17 Bioenergy resources

Raphael Slade and Ausilio Bauen

17.1 Introduction

Biomass is the oldest fuel used by humankind and was the main source of energy for cooking and keeping warm from the dawn of civilization to the industrial revolution. Biomass is defined to include any non-fossilized organic material of plant and animal origin, and most types of biomass can, at least in principle, be used to provide energy services. The most important sources, however, are materials derived from forestry and agriculture, along with industrial and municipal residues and wastes. Specially cultivated energy crops such as coppiced wood and perennial grasses may also play an important role in the future.

Until the eighteenth century, humans were almost completely reliant on wood and charcoal for all of their energy needs. When coal use began in earnest in the early 1800s (and later, oil and gas) the use of biomass declined. Fossil fuels were cheaper, higher energy density, easier to handle, and better able to support rapid industrialization and the demands of a growing population. Yet despite the considerable advantages of fossil fuels, biomass continued to be an important energy resource. Currently biomass accounts for around 50 EJ (~10 per cent) of global primary energy supply. The majority of which (~8 per cent, ~39 EJ) is used by the world's poorest people to provide rudimentary energy services such as cooking and heating[1] (IEA, 2010; IPCC, 2011). The remaining ~2 per cent (~11–12 EJ) includes the provision of high-quality energy services—heat, power, and transport fuels—enjoyed by affluent countries and delivered using modern and efficient conversion technologies.

Over the last three decades there has been resurgent interest in these modern applications of bioenergy. This interest has been driven by concerns about energy security, increasing prices of fossil fuels, and climate change. All of which can be addressed, at least in part, by increasing the proportion of bioenergy in the global energy

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[1] Globally, it is estimated that around 2.6 billion people are still reliant on traditional uses of biomass and burn wood, straw, charcoal, and dung to provide basic energy services such as cooking and heating (REN21, 2010). This use is predominantly restricted to rural areas of developing countries, and it is associated with poverty and deforestation (Ludwig, et al., 2003; Hall, et al., 1983). The quantity of traditional biomass consumption is known with far less certainty than commercially traded energy sources and may be systematically underestimated in government statistics because production and use is largely informal (IPCC, 2011: 9). It is estimated that the least developed countries still rely on biomass for over 90 per cent of their energy needs (IEA, 2009a, 2009b).

mix. Energy scenarios, such as those developed by the International Energy Agency (IEA) and the Intergovernmental Panel on Climate Change (IPCC), also indicate that bioenergy could make a major contribution to a future low-carbon energy system (IPCC, 2007; IEA, 2010; IEA, 2012b). Many governments (including the G8 plus five[2] and all European member states) have responded by giving bioenergy a role in their energy strategies and introducing policies to increase deployment (Faaij, 2006; GBEP, 2007).

Sustained interest has also helped biomass conversion processes develop and improve. Technologies now on the market can more easily accommodate the varied physical and chemical composition of biomass feedstocks and deliver automated and reliable service. Technologies at the research, development, and demonstration stage also promise more efficient and cleaner conversion into an ever broader range of products. The aspiration is that modern bioenergy technologies should be able to provide energy services at comparable levels of convenience and cost as fossil fuels, and with greatly improved environmental performance.

Yet as efforts to accelerate the introduction of bioenergy have gathered pace, the prospect of mobilizing the large quantities of biomass required has become increasingly controversial. Biomass availability tends to be intertwined with activity in other major economic sectors—agriculture, forestry, food processing, paper and pulp, building materials, and so on—and as feedstocks are diverted from established markets some impact on these sectors is almost inevitable (Faaij, 2006). The way in which land resources are used may also be changed, and many commentators foresee growing land and resource conflicts between bioenergy and food supply, water use, and biodiversity conservation. Their fear is that the benefits offered by increased bioenergy production could be rapidly outweighed by the costs, and that increased production could exacerbate existing environmental problems. Sources of concern include both direct impacts, such as the effect of domestic stoves on urban air quality, and indirect impacts, such as land use change mediated through changing market prices (Searchinger, et al., 2008; Eide, 2008; Creutzig, et al., 2012; Agostini, et al., 2013).

Ultimately, the contribution that bioenergy makes to the global energy mix will depend not only on the efficacy of the conversion technology, but also the availability of biomass and the social acceptability of large-scale adoption. In this chapter we explore each of these aspects of modern bioenergy deployment. We start by providing an overview of conversion pathways, and examine how biomass is currently being used to provide heat, power, and transport fuels. We then explore the range of global biomass availability estimates and consider some of their merits and limitations in helping us form a view on what the resource might be. Finally we address the challenge of ensuring biomass supply is sustainable and consider how this might constrain future expansion.

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[2] The G8 countries are Canada, France, Germany, Italy, Japan, Russia, the United Kingdom, and the United States. The plus five are the five leading emerging economies: Brazil, China, India, Mexico, and South Africa.

17.2 Competing options for providing energy services from biomass

Biomass resources include an incredibly diverse range of feedstocks including both wet and dry waste materials (e.g. sewage sludge and municipal solid waste). Generally, drier and un-contaminated feedstocks are easier and cheaper to convert into energy carriers than wet or contaminated ones. This difference is reflected in their relative price and consequently a balance must be struck between the cost of the conversion process and the quality and price of the feedstock. It is important to note that no single conversion technology can use biomass indiscriminately in all its forms. The main biomass energy conversion pathways are shown in Figure 17.1.

