
Hertel et al. 2010 Comprehensive Analysis of CARB's LCFS regulation	**GTAP-BIO** (General Equilibrium)	Modeled the expansion of US maize ethanol use from 2001 levels to the 2015 mandated level of 56.7 gigaliters (GL) per year.	forest, grassland, crop	Europe; developed Pacific; former Soviet Union; North Africa/Middle East; Canada; United States; Latin America; South and South East Asia; Africa; India, China, Pakistan; and the rest of the world (ROW)
Searchinger et al. 2008 Preliminary Analysis	**FAPRI-CARD of 2007, GREET 1.7** (Partial Equilibrium, non-spatial, econometric market models)	Two scenarios comparing the LUC impact of US biofuel projected levels relative to 56 GL above that level by 2015.	forest, grassland, crop	Developed Pacific, North Africa/Middle East, Canada, US, Latin America, Africa, South and Southeast Asia, China and Pakistan and India
Lywood 2008	**Econometric Model and LUC data based on (or modified from) Fehrenbach et al. 2009 (see below).**	N/A	forest, pasture, crop	Global
Tipper et al. 2009	**Spatial Measurements Using Census Data** (Attribution of Responsibility)	Starts with an estimate of total GHG emissions from LUC from 2000 – 2005, which is mostly based on FAO's estimate of 7.3 Mha forest lost per year during this period and IPCC carbon stock factors.	N/A	Global
Fritsche et al. 2008	**Spatial Measurements Using Census Data** (Risk Adder/iLUC Factor)	The maximum land potentially involved in LUC is derived from the shares of agricultural products globally traded in the reference year 2005, that can be theoretically "displaced" by additional biomass cultivation is combined with IPCC carbon stock factors for those regions.	grassland, savanna, tropical rainforest, degraded land	EU, Indonesia, Brazil, US
Fehrenback et al. 2009	**Spatial Measurements Using Census Data** (Risk Adder/iLUC Factor)	(see Fritsche for description, but uses alternate data for a recalculation)	grassland, savanna, tropical rainforest, degraded land	EU, Indonesia, Brazil, US
N/A = not applicable; BAU=business as usual				

Table 2.5.2. Summary of recent papers estimating iLUC by employing macroeconomic/ econometric and/or biophysical models/data for global and feedstock LUC estimates

Reference	*Feedstocks and Biofuels*	*Corn LUC (d+i) Value in g/MJ*	*Sugarcane LUC (d+i) Value in g/MJ*	*Rapeseed LUC (d+i) Value in g/MJ*	*Soya LUC (d+i) Value in g/MJ*	*Clarifying Comments on Paper Results and Methodology*
EPA	**Ethanol**: maize, maize stover, sugarcane, switchgrass **Biodiesel and Renewable Diesel**: soya, microalgae **FT-Diesel**: switchgrass, maize stover **Butanol**: maize Other annual and perennial crops	**Volumes** 2017: 1.3 EJ 2022: 1.3 EJ **2017 Results** Median 54 Low 36 High 76 **2022 Results** Median 30 Low 20 High 43 *30 Year Accounting Time Frame*	**Volumes** 2017: 1.1 EJ 2022: 1.4 EJ **2017 Results** Median 9 Low -8 High 22 **2022 Results** Median 5 Low -5 High 14 *30 Year Accounting Time Frame*	N/A	**Volumes** 2017: 0.08 EJ 2022: 0.08 EJ **2017 Results** Median 59 Low 30 High 95 **2022 Results** Median 40 Low 14 High 72 *30 Year Accounting Time Frame*	Key parameters: elasticities of crop yields, harvested acreage response, and transformation across cropland, pasture, and forest land. Incorporates Brazilian land use data (Nassar e. al. 2009). Thresholds of GHG with LUC of modeled technologies established (vs. 2005 US fossil fuels) are: **20%** for corn starch ethanol produced from corn starch at a new natural gas, biomass, or biogas fired facility using advanced efficient technologies or butanol; **50%** for ethanol from sugarcane; biodiesel and renewable diesel from soy oil or waste oils, fats, and greases; algal oil derived biodiesel and renewable diesel should they reach commercial production. **60%** for cellulosic ethanol/ diesel pathways modeled (for feedstock and production technology) (EPA 2010).
CARB	**Ethanol**: maize, sugarcane **Biodiesel**: soya	32 *30 Year Accounting Time*	46 *30 Year Accounting Time*	N/A	62 *30 Year Accounting Time*	Limited land use types and geographic resolution. A Sustainability Working Group is refining LUC methodology for absolute carbon intensities required by the State of California.
IFPRI	**Ethanol**: maize, wheat, sugar beets, sugarcane **Biodiesel**: palm, rape, soya, sunflower	2020 Results 54 (BAU) 79 (Trade Liberalization) *20 Year Accounting Time*	2020 Results 18 (BAU) 19 (Trade Liberalization) *20 Year Accounting Time*	2020 Results 53 (BAU) 51 (Trade Liberalization) *20 Year Accounting Time*	2020 Results 24 (BAU) 19 (Trade Liberalization) *20 Year Accounting Time*	Limited set of EU imports used. Limited land use types.
Hertel et al.	**Ethanol**: maize	**iLUC Attributable** Median: 27 Lower : 14 Upper : 90 *30 Year Accounting Time*	N/A	N/A	N/A	Comprehensive market-mediated model obtained 1/4 of the figure of Searchinger et al. (2008). Conducted sensitivity analysis and Gaussian quadrature analysis of uncertainties. Methodology used continues to undergo developed and refinement.
Searchinger et al.	**Ethanol**: maize, biomass	104 *30 Year Accounting Time*	N/A	N/A	N/A	Limited land use types (i.e., natural vegetation only; no pastures) and limited geographic resolution.
Lywood	**Ethanol**: maize, wheat, sugarcane **Biodiesel**: soya, rapeseed, palm	-92 *30 Year Accounting Time*	48 *30 Year Accounting Time*	-149 *30 Year Accounting Time*	146 *30 Year Accounting Time*	Results largely determined by linkage of soya meal to LUC in Brazil. Maize, rape, and wheat reduce GHGs through co-products substituting for soy meal. Limited land use type and geographic resolution.
Tipper et al.	**Ethanol**: wheat, sugar beet, maize, sugarcane **Biodiesel**: rapeseed, soya, palm	21 *25 Year Accounting Time*	45 *25 Year Accounting Time*	*10* *25 Year Accounting Time*	N/A	Methods is less resource intensive, but the simplified methodology might lead to the loss of important details of geographic scope and currently lack dynamic capabilities.
Fritsche et al.	**Ethanol**: maize, wheat, sugarcane, switchgrass, poplar **Biodiesel**: jatropha, rape, palm,	LUC Risk Value 48 (25%) 79.5 (50%) 111.5 (75%) dLUC: 16.5 *20 Year Accounting Time*	LUC Risk Values 6.5 (25%) 14 (50%) 29 (75%) dLUC: -1 *20 Year Accounting Time*	LUC Risk Value 91 (25%) 150.5 (50%) 210 (75%) dLUC: 31.5 *20 Year Accounting Time*	N/A	Methods is less resource intensive, but the simplified methodology might lead to the loss of important details of geographic scope and currently lack dynamic capabilities.
Fehrenback et al.	**Ethanol**: maize, wheat, sugarcane **Biodiesel**: rape, palm	iLUC Risk Value 36 (25%) 72 (50%) 108 (75%) *20 Year Accounting Time*	iLUC Risk Values 53 (25%) 106 (50%) 159 (75%) *20 Year Accounting Time*	iLUC Risk Value 60 (25%) 120 (50%) 180 (75%) *20 Year Accounting Time*	N/A	Methods is less resource intensive, but the simplified methodology might lead to the loss of important details of geographic scope and currently lack dynamic capabilities.

2.5.3.3 Environmental impacts other than GHG emissions

Impacts on air quality and water resources

Pollutant emissions to the air depend on combustion technology, fuel properties, combustion process conditions and emission reduction technologies installed. Compared to coal and oil combustion stationary applications, SO2 and NOx emissions are generally lower than coal and oil combustion in stationary applications. When biofuels replaces gasoline and diesel in the transport sector SO2 emissions are reduced but changes in NOx emissions depend on substitution pattern and technology applied. The effects of ethanol and biodiesel replacing petrol depend on engine features. Biodiesel can have higher NOx emissions than petroleum diesel in traditional direct-injected diesel engines that are not equipped with NOx control catalysts. (e.g., Verhaeven et al., 2005; Yanovitz and McCormick, 2009)

Bioenergy production can have positive and negative effects on water resources. The impacts are highly dependent on the supply chain element under consideration. Feedstock cultivation can lead to leaching and emission of nutrients resulting in increased eutrophication of aquatic ecosystems (Millennium Ecosystem Assessment, 2005; SCBD 2006). Pesticide emissions to water bodies may also negatively impact aquatic life. Perennial herbaceous crops and short rotation woody crops generally require less agronomic input – resulting in less impacts – and can also mitigate impacts if integrated in agricultural landscapes as vegetation filters intended to capture nutrients in passing water (Börjesson and Berndes, 2006).

The subsequent processing of the feedstock into solid/liquid/gaseous biofuels and electricity can lead to negative impacts due to potential chemical and thermal pollution loading to aquatic systems from refinery effluents and fate of waste or co-products (Martinelli and Filoso 2008, Simpson et al. 2008). These environmental impacts can be reduced if suitable equipment is installed (Wilkie et al. 2000; BNDES/CGEE 2008) but this may not happen in regions with lax environmental regulations or limited law enforcement capacity.

Most water is lost to the atmosphere in plant evapotranspiration (ET) in the production of cultivated feedstock (Berndes, 2002). Feedstock processing into fuels and electricity requires much less water (Aden et al. 2002; Berndes 2002; Keeny and Muller 2006; Pate et al. 2007; Phillips et al. 2007; Wang et al., 2010), but water needs to be extracted from lakes, rivers and other water bodies. Bioenergy processing can reduce its water demand substantially by means of process changes and recycling (Keeney and Muller, 2006; BNDES/CGEE, 2008).

Strategies that shift demand to alternative – mainly lignocellulosic – feedstock bioenergy expansion can lead to decreased water competition. Given that several types of energy crops are perennials in arable fields, being used temporarily as a pasture for grazing animals, and woody crops grown in multi-year rotations, the increasing bioenergy demand may actually become a driver for land use shifts towards land use systems with substantially higher water productivity. A prolonged growing season may facilitate a redirection of unproductive soil evaporation and runoff to plant transpiration, and crops that provide a continuous cover over the year can also conserve soil by diminishing the erosion from precipitation and runoff outside the growing season of annual crops (Berndes, 2008). Since a number of crops that are suitable for bioenergy production can be grown on a wider spectrum of land types, marginal lands, pastures and grasslands, which are not suitable for conventional food/feed crops, could become available for feedstock production under sustainable management practices (if downstream water impacts can be avoided)).

Habitat Loss

Habitat loss is one of the major causes of biodiversity decline globally and is expected to be the major driver of biodiversity loss and decline over the next 50 years (Convention on Biodiversity, 2008; Sala et al, 2009). While bioenergy can reduce global warming – which is expected to be a major driver behind habitat loss with resulting biodiversity decline – it can also in itself impact biodiversity through conversion of natural ecosystems into bioenergy plantations or changed forest management to increase biomass output for bioenergy. Biodiversity loss may also occur indirectly, such as when productive land use displaced by energy crops is re-established by converting natural ecosystems into croplands or pastures elsewhere.

To the extent that bioenergy systems are based on conventional food and feed crops, biodiversity impacts due from pesticide and nutrient loading can be an expected outcome of bioenergy expansion. On the other hand, bioenergy expansion can lead to positive outcomes for biodiversity. Establishment of perennial herbaceous plants of short rotation woody crops in agricultural landscapes has been found to be positive for biodiversity (Semere et al., 2007; The Royal Society 2008; Lindemeyer, Nix 1993).

Bioenergy plantations that are cultivated as vegetation filters capturing nutrients in passing water can contribute positively to biodiversity by reducing the nutrient load and eutrophication in water bodies (Borjesson and Berndes, 2006; Foley et al. 2005) and provide varied landscape.

Bioenergy plantations can be located in the agricultural landscape so as to provide ecological corridors that provide a route through which plants and animals can move between different spatially separated natural and semi-natural ecosystems. This way they can reduce the barrier effect of agricultural lands. For example, a larger component of willow in the cultivated supports cervids, foxes, hares, and wild fowl.

Properly located biomass plantations can also protect biodiversity by reducing the pressure on nearby natural forests. A study from Orissa, India, showed that with the introduction of village plantations biomass consumption increased (as a consequence of increased availability) and the pressure on the surrounding natural forests decreased (Köhling, Ostwald 2001; Edinger et al. 2005).

When crops are grown on degraded or abandoned land, such as previously deforested areas or degraded crop- and grasslands, the production of feedstocks for biofuels could potentially have positive impacts on biodiversity by restoring or conserving soils, habitats and ecosystem functions. For instance, several experiments with selected trees and intensive management on severely degraded Indian wastelands (such as alkaline, sodic, or salt affected lands) showed increases of soil carbon, nitrogen and available phosphorous after three to 13 years.

Increasing demand for oilseed has put pressure on areas designated for conservation in some OECD member countries begun (Steenblik, 2007). Similarly, the rising demand for palm oil has contributed to extensive deforestation in parts of South-East Asia (UNEP, 2008). Since biomass feedstocks can generally be produced most efficiently in tropical regions, there are strong economic incentives to replace tropical natural ecosystems – many of which host high biodiversity values. (Doornbosch and Steenblik, 2007). However forest clearing is most influenced by local social, economic, technological, biophysical, political and demographic forces (Kline and Dale 2008).

2.5.3.3.1 Impacts on soil resources

Increased biofuel production based on conventional annual crops may result in changed rates of soil erosion, soil carbon oxidation and nutrient leaching owing to the increased need for tillage depending on the crop used and replaced (UNEP 2008). For instance, wheat, rapeseed and corn require significant tillage compared to oil palm and switchgrass (FAO 2008b; United Nations 2007). Excess removal of harvest residues such as straw may lead to similar types of soil degradation.

If energy crop plantations are established on abandoned agricultural or degraded land, levels of soil erosion could be decreased because of increased soil cover. This would be especially true with perennial species. For example, Jatropha can stabilize soils and store moisture while it grows (Dufey 2006). Other potential benefits of planting feedstocks on degraded or marginal lands include reduced nutrient leaching, increased soil productivity and increased carbon content (Berndes 2002).

2.5.4 Environmental health and safety implications

2.5.4.1 Feedstock Issues

Currently, the crops used in fuel ethanol manufacturing are the same as those used as traditional feed sources (e.g. corn, soy, canola and wheat). However, there is considerable in new crops, with characteristics that either enhance fuel ethanol production (e.g. high-starch corn), or are not traditional food or feed crops (e.g., switchgrass). These crops, developed for industrial processing, may necessitate a pre-market assessment of their acceptability in feed prior to their use in fuel ethanol production, if the resultant distillers' grains (DGs) are to be used as livestock feeds, or if the new crop could inadvertently end up in livestock feeds (Hemakanthi et al., 2010).

As with any genetically modified or enhanced organism, the energy-designed crop may raise concerns related to cross-pollination, hybridisation, and other potential environmental impacts such as pest resistance and disruption of ecosystem functions (FAO, 2004).

The first assessment of the impact of genetically engineered (GE) crops in the U.S., which have been in use since 1996 has now been published by the National Academy of Sciences (NAS, 2010). GE crops are currently responsible for 80 percent of corn, soya, and cotton, production and represent nearly 35 percent of the entire cropped area of the USA. Some highlights are: (i)Benefits to the farmer, including increased worker safety, flexibility in farm management, and lower cost of production due to a decline in the use of insecticides. (ii) Anticipation that water quality improvements will prove to be the largest benefit of GE crops. (iii) Acknowledgement that that more work needs to be done, particularly as it relates to installing infrastructure to measure water quality impacts, developing weed management practices, and addressing the needs of farmers whose markets depend on an absence of GE traits.

Several grasses and woody species which are potential candidates for future biofuel production also have traits which are commonly found in invasive species (Howard and Ziller, 2008). These traits include rapid growth, high water-use efficiency, and long canopy duration. It is feared that should such crops be introduced they could become invasive and displace indigenous species and result in a decrease in biodiversity. For example *Jatropha curcas*, a potential feedstock for biofuels, is considered weedy in several countries, including India and many South American states (Low and Booth, 2007). Warnings have been raised about species of Miscanthus and switchgrass (*Panicum virgatum*). Biofuel crops such as Sorghum halepense (Johnson grass), Arundo donax (giant reed), Phalaris arundinacea (reed canary grass) are known to be invasive in the United States. A number of protocols have evolved that allow for a more systematic assessment and evaluation of inherent risk associated with species introductionn.

2.5.4.2 Biofuels Production Issues

Most biofuels produced globally use conventional production technologies (see Section 2.3) that have been used in many industries for many years (Abassi, Abassi 2010; Gunderson, 2008). Hazards associated with most of these technologies have been well characterized, and it is possible to control risks to very low levels by applying existing knowledge and standards which are also applied to other fuels technologies (see, for instance, Williams et al., 2009; Astbury 2008; Hollebone, Yang, 2009; Marlay et al., 2009) and their typology is under development (Rivère, Marlair, 2009 and 2010).

As new technologies (see Section 2.6) are developed the literature highlights areas for further evaluation (e.g., Gunderson, 2008; Hill et al., 2009; Madsen, 2006; Madsen et al., 2004; Martens, Böhm, 2009; McLeod et al., 2008; Moral et al. 2009; Narayanan et al., 2008; Perry, 2009; Sumner, Layde 2009; Vinneraas et al.. 2006). Examples of areas: (i) Health risk to workers using engineered micro-organisms in biofuel production, or their metabolites. (ii) Potential ecosystem effects from the release of engineered micro-organisms. (iii) Impact to workers, biofuel consumers, or the environment of pesticides and mycotoxins accumulation in processing intermediates, residues, or products (e.g., spent grains, spent oil seeds). (iv) Risks to biofuel workers of infectious agents that can contaminate feedstocks in production facilities. (v) Exposure to toxic substances particularly workers at biomass thermochemical processing facilities different than those routes practiced by the current fossil fuels industry (vi) Fugitive air emissions and site run-off impacts on public health, air quality, water quality, and ecosystems exposure to toxic substances particularly if such production facilities became as commonplace as landfill sites or natural gas-fired electricity generating stations. (vii) Estimate the cumulative environmental impacts accruing from the siting of multiple biofuel / bioenergy production facilities in the same air and/or water shed.

2.5.5 Socioeconomic Aspects

The large-scale development of bioenergy at the global level will be associated with a complex set of socio-economic issues and trade-offs, ranging from local income and employment generation, improvements in health conditions near and far away, potential changes in agrarian structure, land-tenure, land-use competition, and strengthening of regional economies, to national issues such as food and energy security and balance of trade. The degree to which these impacts are mostly positive depends on the extent to which sustainability criteria are clearly incorporated in project design and implementation. Participation of local stake-holders, in particular small-farmers and poor households, is key to assure socio-economic benefits from bioenergy projects.

Up to now, the large perceived socio-economic benefits of bioenergy use –such as regional employment and economic gains- can clearly be identified as a significant driver for increased bioenergy production. Other “big issues” such as mitigating carbon emissions, ensuring wider environmental protection, and providing a secure energy supply are an added bonus for local communities. Benefits will result in increased social cohesion and conditions for greater social stability.

On the other hand, substantial opposition has been raised against the large-scale deployment of bioenergy, particularly regarding projects aimed at producing liquid fuels from mainly food crops with potential negative impact on food security, the extent to which current strategies and policies will actually benefit poor farmers, the potential disruption of local production systems and concentration of land and other social effects.

2.5.5.1 Socio-economic impact studies and sustainability criteria for bioenergy systems

Analyzing the socio-economic impacts of bioenergy, dependent on many exogenous factors affected by scale, is daunting ex ante or ex post. Typically, economic indicators such as employment and financial gain measure impacts. In effect, the analysis relates to a number of other aspects such as cultural and social issues. These elements are not always amenable to quantitative analysis and, therefore, have been excluded from the majority of previous impact assessments, even though they may be somewhat significant. The complex nature of biomass and possible routes for conversion make this topic a complex subject, with many potential outcomes. To overcome these problems methods for projecting social dimension accounting using a semi-quantitative approaches based on stakeholder involvement to assess social criteria such as societal product benefit and social dialogue[5] (Von Geibler et al 2006). Obtaining extensive feedback from local stakeholders, usually through the organisation of several workshops, roundtables and other similar meetings through the various project implementation stages is crucial, because basic economic information is often not available from national statistical agencies..

Most commonly reported economic criteria are private production costs over the value-chain, assuming a fixed set of prices for basic commodities (e.g., for fossil fuels and fertilizers). The bioenergy costs are usually compared to alternatives already on the market (fossil based), to judge the potential competitiveness. Externalities (environmental or societal) are seldom quantified in cost/benefit analyses, since they are difficult to value (Costanza et al., 1997). Policy instruments might already be in place to address these externalities, such as environmental regulations or emission-trading schemes. Bioenergy systems are mostly analysed at a micro-economic level, although interactions with other sectors cannot be ignored because of the competition for land and other resources. Opportunity costs may be calculated from food commodity prices and gross margins to take food-bioenergy interactions into account. Social impact indicators include consequences on local employment, although they are difficult to assess because of possible offsets between fossil and bioenergy chains. At a macro-economic level, other impacts include the social costs incurred by the society because of fiscal measures (e.g., tax exemptions) to support bioenergy chains, or additional road traffic resulting from biomass transportation (Delucchi, 2005). Symmetrically, fossil energy negative externalities need to be assessed (Bickel and Friedrich, 2005).

Diverse sustainability criteria and indicators have been proposed as a way to better assess the socio-economic implications of bioenergy projects (Bauen et al., 2009a; WBGU, 2009; see Section 2.4). These criteria relate to: (i) Human rights, including gender issues; (ii) Working and wage conditions, including health and safety issues; (iii) Local food security, and (iv)Rural and social development, with special regards to poverty reduction. These criteria also address issues of cost-effectiveness and financial sustainability (Table 2.5.4)

Table 2.5.4. Selected Socio-economic Sustainability Criteria for Bioenergy Systems

Criteria	Issues Addressed
Rural and Social Development	Improved access to basic services and livelihoods; Creation or displacement of jobs, Creation of infrastructure
Human Rights and Working Conditions	Freedom of association, Access to Social Security, Average Wages, Discrimination.
Health and Safety	Health Improvements or Impacts on Workers and Users; Safety Conditions at Work
Gender	Changes in Power or Access to resources or decision making

Socio-economic impacts of bioenergy systems are addressed in household applications (small-scale) and larger scale systems for industry, electricity generation, and transport.

2.5.5.2 Socio economic impacts of small-scale systems

The inefficient use of biomass in traditional devices such as open fires leads to significant social and economic impacts related to: the resources devoted to fuel collection, the monetary cost of satisfying cooking needs, gender issues, and significant health impacts of high levels of indoor air

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[5] Multi Criteria Analysis (MCA) methods have been applied in the bioenergy field during the past 15 years (Buchholz at al., 2008).

pollution, which affects in particular women and children during cooking. The inefficient use of biomass in traditional devices such as open fires leads to significant social and economic impacts including drudgery for getting the fuel, cost of satisfying cooking needs, and significant health impacts associated to very high levels of indoor air pollution, which affects in particular women and children during cooking (Biran et al., 2004; Romieu et al., 2009; Masera et al., 1997; Bruce et al., 2006).

Four billion people suffer from continuous exposure to high levels of indoor air pollution by cooking food over open wood burning fires (Pimentel et al, 2001). The pollutants include respirable particles, carbon monoxide, oxides of nitrogen and sulfur, benzene, formaldehyde, 1, 3-butadiene, and polyaromatic compounds, such as benzo(a)pyrene (Smith 1987). Human health effects from wood-smoke exposure have contributed towards an increased burden of respiratory symptoms and problems (Boman et al, 2006; Mishra et al., 2004; Schei et al., 2004; Thorn et al., 2001). Exposures experienced by household members, particularly women and young children who spend a large proportion of their time indoors, have been measured to be many times higher than World Health Organization (WHO) guidelines and national standards (Bruce et al., 2006; Smith, 1987). More than 200 studies in the past two decades have assessed levels of indoor air pollutants in households using solid fuels. The burden from relateddiseases was estimated at 1.6 million excess deaths/year including 900,000 children under five, and the loss of 38.6 million DALY (Disability Adjusted Life Year)/yr (Smith and Haigler, 2008). This is similar in magnitude to the burden of disease from malaria and tuberculosis (Ezzati et al., 2002).

The new generation of improved cookstoves and their dissemination described in section 2.4 have shown that properly designed and implemented ICS projects can lead to health improvements (Ezzati et al., 2004;von Schirnding et al., 2001). Figure 2.5.7 shows high and low estimates of cost effectiveness for treatment options related to eight major risk factors accounting for 40 percent of the global burden of disease (DCPP, 2006).

ICS health benefits include a 70%-90% reduction in indoor air pollution, and 50% reduction in human exposure as well as reductions in respiratory and other illnesses (Armendariz et al. 2008; Romieu et al, 2009). In India, it is estimated that an intensive program to introduce advanced biomass stoves in 87% of households would achieve in 10 yrs, 240,000 averted premature deaths from acute lower respiratory infections in children aged younger than 5 years, and more than 1.8 million averted premature adult deaths from ischaemic heart disease and chronic obstructive pulmonary disease (COPD) (Wilkinson et al. 2009)

Increased use of ICS frees up more time for women to engage in income generating activities. Reduced fuel collection times and savings in cooking time can also translate to increased time for education of rural children especially the girl-child (Karekezi et al. 2002). ICS use fosters improvements in local living conditions, kitchens and homes, and quality of life (Masera et al, 2000). The manufacture and dissemination of ICS represents also an important source of income and employment for thousands of local small-businesses around the world (Masera et al, 2005). Similar impacts were found for small scale biogas plants with the added benefits of lighting of individual households and villages, increasing the quality of life.

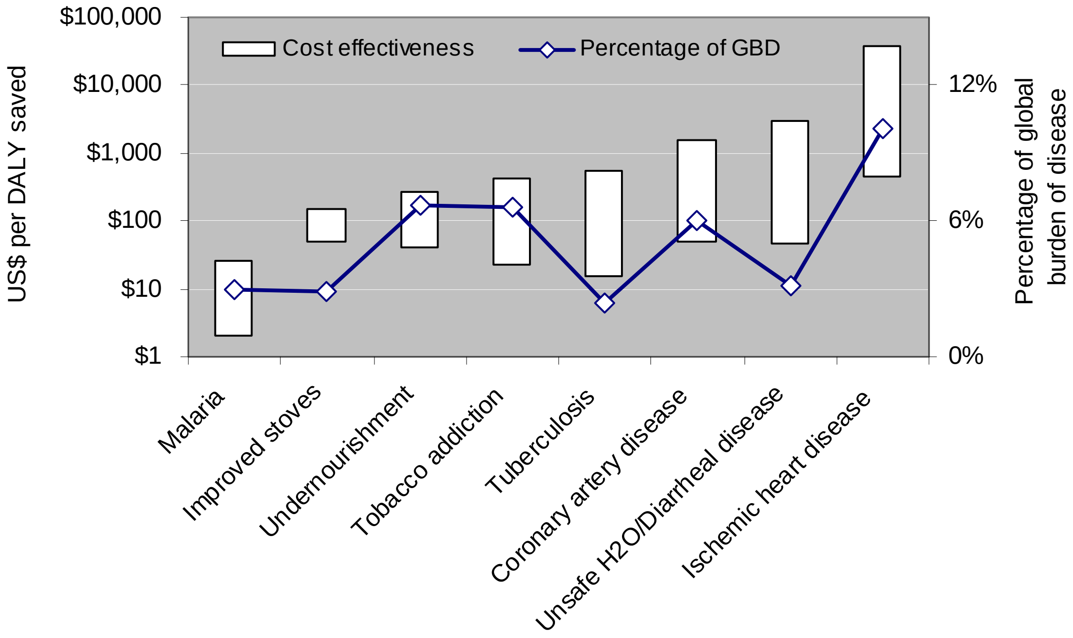

Figure 2.5.4.: Cost effectiveness of interventions expressed in dollars per Disability Adjusted Life Year (DALY) saved (DCPP, 2006) in the left scale (logarithmic scale) and contributions to the global burden of disease from eight major risk factors and diseases (in %, right scale). Source: Bailis et al., 2009.

Overall ICS and other small-scale biomass systems represent a very cost-effective intervention B/C (benefits to cost) ratio of 5.6 to 1, 20:1, and 13:1 were found in Malawi, Uganda and Mexico (Frapolli et al., 2010).

2.5.5.3 *Socioeconomic aspects of large-scale bioenergy systems*

Large scale bioenergy systems raise several important socioeconomic issues, and have sparked a heated controversy around food security, income generation, rural development and land tenure. The controversy makes clear that there are both advantages and disadvantages to the further development of large scale bio-energy systems.

Impacts on job and income generation

In general, bionergy generates more jobs per energy delivered than other energy sources, largely due to production of feedstocks which offers income-generating opportunities in developing countries, especially in rural areas. The extent of benefits are greater if the feedstock crop is more labor-intensive than the crop that was previously grown on the same land, because wage income is a key part of livelihoods for many poor rural dwellers.

The number of jobs created is very location specific, and varies considerably with plant size and the degree of feedstock production mechanization (Berndes and Hansson, 2007). Estimates of the employment creation potential of bioenergy options differ substantially, but liquid biofuels based on traditional agricultural crops seem to be best especially when the biofuel conversion plants are small (Berndes and Hansson, 2007). Even within liquid biofuels, the use of different crops introduces wide differences. For example, employment generation ranges from 1 to 5 direct jobs/Mlit-yr (or 45 to 220 direct and indirect jobs/PJ-yr) of ethanol using corn and sugarcane, respectively, to 3.5 to 73 direct jobs/Mlit-yr (or 100 to 2000 direct and indirect jobs/PJ-yr) biodiesel for soybean and oil palm, respectively (APEC, 2010). For electricity production, mid-scale power plants in developing countries assuming a low-mechanized system (25 MW) are estimated to generate 8 full jobs/MWe and approximately a total of 400 jobs/plant, of which 94% are in the production and harvesting of feedstocks. In developed countries the number of jobs for this size plant is estimated as 35 direct and indirect jobs/PJ (EPRI, 2008). A multiplier of five was used for the indirect to direct ratio (DOE/SSEB 2005) but could vary regionally even within a country.

The net impact of bioenergy on future employment creation is generally seen as positive; but specific figures are highly dependent on displaced crops/management systems. In Europe, if the EU25 scenario is followed, Berndes and Hansson (2007) estimate that the production of biomass for energy has the potential to contribute to employment creation at a magnitude that is significant relative to total agriculture employment (up to 15% in selected countries), but small compared to the total employment in industry in a country. Analysis also shows that there are some tradeoffs – for instance, bioenergy options promoted as agricultural options oriented to liquid biofuels create more employment, but forest-based options oriented to electricity and heat production produce more climate benefits. In Brazil, the biofuel sector accounted for about 1 million jobs in rural areas in 2001, mostly for unskilled labor (Moreira, 2006). Mechanization is already ongoing in about 50% of the Center South production (90% of the country's harvest) thus reducing unskilled labor for manual harvest after fire, and producing an environmental benefit. Worker productivity continues to grow and part of the workforce is retrained to skilled higher paying jobs for mechanized operations (Oliveira, 2009).

2.5.5.4 Risks to food security

Liquid biofuel production creates additional demand for agricultural commodities, including foodstuffs that place additional pressure on natural resources such as land and water and thus raise food commodity prices. Lignocellulosic biomass biofuels can reduce it but not eliminate competition. To the extent that domestic food markets are linked to international food markets, even countries that do not produce bioenergy will be affected by the higher prices.

The OECD-FAO Agricultural Outlook (2008) model found that if biofuel production were to be frozen at 2007 levels, coarse grains prices would be 12% lower and vegetable oil prices 15% lower in 2017 compared to expected biofuels increases. Rosegrant et al (2008) estimated that world maize prices would be 26% higher under a scenario of continued biofuel expansion according to then-existing national development plans, and more than 70% higher under a drastic biofuel expansion scenario where biofuel demand is double that under the first scenario (these scenarios are relative to a baseline of modest biofuel development where biofuel production remains constant at 2010 levels in most countries). World prices for wheat, sugar and other crops would increase with greater biofuels production, but would be less than in the case of maize and oilseeds. IFPRI (2008) estimated that 30 percent of the weighted average increase of world cereal prices was attributable to biofuels between 2000 and 2007. The eventual impact of biofuels on prices will depend on the specific technology used, the strength of government mandates for biofuel use, the nature of trade policies that can favour inefficient methods of biofuel production, and the level of oil prices.

The impact of higher prices on the welfare of the poor depends on whether the poor are net sellers of food (benefit from higher prices) or net buyers of food (harmed by higher prices). The poor are a heterogeneous group, with some being net sellers of food while others are net buyers. On balance, the evidence indicates that higher prices will adversely affect poverty and food security, even after taking account of the benefits of higher prices for farmers (Ivanic and Martin, 2008; Zezza et al., 2008). A major study of FAO on the socio-economic impacts of the expansion of liquid biofuels (FAO, 2008b) indicates that poor urban consumers and poor net food buyers in rural areas are particularly at risk. Rosegrant et al., (2008) estimate that the number of malnourished children would increase by 4.4 to 9.6 million under the two above mentioned scenarios.

Higher food prices will have negative consequences for net food-importing developing countries. Especially for the low-income food-deficit countries, higher import prices can severely strain their balance of payments. Food exporting countries will benefit from higher prices, but the number of such countries is limited and they tend to be more developed (e.g. Thailand, Brazil, and Argentina).

Very recent commodity price analysis shows that food has been kept almost constant during the period Jan 2009- Jun 2010, while industrial commodities have increased by around 80%, bringing average commodity prices some 25% higher at the end of the period (The Economist, 2010). What we learn from this information is that it is very difficult to make forecast based in price changes that occurred in a short time spam (1 to 2 years) since agricultural prices are very volatile.

A significant increase in the cultivation of crops for bio-energy implies a close coupling of the markets for energy and food (Schmidhuber, 2007). As a result, food prices may become more closely linked to the dynamics of world energy markets. Political crises that affect energy markets would thus affect food prices. For around one billion people in the world who live in absolute poverty, this situation poses additional risks to food security.

Meeting the food demands of the world's growing population will require an increase in global food production of 70 percent by 2050 (Bruinsma, 2009). This FAO study also estimates that the increase in arable land between 2005/07 and 2050 will be just 4 percent. Given this limited increase, at global scale, competition between food and fuel may not be a serious issue. Increased biofuels production could also reduce water availability for food production (as more water is diverted to production of biofuel feedstocks). Cash crops can represent an additional incomes source and do not necessarily compete with food crops, and may contribute to improving food security (Tefft, 2010). However, there are instances of negative effects of cash crops on food security (Binswanger and von Braun, 1991; von Braun, 1994).

2.5.5.5 Impacts on Rural and Social Development

Growing demand for biofuels and the resulting rise in agricultural commodity prices can present an opportunity for promoting agricultural growth and rural development in developing countries. The development potential critically depends on whether it is economically sustainable without government subsidies. If long-term subsidies are required, there will be fewer government funds available for investment in a wide range of public goods that are essential for economic and social development, such as agricultural research, rural roads, and education. Even short-term subsidies need to be considered very carefully, as once subsidies are implemented they can be difficult to remove. Experience from Latin America shows that governments that utilize agricultural budgets for investment in public goods instead of subsidies experience faster growth, more rapid poverty alleviation, and less environmental degradation (Lopez and Galinato, 2007).

Bioenergy may reduce dependence on fossil fuel imports and increase energy supply security, although the benefits are not likely to be large (FAO, 2008b). Case studies for several Caribbean countries have been completed and indicate large potential benefits (see Section 2.4.6.8). Recent analyses of The use of indigenous resources implies that much of the expenditure on energy provision is retained locally and re-circulated within the local/regional economy, but there are trade-offs to consider. For example the increased use of biomass for electricity production and the corresponding increase in demand for some types of biomass (e.g., pellets) could cause distortions leading to the temporary lack of supply of biomass during periods of high demand. Households are particularly vulnerable in this regard.

The technology and institutions used for biofuels production will also be an important determinant of rural development outcomes. For example, private investors in some instances will look to the establishment of biofuel plantations to ensure security of supply. If plantations are established on non-productive land without harming the environment, then there should be benefits to the economy. It is essential not to overlook the uses of land that is important to the poor. Governments need to establish clear criteria for determining marginal or productive land, and criteria must aim to protect vulnerable communities and female farmers who may have less secure land rights (FAO, 2008b). Research in Mozambique (Arndt et al 2008) shows that an outgrower approach to producing biofuels is more pro-poor, due to the greater use of unskilled labor and accrual of land rents to smallholders in this system, compared with a more capital-intensive plantation approach.

Increased investment in rural areas will be crucial for making biofuels a positive development force. If governments rely exclusively on short-term farm-level supply response, the negative effects of higher food prices will predominate. If higher prices motivate greater investment in agriculture (e.g. rural roads and education, research and development) from public and private sectors, there is tremendous potential for sparking medium and long term rural development. As one example, proposed biofuel investments in Mozambique could increase annual economic growth by 0.6 percentage points and reduce the incidence of poverty by about six percentage points over a 12-year period (Arndt et al, 2008).