Thermo-chemical pathways preferentially use dry feedstocks and include combustion, gasification, and pyrolysis. Combustion involves the complete oxidation of biomass to provide heat. This may be used directly, or may be used to raise steam and produce electricity. Gasification involves the partial oxidation of the biomass at high temperatures (>500 °C) and yields a mixture of carbon monoxide and hydrogen (syngas), along with some methane, carbon dioxide, water, and small amounts of nitrogen and heavier hydrocarbons (Hamelinck et al., 2004). The quality of the gas

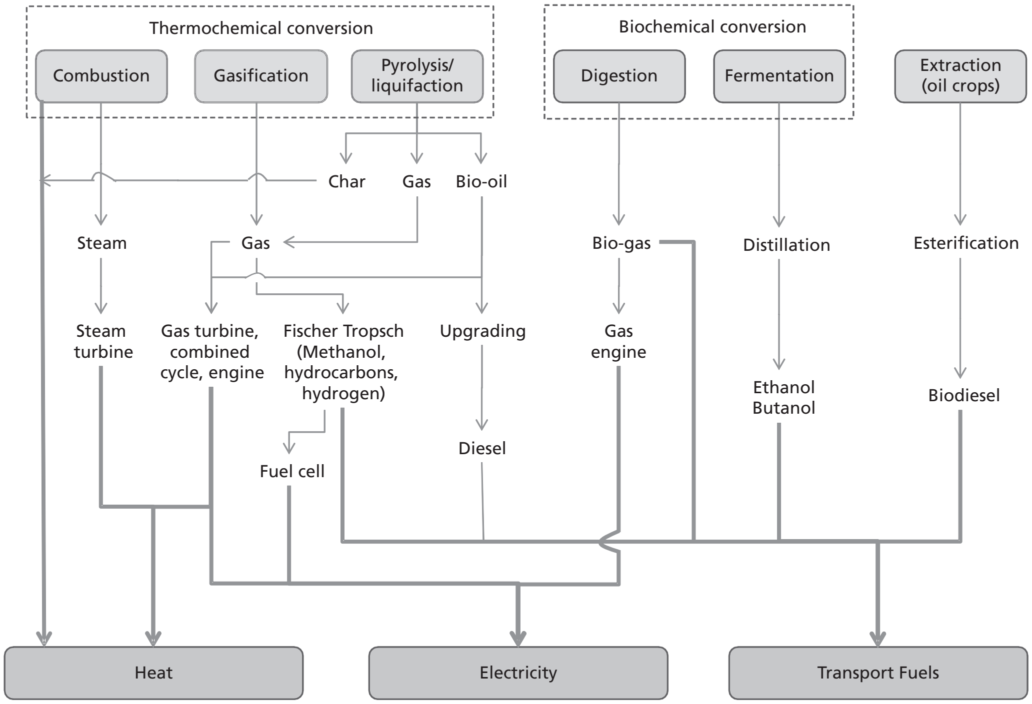

Figure 17.1 The major bioenergy conversion pathways

Source: Adapted from Turkenburg (2000).

depends on the temperature of the gasification process: a higher temperature process will yield more syngas with fewer heavy hydrocarbons. Syngas may be converted into a wide range of fuels and chemicals; alternatively, it can be used to produce electricity, or cleaned and injected into the gas distribution network. Pyrolysis involves heating biomass in the absence of oxygen at temperatures up to 500 °C and produces an energy-dense bio-oil along with some gas and char. This bio-oil is corrosive and acidic, but could in principle be upgraded for use as a transport fuel. Bio-oil from pyrolysis most often receives attention as a pre-treatment and densification step that could make the long distance transport of biomass more economic (Faaij, 2006).

Biochemical conversion pathways use microorganisms to convert biomass into methane or simple alcohols, usually in combination with some mechanical or chemical pre-treatment step. Anaerobic digestion is a well-established technology and is suited to the conversion of homogenous wet wastes that contain a high proportion of starches and fats—for example food waste—to methane. Fermenting sugars and starches to alcohols using yeast is also a fully mature technology. Woody biomass can potentially be used as a feedstock for both anaerobic digestion and fermentation processes, but requires an additional pre-treatment step in order to release the sugars that these feedstocks contain; technologies adopting this approach are being demonstrated but are not yet fully mature.

Lastly, plant oils may be extracted mechanically, reacted with alcohols or treated with hydrogen and used as substitute for diesel and other fuels.

17.3 Biomass for heat, power

Biomass can be used to generate heat at all scales, ranging from a single household to a large industrial complex, and using all types of biomass. Systems are fully commercial, and in many cases they are also cost competitive with their fossil fuel alternatives, particularly in off-grid locations (IEA, 2009a). The principal technologies used to deliver modern biomass heat are *combustion*, *gasification*, and *digestion*.

Biomass is extensively used for domestic heating in industrialized countries. While some biomass continues to be used in open fireplaces, this is principally for aesthetic reasons, and where biomass is the main source of heating automated boilers for logs or pellets are widely available.

Estimating how much heat is provided via modern systems is difficult, however, as government statistics tend only to record large systems, such as district heating networks and power plants. Small appliances, such as log burning stoves and pellet boilers, are only visible at point of sale or if they use biomass that appears in retail statistics. Nevertheless, there is evidence of a growing market for modern boilers and stoves in the OECD. In the USA, for example, it is estimated that ~800,000 households use wood as their primary heat source, whereas in the top nine bioenergy-using European countries[3] the number of domestic stoves and boilers is estimated to exceed 1.3 million and accounts for the majority of solid biomass sold in Europe (AEBIOM, 2010; REN21, 2010). Bioenergy demand in the residential sector is expected to also double in OECD countries from ~3 EJ in 2009 to 6 EJ in 2050, driven predominantly by space heating demand (IEA, 2012a).