The increased use of residues for some feedstocks -such as pellets or used cooking oil- require careful analysis. While residues are presently inexpensive, as the market expands or as other uses are found, the price could change dramatically. For example, used cooking oil in Europe went from a waste product to a valuable commodity. One must also assess the long-term supply picture. For example, beetle-killed timber in British Columbia, Canada is a large source material for pellet manufacture for the European market, but it is not clear for how long will it be available.

2.5.5.6 Trade-offs between social and environmental aspects

Some important trade-offs between environmental and social criteria exist and need to be considered in the future bioenergy development. In the case of sugarcane, the environmental sustainability criteria promoted by certification frameworks (such as the Roundtable for Sustainable Biofuels) favor the mechanization of harvesting due to the emissions from burning the cane in manual systems. Several working organizations are concerned about the fate of the large number of workers that will be displaced by the new systems (Huerta et al, 2010). Also, the mechanized model tends to favor further land ownership concentration in the sector, with the resulting potential exclusion of small/medium scale farmers and reduced employment opportunities for rural workers.

Strategies for addressing such concerns can include (i) support for small/medium size stakeholders lacking own capacity to manage all challenges of meeting the requirements in the certification systems and/or (ii) support aiming at mitigating possible negative socioeconomic effects of outcomes that are found to be unavoidable consequences of the transformation process. For example, there is already an established time plan for the phase out of manual harvesting in the State of São Paulo, which considers the need to develop alternative income possibilities for the seasonal workers that presently earn a substantial part of their annual income based on cutting sugarcane. Implementation of sustainability certification may need to consider that a shift to mechanised harvesting cannot be made too rapidly (Huerta et al. 2010; Oliveira, 2009).

2.5.6 Summary

The effects of bioenergy on social and environmental issues – ranging from health and poverty to biodiversity and water quality – may be positive or negative depending upon local conditions, how criteria and the alternative scenario are defined, and how actual projects are designed and implemented, among other variables.

Climate change and biomass production can be influenced by interactions and feedbacks among land use, energy and climate in scales that range from micro through macro (see Figure 2.5.5).

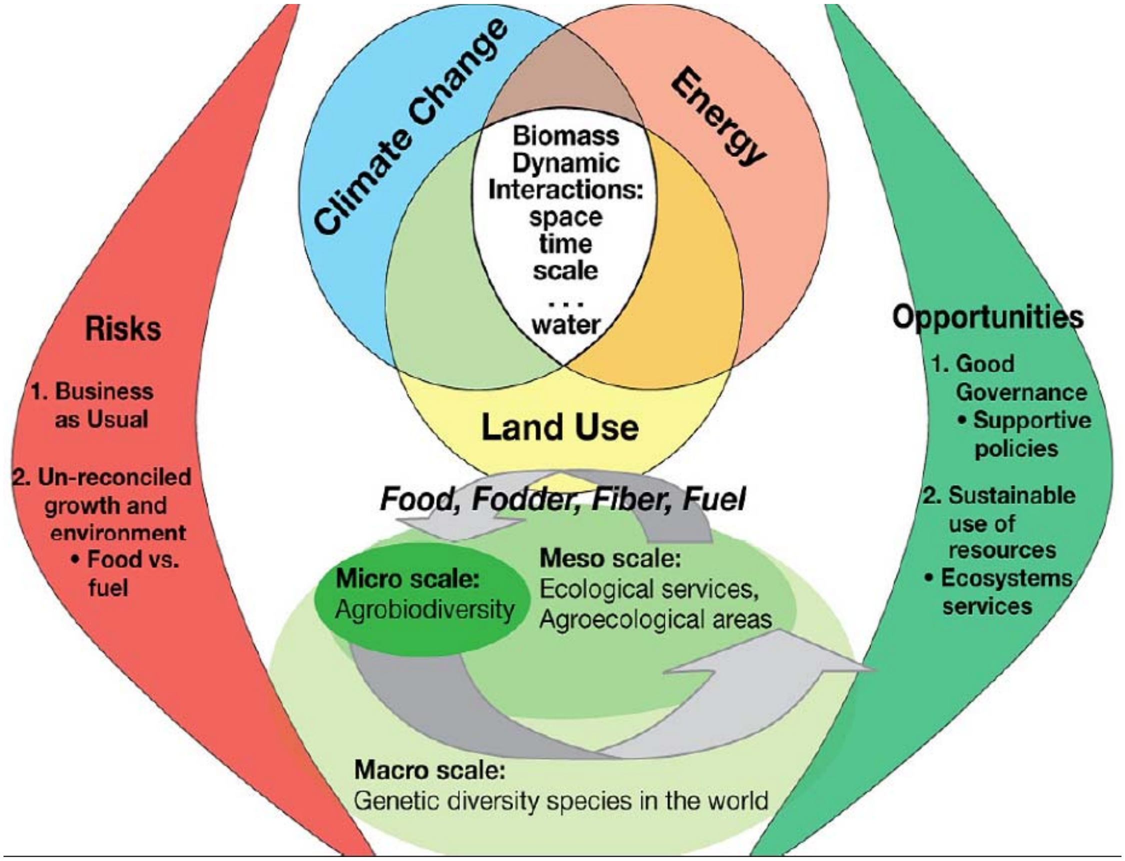

Figure 2.5.5.: Climate Change-Land Use-Energy Nexus. Adapted from Dale et al., submitted and van Dam et al. 2009.

Bioenergy is a part of complex interlinked system whose sustainability is being evaluated, in part, through Lifecycle Assessment (LCA) methodologies analyzing inputs and outputs of the system. In our review of the literature, we found that the attributional LCA analysis of GHGs emissions for several bioenergy systems is known fairly in depth, and is convergent for ethanol and biodiesel in many parts of the world, when consistent boundaries and methodologies such as those for coproduct allocation are employed. The biofuel LCA is compared with the LCA of the fossil (or other) energy system it replaces. Although many studies provide data on GHG emissions savings compared to the fossil system replaced, to the renewable energy produced, and some level of characterization of the amount of renewable energy provided relative to fossil energy employed in the biofuel production, few studies comprehensively analyze the whole chain from feedstock to final energy use. When such studies are available, it was possible to measure bioenergy GHG emissions per unit land area used, a very important measure of land use. Initial studies also report water use throughout the feedstock to final energy use chain. The description of the specific biofuel production (and use) with many functionalities is important. With this information, environmental impact assessments more broadly quantify environmental, ecological, health impacts, landscape habitat and response, and obtain an economic analysis of benefits and impacts.

From this perspective we illustrate improvements in the production of ethanol from sugarcane with time based, show emissions reductions' data, even more as both fuels and electricity are products, in addition to sugar, confirming that a rain fed semi-perennial plant in appropriate climates, produced under mechanized conditions, with an infrastructure and distribution that minimizes losses, achieves substantial GHG reductions – and can make much more contributions in the future. Progress is reported as well in relation to a landscaped environment around rivers to minimize effluent discharges. Similarly, the ethanol production from grains in the Americas and Europe has improved over time through energy efficiency and increased crop productivity, although being annual plants does not enable as good a performance in GHG emissions reductions as perennial plants as sugarcane managed with multi-year ratoons. The bulk of the ethanol production from grain uses natural gas (some biomass) for process heat and some cogeneration. Electricity generation from biomass produces consistently high GHG emissions reductions, even more in cases where methane emissions would otherwise occur. This agreement is for the directly attributional part of the LCA analysis.

As bioenergy production grew more rapidly in the past ten years, in concert with rapidly rising oil and food prices for a period, the consequences of its development throughout the world in terms or land use and impacts on the global economic system were questioned. The initial LCA tool was then coupled to a variety of macroeconomic/econometric models and to biophysical models or actual specific satellite/statistical data to assess the consequences of fuel levels proposed by legislation in several countries to the economic system of agriculture, forestry, and related sectors. We show that initial models were lacking in geographic resolution leading to higher proportions of assignments of land use to deforestation than necessary as the models did not have other kinds of lands such as pastures in Brazil that could be used. Increased model sophistication to adapt to the complex type of analysis required and improved data on the actual dynamics of land distribution in the major biofuel producing countries is now producing results that are converging to lower overall land use change impacts for ethanol production. Examples from Finnish forestry highlights the need to include the dynamics forest stocks. Indeed, the approach that EPA took is, so far, the most complete modeling effort that includes such dynamic aspects. Models and data need to improve and be validated.

Estimates of LUC effects require value judgments on the temporal scale of analysis, on land use under the assumed "no action" scenario, on expected uses in the longer term, and on allocation of impacts among different uses over time. Regardless, a system that ensures consistent and accurate inventory and reporting on carbon stocks is considered an important first step toward LUC carbon accounting.

Bioenergy is a component of the much larger agriculture and forestry systems of the world, and that land and water resources need to be properly managed in concert with the type of bioenergy most suited to the specific region and its natural resources and economic development situation. Bioenergy has the opportunity to contribute to climate mitigation, energy security and diversity goals, and economic development in developed and developing countries alike but the effects of bioenergy on environmental sustainability may be positive or negative depending upon local conditions, how criteria are defined, how actual projects are designed and implemented, among many other factors.

2.6 Prospects for technology improvement, innovation and integration

This section provides an overview of potential performance of biomass-based energy in the future (within 2030) due to progress on technology.

2.6.1 Feedstock production

2.6.1.1 Yield gains

Increasing land productivity is a crucial prerequisite for realizing large scale future bioenergy potentials, provided land becomes available as discussed in section 2.2. Much of the increase in agricultural productivity over the past 50 years came about through plant breeding and improved agricultural management including irrigation, fertilizer and pesticide use. The adoption of these techniques in the developing world is most advanced in Asia, where it entailed a strong productivity growth during the past 50 years, and also in Brazil with sugar-cane. Considerable potential exists for extending the same kind of gains to other regions, particularly Sub-Saharan Africa, Latin America, Eastern Europe and Central Asia where adoption of these techniques was slower (FAO, 2008b). A recent long-term foresight by the FAO expects global agricultural production to rise by 1.5 percent a year for the next three decades, still significantly faster than projected population growth (World Bank, 2009). For the major food staple crops, maximum attainable yields may increase by more than 30% by switching from rain-fed to irrigated and optimal rainwater use production (Rost et al., 2009), while moving from intermediate to high input technology may result in 50% increases in tropical regions and 40% in subtropical and temperate regions. The yield increase when moving from low input to intermediate input levels can reach 100% for wheat, 50% for rice and 60% for maize (Table 2.6.1), due to better control of pests and adequate supply of nutrients. However, one should note that important environmental tradeoffs may be involved under strong agricultural intensification, and that avenues for more sustainable management practices should be explored and adopted (IAASTD, 2009).

Table 2.6.1: Long-term (15-25 years) prospects for yield improvements relative to current levels (given in Table 2.3.1).

Feedstock type	Region	Yield trend (%/yr)	Potential yield increase (2030)	Improvement routes	Ref.
DEDICATED CROPS					
Wheat	Europe	0.7	50%	New energy-orientated varieties	1
	Subtropics		100%	Higher input rates, irrigation.	
Maize	N America	0.7	35%	Genotype optimization, GMOs, higher plantation density, reduced tillage. Higher input rates, irrigation.	
	Subtropics		60%		
	Tropics		50%		
Soybean	USA	0.7	35%	Breeding	2,3
	Brazil	1.0	60%		
Oil palm	World	1.0	30%	Breeding, mechanization	3
Sugar cane	Brazil	1.5	40%	Breeding, GMOs, irrigation inputs	2,3,8
SR Willow	Temperate	-	50%	Breeding, GMOs.	3
SR Poplar	Temperate	-	45%		

Miscanthus	World	-	100%	Breeding for minimal input requirements, improved management	
Switchgrass	Temperate	-	100%	Genetic manipulation	
Planted forest	Europe	1.0	30%	Traditional breeding techniques (selection for volume and stem straightness)	4
PRIMARY RESIDUES					
Cereal straw	World	-	15%	Improved collection equipment; breeding for higher residue-to-grain ratios (soybean).	5,6
Soybean straw	N America	-	50%		
Forest residues	Europe	1.0	25%	Ash recycling.	4,7

References: 1: Fischer, 2001a; 2: IEA Bioenergy, 2009; 3: WWI, 2006; 4: Dupouey et al., 2006; 5: Paustian et al., 2006; 6: Perlack et al., 2005; 7: EEA, 2007; 8: Matsuoka et al., 2009.

These increases reflect present knowledge and technology (Fischer, 2001b; Duvick and Cassman, 1999), and vary across the regions of the world (FAO, 2008b), being more limited in developed countries where cropping systems are already highly input-intensive. Also, projections do not always account for the strong environmental limitations that are present in many regions, such as water or temperature. Biotechnologies or conventional plant breeding could contribute to improve biomass production by focusing on traits relevant to energy production. The plant varieties currently being used for first-generation biofuels worldwide have been genetically selected for agronomic characteristics relevant to food and/or feed production and not for bioconversion to energy. Varieties could be selected with increased biomass per hectare, increased oil or fermentable sugar yields, or characteristics that facilitate their conversion to biofuels. Considerable genetic improvement is still possible including for draught tolerant plants (Nelson et al., 2007; Castiglioni et al., 2008;FAO, 2008d). Doubling the current yields of perennial grasses appears achievable through genetic manipulation such as marker-assisted breeding (Eaton et al., 2008; Turhollow, 1994). Shifts to sustainable farming practices and large improvements in crop and residue yield could increase the outputs of residues from arable crops (Paustian et al., 2006).

Shifts to sustainable farming practices and large improvements in crop and residue yield could increase the outputs of residues from arable crops (Paustian et al., 2006).

2.6.1.2 Aquatic biomass

The general term “algae” can refer to both microalgae and macroalgae (i.e., seaweeds). Together with cyanobacteria (also called “blue-green algae”) these organisms dominate the world’s ocean, contributing to the estimated 350-500 billion metric tons of aquatic biomass produced annually (Garrison, 2008). Of these, oleaginous microalgae have garnered the most attention as the preferred feedstock for a new generation of advanced biofuels. Lipids from microalgae, such as triacylglycerides and free fatty acids, can be converted to fungible, high energy-density biofuels via existing petrorefinery processes (Tran et al., 2010). Certain algal species, such as Schizochytrium and Nannochloropsis, reportedly can accumulate lipids at greater than 50% of their dry cell weight (Chisti, 2007). A realistic yield of unrefined algal oil from algal biomass with a 50% oil content located on the equator was estimated to be 40,470-53,200 L ha-1year-1 which is significantly higher than most terrestrial crops (Weyer et al., 2009). Cyanobacteria have long been cultivated commercially for nutraceuticals (Colla et al., 2007; Lee, 1997) however, the accumulation of substantial amounts of triacylglycerides has not been reported in naturally occurring cyanobacterial strains (Hu et al., 2008). It is likely, though, that biofuels from cyanobacteria, will likely face the same scale-up challenges as eukaryotic microalgae as well as having to deal with an unclear regulatory landscape. Macroalgae also do not accumulate lipids like many microalgal species. Macroalgae synthesize complex polysaccharides from which various fuels could be made.

Microalgae can be cultivated in open ponds and closed photobioreactors (PBRs) located on currently unproductive land (Sheehan et al., 1998; van Iersel et al., 2009). Despite these potential advantages, scaling up of algal biofuels production is not without substantial challenges, both from a feedstock logistics viewpoint (Molina Grima et al., 2003), as well as the cost to produce the biomass itself (Borowitzka, 1999). Closed photobioreactor systems at this point in time are cost prohibitive for large-scale production of algal biomass. While the costs associated with cultivating algae in open pond systems is typically less than that of closed systems, the costs of operating open ponds must also be reduced. Macroalgae are typically grown in offshore cultivation systems (van Iersel et al., 2009). Over a million metric tons of macroalgae are cultivated and harvested every year for human dietary consumption (Zemke-White and Ohno, 1999). A few investigations into the use of seaweed for biofuels production have recently been reported (Ross et al., 2008; Aresta et al., 2005), and cultivation optimization strategies are being explored (Kraan and Barrington, 2005). However, it is unclear how large-scale production of macroalgae for bioenergy will impact marine eco-systems and competing uses for fisheries and leisure, posing zoning and regulatory hurdles at a minimum.

Productivity could reach up to several hundreds of EJ for microalgae and up to several thousands of EJ for macro-algae (Sheehan et al., 1998; van Iersel et al., 2009). Given the large number of algal species in the world, the challenge from the biological side will be to select a starting strain with the appropriate growth and production characteristics. In addition to identifying and isolating appropriate production strains required for large scale cultivation, the engineering of cost effective harvesting and extraction technologies as well as determining the appropriate use of the remaining algae components (proteins and carbohydrates) in the overall process will contribute to lower production costs. It is still difficult to assess the sustainability and economic competitiveness of algal biofuels options. While Figure 2.5.2 shows broad ranges, preliminary technoeconomic estimates and lifecycle assessment, both with large uncertainties, indicate that these fuels could offer the same range of emissions reductions or better, compared to seed oil biodiesel, with successful science and engineering and commercialization (EPA, 2010)..

Some general, but important conclusions taken from the IEA Bioenergy report and the DOE Roadmap work (DOE, 2009 microalgae) are as follows: (i) Microalgae can offer productivity levels above those possible with terrestrial plants. (ii) There are currently several significant barriers to widespread deployment and many information gaps, but there is still significant room for improvement and breakthroughs. (iii) Many different options are still being considered and this is likely to continue with different systems suited to different types of algal organisms, climatic conditions, and ranges of products. Much of the basic information related to genomics, industrial design, and performance is not yet defined. (iv) Cost estimates for algal biofuels production vary widely, but the best estimates are promising at this early stage of the technology development. (v) The cost of producing algae is still too expensive for fuel production alone. The use of algae to produce a range of products for the food, feed and fuel markets via a ‘biorefinery approach’ is likely to prove to be an attractive strategy offering better chances for economic operation than systems aimed at solely producing biofuels. (vi) Lifecycle Assessments (LCA) are inevitably difficult to do at this stage in the development of the technology. However these studies indicate that careful design of systems will be required to ensure that there is a positive energy and carbon balance associated with algae production. Excessive energy requirements for pumping, concentration, and drying must be avoided, along with efficient use of residues and any waste heat generated.

2.6.1.3 Vulnerability and adaptation to climate change

Climate change is expected to have significant impacts on biomass production, causing yields to increase or decrease by up to 20% relative to current levels at 550 ppm CO2, depending on world regions (Easterling et al., 2007). Biomass feedstocks will be affected through either a change of the agro-ecological zones suitable for them or, for those plantations already established, increased environmental stresses and higher risks of yield losses. Since some candidate feedstocks are perennial species with cultivation cycles of 20 or more years, climate impacts should be anticipated for these particular systems, and are likely to be stronger than for annual crops (Easterling et al., 2007). However, there is currently limited knowledge on the impacts of climate change on energy feedstocks.

The largest ecophysiological uncertainty in future production changes is the magnitude of the CO2 fertilisation effect on plant growth, which can cause an enhancement of net primary production of around 20% under doubled free air CO2 concentration, under controlled experimental conditions (Easterling et al., 2007). Most current biogeochemical models assume a strong CO2 fertilisation effect with a levelling off at large atmospheric concentrations, due to .enhanced growth and increased water use efficiency. Indirect effects of climate change such as increased fire risk or the spread of pests cannot be quantified but may also come into play (Easterling et al., 2007).

2.6.1.4 Future outlook and costs

While area expansion for feedstock production is likely to play a significant role in satisfying an increased demand for biomass over the next decades, the intensification of land use through improved technologies and management practices will have to complement this option, especially if production is to be sustained in the long term. Crop yield increases have historically been more significant in densely populated Asia than in sub-Saharan Africa and Latin America and more so for rice and wheat than for maize and sugar cane. Actual yields are still below their potential in most regions (FAO, 2008b). Evenson and Gollin (2003) documented a significant lag in the adoption of modern high-yielding crop varieties, particularly in Africa. Just as increased demand for bioenergy feedstock induces direct and indirect changes in land use, it can also be expected to trigger changes in yields, directly in the production of energy crops and indirectly in the production of other crops – provided appropriate investments are made to improve infrastructure, technology and access to information, knowledge and markets. A number of analytical studies are beginning to assess the changes in land use to be expected from increased bioenergy demand. Even without genetic improvements in sugar cane in Brazil, yields could increases 20 percent over the next ten years simply through improved management in the production chain (Squizato, 2008).

Projections of future costs for biomass production are scant because of their connections with food markets (which are, as all commodities, volatile and uncertain), and the fact that many candidate feedstock types are still in the research and development phase. Costs figures for growing these species in commercial farms are little known yet, but will likely reduce over time as farmers ascend the learning curves, as past experience has shown for instance in Brazil (Wall-Blake et al., 2009). Under temperate conditions, the expenses related to the farm- or forest-gate supply of lignocellulosic biomass from perennial grasses or short rotation coppice is expected to fall under 2.5 US$/GJ by 2020 (WWI, 2006), from a 3-16 US$/GJ range today (see Table 2.3.1). However, another study in Northern Europe reports much higher projections, in a 3.7-7.5 US$/GJ range (Ericsson et al., 2009). These marginal expenses will obviously depend on the overall demand in biomass, increasing for higher demand levels due to the growing competition for land with other markets (hence the notion of supply curves, addressed in section 2.7; see Figure 2.2.5). For perennial species, the transaction costs required to secure a supply of energy feedstock from farmers may increase the production costs by 15% (Ericsson et al., 2009).

2.6.2 Improvements in biomass Logistics and supply chains

Optimization of supply chains includes the role of economies of scale in transport pre-treatment as well as in conversion technologies. Relevant factors include spatial distribution and seasonal supply patterns of the biomass resources, transportation, storage, handling and pre-treatment costs, scale economy of central plants (Nagatomi et al, 2008, Dornburg & Faaij, 2001). Smart combinations of biomass resources over time can help to gain economies of scale and year round supplies of biomass and thus efficient utilization of equipment (Nishii et al, 2005, Junginger et al., 2001, Hamelinck et al., 2005):

Advanced pre-treatment technologies

Torrefied wood is manufactured by heating wood in a process similar to charcoal production. At temperatures up to 160 ºC, wood loses water and little else. Most of its physical and mechanical properties remain intact, particularly its ability to absorb moisture. Torrefied wood typically contains 70% of its initial weight and 90% of the original energy content (Bradley et al, 2009). The moisture uptake of torrefied wood is very limited, varying from 1% to 6% (Uslu et al 2008 Torrefaction serves as a pre-conditioning process, producing uniform quality feedstock which eliminates inefficient and expensive methods to handle feedstock variations and thus make conversion and use of biomass feedstocks more efficient (Anon, 2000). Torrefaction technology is however not yet commercially available, but outlook studies suggest that the overall costs of producing torrefied biomass pellets results in lower production costs of pellets compared to conventional wood pellets, and lower energy costs. Overall energy efficiency of converting wood to torrefied wood pellets may amount over 90% for fully commercial systems.

Advanced pyrolysis processes converts solid biomass to liquid bio-oil, a complex mixture of oxidized hydrocarbons. Although toxic in nature and stabilization of the oil is needed for longer term storage, this liquid product is relatively easy to transport. Although pyrolysis oil production is more expensive and less efficient per unit of energy delivered compared to torrefied wood pellets pyrolysis offers specific advantages, compared with liquid fuels it has an estimated production cost of US$6.5/GJ, when using char and gases for process heat (Bain, 2007). The process allows for separation of a solid fraction (biochar) that contains the bulk of the nutrients of the biomass. With proper handling, such biochars can be used locally to improve soil quality, recycle nutrients and possibly store additional carbon in the soil for longer periods of time while at the same time improving soil properties and fertility. The economic prospects of this route are at the moment however poorly understood and the technology and biochar application need further research and optimization (Laird et al. 2009).

Learning and optimization in the past 1-2 decades in regions as Europe (Scandinavia and the Baltic in particular), North America, Brazil, but also in various developing countries have shown steady progress in market development and lowering costs of biomass supplies (see e.g. Junginger et al. 2006). Well working international biomass markets and substantial investments in logistic capacity are key prerequisites to achieve this (see also section 2.4).

It should however also be noted that while over time the lower costs biomass residues resources are increasingly utilized, more expensive (e.g., cultivated) biomass needs to cover growing demand. This may in some case off-set part of the lower supply costs due to learning and optimization as (E4tech, 2010) concludes that heat generation from pellets in the UK may be more costlier in future (2020) than today due to a shift from local to imported feedstocks. Similar (although limited) effects are found in (Londo et al., 2010) for scenario's of large scale deployment of biofuels in Europe.

2.6.3 Conversion technologies & bioenergy systems

As shown on Table 2.6.2, recent research and development emphasis is focused on producing hydrocarbon fuels from biomass. Among the drivers is the fact that jet fuels require nearly double the energy density of the most common commercial biofuel, ethanol, and more than ten percent higher energy density of biodiesel. In addition, fuels for military applications are also being developed from biomass, which also demand high energy density and strict specifications. Biofuel aviation tests are already ongoing both for commercial and military operations even though the technologies are not cost competitive yet (see, for instance, E4tech, 2009; DOE, 2009 microalgae; DOE, 2009).

There is significant room for research breakthroughs in this area generated by increased scientific understanding of biomass conversion with the increased ability to understand the chemistry, the biology, and the biochemistry at the molecular level with complex biomass materials. Biomass conversion have a broader range of conditions compared with those of conventional petrochemical processes. The presence of many carbon-oxygen bonds enables lower temperature processing leading to the exploration of a variety of conditions for chemical reactions such as mild conditions of aqueous phase reforming, molecular rearrangements such as isomerization and condensation reactions leading to molecular building in the appropriate molecular sizes and properties, as well as exploration of higher reactivity of biomass in vapor phase catalytic reactions (NSF, 2008).

An evolving emerging field is synthetic biology where microorganisms are engineered to produce biofuels – bringing scientific advances and tools from the medical field and high value drug production to the design of high volume fuels and chemicals (Keasling and Chou, 2008). Synthetic biology aims to bring engineering principles of modularization and componentization to the manipulation of genetic circuitry in microorganisms, so that engineering an organism for fuel production is as easy as assembling a computer (Lee et al., 2008). The U.S. Department of Energy (DOE, 2009) is fostering this field from its basic science to nurturing startup companies and partnerships toward development and commercialization.

Table 2.6.3 displays information on relevant bioenergy systems and chains, in various stages of development, which were illustrated in Figure 2.3.1. Where publicly available from the literature cost information is also provided. The technologies from Table 2.6.2 and Table 2.6.3 could be in commercial operation at global level by 2020 to 2030, depending on investments in support of continued research, development, demonstration, and results of first-of-a-kind plants under construction. For each end use of a bioenergy product, Table 2.6.3 presents information about the feedstock, processing technology, examples of country or region developing these technologies, and the estimated production cost, when available, projected usually from the performance of nth plants. Additional information about relevant technology development needs, and general comments, are also provided.

Table 2.6.2 Developing **Biofuels as Direct Replacement of Conventional Hydrocarbon Fuels (Source: E4tech, 2009; IEA ExCo, 2009). See Table 2.6.3 for available cost information.**

Renewable Fuel for Jet Fuel, Diesel, or Gasoline	Feedstock(s)	Conversion process	Development needed
Biomass to liquids (BTL)	Lignocellulosic materials (energy crops, forestry residues, wastes)	Gasification and Fischer Tropsch synthesis	Demonstration of plants at commercial scale
HRJ (Hydrotreated renewable jet) or Renewable Diesel	Conventional oil crops (soy, palm, rapeseed)	Oil extraction and hydrotreating	Deployment of conversion plants
	New oil crops under development: algae, carmelina, jatropha, saltwater farming (halophytes)	Oil extraction and hydrotreating. Whole algae solution could undergo catalytic liquefaction	RD&D on yield improvements, agronomy, and algal systems
'Synthetic hydrocarbons' also called drop-in hydrocarbons[1,2,3]	Nearer term: Sugars from sugar-rich crops like sugarcane or hydrolysis of starch from grains Longer term: Lignocellulosic materials after pretreatment and hydrolysis to mixtures of sugars	Biological syntheses to, e.g., isoprenoids[4,5]	RD&D to prove routes pilot stage
		Chemical catalytic routes for alkanes from aqueous phase reforming that combine hydrogenation and carbon-carbon condensation[6,7]	RD&D to prove routes at the pilot stage[8]
		Fermentation with engineered organisms to Butanol to Butene catalytic conversion to hydrocarbons	RD&D to prove routes at the pilot stage
Pyrolysis derived fuels	Lignocellulosic materials (energy crops, forestry residues, wastes)	Pyrolysis and upgrading through hydrotreating that could be done in an oil refinery[9]. Fossil fuel blendstocks as products[10]	RD&D on upgrading processes
Algal biomass derived fuels -- biodiesel, renewable diesel, HRJ and others	Whole algae, or the residues remaining after algal oil extraction	Routes above such as gasification, pyrolysis; from lipid fraction through esterification biodiesel or renewable diesel by hydrotreatment.	RD&D on production of feedstocks and conversion technologies. Multiple products possible
Biodiesel or Renewable Diesel	Sugars sugar crops or hydrolysis of starch (later lignocellulosic)	Dark fermentation using microalgae to triacyl-glycerides; extraction and esterification or hydro-treating to renewable diesel	RD&D to prove routes at the pilot stage

NSF, 2008; 2. DOE, 2009; 3. Tang, Zhao, 2009;4.Fortman et al., 2008; 5. Renninger and McPhee, 2008; 6. Huber et al., 2005; 7. Gurbuz et al. 2010; 8. Blommel and Cortright, 2008; 9. Holmgren, J. 2009; 10. Brandvold, 2009.

Table 2.6.3. **Table summarizing the state of the art of the main chains for future production of end use biofuels.**

Energy Product and End Use	**Processing**	**Feed-stock**	**Site**	**Efficiency and process economics Eff. = Energy Product Energy/Biomass Energy**	**% GHG reduction from fossil reference**	**Technical Advances**	**Production Cost by 2030 (US$/GJ)**	**Industrial Development**
Ethanol/ Transport	Separate Hydrolysis/ Fermentation	Ligno-cellulosic Barley straw	USA Finland	Eff. = 0.49 for wood and 0.42 for straw; includes integrated electricity production of unprocessed components[1]. Barley straw steam explosion followed by hydrolysis and fermentation estimated current production cost at $30/GJ [9]	NA	Efficient C5 conversion[2-4] Significant amount of investment in R&D[5] Engineering of enzymes using advanced biotechnologies[6]	8.5 to 10.5[1]	Many demonstration and pilots on various parts of the processes under way. Key are enzyme costs and pretreatment
	Simultaneous Saccharification &Fermentation						30[9] (Finland barley straw)	
	Consolidated Bioprocessing					lignin dissolution to produce a cellulose-rich residue[7]	13.5 to 16 [8] benchscale	
	Simultaneous Saccharification and Fermentation	Ligno-cellulosic	USA	Process efficiencies in kg/gallon for poplar, miscanthus, switchgrass, corn stover and wheat are: 14, 12, 10, 10, and 9, respectively. Plant sizes 1500 to 1000 tonnes/day. Raw material about 50% of total cost.[10]	83-88 Depending on co-product credit method[25]	Process integration - capital costs per installed liter of product range from $0.9 to $1.3 for plants of 150 to 380 million liters per annum. (2020 estimates)	18-22[10] (U.S. costs for wheat straw to poplar) Costs from pilot data	Several pilots and 1st commercial plants under way
		Bagasse	Brazil	Standalone plant[35] 370 L/t dry (ethanol) + 0.56 kWh/L EtOH (electricity)	86[36]	Improvements in mechanical harvest of sugarcane residues (already occurring)	6[35] w/o feed cost 15[35] w/ feed cost	
Hydro-carbons: gasoline/ diesel/jet fuel/waxes Transport	Gasification followed by Fischer-Tropsh process - Biomass to Liquids	Ligno-cellulosic	USA		91 [26]	BCCS for CO2 from processing	24 to 30[11]	One first commercial plant (wood) under way. Many worldwide demonstration & pilots processes under way.
			US	Eff.= 0.52 w/o CCS and 0.5 w/CCS with electricity coproduction of 35 and 24 MWe. 4000 tons/day of switchgrass. Plant cost ~$650 million		Gas clean up costs and scale. 2020 cost projections; could decrease with increased volume	25[10] (w/o BCCS)[10] 30[10] (w/ BCCS)	
	Fischer-Tropsh	Ligno-cellulosic	EU	via biomass gasification and subsequent syngas processing	90 [27]	Diesel without BCCS	14 to 18[5]	
Alcohols or bioplastics	Gasification followed by bioprocessing	Ligno-cellulosic	US/EU/ Canada	Syngas fermentation to ethanol or other alcohol; polyalkanoates from syngas by bacterial or other systems	NA	NA	NA	Exploratory phase to pilot (ethanol)

Energy Product and End Use	**Processing**	**Feed-stock**	**Site**	**Efficiency and process economics Eff. = Energy Product Energy/Biomass Energy**	**% GHG reduction from fossil reference**	**Technical Advances**	**Production Cost by 2030 (US$/GJ)**	**Industrial Development**
Renew-able Diesel/Jet Fuel Transport	Hydrogenation	Large variety of plant oils, animal fats	Many countries	Technology well known. Cost of feedstock is the barrier. Lower cost animal fats' processing under way	63-130 Depending on co-product credit method[26]	Feedstock costs drive this process. Process is standard in petrochemical operations	15-17[12] 17-18[34] Feed cost most important	Demonstrations and product tests in U.S., Brazil, EU. A few flights on biojet fuel from various plant oils conducted[33]
Fuel/ Power	Gasification/ Synthesis	Ligno-cellulosic	USA/ EU	Combined fuel and power production possible. Power at $0.07/kWh (2008) in Finland[13]	NA	BCCS for CO2 from processing	7 to 9.5[11]	NA
Bio-Butanol Transport	Fermentation; product compatible with gasoline infrastructure	sugar/ starch	USA/ EU	The development of an integrated system for biobutanol production and removal may have a significant impact on commercialization of this process using the solvent producing *Clostridia*[14] - initial acetone, butanol ethanol (ABE) fermentation is costly.	5-31% Depending on co-product credit method[29]	Recent developments [15, 16] lead to higher selectivity to butanol: e.g., mutated strain of *Clostridium beijernekei* BA101, or protein engineering in E. coli to increase selectivity and downstream processing of biobutanol. Alternatively a dual fermentation process to buryric acid and reduction to ethanol (Dual). Estimated production costs include return on capital[17]	Nearer term production costs from 29 for ABE to 22 for mutated Clostridia and 22 for Dual process[17] 18[18]	Large and small companies and ventures pursuing different routes. Gasoline additive and also jet fuel applications are being pursued.
	Gasification	Ligno-cellulosic	USA/ EU	Catalytic process for synthesis of predominantly butanols	NA	Estimated production costs include return on capital [17]	12-15 [17]	
Ethanol primarily Transport	Gasification/ Synthesis	Ligno-cellulosic	USA	Gasification followed by catalytic synthesis of ethanol and smaller amounts of propanol and butanol. Catalyst development and syngas cleaning issues	88 [30]	170 Million l per year plant (Ref 12 varies size).	12[12] to 15[18]	
Hydrogen Transport	Gasification/ Syngas processing	Ligno-cellulosic	USA/ EU	Combined fuel and power production possible	88 [30]	Research in gasification as basis for hydrogen production for fuel cells[19]	6 to 9.5 [19] 6[20] to 12[12]	R&D stage
Methane Heat, Power or Transport	Gasification/ Methanation	Ligno cellulosic	EU/ UK	Combined fuel and power production possible	98 [27]	RD&D on gas clean up and methanation catalysts	15.5 [21]	RD&D stage

Energy Product and End Use	Processing	Feed-stock	Site	Efficiency and process economics Eff. = Energy Product Energy/Biomass Energy	% GHG reduction from fossil reference	Technical Advances	Production Cost by 2030 (US$/GJ)	Industrial Development
Methanol	Gasification/ Synthesis	Ligno-cellulosic	US/ EU	Combined fuel and power production possible	90 [27]	Methanol and dimethylether production possible in various configurations that coproduce power	12 to 18 [11]	RD&D stage
CHP	Integrated Gasification Combined Cycle	Ligno-cellulosic	World-wide	In district heat production, the power-to-heat ratio of this concept is 0.8 – 1.2, the power production efficiency 40-45 % and the total efficiency 85 to 90 %. Investment 1200$/kWh*th*. Feedstocks wood residues in Finland[22]	96 [31]	Gas cleaning, increased efficiency cycles, cost reductions	8 to 11[11]	Actively pursued with many demonstrations worldwide
Algal Biodiesel or Renew-able Diesel	Lipid production, extraction, and conversion to biofuel. Remainder of algal mass can also be converted to fuels through other processes	Micro-algae	USA/EU/ Israel	Assuming biomass production capacity of 10,000 t/yr, cost of production per kg is $0.47 and $0.60 for photobioreactors and raceways, respectively.[23]	68-89 Scenarios for open pond and bio-reactor[32]	Assuming[32] biomass contains 30% oil by weight, cost of biomass for providing a liter of oil would be $1 to $3 and $1.5- to $5 for algae of Low Productivity =2.5 g/m^2/day or High Productivity=10 g/m^2/day in open ponds or photobiological reactors (PBR)	Preliminary Results 95 or more[23] 30-80[32] for open ponds 50-140[32]for PBR going from low to high productivity	R&D actively pursued by companies small and large including pilots pursuing jet and diesel fuel substitutes.