The northern European countries—Sweden, Finland, Denmark, and Germany—lead in the deployment of large-scale biomass heating systems. Much of this heat is generated in large combined heat and power (CHP) facilities and delivered via extensive district heating networks. Sweden provides a good example of a country that has successfully increased bioenergy provision, and in 2013, over 70 per cent of total district heating fuel demand was provided from biomass (Bayar, 2013). The Danish government has similar ambitions, and to encourage greater biomass use and connection to district heating networks has banned fossil-fuel fired boilers in new buildings from 2013 (Leidreiter, 2013).

Large combustion plants offer a number of advantages. They can deliver greater thermal efficiency than domestic boilers and this may result in a reduced capital cost per unit of heat delivered. They may also be able to use lower quality or contaminated biomass, such as waste derived fuels. These fuels are cheaper than alternatives but usually require flue gas cleaning technologies that are only economically viable at a larger scale (Dornburg and Faaij, 2001). CHP systems based on biomass combustion can be very efficient (60–90 per cent) (see Box 17.1), although for maximum efficiency they require large and stable heat loads and they are therefore most economical in colder climates where district heating is installed, or where there is an industrial heat demand.

Biomass is also used to provide process heat to industry, most frequently in the agricultural and forestry product processing industries where biomass is a byproduct of the main process and can be used as fuel. On larger sites CHP is widely adopted, for example co-production of steam and electricity from sugar cane residue (bagasse) is common practice in Brazilian sugar and ethanol mills. Industrial bioenergy demand appears set to increase, and the IEA envisages that it will be one of the fastest growing sectors, potentially increasing from ~ from 8 EJ in 2009 to ~22 EJ in 2050 (around 15 per cent of industrial final energy demand) (IEA, 2012a).

Whereas statistics for biomass heat provision are somewhat sketchy, far better data exists for global power generation. In 2011 it is estimated that global power production from biomass and wastes was in the region of ~ 1.3 EJ (355 TWh), roughly equivalent to total annual electricity generation of the UK (EIA, 2014). Although this represents only a small fraction of global electricity supply, generation capacity has grown rapidly over the last ten years, particularly in Europe and Asia where policy incentives have been favourable and fossil fuel prices comparatively high, see Figure 17.2.

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[3] Austria, Belgium, Denmark, Finland, France, Germany, Italy, Spain, Sweden.

BOX 17.1. CHP IN SWEDEN—THE IGELSTA CO-GENERATION PLANT

One of the world's largest and most efficient biomass CHP plants is the Igelsta plant in Sodertalje, near Stockholm, Sweden (Söderenergi, 2010). Commissioned in March 2010, this plant produces 200 MW of heat and 85 MW of electricity, sufficient to heat ~50,000 private houses and provide power for 100,000 homes.

The combustion technology used at Igelsta is a sophisticated circulating fluidized bed and incorporates state-of-the-art flue gas cleaning. The heat produced is used to raise steam: used first for electricity production (85 MW) and then to deliver low grade heat to the local district heating network (140 MW). By condensing the steam in the flue gas the plant is able to deliver an additional 60 MW heat to the heating network, and this gives the combined system an overall efficiency in excess of 90 per cent.

The fuel used in the Igelsta plant is a combination of wood chip from forest residues (75 per cent) and recovered fuels from waste (25 per cent). When running at full capacity the plant uses ~17,000 tonnes of biomass per week. Wood chips from forestry operations are transported by road, rail, and boat from all over Sweden and neighbouring Baltic countries. The recovered fuels include scrap paper, wood, and plastic that is not suitable for recycling and is sourced from offices, shops, and industries in the Stockholm region. Pelletized waste from similar sources is imported by boat from Germany and the Netherlands, around 100,000 tonnes of waste wood is also imported from Norway, Belgium, and the UK. The municipality that owns the plant considers that such fuel flexibility will be critical as competition for bio-fuels increases.