1UK DFT, 2008; 2Jeffries, 2006; 3Jeffries et al., 2007; 4Balat et al, 2008; 5Sims et al, 2008; 6 Bom and Ferrara, 2007; 7 Tuskan, 2007; 8Kumar et al, 2008; 9 von Weyman, 2007; 10 NRC, 2009; 11 IEA Bioenergy: ExCo,2007; 12 Bain 2007; 13 McKeough et al. 2008; 14 Wu et al., 2007;15 Ezeji et al., 2007a;16 Ezeji et al., 2007b; 17 Cascone 2008; 18 Tao and Aden 2009; 19Riegelhaupt et al., 2009; 20 Hoogwijk, 2004; 21 Sustainable Transport Solutions 2006; 22 Helynen et al. 2002; 23 Chisti, 2007; 24Pienkos, Darzins 2009; 25. Wang, 2010; 26. Kalnes et al., 2009; 27. Edwards et al., 2008; 28. Huo et al., 2009; 29. Wu et al., 2007; 30. Laser et al., 2009; 31. Daugherty, 2001; 32. IEA, 2010; 33. E4tech, 2009; 34. EPA, 2010; E4tech, 2009; 34. EPA, 2010; 35. Seabra et al., 2010; 36. Macedo and Seabra, 2008.

2.6.3.1 Liquid Fuels

Gasification of solid biomass is a promising technology for production of power and or heat based in the use of solid biomass, with high efficiency gains expected especially in the case of polygeneration with Fischer-Tropsch fuels (Williams et al., 2009).

Biotechnology can be applied to improve the conversion of biomass to liquid biofuels. Several strains of micro-organisms have been selected or genetically modified to increase the efficiency with which they produce enzymes (FAO, 2008d). Many of the current commercially available enzymes are produced using genetically modified (GM) micro-organisms where the enzymes are produced in closed fermentation tank installations (e.g., Novozymes, 2008). The final enzyme product does not contain GM micro-organisms (The Royal Society, 2008) suggesting that genetic modification is a far less contentious issue here than with GM crops.

Coupled to improved corn ethanol facilities or any other biomass processing method that releases concentrated forms of CO2, coproduct CO2 utilization is likely to continue. Most of the ethanol plants, because of the low commercial value of CO2, simply vent it into the air. CO2 capture from sugar fermentation to ethanol is possible (Mollersten, et al., 2003). The experience of ethanol manufacturers from corn of supplying CO2 for carbonated beverages, flash freezing meet, and enhanced oil recovery of depleted fields may be useful now in the biological carbon sequestration BCCS area. A few companies are demonstrating these concepts in the United States such as the Midwest Geological Sequestration Consortium will inject nearly a million tonne of CO2 from an ethanol plant over three years into the Mount Simon sandstone formation in central Illinois. An evaluation of the impact of this technology ((S&T)2 Consultants Inc., 2009) showed that it could reduce the life-cycle GHG emissions of ethanol by 70% at the expense of degrading its energy balance by only 3.5% (see Table 2.5.2 for performance in different functional units).

Internationally, there is an increased interest in the commercialization of lignocellulose to ethanol technology (a 2nd generation pathway). It involves a pre-treatment to separate and partially hydrolyze fibers, usually with acid solutions or steam explosion, to release cellulose and hemicellulose compounds. The resulting sugar stream can then be fermented, using improved methods to allow both hexose and pentose sugars to be fermented simultaneously into ethanol. Research efforts have improved yields and reduced the time to complete the process, and a total of 16 plants were under construction in the USA in 2009 (US Cellulosic, 2009). Nevertheless, attempts to economically transform cellulose in sugars date back at the start of the 20th-century. It is expected that, at least in the near to medium-term, the biofuel industry will grow only at a steady rate and encompass both 1st- and 2nd-generation technologies that meet agreed environmental, sustainability and economic policy goals. The transition to an integrated 1st- and 2nd generation biofuel landscape is therefore most likely to encompass another decade or two (Sims et al, 2008).

Regarding diesel substitution, the difficulty to reduce cost through the first generation process (see Table 2.3.3 for examples of conditions) suggests as a possible alternative the thermo-chemical route. The thermo-chemical route is largely based on existing technologies that have been in operation a number of decades. Hydrogenation technologies have already produced significant quantities of direct diesel substitutes for testing. However, their costs are also highly dependent on the plant oil cost and of the subsidies. Using lignocellulosic materials would lead to the most cost effective options. Some routes produce and upgrade liquids from fast pyrolysis processes (see Table 2.6.2) while others employ the versatile gasification of the biomass, producing a clean gas of an acceptable quality and the high intrinsic cost of the process. Gasification elements of the thermo-chemical platform for the production of biofuels are close to commercial viability today using various technologies and at a range of scales (see Table 2.6.3), although reliability of the process is still an issue for some designs. Another area where some progress may be expected is the possibility of using biomass residues from vegetable oil feedstocks as a source of energy. The utilisation of straw to produce process heat and power would make a strong contribution to the total net energy supply from crops (BABFO, 2000).

There is currently no clear commercial or technical advantage between the biochemical and thermochemical pathways for liquid biofuels, even after many years of RD&D and the development of near-commercial demonstrations (Foust et. al., 2009). Both sets of technologies remain unproven at the fully commercial scale, are under continual development and evaluation, and have significant technical and environmental barriers yet to be overcome. Given the uncertainties in the estimates, the various routes are not distinguishable in costs (McAloon et al., 2000; Hamelinck et al., 2005, Kumar et al., 2008). Alternative technologies for diesel and gasoline substitution include biomass pyrolysis oil upgrading in conjunction with hydrodeoxygenation and catalytic upgrading (de Feber and Gielen, 1999). Proof of principle exists for this route for corn stover-derived pyrolysis oils and through the examples shown on Tables 2.6.2 and 2.6.3.

2.6.3.2 Gaseous Fuels

Anaerobic digestion New technologies like fluorescence in situ hybridisation (Cirne et al., 2007) allows the development of strategies to stimulate hydrolysis further and ultimately increasing the methane production rates and yields from reactor-based digestion of these substrates (FAO, 2008d). A range of other biotechnologies are also being applied in this context, such as the use of metagenomics (i.e. isolating, sequencing and characterising DNA extracted directly from environmental samples) to study the micro-organisms involved in a biogas producing unit in order to improve its operation.[6] Recently marine algae have also been studied for biogas generation (Vergana-Fernandez, 2008). These advances could lead to significant cost reductions in the production of methane from a variety of waste streams combined, with a higher proportion of lignocellulosic materials. Control and automation technologies may make increase reliability of this technology and along with improved gas clean up and upgrading could make gas injection to natural lines (stand alone or grid) a more widespread application at small or large scales.

Microbial fuel cells using organic matter as a source of energy are being developed for direct generation of electricity, through what may be called a microbiologically mediated oxidation reaction. This implies that the overall conversion efficiencies that can be reached are potentially higher for microbial fuel cells compared to other biofuel processes. Microbial fuel cells could be applied for the treatment of liquid waste streams (Rabaey and Verstraete, 2005.

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[6] (See, for instance, http://www.jgi.doe.gov/sequencing/why/99203.html)

Synthesis gas Progresses in scale-up, exploration of new and advanced applications, and efforts to improve operational reliability, have identified several hurdles to advance the state-of-the-art of biomass gasifiers. They include among others handling of mixed feed stocks, minimising tar formation in gasification, tar removal, and process scale-up (Yokoyama and Matsumura, 2008). To tackle the problem of tar content, particularly for power generation, multistage gasification systems (BMG) technologies are being designed and developed to produce Medium Calorific Value (MCV) gas (Fargernas et al., 2006).

2.6.3.3 Biomass with CO2 capture and storage (CCS): negative emissions

Biomass-CCS (Obersteiner et al., 2001; Yamashita and Barreto, 2004; Mollersten et al., 2003; Rhodes and Keith, 2007, Pacca and Moreira, 2009) could substantially change role of biomass-based mitigation. Biomass-CCS may be capable of cost-effective indirect mitigation—through emissions offsets—of emission sources that are expensive to mitigate directly (Rhodes and Keith, 2007). More generally, the most expensive emissions to abate directly could be mitigated indirectly with offsets from biomass-CCS systems deployed wherever (in the world) they are least expensive.

2.6.3.4 Biorefineries

The concept of biorefining is analogous to current petroleum refining, which leads to an array of products including liquid fuels, other energy products and chemicals (NREL, 2009; Kamm, Gruber and Kamm, 2006). Although the biofuel and associated co-products market are not fully developed, first generation operations that focus on single products (such as ethanol and biodiesel) are regarded as a starting point in the development of sustainable biorefineries, mainly the ones using sugar cane where electricity is usually generated and even exported to the grid (EPE, 2008). Advanced or second generation biorefineries are developing on the basis of more sustainably-derived biomass feedstocks, with a further essential feature being the enhanced integration of energy and material flows. These biorefineries optimize the use of biomass and resources in general (including water and nutrients), while mitigating GHG emissions (Ragauskas et al., 2006).

2.6.3.5 Bio-based products

Bio-based products are defined as non-food products derived from biomass (e.g., from plants, algae or biological waste from households). The term is typically used for new non-food products and materials such as bio-based plastics lubricants, surfactants, solvents and chemical building blocks. Traditional paper and wood products, but also biomass as an energy source are generally excluded (EU Commission Report, 2007). In today's chemical and petrochemical industry, plastics represent 73% of the total petrochemical product mix, followed by synthetic fibres, solvents, detergents, and synthetic rubber (Gielen et al., 2008). These product categories, and in particular plastics and fibres, can therefore be expected to play a pivotal role among the bio-based products.

The four principal ways of producing polymers and other organic chemicals from biomass are: (i) Direct use of several naturally occurring polymers usually modified with some thermal treatment, chemical derivatization, or blending. (ii) Convert biomass thermochemically (e.g., pyrolysis or gasification), followed by synthesis and further processing. (iii) Convert biomass-derived sugars or other intermediates using fermentation processes (for most bulk products) or enzymatic conversions (mainly for specialty and fine chemicals). (iv) Bioproduction of polymers or precursors in genetically modified field crops such as potatoes or miscanthus.

Many bio-based plastics and other bio-based products are likely to be produced in energy self sufficient ways and could deliver additional energy using renewable biomass, thereby completely replacing fossil energy sources. As a consequence, a biorefinery could actually be carbon neutral. This is not yet the case today. However, it can be expected that the energy use and the concomitant impacts related to biomaterials production will decrease in future not only as a consequence of technical progress within these processes but also due to the use of cleaner grid power.

A study carried out in 2009 (Shen et al., 2009) estimated the worldwide production of recently emerging bio-based plastics is expected to grow from less than 0.4 million tonnes in 2007 (and expected 2.3 Mt in 2013, see above) to 3.45 Mt in 2020 (now potentially delayed). Model calculations for Europe (EU-25) for an extended timeframe until 2050 show largely diverging results: in case of disadvantageous conditions (i.e., high prices for fermentable sugar and low fossil fuel process) bio-based polymers and chemicals hardly emerge while under favourable conditions (low prices for fermentable sugar, large fossil fuel process increasing up to US$ 85/barrel and large growth of the sector) approximately 110million tonnes of (fermentation-based) could be produced in EU-25 (Dornburg et al., 2008; see also Hermann et al., 2007b). Compared to frozen efficiency this would offer savings by 2050 of up to nearly 40% for starch as feedstock and up to 67% for lignocellulosic feedstocks.

For the production of synthetic organic materials, land use typically ranges from 0.2 to 0.35 hectares/tonne, with larger land requirements for specific products (e.g., nearly to 0.5 hectares/tonne for polyethylene; Patel et al., 2006). Under the assumption producers of bio-based polymers and chemicals will minimize their resource requirements, at productivity of 0.15 hectares/tonne, an area of 75 million hectares globally around by the year 2020 or to 15-30 EJ, could lead to value added products.

Given the early stage of development, the abatement costs differ substantially. For high-value starch plastics with a large content of petrochemical compounds, GHG abatement costs may today be in the order of US$ 500/t CO_2 and even more while simple starch/polyolefin blends may be sold at lower prices than petrochemical polyolefins, resulting in negative abatement costs (win-win situation). However, the latter type of material has less attractive material properties and is therefore quite limited regarding its application potential. The current abatement costs related to polylactic acid are estimated at US$ 100 to US$ 200 per tonne of abated CO_2. Today's abatement costs related to bio-based polyethylene, if produced from sugar cane based ethanol, may be in the order of US$ 100/t CO_2 or lower.

2.6.4 Conclusions

Estimated production costs of a variety of these advanced technology products (see Table 2.6.3) could become competitive with the price of fossil derived fuels with continued RD&D. Since many of the options require a much more difficult set of pretreatment of the biomass material than the starch/sugar counterparts, overcoming this recalcitrance is of paramount importance. Ongoing science and technological developments are continuing to overcome this significant challenge. Once unlocked, these biomass derived sugars could expand the range of biomass derived products that can be made and truly become the renewable carbon “petroleum”. Science and technology of the past ten years shows that chemical, catalytic, biological syntheses and biochemical routes can make ethanol, simple alcohols, as well as any carbon based fuel molecule present in today’s gasoline, diesel and jet fuel. This versatility is important as there are potential substitutes for gasoline (electric vehicles or electric drives in hybrids) but there are many applications that require high energy density fuels.

Sugars are not the only intermediates from which today’s set of fuels can be derived. Gasification is another route that unlocks the potential of a more developed catalytic chemistry and engineering that is already in practice today with coal and natural gas to be applied to biomass. Should the carbon capture and storage technologies under investigation to sequester fossil carbon reach commercialization, the companion biomass routes will enable renewable carbon to be added to fossil carbon sequestration (see Figure 2.5.1). Newer discoveries of transforming pyrolysis oils, which maintain most of the energy of the wood in liquid form for processing, in a centralized or distributed manner, open a route to utilizing petroleum processing facilities on biomass feedstocks. Decentralized routes can provide rural development opportunities to countries small and large.

Significant progress has been made in utilizing organic wastes from various sources as a source of biomethane. European countries are ahead in the utilization of these routes. These natural gas supplements or substitutes are important fuels where natural gas use is prevalent in the specific country matrix and for diversification of energy sources.

While the science and the technology are moving and indicating substantial potential, it will not be achieved unless the demonstration, first commercial, and follow up plants continue to be demonstrated on an integrated basis. There are many parts of the new bioenergy chains that have not been demonstrated for the types of processes discussed here. The demonstration and commercialization will enable better knowledge of production costs and decreased risk for investors in these technologies. These efforts are expensive but required for the development of broad range of biomass derived products. Industry is already taking on the development of several new biobased products because of their properties and the need to address alternative resources that could be or become less expensive than their conventional counterparts. Energy research needs to continue addressing key barriers – one of which is the integration of the overall system from seedling to the final emissions of last product use (or reuse or recycle as in cascading uses of biomass products) in conjunction with measures of overall system sustainability as discussed (see Table 2.5.2). Technology development mindful of the environmental and social aspects described in Section 2.5 can deliver sustainable bioenergy technologies for the world at large.

Table 2.7.1: Estimated geographical potential of energy crops for the year 2050, at abandoned agricultural land and rest land at various cut off costs (in U$2005) for the two extreme land-use scenarios A1 (e.g., high crop growth intensity and high trade in 2050) and A2 (e.g., low crop intensity growth and low international trade in 2050) [Hoogwijk et al., 2009]

Region	A1			A2		
	> 1 $ GJ^{-1}	> 2 $ GJ^{-1}	> 4 $ GJ^{-1}	> 1 $ GJ^{-1}	> 2 $ GJ^{-1}	> 4 $ GJ^{-1}
Canada	0	12.9	16.2	0.0	9.0	10.7
USA	0	20.2	38.5	0.0	7.8	21.2
C. America	0	7.9	14.7	0.0	2.3	3.3
S.America	0	13.3	83.3	0.0	6.0	16.8
N.Africa	0	1.0	2.3	0.0	0.8	1.5
W Africa	7.5	29.9	32.3	9.0	16.6	17.6
E. Africa	9.2	27.0	27.7	4.1	7.0	7.3
S.Africa	0	14.2	18.8	0.1	0.3	0.8
W.Europe	0	3.4	13.0	0.0	6.3	14.2
E. Europe	0	7.7	10.1	0.0	7.0	7.1
F.USSR	0	89.1	96.3	0.9	47.5	52.8
Middle East	0	0.1	3.4	0.0	0.0	1.5
South Asia	0.1	13.7	17.3	0.7	9.3	11.1
East Asia	0	18.5	72.1	0.0	0.0	6.6
S. East Asia	0	10.0	11.0	0.0	7.8	7.9
Oceania	0.8	37.9	39.9	1.8	18.8	20.4
Japan	0	0.0	0.1	0.0	0.0	0.0
Global	17.6	306.8	496.8	16.6	146.6	200.7

2.7 Cost trends

2.7.1 Determining factors

Determining the costs of production of energy (or materials) from biomass is complex because of the regional variability of the costs of feedstock production and supply and the wide variety of biomass – technology combinations that are either deployed or possible. Key factors that affect the costs of bioenergy production are:

- For crop production: the cost of land and labor, crop yields, prices of various inputs (such as fertilizer), supply of water, and the management system (e.g., mechanized versus manual harvesting).
- For the supply of biomass to a conversion facility, spatial distribution of biomass resources, transport distance, mode of transport and the deployment of pre-treatment technologies (early) in the chain are key factors. Supply chains ranges from use on-site (e.g., fuel wood or use of bagasse in the sugar industry, or biomass residues to other conversion facilities) up to international supply chains with shipping pellets or liquid fuels such as ethanol.

- For final conversion to energy carriers (or biomaterials) the scale of conversion, interest rate, load factor, production and value of co-products and costs of energy carriers (in the production facility) required for the process are key factors that vary between technology and location. Types of energy carrier used in the process influence the climate mitigation potential.

Biomass supplies are, as any commodity, subject to pricing mechanisms. Biomass supplies are strongly affected by fossil fuel prices (see, for instance, global trade models of the OECD, Global Trade Analysis Project of Purdue University) as well as agro-commodity and forest product markets. Although in an ideal situation demand and supply will balance and production and supply costs provide a good measure for actual price levels, this is not a given (see also Section 2.5.3 discussions on land use change). At present, market dynamics determines the costs of the most important feedstocks for biofuels, such as corn, rapeseed, palm oil and sugar. For wood pellets, another important fuel for modern biomass production which is internationally traded, prices have been strongly influenced by oil prices (since wood pellets partly replace heating oil) and by supportive measures to stimulate green electricity production, such as feed-in tariffs of co-firing. (see, e.g., Junginger et al., 2008 and Section 2.4). In addition, prices of solid and liquid biofuels are determined by national settings and specific policies and the market value of biomass residues is often determined by price mechanisms of other markets for which there may be alternative applications influenced by national policies (see Junginger et al., 2001).

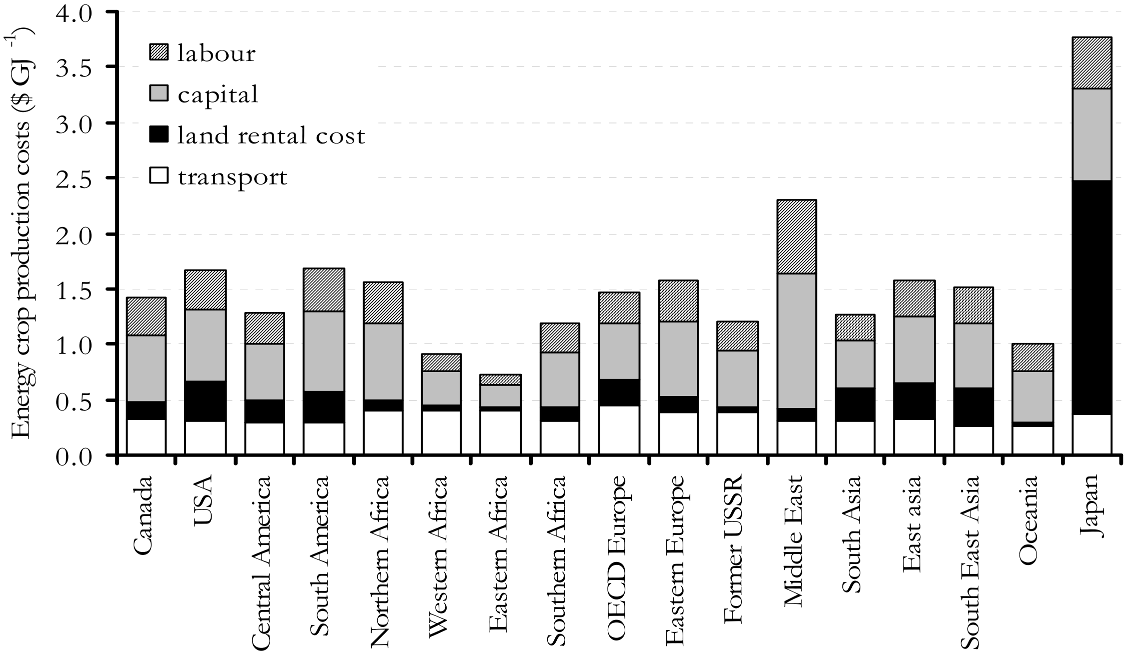


Figure 2.7.1: Cost breakdown for energy crop production costs in the grid cells with the lowest production costs within each region for the A1 scenario in year 2050 (Hoogwijk et al., 2009).

On a global scale and longer term, the analyses of Hoogwijk et al. 2009 provide a long-term outlook of potential biomass production costs (focused on perennial cropping systems) on the long term, related to the different SRES scenario's (see Table 2.7.1, and Figure 2.7.1). Land rents, although a smaller cost factor in most world regions, is made dependent on intensity of land use in the underlying scenarios. Based on these analyses, a sizeable part (100 – 300 EJ) of the technical biomass potentials on long term could lay in a cost range around U.S. $2.4/GJ.

Table 2.7.2: Generic overview of performance projections for different options to produce heat and power from different biomass resource categories on shorter (~5) and longer (>~20) years (e.g., based on: Hamelinck and Faaij, 2006; Faaij, 2006; Bauen et al., 2009b; IEA Bioenergy, 2007).

Biomass feedstock	**Heat**		**Electricity**	
	Short term; roughly stabilizing market	Longer term	Short term; strong growth market worldwide	Longer term; growth may stabilize due to competition of alternative options
Organic wastes (i.e. MSW etc.)	Undesirable for domestic purposes (emissions); industrial use attractive; in general competitive.	Especially attractive in industrial setting and CHP. (Advanced combustion and gasification for fuel gas)	<3 – 5 U$ct for state-of-the art waste incineration and co-combustion as well as digestion of wet organic wastes. Economics strongly affected by tipping fees and emission standards.	Similar range; improvements in efficiency and environmental performance, in particular through IG/CC technology at large scale.
Residues: Forestry Agriculture	Major market in developing countries (<1-5 U$/kWhth); stabilizing market in industrialized countries.	Especially attractive in industrial setting and CHP. Advanced heating systems (domestic) possible but not on global scale	4-12 U$ct/kWh (see below; major variable is supply costs of biomass); lower costs also in CHP operation and industrial setting depending on heat demand.	2-8 U$ct/kWh (see below; major variable is supply costs of biomass)
Energy crops: (perennials)	N.A.	Unlikely market due to high costs feedstock for lower value energy carrier; possible niches for pellet or charcoal production in specific contexts	6-15 U$ct/kWh High costs for small scale power generation with high quality feedstock (wood) lower costs for large scale (i.e. >100 MWth) state-of-the art combustion (wood, grasses) and co-combustion.	3-9 U$ct/kWh Low costs especially possible with advanced co-firing schemes and BIG/CC technology over 100-200 MWe.

As discussed in Sections 2.3 and 2.6, biomass energy systems are very flexible and can provide wide range of different energy and other products. The bioenergy production costs vary depending on feedstock type, conversion technology and scale, type of process energy used, and final energy carrier produced and coproducts.

Table 2.7.2 summarizes literature data for power and heat from various sources of literature for a variety of systems and scales of production in the near and longer term. In Table 2.7.3 we summarize the estimated production costs collected from various references in the literature and from a variety of countries in Sections 2.3 and 2.6. We did not perform a harmonization study on these various costs but reported them from the literature. As many of the technologies are under development in 2.6, cost knowledge only improves with demonstrations and commercial implementation.

Table 2.7.3: Global overview of current and projected select bioenergy technology estimated production costs. For technology performance data and references see Tables 2.3.3 and 2.6.3

End Use	Select Bioenergy Technology	Energy Sector (Electricity, Thermal, Transport)*	Present Estimated Production Costs (US$)	2020-2030 Estimated Production Costs (US$)
HEAT	Fuelwood and charcoal direct use (traditional)	Thermal	6.3-9.6/GJ	1-6/GJ
	Cookstoves (primitive and advanced)		0-8/GJ	N/A
	Smaller and large scale boilers		1-12.5/GJ	N/A
ELECTRICY	CHP in key industries (paper & pulp, sugar)	Electricty (some options CHP)	4.8/GJ (BR, sugarcane)	8.5-11/GJ
	Combustion (large and small), gasification (small), and co-firing based stand alone power generation		4.2-10/GJ (large) 1-4/GJ gasif.(small, India)	6-8/GJ
	Digestion (larger scale)		20-28/GJ	N/A
	Gasification based power generation (larger scale; BIG/CC)	Could be combined with fuels for Transport (CCS possible)	Not commercially available	7-9.5/GJ
FUELS	Sugar cane based ethanol production	Transport Fermentation routes (CCS possible)	10-15/GJ (BR)	9-10/GJ (BR)
	Corn based ethanol production		20-21/GJ (US)	18/GJ (US)
	Wheat based ethanol production		41/GJ (EU)	Approx. 39/GJ
	Soy, rapeseed, and palm based biodiesel production	Transport (heavy duty) and electricity in developing countries (includes raw oil)	23.5-49/GJ (US)	25-37/GJ
	Jatropha based biodiesel production		N/A	15-25/GJ (Feed 2.9/GJ)
	Plant oil or biomass pyrolysis oil derived hydrotreatment/hydrocracking to gasoline, diesel, and jet fuel (Drop in substitutes)	Multimodal Transport: Gasoline, Diesel, and Jet Fuels and a variety of coproducts (CCS possible)	Not commercially available	15-18/GJ Renewable Diesel
	Lignocellulose sugar-based ethanol, butanol, or renewable gasoline, diesel, and fuel production (can be equiped with CCS). Can also use sugarcane, corn, wheat and other crops.		Not commercially available	8.5-17/GJ (US/EU) (for lignocellulosic ethanol); 6-15 (BR) bagasse
	Lignocellulose based synfuel production (i.e., synthetic diesel, MeOH, DME, H2; and fermentation of biological routes to ethanol or plastics).		Not commercially available	12-18/GJ (US/EU) alcohols 14-30/GJ (US/EU) synth. Diesel

*Algae-based fuels and chemicals are also categories under development with higher cost uncertainties at this stage of development. Industrial products include biobased chemicals as replacements of traditional ones or new for polymers for packaging, carpets, surfactants, and other products and biobased construction materials.

2.7.2 Technological learning in bioenergy systems

Cost trends and technological learning in bioenergy systems have long been less well described than solar or wind energy technologies. Recent literature however gives more detailed insights in the experience curves and progress ratio's of various bioenergy systems. Table 2.7.4 and Figure 2.7.2 summarizes a number of analyses that have quantified learning as expressed by their progress ratio (PR) and experience curves for three commercial biomass systems: (i) sugarcane based ethanol production (Van den Wall Bake et al., 2009), (ii) corn based ethanol production (Hettinga et al., 2009), (iii) wood fuel chips and CHP in Scandinavia (Junginger et al., 2005 and a number of other sources). PR denotes the progress ratio, expressing the rate of unit cost decline with each doubling of cumulative production. For example, a PR of 0.8 implies that after one doubling of cumulative production, unit costs are reduced to 80% of the original costs or, in other words, the cost decreased by 20%. The definition of the 'unit' may vary depending on the study variable. See also absolute performance of the two major commercial ethanol systems, shown in Table 2.5.1 in terms of a variety of functional units related to climate impact and fossil energy, as a function of time.

Table 2.7.4. Overview of experience curves for biomass energy technologies / energy carriers. Cost/price data collected from various sources (books, journals, press releases, interviews) PR = Progress Ratio, R2 is the correlation coefficient of the statistical data.

Learning system	PR (%)	Time frame	Region	n	R^2
Feedstock production					
Sugarcane (tonnes sugarcane) Van den Wall Bake et al.; 2009	68±3	1975-2003	Brazil	2.9	0.81
Corn (tonnes corn) Hettinga et al, 2009	55±0.02	1975-2005	USA	1.6	0.87
Logistic chains					
Forest wood chips (Sweden) Junginger et al., 2005	85-88	1975-2003	Sweden / Finland	9	0.87-0.93
Investment & O&M costs					
CHP plants (€/kW$_e$) Junginger et al., 2005	75-91	1983-2002	Sweden	2.3	0.17-0.18
Biogas plants (€/m^3 biogas/day) Junginger et al., 2006a	88	1984-1998		6	0.69
Ethanol production from sugarcane Van den Wall Bake et al.; 2009	81±2	1975-2003	Brazil	4.6	0.80
Ethanol production from corn (only O&M costs) Hettinga et al, 2009	87±1	1983-2005	USA	6.4	0.88
Final energy carriers					
Ethanol from sugarcane Goldemberg et al., 2004	93 / 71	1980-1995	Brazil	~6.1	n.a.
Ethanol from sugarcane Van den Wall Bake et al., 2009	80±2	1975-2003	Brazil	4.6	0.84
Ethanol from corn Hettinga et al., 2009	82±1	1983-2005	USA	6.4	0.96
Electricity from biomass CHP Junginger et al., 2006a	91-92	1990-2002	Sweden	~9	0.85-0.88
Electricity from biomass IEA, 2000	85	Unknown	EU (?)	n.a.	n.a.
Biogas, Junginger et al., 2006a	85- 100	1984-2001	Denmark	~10	0.97

n Number of doublings of cumulative production on x-axis.

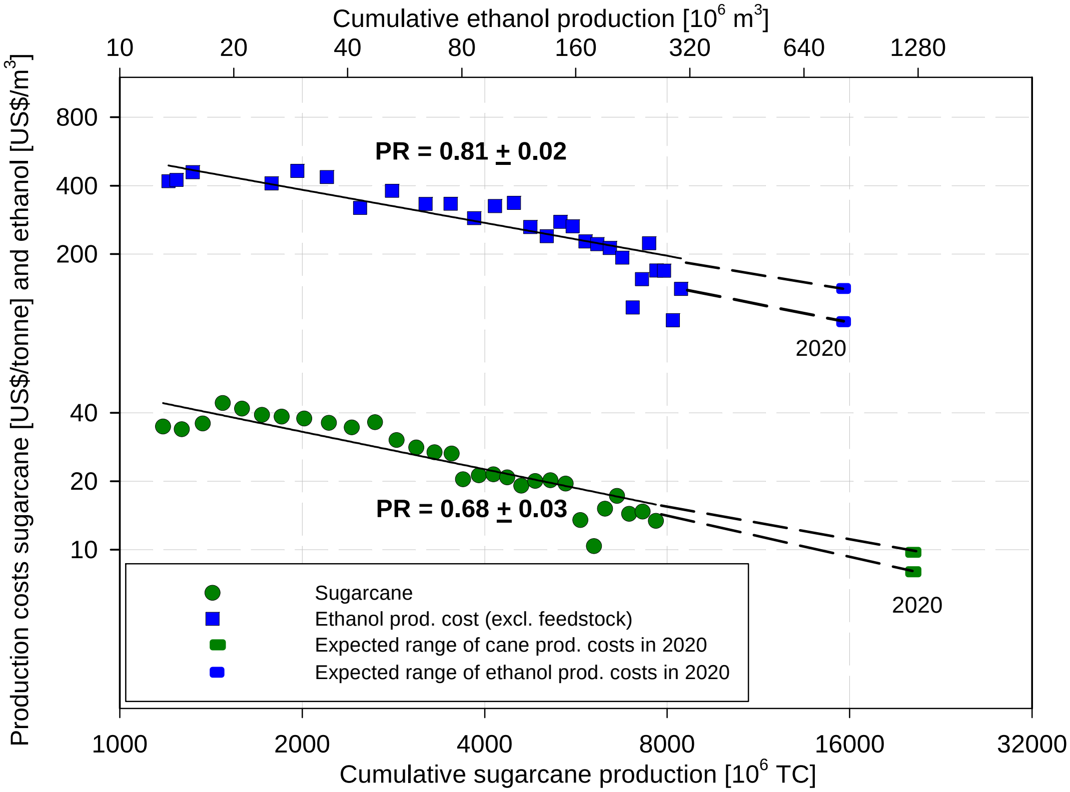


Figure 2.7.2: Experience curves for sugarcane production costs and ethanol production costs in Brazil between 1975-2005, and extrapolation to 2020 (Wall-Bake et al., 2009).

Learning and experience curves studies has accuracy limitations (Junginger et al., 2008). Yet, there are a number of general factors that drive cost reductions that can be identified:
For the production of sugar crops (sugarcane) and starch crops (corn) (as feedstock for ethanol production), increasing crop productivity yields has been the main driving force behind cost reductions. For instance, for sugarcane, varieties of sugarcane developed through R&D efforts by research institutes with increased sucrose content and thus ethanol yield; prolongation of the ratoon systems, increasingly efficient manual harvesting and the use of larger trucks for transportation reduced feedstock costs. More recently, mechanical harvesting of sugarcane is replacing manual harvest, increasing the amount of residues for electricity production (Wall Bake et al. 2009; Seabra et al., 2010; see Table 2.5.1). For the production of corn, highest cost decline occurred in costs for capital, land, and fertilizer until 2005. Main drivers behind cost reductions were increased plant sizes through cooperatives that enabled higher production volumes, efficient feedstock collection, and decreased the investment risk through government loans and the introduction of improved efficiency natural gas-fired ethanol plants, now responsible for nearly 90% of production. Higher corn yields by introducing corn hybrids genetically modified to have higher pest resistant enabled increasing adoption of no-till practices and significantly improved water quality (Hettinga et al., 2009; NAS, 2010; see Table 2.5.1). While it is difficult to quantify the effects of each of these factors, it seems clear that R&D efforts (realizing better plant varieties), technology improvements, and learning-by-doing (e.g., more efficient harvesting) played important roles.

Industrial production costs for ethanol production from both sugarcane and corn mainly decreased because of increasing scales of the ethanol plants. Cost breakdowns of the sugarcane production process showed reductions of around 60 percent within all sub processes. Ethanol production costs (excluding feedstock costs) declined by a factor of three between 1975 and 2005 (in real terms, i.e., corrected for inflation). Investment and operation and maintenance costs declined mainly due to economies of scale. Other fixed costs, such as administrative costs and taxes did not fall dramatically, but cost reduction can be ascribed to application of automated administration systems. Declined costs can mainly be ascribed to increased scales and load factors.

For ethanol from corn, ethanol processing costs (without costs for corn and capital) declined by 45% from 240 U$ per m^3 in the early 1980's to 130 U$ per m^3 in 2005. Costs for energy, labour and enzymes contributed in particular to the overall decline in costs. Key drivers behind these reductions are higher ethanol yields, the introduction of specific and automation and control technologies that require less energy and labour and lastly the upscaling of average dry grind plants (Hettinga et al, 2009).

2.7.3 Future scenarios for cost reduction potentials

Only for the production of ethanol from sugarcane and corn, future production cost scenarios based on direct experience curve analysis were found in the literature:

For ethanol from sugarcane (Wall Bake et al., 2009), total production costs at present are approximately 780 RS_{2005}/m^3 ethanol. Based on the experience curves for feedstock and industrial costs, total ethanol production costs in 2020 are estimated between 460 – 600 RS_{2005}/m^3 Values in U$ come with uncertainty, because the exchange rate of the Brazilian Real fluctuated from 2.3 RS/U$ in 2005 to 3.6RS/U$ in 2004 (while in such a short timeframe production costs did not change significantly). Production costs of ethanol expressed in $U\$_{2005}$ therefore lay in a range of 220 –340 U$/m3 (10 – 16 U$/GJ) at present and could amount 8-12 U$/GJ by 2020 following the identified improvement potential in that timeframe.

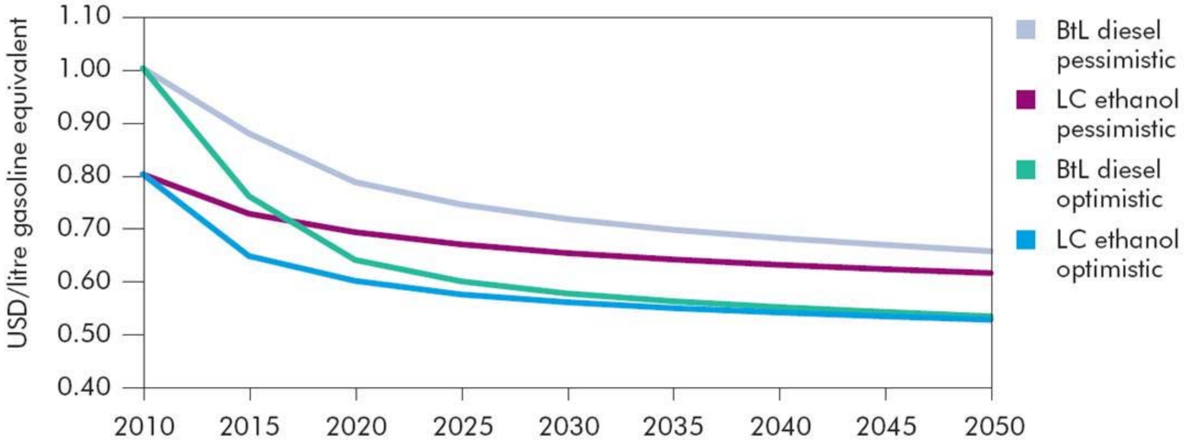
For ethanol from corn (Hettinga et al, 2009), production costs of corn are estimated to amount to 75 $US\$_{2005}$ per tonne by 2020 and ethanol processing costs could reach 60 - 77 US$/$m^3$ in 2020. Overall ethanol production costs could decline from currently 310 US$/$m^3$ to 248 US$/$m^3$ in 2020. This estimate excludes the cost of capital and the effect of probably corn prices in the future.