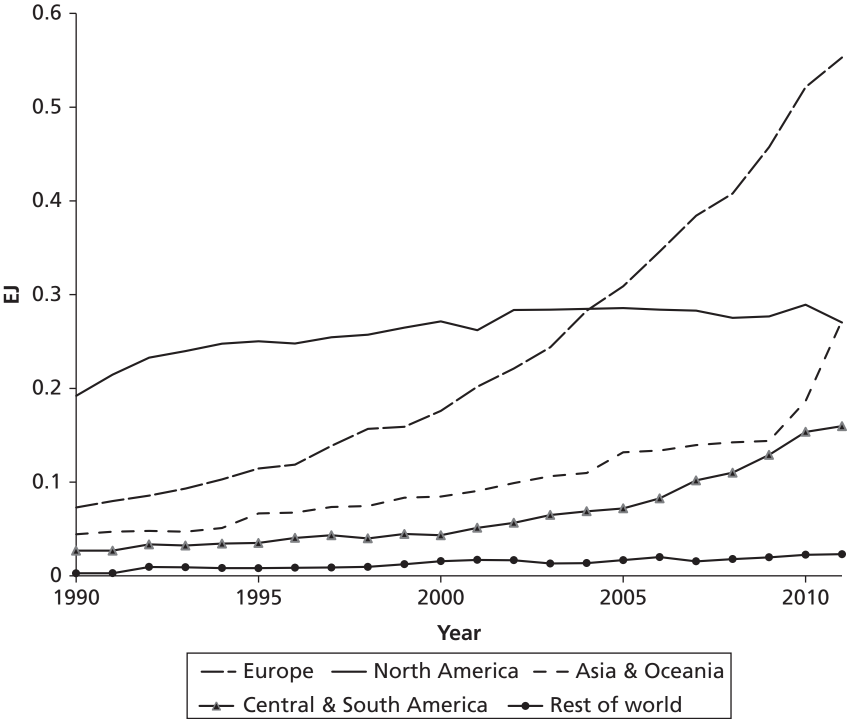

Figure 17.2 Global net electricity generation from biomass and waste

Source: Data from (EIA, 2014).

The vast majority (~90 per cent) (REN 21, 2013) of biomass electricity is generated from burning solid biomass and includes the following applications:

- co-firing wood pellets in coal power stations;
- combustion-based CHP plants—for countries that possess district heating systems and industries with available process residues (e.g. pulp and paper);
- municipal solid waste (MSW) incineration; and
- stand-alone power plants where large amounts of agricultural residues are available (e.g. the UK has a 38 MW dedicated straw-burning power station at Ely in East Anglia).

All these applications depend on locally available biomass, with the exception of internationally sourced wood pellets.[4] Wood pellets have emerged over the last ten years as a commodity energy vector and are now traded internationally, albeit in far smaller quantities than coal, oil, and gas. Global pellet production has grown rapidly from ~10 Mt in 2007 to ~18 Mt in 2011, and Europe is the largest consumer (estimated at 12.3 million tonnes in 2011). The majority of demand for pellets comes from the Netherlands, Belgium, Denmark, Sweden, and the UK and is a direct result of aggressive biomass co-firing targets (Verhoest and Ryckmans, 2012; Joudrey et al., 2012).

The remaining ~10 per cent of global bio-electricity is generated from biogas that is either captured from landfill sites or produced by anaerobic digestion. Europe is the leading producer of biogas and the market growth has been driven by both renewable energy targets and increasingly strict waste handling legislation (see Box 17.2). In 2011, total European biogas production was ~0.42 EJ, around just over half of which (56 per cent) was produced by anaerobic digestion from agricultural residues, putrescible waste, and dedicated crops such as maize silage. The remainder was produced from landfill sites and water treatment works (DENA, 2013). Biogas systems are also increasingly common in China where large numbers of small-scale systems have been installed for rural electrification (REN 21, 2013).

17.4 Transport fuels from biomass

Biofuels make a modest contribution to global transport fuel supply (~3 per cent, 3 EJ) and production is dominated by two liquid fuels: ethanol, which can substitute for gasoline, and biodiesel (produced from vegetable oil), which can substitute for diesel. Many other biofuel options exist, for example biogas is a viable fuel for fleet vehicles such as busses and bio-kerosene is attracting increasing interest for aviation, but the use of these alternatives is negligible on a global scale.

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[4] Some very large CHP facilities, such as Igelsta in Sweden, also source biomass internationally.

BOX 17.2. BIOGAS IN GERMANY

Germany is a technology leader in anaerobic digestion and generates over half of all the biogas produced in the EU. The German market has grown exponentially over the last eighteen years supported by favourable policy incentives and generous feed in tariffs (see Figure 17.3). By the end of 2012, there were over 7500 biogas plants (mostly biogas CHP facilities) operating in Germany and supplying around 83 PJ (23 TWh) of electricity. Gas clean-up and injection into the national gas grid started in 2009 and has become an increasingly attractive option for large plants; by July 2013, 116 biogas plants had adopted this technology (DENA, 2013).

Germany also hosts the world's largest biogas plant at Güstrow, Western Pomerania. This plant came online in 2009 and can digest 450,000 tons of biomass per year including maize silage, grain, and crop silage cultivated on an area of ~10,000 ha. The plant's output is equivalent to roughly 0.58 PJ (160 GWh) of electricity and 0.65 PJ (180 GWh) of heat. This is sufficient to cover the energy needs of a small town of ~50,000 households (Nawaro, 2013; EnviTech, 2008–9).

The use of maize silage as an energy crop has become increasingly controversial as it is perceived to compete with food production. Legislative changes introduced in 2012 sought to address this concern by limiting the use of maize to a maximum of 60 per cent of input biomass, and mandating for a minimum level of heat recovery. This change in the subsidy regime has caused a sharp decline in the domestic industry and many technology developers are now focusing their attention on the export market (RENI, 2013; DENA, 2013).