In the REFUEL project that focused on deployment of biofuels in Europe, (de Wit et al., 2009; Londo et al., 2009) specific attention was paid to the projections of future costs due to learning for lignocellulosic biofuels technologies. The analyses showed two key things:

- Lignocellulosic biofuels have a considerable learning potential with respect to crop production, supply systems, and the conversion technology. For conversion in particular, economies of scale are a very important element of the future cost reduction potential as specific capital costs can be reduced (partly due to improved conversion efficiency). Biomass resources may become somewhat more expensive due to a reduced share of (less costly) residues over time. It was estimated that lignocellulosic biofuel production cost could compete with gasoline and diesel from oil at 60-70 U$/barrel.

- The penetration of lignocellulosic biofuel options depends considerably on the rate of learning. Although this is a straightforward finding at first, it is more complex in policy terms, because learning is observed with increased market penetration (which allows for producing with larger production facilities).

In the IEA Energy Technology Perspectives report and IEA-WEO 2009, especially between 2020 and 2030 sees a rapid increase in production of lignocellulosic biofuels (sometimes referred to as 2nd generation fuels), accounting for all incremental biomass increase after 2020. The analysis on biofuels projects an almost complete phase out of cereal and corn based ethanol production and oilseed based biodiesel after 2030. The projected potential cost reductions for production of specific lignocellulosic biofuels investigated are shown in figure 2.7.3.



Note: BtL = Biomass-to-liquids; LC= ligno-cellulose.

Figure 2.7.3. Cost projections for lignocellulosic ethanol and BTL diesel. Source: IEA-ETP, 2008 and see also IEA (2008) for data figures.

2.7.4 Closing remarks on cost trends

Despite the complexities of determining the economic performance of bioenergy systems and regional specificities there are several key conclusions that can be drawn from available experiences and literature:

- There are several important bioenergy systems today, most notably sugar cane based ethanol and heat and power generation from residues and waste biomass that can be deployed competitively.
- Several important bioenergy systems have reduced their cost and improved environmental performance over time but require government subsidies provided usually for economic development, including poverty elimination, energy security and diversity, and other specific country reasons.
- There is clear evidence that further improvements in power generation technologies, supply systems of biomass and production of perennial cropping systems can bring the

costs of power (and heat) generation from biomass down to attractive cost levels in many regions, especially when competing with natural gas. In case of deployment of carbon taxes of up to 50 U$/ton (or CCS), biomass can also be competitive with coal based power generation. Nevertheless, the competitive production of bio-electricity depends also on the performance of alternatives such as wind and solar energy, CCS coupled with coal, and nuclear energy.

- Bioenergy systems namely for ethanol and biopower production show technological learning and related cost reductions with progress ratios comparable to those of other renewable energy technologies. This applies to cropping systems (following progress in agricultural management when annual crops are concerned), supply systems and logistics (as clearly observed in Scandinavia, as well as international logistics) and in conversion (ethanol production, power generation, biogas, and biodiesel).
- With respect to lignocellulosic biofuels, recent analyses have indicated that the improvement potential is large enough to make them compete with oil prices of 60-70 U$/barrel. Currently available scenario analyses indicate that if shorter term R&D and market support is strong, technological progress could allow for commercialization around 2020 (depending on oil price developments and level of carbon pricing). Some scenarios also indicate that this would mean a major shift in the deployment of biomass for energy, since competitive production would decouple deployment from policy targets (mandates) and demand from biomass would move away from food crops to biomass residues, forest biomass and perennial cropping systems. The implications of such a (rapid) shift are so far poorly studied.
- Data availability is poor with respect to production of biomaterials; cost estimates for chemicals from biomass are rare in peer reviewed literature and future projections and learning rates even more so, linked, in part, to the fact that successful biobased products are entering the market place either as partial components of otherwise fossil derived products (e.g., poly(1,3)propylenetherephtalates based on 1,2-propanediol derived from sugar fermentation) or as fully new synthetic polymers such as polylactides based on lactic acid derived from sugar fermentation. This is also the case for bio-CCS concepts, which are not deployed at present and cost trends are not available in literature. CO2 from ethanol fermentation is commercially sold to carbonate beverages, flash freeze meats, or enhance oil recovery, and demonstrations of bio-CCS are ongoing (see 2.3.5). Nevertheless, recent scenario analyses indicate that advanced biomaterials (and cascaded use of biomass) as well as bio-CCS may become attractive medium term mitigation options. It is therefore important to gain experience so that more detailed analyses on those options can be conducted in the future.

2.8 Potential Deployment

The expected deployment of biomass for energy on medium to longer term differs considerably between studies. A key message from the review of available insights on large scale biomass deployment is it’s role is mostly conditional: deployment strongly depends on sustainable development of the resource base and governance of land use, development of infrastructure and cost reduction of key technologies, e.g., efficient and complete use of primary biomass energy from most promising first generation feedstocks and new generation lignocellulosic biomass, and a variety of biofuels.

2.8.1 2.8.1. SRREN Chapter 10 review

The results of the review of studies with respect to bioenergy deployment under different scenarios as presented in chapter 10 of the SRREN are summarized in figures 2.8.1 and 2.8.2. For medium term (2030), estimates for primary biomass use range (rounded) between 7 to 180 EJ for the full range of results obtained. The 25-75% quantiles deliver a range of 30-117 EJ. This is combined with a total final energy delivered of 0-61 EJ. For 2050, these ranges amount for primary biomass supplies 10-305 EJ for the full range and 22-184 EJ for the 25-75% quantiles and 0 – 76 EJ (22-57 EJ for the 25-75% quantiles) for final energy delivered.

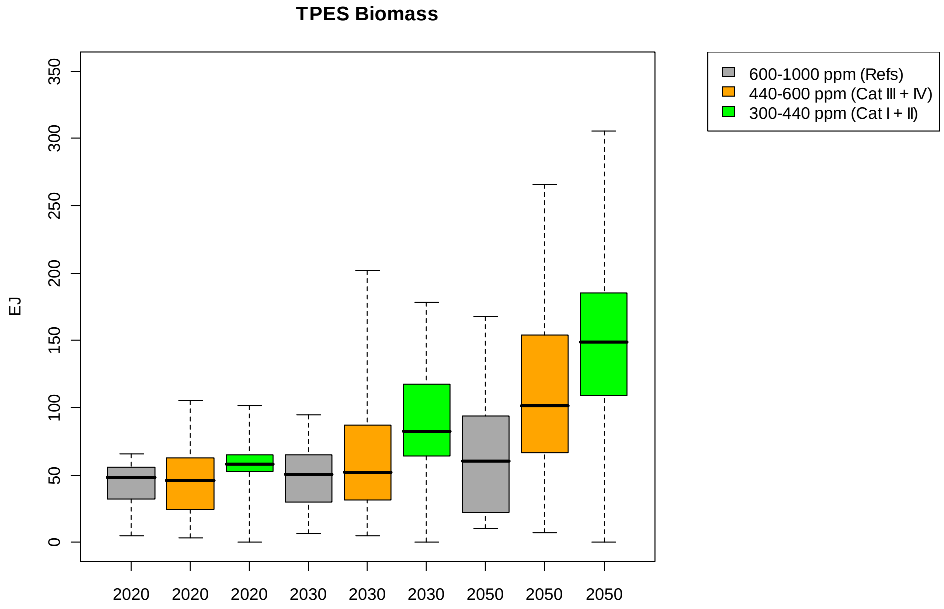


Figure 2.8.1. The Total Primary Energy Supply (TPES) biomass utilization according to the scenario review of Chapter 10, divided into projections for reference scenarios, scenarios that target 440-600 ppm and scenario's that target 330-440 ppm. The colored bars represent the 25-75% quantiles of the obtained results. The dotted bars represent the full range of estimates.

High quality data on performance prospects (and thus learning potential and rates) of energy technologies is essential to avoid neglecting potentially important contributor to the energy future and for such strategic studies. In addition, since the cost data is not static but improves as development continues, the information needs to be updated periodically and refined, as through harmonization studies that enable direct comparison of alternative uses of biomass.

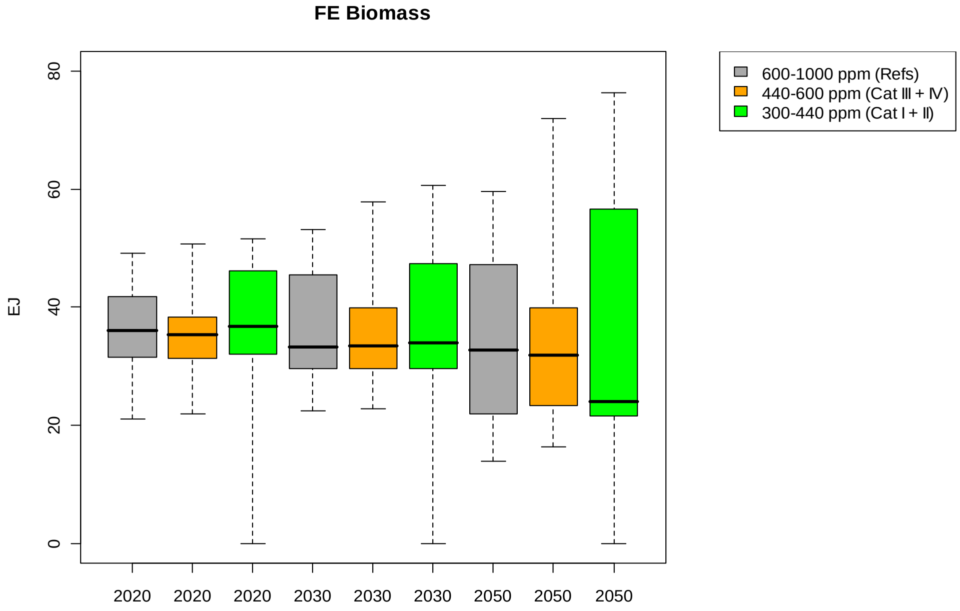


Figure 2.8.2. The Final Energy (FE) delivered via biomass utilization according to the scenario review of Chapter 10, divided into projections for reference scenarios, scenarios that target 440-600 ppm and scenarios that target 330-440 ppm. The colored bars represent the 25-75% quantiles of the obtained results. The dotted bars represent the full range of estimates.

2.8.2 Synthesis of findings from this chapter and chapter 10.

Although there is an impressive literature base on global potentials of bioenergy and potential impacts on the environment with deployment, there are very few analyses that provide a coherent and integrated picture taking key relevant relationships (see sections 2.2 and 2.5 of this chapter) into account. The focus of many recent analyses was on the possible conflicts and limitations of first generation biofuels deployment using food crops [see e.g. FAO’s State of Food & Agriculture, 2008 for an overview].

Studies of the use of biomass for heat and power, lignocellulosic biofuels and biomaterials taking into account a range of biomass resources such as forestry and agriculture residues, organic wastes, and perennial plants (herbaceous and woody crops) cultivated on arable, pasture and marginal and degraded lands, provide a different outlook. There are conditions under which environmental, ecological, and socio-economic impacts of further deployment of bioenergy also enhance the environment, the development, the economy and provide independent energy sources. This is extensively discussed in section 2.5, where potential conflicts and synergies or benefits of development of biomass resources for, e.g. , biodiversity, rural development, water demand and soil quality have been identified, which depend on the implementation route at the local level, plant/crop choice, governance of land-use and management of agricultural productivity and water resources. The following key points have been made:

The effects of bioenergy on social and environmental issues – ranging from health and poverty to biodiversity and water quality – may be positive or negative depending upon local conditions, the specific feedstock production system and technology paths chosen, how criteria and the alternative scenarios are defined, and how actual projects are designed and implemented, among other variables. Perhaps most important is the overall management and governance of land-use when biomass is produced for energy purposed on top of meeting food and other demands from agricultural production (as well as livestock). In case biomass production is in balance with improvements in agricultural management undesirable (i)LUC effects can be avoided, while unmanaged, conflicts may emerge. The overall performance of bioenergy production systems is therefore interlinked with management of land-use and water resources. Trade-offs between those dimensions exists and need to be resolved through appropriate strategies and decision making. Such strategies are currently emerging due to many efforts targeting the deployment of sustainability frameworks and certification for bioenergy production (see also section 2.4), setting standards for GHG performance (including LUC effects), addressing environmental issues and taking into consideration a number of social aspects., etc.

GHG performance evaluation of key biofuel production systems deployed today and possible 2nd generation biofuels using different calculation methods is available (see, Section 2.5 and Hoefnagels et al., 2010). Recent insights converge by concluding that well managed bioenergy production and utilization chains can deliver high GHG mitigation percentages (80-90%) compared to their fossil counterparts, especially for lignocellulosic biomass used for power generation and heat and, when the technology would be commercially available, for lignocellulosic biofuels. The use of most residues and organic wastes for energy result in such good performance. Also, most current biofuel production systems have positive GHG balances, if no iLUC effects are to be incorporated.

LUC can strongly affect those scores and when conversion of land with large carbon stocks takes place for the purpose of biofuel production, then directly emission benefits can shift to negative levels in the near term. This is most extreme for palm oil based biodiesel production where extreme carbon emissions are obtained if peatlands are drained and converted to oil palm (Wicke et al., 2008). Establishing causal relationship between biofuel development and distal land use change is still controversial. The GHG mitigation effect of biomass use for energy (and materials) therefore strongly depends on location (in particular avoidance of converting carbon rich lands to carbon poor cropping systems), feedstock choice, and avoiding iLUC (see below). In contrast, using perennial cropping systems can store large amounts of carbon and enhance sequestration on marginal and degraded soils, and fuel production replaces fossil fuels use. Governance of land-use and proper zoning and choice of biomass production systems is therefore a key to achieve good performance.

Other key environmental impacts cover use of water, biodiversity and other emissions. Just as for GHG impact, proper management determines emission levels to water, air and soil. Development of standards or criteria (and continuous improvement processes) will push bioenergy production to low emissions and higher efficiency than today’s systems.

Water is a critical issue that needs to be better analysed on regional level to understand the full impact of changes in vegetation and land-use management. Recent studies do indicate (Dornburg et al., 2008, Berndes, 2002; Wu et al., 2009; Rost, S. et al., 2009) that considerable improvements can be made in water use efficiency in conventional agriculture, as well as biomass crops and that, depending on location and climate, perennial cropping systems in particular can achieve benefits in terms of improved water retention and lowering direct evaporation from soils. Nevertheless, without proper management, increased biomass production could come with increased competition for water in critical areas, which is highly undesirable (Fingerman et al., 2010).

Similar remarks can be made with respect to biodiversity, although for this topic, more scientific uncertainty exists due to ongoing debate on methodologies how to quantify biodiversity impacts in general. Clearly, large scale monocultures that would go at the expense of nature areas are detrimental for biodiversity (for example highlighted in CBD, 2007). However, as discussed and referenced in Section 2.5, bioenergy can also lead to positive effects such as the environmental benefits that can be derived from integrating different perennial grasses and woody crops into agricultural landscapes, including enhanced biodiversity, soil carbon increase and improved soil productivity, reduced shallow landslides and local 'flash floods', reduced wind and water erosion and reduced volume of sediment and nutrients transported into river systems. Forest residue harvesting improves forest site conditions for replanting and thinning generally improves the growth and productivity of the remaining stand. Removal of biomass from over dense stands can reduce wildfire risk. This is also an area that deserves considerably more research, data collection, and proper monitoring, as exemplified by ongoing activities of governments and roundtables in case or pilot studies (e.g., DOE, 2010; RSB, 2010).

With respect to iLUC, the assessment of available literature (see table 2.5.3) showed that initial models were lacking in geographic resolution leading to higher proportions of assignments of land use to deforestation than necessary as the models did not have other kinds of lands such as pastures in Brazil that could be used. While the early paper of Searchinger et al. (2008) claimed an iLUC factor of 1 (losing one hectare of forest land for each hectare of land used for bioenergy), later macro-economic coupled to biophysical model studies tuned that down to 0.3 – 0.15 and more detailed evaluations of e.g. (Lapola et al., 2010 and IFRI (Al-Fiffai et al., 2010) suggest that any iLUC effect strongly (up to fully) depends on the rate of improvement in agricultural and livestock management and the rate of deployment of bioenergy production. This balance in development is also the basis for the recent European biomass resource potential analysis, for which expected gradual productivity increments in agriculture are the basis for possible land availability as reported in (Fischer et al, 2010 and de Wit & Faaij, 2010) and that take avoidance of competition with food (or nature) as a starting point. Increased model sophistication to adapt to the complex type of analysis required and improved data on the actual dynamics of land distribution in the major biofuel producing countries is now producing results that are converging to lower overall land use change impacts and acknowledgement that land use management at large is key. .

Social impacts from a large expansion of bioenergy are very complex and difficult to quantify. In general, bioenergy options have a much larger positive impact on job creation in rural areas than other energy sources. Also when conventional agriculture would rationalize to 'free up land'' for bioenergy, the total job impact and value added generated in rural regions increases when bioenergy production increases (see e.g. Wicke et al., 2009). For many developing countries, the potential bioenergy has for generating employment and economic activity in rural regions is a key driver. In addition, expenditures on fossil fuel (imports) can be (strongly) reduced. However, whether such benefits end up with rural farmers depends largely on the way production chains are organized and how land-use is governed. In case (too) rapid bioenergy deployment competes with food production, increases in food prices can be significant as shown by many recent studies that focused on implications of rapid expansion of first generation biofuels produced from food crops: impacts on food prices – and more in general on food security- may be significant, particularly for poor people

The way bioenergy is developed, under what conditions and what options will have a profound influence on whether those impacts will largely be positive or negative (see for example van Dam et al., 2008 and van Dam et al., 2009) with examples of such scenarios for Argentina). Bioenergy has the opportunity to contribute to climate mitigation, energy security and diversity goals, and economic development in developed and developing countries alike but the effects of bioenergy on environmental sustainability may be positive or negative depending upon local conditions, how criteria are defined, how actual projects are designed and implemented, among many other factors.