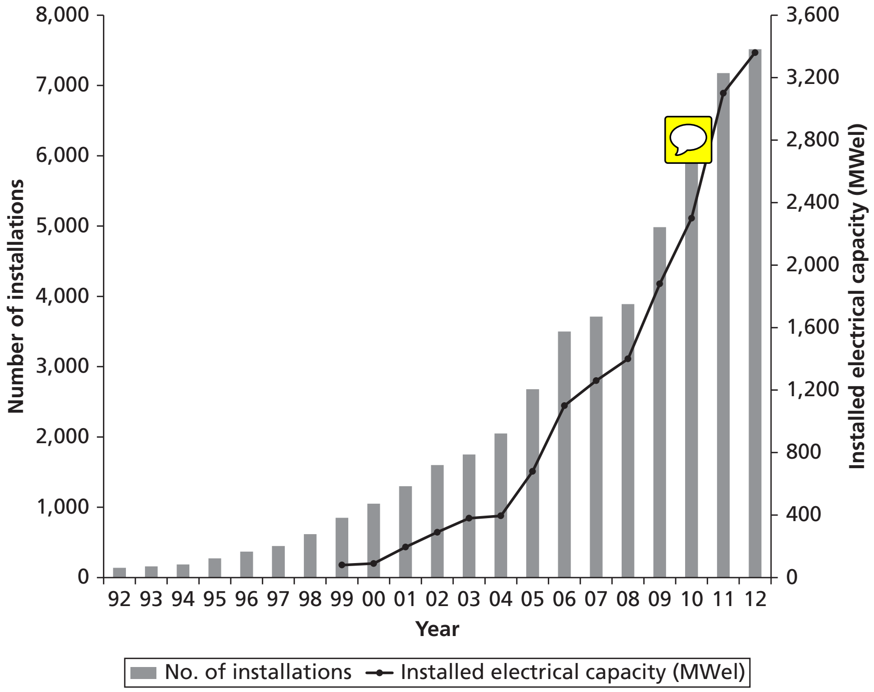

Figure 17.3 Biogas production in Germany 1992–2013

Source: Data from (DENA, 2013).

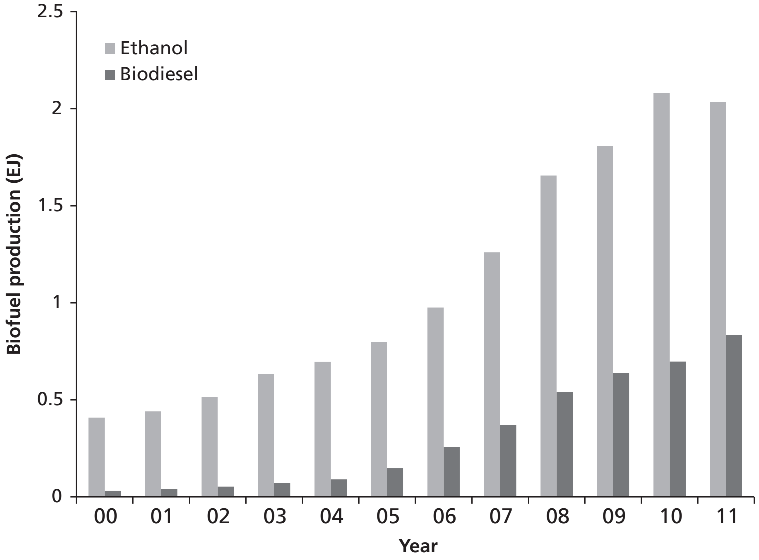

Figure 17.4 Global production of bioethanol and biodiesel 2000–11
Source: Data from (EIA, 2014).

In 2011, bioethanol accounted for over two thirds (71 per cent, 2 EJ) of global biofuel supply, the majority of which was produced from maize in the USA (1.2 EJ) and sugarcane in Brazil (0.5 EJ). The global production of biodiesel is smaller but still significant (29 per cent, 0.8 EJ). The most important global producers were Argentina, Brazil, and the USA (0.32 EJ from soy oil), Germany and France (0.18 EJ from rape seed oil), and Indonesia and Thailand (0.06 EJ from palm oil)[5] (EIA, 2014).

Biofuel production has grown rapidly in the last ten years (see Figure 17.4), and this has resulted in the diversion of large quantities of commodity food crops to energy production. The scale of the change has triggered a backlash against biofuel policies and mandates and this may limit future production growth from these feedstocks. At the time of writing in 2013, global use of cereals had decreased by ~2 per cent and virgin vegetable oils by ~10 per cent over 2012 levels, and this decline has been largely attributed to policy changes brought about by sustainability concerns (F. O. Lichts, 2013).

17.5 The future availability of biomass

Expanding the use of biomass to make a major contribution to the global energy mix would require significant and sustained investment, both to develop sustainable sources

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[5] Malaysia is one of the largest producers and exporters of palm oil; however, due to high palm oil prices, subsidized petroleum, and little domestic demand the majority of Malaysia's biodiesel plants were idle in 2011 (Wahab, 2012).

of supply and to build the infrastructure required to use it effectively. In this context, estimates of the current and future biomass resource underpin many of the strategic investment and policy decisions that must be made. Investments in new technology, for example, may be justified on the basis that a large and accessible resource exists. Similarly, the prominence given to biomass in international negotiations as a means to mitigate climate change depends on both a quantification of the resource and the impacts associated with its development.

A great many studies over the last twenty years have sought to quantify the availability of biomass for energy purposes at global, regional, and sub-regional scales. Models used to calculate biomass potentials vary in complexity and sophistication, but all aim to integrate information from sources such as the Food and Agriculture Organization's (FAO) databases, field trials, satellite imaging data, and demand predictions for energy, food, timber, and other land-based products, to elucidate bioenergy's future role (see Box 17.3: Calculating biomass potentials). The least complex approaches use simple rules and judgement to estimate the future share of land and residue streams available for bioenergy. The most complex use integrated assessment models which allow multiple variables and trade-offs to be analysed. There is good agreement, however, about the modelling parameters that are most important. These are: the availability (and productivity) of land for energy crops and food, and the accessibility of residues and wastes from existing and anticipated economic activity. Land availability estimates are strongly influenced by assumptions about how much land should be set aside for nature conservation, and how much will be needed to feed a growing population. Anticipated dietary changes are also important as a meat-rich diet requires far more land per person than is needed to support a vegetarian diet. Land productivity estimates are strongly influenced by technology scenarios and assumptions about how fast crop yields might be increased. Particularly important is the potential to increase crop yields and close the gap between optimal yields and those achieved by farmers when faced with environmental constraints such as water and nutrient scarcity, soil degradation, and climate change (Berndes et al., 2003; Lysen et al., 2008; Thrän et al., 2010).