Based on this review, it is not possible to deliver conclusive information on *the* deployment of biomass for energy and climate change mitigation on shorter and longer term. Upon reviewing the information from the various studies conducted (see Sections 2.2 and 2.5), the IPCC group of technical experts writing this Chapter, concluded that the most likely range is between 100 and 300 EJ for penetration by 2050 (see Biomass Technical Potential 1 in Figure 2.8.3). Since 80% of the total biomass use is traditional heating, cooking, and lighting applications in the developing world, and we expect increased efficiency of biomass use that will offset increases by perhaps as much as 10 to 17 EJ (GEA, 2010; see Section 2.5.3.4,) to be offset somewhat by population increase. Taking improved traditional use of biomass energy to 25 EJ by 2050, to reach 100 to 300 EJ would require increases of factors of four to twelve in modern bioenergy. If these increases had to rely only on modern bioenergy's contribution of 10 EJ alone, it would means ten- to thirty-fold increases required by 2050.

To put numbers of 100 to 300 EJ in perspective, in the United States, a two-hundred-fold primary bioenergy increase occurred in the area of waste/residue to energy since the creation of the Environmental Protection Agency nearly 40 years ago with legislation to clean air, water, and solid emissions alongside energy legislation. A factor of 20 in 20 years was reached by ethanol primarily from corn with production incentives among other tools (see Section 2.4.6.7). Then an increase by a factor of five took place in the subsequent eight years with additional incentives for production for energy security, economic development of rural regions, and environmental reasons. This rapid growth caused significant industrial investment in new production based on legislation with more certainty of future markets (Chum and Overend, 2005). A factor of three was reached by the biopower industry in the eighties in ten years. These increases are impressive for total of 4.1 EJ (primary, 2008 estimate; biofuels consumption 1.4EJ). To implement the Energy Independence and Security Act the biofuels volume in 2022 would more than triple today's levels and require an estimated $90 billion capital investment in 12 years (EPA, 2010). These historical parameters frame the significant levels of investments and infrastructure for biomass collection and processing required to reach 75 to 300 EJ.

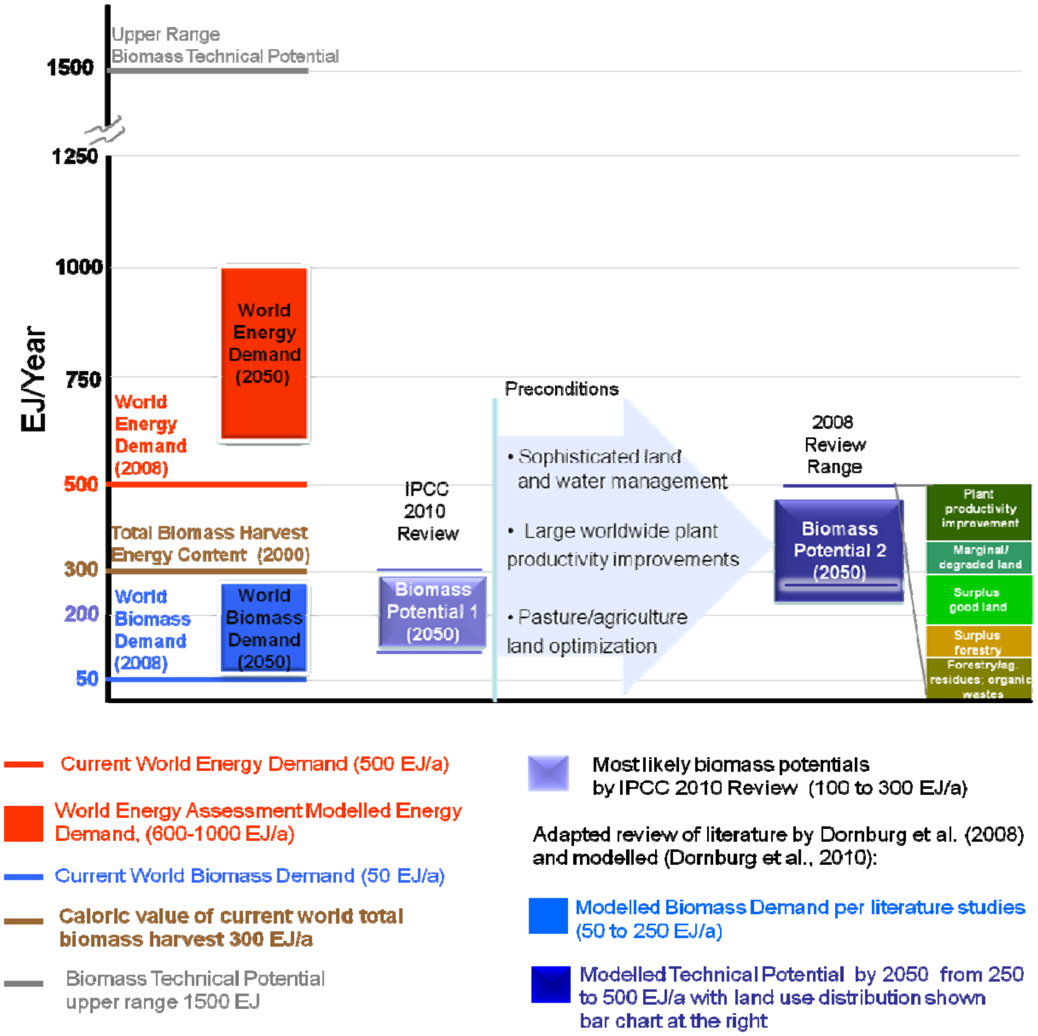


Figure 2.8.3. Upper technical biomass supply potentials, most likely biomass potential (IPCC review, this Chapter), modelled biomass potential (Dornburg et al., 2010), expected demand for biomass (primary energy) based on global energy models and expected total world primary energy demand in 2050. The Biomass Potential 2 scenario incorporates some key limitations and criteria with respect to biodiversity protection, water limitations, soil degradation, and considers developments in agricultural management between A2 versus A1/B1 scenario conditions. The breakdown consist of: (i) Residues: Agricultural and forestry residues; (ii) Forestry: surplus forest material (net annual increment minus current harvest); (iii) Exclusion of areas: potential from energy crops, leaving out areas with moderately degraded soils and/or moderate water scarcity; (iv) No exclusion: additional potential from energy crops in areas with moderately degraded soils and/or moderate water scarcity; (v) Learning in agricultural technology: additional potential when agricultural productivity increases faster than historic trend. Adapted from Dornburg et al. (2008) and Dornburg et al. (2010) based on several review studies

Based on the current state-of-the-art analyses that took into consideration key sustainability criteria as of 2007-2008 literature, the upper bound of the biomass resource potential halfway this century can amount over 400 EJ (see Biomass Potential 2 of figure 2.8.3). This could be roughly in line with the conditions sketched in the IPCC SRES A1 and B1 storylines, assuming sustainability and policy frameworks to secure good governance of land-use and improvements in agricultural and livestock management (see also van Vuuren et al., 2009). These findings are summarized in (Biomass Potential 2) based on an extensive assessment of recent literature and additional studies with the IMAGE-TIMER modeling framework that include known and projected future water limitations, biodiversity protection, soil degradation and competition with food (Dornburg et al., 2008; Dornburg et al., 2010).

As shown above, narrowing down the biomass resource potential to distinct numbers is not possible. But it is clear that several hundred EJ per year can be provided for energy in the future, given favourable developments. This can be compared with the present biomass use for energy at about 50 EJ per year. It can also be concluded that:

- The size of the future biomass supply potential is dependent on a number of factors that are inherently uncertain and will continue to make long term biomass supply potentials unclear (Hoogwijk et al. 2003, 2005, Smeets et al. 2007, WBGU 2009). Important factors are (i) population and economic/technology development and how these translate into fibre, food and fodder demand (including diets), and development in agriculture and forestry; (ii)climate change impacts on future land use including its adaptation capability (Schneider et al 2007, Lobell et al 2008, Fischer 2009); (iii) and restrictions set by land degradation, water scarcity, and biodiversity and nature conservation requirements (WBGU 2009, Molden 2007, Bai et al. 2008, Berndes 2008).
- Studies point that residue flows in agriculture and forestry and unused (or extensively used, marginal/degraded) agriculture land are important sources for expansion of biomass production for energy, both on the near term and on the longer term. Biodiversity-induced limitations and the need to ensure maintenance of healthy ecosystems and avoid soil degradation set limits on residue extraction in agriculture and forestry (Lal 2008, Blanco-Canqui and Lal 2009, WBGU 2009)
- The cultivation of suitable plants crops can allow for higher potentials by making it possible to produce bioenergy on lands where conventional food crops are less suited – also due to that the cultivation of conventional crops would lead to large soil carbon emissions. Landscape approaches integrating bioenergy production into agriculture and forestry systems to produce multi-functional land use systems could contribute to development of farming systems and landscape structures that are beneficial for the conservation of biodiversity and helps restore/maintain soil productivity and healthy ecosystems. (Hoogwijk et al. 2005, Berndes et al. 2008, Folke et al. 2009, IAASTD 2009, Malezieux et al. 2009)
- Water constraints may limit production in regions experiencing water scarcity. The possibility that conversion of lands to biomass plantations reduces downstream water availability needs to be considered. The use of suitable energy crops that are drought tolerant can help adaptation in water scarce situations. Assessments of biomass resource potentials need to more carefully consider constraints and opportunities in relation to water availability and competing use (Jacksson et al. 2005, Zomer 2006, Berndes et al. 2008, De Fraiture and Berndes).

The energy potential ranges for different biomass resources summarized below are derived from the assessment combined with modelling efforts of the Dornburg review. These are compared in figure 2.8.3 with the expert review made for this report. For the latter, no new modelling efforts were carried out, but they incorporate the quantitative results from Dornburg as well as a wide range of other studies and viewpoints reviewed in sections 2.2 and 2.5.

- Residues from forestry and agriculture and organic wastes (including the organic fraction of MSW, dung, various process residues, etc.), which in total represent between 40 - 170 EJ/yr, with a mean estimate of around 100 EJ/yr. This part of the potential biomass supplies is relatively certain, but competing applications may push net availability for energy applications to the lower end of the range.
- Surplus forestry, i.e. apart from forestry residues an additional amount about 60-100 EJ/yr of surplus forest growth may be made available.
- Biomass produced via cropping systems:
    - A lower estimate for energy crop production *on possible surplus good quality agricultural and pasture lands*, including far reaching corrections for water scarcity, land degradation and new land claims for nature reserves represents an estimated 120 EJ/yr.
    - The potential contribution of *water scarce, marginal and degraded lands* for energy crop production, could amount up to an additional 70 EJ/yr. This would comprise a large area where water scarcity provides limitations and soil degradation is more severe and excludes current nature protection areas from biomass production.
    - Learning in agricultural technology assumes that improvements in agricultural and livestock management or more optimistic than in the baseline projection (i.e. comparable to conditions sketched in the SRES A1 and B1 scenarios) would add some 140 EJ/yr to the above mentioned potentials of energy cropping.

The three categories added together lead to a biomass supply *potential* of up to about 500 EJ, represented in the right hand stacked bar of figure 2.8.3.

Energy demand models calculating the amount of biomass used if energy demands are supplied cost-efficiently at different carbon tax regimes, estimate that in 2050 about 50-250 EJ/yr of biomass are used. This is roughly in line with the projections given in chapter 10 and figure 2.8.3. At the same time, scenario analyses project a global primary energy use of about 600 – 1040 EJ/yr in 2050. Thus, up to 2050, biomass has the potential to meet a substantial share of the worlds energy demand; the average of the range given in figure 2.8.3 results in potential a contribution bioenergy of some 30% to total primary energy demand with the possibility of impacting rural and industrial development in developing and developed regions.

However, if the sketched conditions are not met, the biomass resource base may be largely constrained to a share of the biomass residues and organic wastes, some cultivation of bioenergy crops on marginal and degraded lands and some regions where biomass is evidently a cheaper energy supply option compared to the main reference options (which is the case for sugarcane based ethanol production). Biomass supplies may than remain limited to an estimated 100 EJ in

2050. Also this is discussed in, for example, van Vuuren et al. (2009) and WBGU (2009) and confirmed by the scenario review in chapter 10 of the SRREN.

2.8.3 Limitations in available literature and analyses

The demand for bioenergy will, as argued earlier, depend on the relative competitive position of bioenergy options in the energy system compared to main alternatives. Available analyses indicate that on the longer term, biomass will be especially attractive for production of transport fuels and feedstock for industry and that the use of biomass for electricity may become relatively less attractive in the longer run.

Innovations in biofuel production and biorefining technologies however, combined with high oil prices as projected in IEA's World Energy Outlook and in addition CO2 pricing, are likely to result in competitive biofuel production in many parts on the globe on medium term and may lead to an acceleration of biomass use and production compared to available projections. This mechanism is basically projected in the 2020-2030 timeframe of the 450 ppm scenario in the 2009 World Energy Outlook (IEA-WEO, 2009). In such a scenario, the sustainable development of the biomass resource base may become the limiting factor, especially after 2030.

Also poorly investigated so far is the possible role of biomass with Carbon Capture & Storage, an option that may become very important under stringent mitigation scenarios (i.e., aiming for a 350 ppm scenario in 2050) where negative emissions are required to meet set targets. The use of biomass becomes absolutely essential to achieve the set targets and demand may further increase.

It is also still poorly understood what the impact of electric vehicles and drive chains in transport may be on the potential demand for biofuels. Electric drive chains in passenger vehicles have good potential to increase energy efficiency of vehicles. IEA (WEO, 2009) projects a limited inroad of fully electric vehicles for the coming decades and rapid introduction of hybrid vehicles of which energy use will be partly (in case of plug-in hybrids) or fully be covered by liquid fuels. In addition, on long term (and rapidly growing) demand of liquid fuels from aviation, shipping and truck transport (for which full electric driving is not feasible) remain responsible for some 60% of the (growing) global demand for transport fuels.

The costs of biomass supplies in turn are influenced by the degree of land-use competition, availability of (different) land (classes) and optimisation (learning and planning with sustainability in mind) in cropping and supply systems. The latter is still relatively poorly studied and incorporated in scenarios and (energy and economic) models, which can be improved. The variability of biomass production costs seems far less than that of oil or natural gas, so uncertainties in this respect are relatively limited.

Given the relatively small number of comprehensive scenario studies available to date, it is fair to characterize the role of biomass role in long-term stabilization (beyond 2030) as very significant but with relatively large uncertainties. One additional model that supports this importance is shown on Figure 2.5.4: an agricultural intensification scenario reflecting the actual rate of land use change observed since the year 2000 is investigated projecting biofuels expansion mostly through agriculture intensification. Climate mitigation is initially negative (20 years) but then increases (Melillo et al. 2009) to a biofuel energy contribution of 320 EJ by 2100. Further research is required to better characterize the potential; for regional conditions and over time. A number of key factors have been identified in this last section and throughout the report.

Given that there is a lack of studies on how biomass resources may be distributed over various demand sectors, no detailed allocation of the different biomass supplies for various applications is suggested here. Furthermore, the net avoidance costs per tonne of CO2 of biomass usage depends on a large variety of factors, including the biomass resource and supply (logistics) costs, conversion costs (which in turn depends on availability of improved or advanced technologies) and fossil fuel prices, most notably of oil.

2.8.4 Key messages and policy

Table 2.8.1 describes key preconditions and impacts for two possible extreme biomass scenarios.

Table 2.8.1: Two opposing storylines and impacts for bioenergy on long term.

Storyline	Key preconditions	Key impacts
- High biomass scenario		
Largely follows A1/B1 SRES scenario conditions,	Assumes: - well working sustainability frameworks and strong policies - well developed bioenergy markets - progressive technology development (biorefineries, new generation biofuels and multiple products - successful deployment of degraded lands. - Developing countries successfully transition to higher efficiency technologies and implement biorefineries with scales compatible with the resources available. Satellite processing emerges	- Energy price (notably oil) development is moderated due to strong increase supply of biomass and biofuels. - Some 300 EJ of bioenergy delivered before 2050; 35% residues and wastes, 25% from marginal/degraded lands (500 Mha), 40% from arable and pasture lands 300 Mha). - Conflicts between food and fuel largely avoided due to strong land-use planning and aligning of bioenergy production capacity with efficiency increases in agriculture and livestock management. - Positive impacts with respect to soil quality and soil carbon, negative biodiversity impacts minimised due to diverse and mixed cropping systems.
Low biomass scenario		
Largely follows A2 SRES scenario conditions, assuming limited policies, slow technological progress in both the energy sector and agriculture, profound differences in development remain between OECD and DC's.	- High fossil fuel prices expected due to high demand and limited innovation, which pushes demand for biofuels for energy security perspective - Increased biomass demand directly affects food markets	- Increased biomass demand partly covered by residues and wastes, partly by annual crops. - Total contribution of bioenergy about 100 EJ before 2050. - Additional crop demand leads to significant iLUC effects and impacts on biodiversity. - Overall increased food prices linked to high oil prices. - Limited net GHG benefits. - Socio-economic benefits sub-optimal.

2.8.5 Key messages and policy recommendations from the chapter 2

- The biomass resource potential, also when key sustainability concerns are incorporated, is significant (up to 30% of the world's primary energy demand in 2050) but also conditional. The larger part of the potential biomass resource base is interlinked with improvements in agricultural and forestry management, investment in infrastructure, good governance of land and smart land use and introduction of effective sustainability frameworks and land-use monitoring.
- If the right policy frameworks are *not* introduced, further expansion of biomass use can lead to significant conflicts in different regions with respect to food supplies, water resources and biodiversity. However, such conflicts can also be avoided and synergies with better management of land and other natural resources (e.g., soil carbon enhancement and restoration, water quality improvements) and especially agriculture and livestock management and contributing to rural development are possible. Logically, such synergies should explicitly be targeted in comprehensive policy frameworks.
- Bioenergy at large has a significant GHG mitigation potential, provided resources are developed sustainably and provided the right bioenergy systems are applied. Perennial cropping systems and biomass residues and wastes are in particular able to deliver good GHG performance in the range of 80-90% GHG reduction compared to the fossil energy baseline.
- Optimal use and performance of biomass production and use is regionally and site specific. Policies therefore need to take regionally specific conditions into account and need to incorporate the agricultural and livestock sector as part of good governance of land-use and rural development interlinked with developing bioenergy.
- The recently and rapidly changed policy context in many countries, in particular the development of sustainability criteria and frameworks and the support for advanced biorefinery and lignocellulosic biofuel options drives bioenergy to more sustainable directions.
- Technology for lignocellulose based biofuels and other advanced bioelectricity options, biomass conversion combined with Carbon Capture and Storage, advanced biorefinery concepts, can offer fully competitive deployment of bioenergy on medium term (beyond 2020). Several short term options can deliver and provide important synergy with longer term options, such as co-firing, CHP and heat production and sugarcane based ethanol production. Development of working bioenergy markets and facilitation of international bioenergy trade is another important facilitating factor to achieve such synergies.

Biomass potentials are influenced by and interact with climate change impacts but the detailed impacts are still poorly understood; there will be strong regional differences in this respect. Bioenergy and new (perennial) cropping systems also offer opportunities to combine adaptation measures (e.g. soil protection, water retention and modernization of agriculture) with production of biomass resources.

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