Modelling results are most often discussed in terms of a hierarchy of potentials: theoretical > technical/geographic > economic > realistic/implementable, although these terms are not always used consistently. A theoretical potential estimate, for example, might be made by assuming that all net primary productivity (NPP) not needed for food could be available for bioenergy purposes. This assumption would lead to a very large and abstract number because it would ignore all competing land uses and socio-economic constraints. At the other end of the spectrum, an economic potential would constrain the useable quantity of biomass to the amount that could be produced at a specific price. This would lead to an inherently more subjective and smaller number, but one that may be far more appropriate for informing policy decisions.

The most important potential sources of biomass and the range of technical potentials found in the academic literature are energy crops (22–1272 EJ), agricultural residues (10–66 EJ), forestry residues (3–35 EJ), wastes (12–120 EJ), and forestry (60–230 EJ),

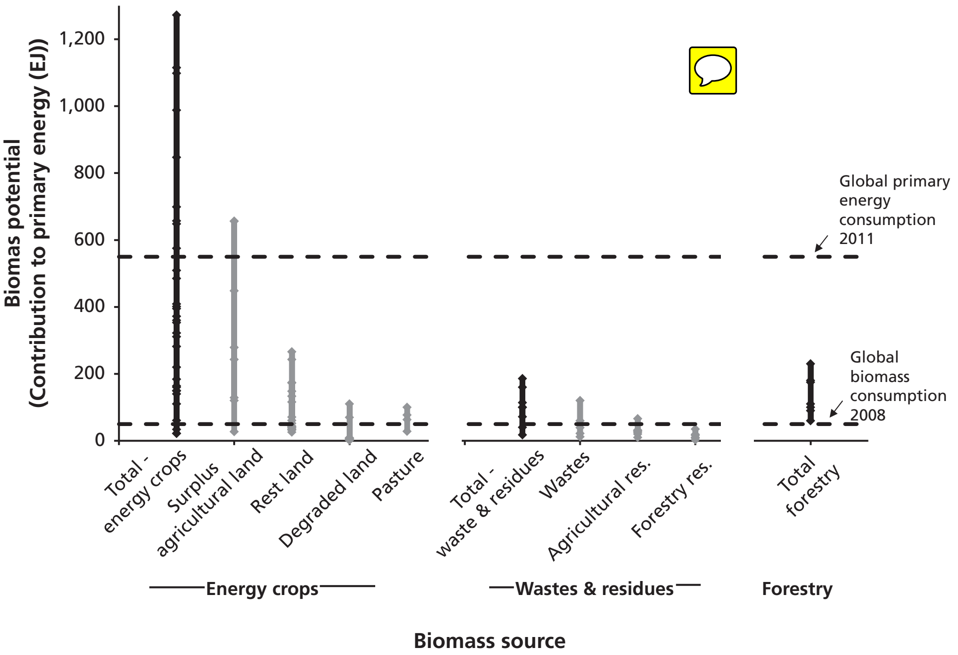


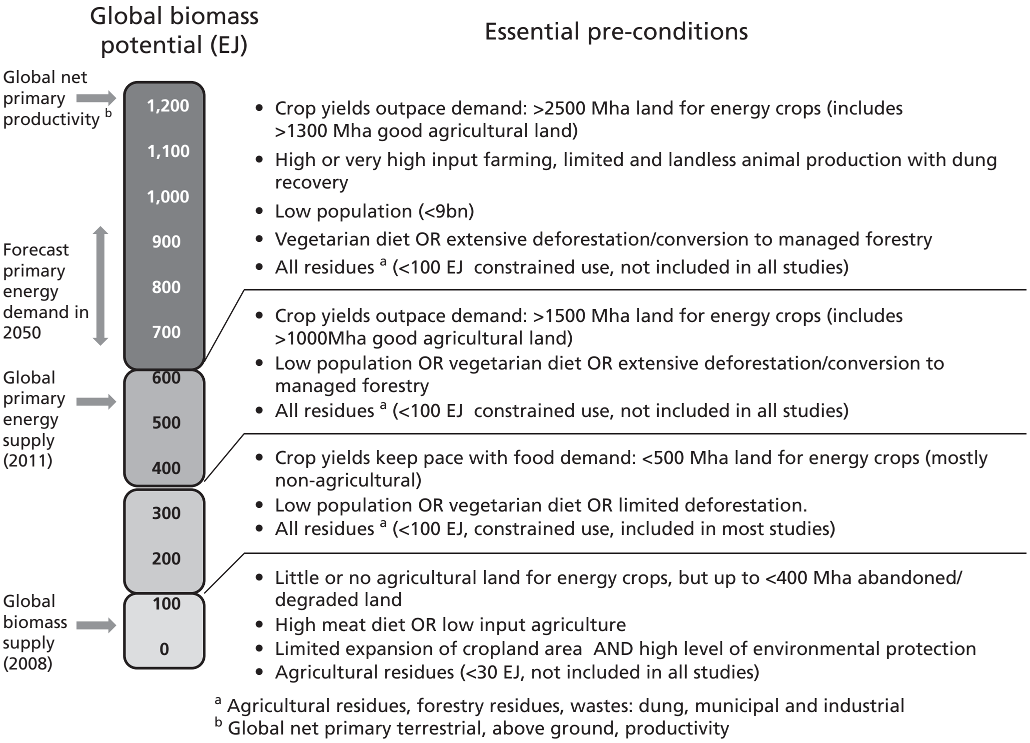
Figure 17.5 Estimates for the contribution of energy crops, wastes, and forest biomass to future energy supply

Source: adapted from (Slade et al., 2011).

summarized in Figure 17.5. Not all studies include all these categories in their analysis, and the broad range of estimates reflects the fact that some of the studies aim to test the boundaries of what might be physically possible rather than explore the boundaries of what might be socially acceptable or environmentally responsible. In particular, biomass extraction from forests is not considered by many authors because of concern about the potential impacts on biodiversity and carbon stocks. By way of comparison, the total human appropriation of net terrestrial primary production (including the entirety of global agriculture and commercial forestry) is around 320 EJ, of which 220 EJ is consumed and 100 EJ discarded as residues or otherwise destroyed during harvest. This is considerably less than current global primary energy supply (~500 EJ).

As the proportion of energy supplied from biomass in future global energy scenarios increases, the modelling assumptions required to make sufficient biomass available become increasingly demanding. The most important combinations of assumptions used to calculate estimates of the future technical biomass potential are summarized in Figure 17.6.

Estimates up to ~100 EJ (around 1/5th of current global primary energy supply) assume that there is limited land available for energy crops. This assumption is driven by scenarios in which there is a high demand for food, limited productivity gains in food production, and limited expansion of land under agriculture. Diets are assumed to evolve along the existing trend of increasing meat consumption. The contribution



- Crop yields outpace demand: >2500 Mha land for energy crops (includes >1300 Mha good agricultural land)
- High or very high input farming, limited and landless animal production with dung recovery
- Low population (<9bn)
- Vegetarian diet OR extensive deforestation/conversion to managed forestry
- All residues [a] (<100 EJ constrained use, not included in all studies)

- Crop yields outpace demand: >1500 Mha land for energy crops (includes >1000Mha good agricultural land)
- Low population OR vegetarian diet OR extensive deforestation/conversion to managed forestry
- All residues [a] (<100 EJ constrained use, not included in all studies)

- Crop yields keep pace with food demand: <500 Mha land for energy crops (mostly non-agricultural)
- Low population OR vegetarian diet OR limited deforestation.
- All residues [a] (<100 EJ, constrained use, included in most studies)

- Little or no agricultural land for energy crops, but up to <400 Mha abandoned/degraded land
- High meat diet OR low input agriculture
- Limited expansion of cropland area AND high level of environmental protection
- Agricultural residues (<30 EJ, not included in all studies)

[a] Agricultural residues, forestry residues, wastes: dung, municipal and industrial
[b] Global net primary terrestrial, above ground, productivity

Figure 17.6 Pre-conditions for increasing levels of biomass production
Source: adapted from (Slade et al., 2014).

from energy crops (8–71 EJ, ~140-400 Mha) predominantly comes from agricultural land identified as abandoned, degraded or deforested, and from limited expansion of energy crops onto pasture. The contribution from wastes and residues is considered in only a few studies, but where included the net contribution is in the range 17–30 EJ. Most studies in this range exclude biomass extraction from non-commercial forestry.

Estimates falling within the range 100–300 EJ (roughly half current global primary energy supply at the top end), all assume that increasing food crop yields keep pace with population growth and the trend of increasing meat consumption. Limited good quality agricultural land is made available for energy crop production, but these studies identify areas of natural grassland, marginal, degraded, and deforested land ranging from twice to ten times the size of France (100–500 Mha) yielding 10–20 odt. ha^{-1}. In scenarios where demand for food and materials is high, achieving biomass potentials in this range implies a decrease in the global forested area (up to 25 per cent), or replacing mature forest with younger, more rapidly growing, forest. The majority of estimates in this range also rely on a larger contribution from residues and wastes (60–120 EJ). This is partly achieved by including a greater number of waste and residue categories in the analysis, and partly by adopting more ambitious assumptions on recoverability.

BOX 17.3. CALCULATING BIOMASS POTENTIALS

Estimating the potential of energy crops

The future availability of energy crops depends on the availability and productivity of land. Two broad approaches to modelling future land availability can be distinguished: *availability factors* and *land balance models*. The *availability factor* approach simply identifies different categories of land and multiplies the area in each category by the fraction deemed suitable for energy crops. This fraction may be informed by information about agricultural surpluses, or may be purely hypothetical. An influential study from 1993, for example, assumes that 100 per cent of all areas of logged forest in Africa may be suitable for re-afforestation (Johansson et al., 1993). This approach has the advantage of a high level of transparency, but is simplistic and cannot capture the dynamics of competing demands for land or spatial variation in yields. *Land balance models* in contrast identify land areas on which crops may be cultivated (depending on soil, climate, and terrain);[6] they then exclude areas required for food production and other land uses such as urbanization and nature conservation. The area that remains is allocated to energy crops (see for example Hoogwijk et al. (2005) and Erb et al. (2009)). This more sophisticated approach can investigate the interactions between changing food demand, climate change, and land availability over time. Yet it may also overestimate the land available because uncultivable areas that only show up at high resolution may not be excluded. Also, land in cultivation may be underestimated in national statistics, and some land uses such as human settlements, forest, and conservation areas may not be recognized.

If food crop yields can be increased then agricultural land may become available for energy crops. Similarly, if energy crop yields can be increased then more energy can be produced for any given amount of land. Crop yields are a function of the amount of sunlight, the proportion of that light intercepted by the crop, the efficiency with which it is converted to biomass by photosynthesis, and the proportion of that biomass partitioned to the harvested product (Monteith, 1977; Hay and Walker, 1989). At any given location, the yield achieved will be determined by complex interactions between plant physiology, local ecology and climate, and management practices. Yields that can be achieved on poor quality soil, or in areas where water is scarce, may be far less than those achieved under optimum conditions. There are two approaches to estimating the productive yield: extrapolation from case-studies and sample plots, and model-based predictions. Uncertainty about how model parameters will change with location and over time, and limitations in the number of sample plots available, mean that both these methods are highly uncertain (Berndes et al., 2003).

Estimating the potential of agricultural residues

In contrast to the uncertainties that beset energy crop estimates, comparatively good data about the production of major food crops is collated and published by the FAO. From this data it is possible to estimate the quantity of residues produced by applying availability factors. The basic calculation for each crop is as follows:

*Resource = Total crop * Harvest index * Recoverability − Residues dedicated to other uses*

The harvest index is the fraction of the above ground biomass that is the primary crop. In the case of wheat and barley in the UK this is ~51 per cent, and for rapeseed it is about 30 per cent (Kilpatrick, 2008). Because past improvements in the major food crop species such as wheat have largely resulted from increases in the harvest index rather than increases in the total biomass produced by each plant (Hay, 1995), residue production may decrease as cereal yields increase. This effect may, however, be offset by increases in total crop production. It

(continued)

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[6] Most assessments use the FAO Agro-ecological Zoning (AEZ) methodology to match crop and land types.

BOX 17.3. (CONTINUED)

should also be noted that not all biomass residues will be recoverable: some may be left in the field to maintain soil fertility or may already be dedicated to existing uses—such as animal bedding.

Estimating the potential of wastes and residues

Robust data on waste production is seldom available. Consequently, most attempts to quantify the resource are limited to top-down estimates of the amount of waste likely to be produced per unit of economic activity in different industrial sectors, per head of population, or per head of livestock.[7] The basic calculation for each waste sub-category is:

*Resource = Level of economic activity * Waste generation fraction* Recoverability*

Estimates may also be projected into the future, moderated by judgements about the effect of economic growth or other anticipated changes such as increased recycling rates. The principal source of variation between estimates is the inclusion/exclusion of waste categories in the resource inventory. The main source of data is the FAO.

Estimating the potential of forestry

Forestry residues may be estimated in the same way as other wastes: as a fraction of the unused biomass produced by existing forest industries—again relying on FAO data. Harvesting biomass from mature forests, however, is a more controversial area. Many recent studies exclude mature forestry directly from biomass-for-energy estimates considering it better to retain the carbon stored in mature forest. The rationale for this is twofold: firstly, the impact on biodiversity would be unacceptable; and secondly, the carbon emitted as a result of changing the land use could be significant. Nevertheless a number of studies do include estimates of wood production from natural forests in their calculations (Smeets et al., 2007; Fischer and Schrattenholzer, 2001; Yamamoto et al., 1999, 2000, 2001). There is very limited data on the harvest intensity of mature forests and so the approach taken is to estimate the gross annual forest growth increment (a measure of net primary production, or NPP) as a proxy for the technical potential, and limit this by the fractions deemed available and accessible. Implicit in this approach is that a proportion of mature forest would become managed 're-growth' forest. This category of biomass would also overlap with traditional firewood gathering.

Estimates in excess of 300 EJ and up to 600 EJ (600 EJ is slightly more than current global primary energy supply) are all predicated on the assumption that increases in food crop yields could significantly outpace demand for food, with the result that an area of high yielding agricultural land the size of China (>1000 Mha) could be made available for energy crops. In addition, these estimates assume that an area of grassland and marginal land larger than India (>500 Mha) could be converted to energy crops. The area of land

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[7] For example, Johansson et al. (1993), assume that Municipal Solid Waste (MSW) in OECD countries will be generated at a constant rate of 300 kg per capita per year, and that 75 per cent of this will be recoverable for energy purposes. In another example, Yamamoto et al. (1999) estimates that 20 per cent of food supply will end up as kitchen refuse and that 75 per cent of this could be used for energy purposes. These authors also estimate that 20 per cent of food supply will end up as human faeces and that 25 per cent of this could be recovered.

allocated to energy crops could thus occupy over 10 per cent of the world's land mass, equivalent to the existing global area used to grow arable crops. For most of the estimates in this range a high meat diet could only be accommodated with extensive deforestation. It is also implicit that most animal production would have to be landless to achieve the level of agricultural intensification and residue recovery required.

Estimates in excess of 600 EJ are extreme. The primary purpose of scenarios in this range is to provide a theoretical maximum upper bound and to illustrate the sensitivity of the models to key variables such as population, diet, and technological change. Estimates in this range are not intended to represent *socially acceptable* or *environmentally responsible* scenarios and none of the studies analysed here suggests that they are plausible.

Global biomass potential studies do not try to describe what is likely to happen. Rather, they describe scenarios in which biomass makes an increasing contribution to primary energy supply while attempting to minimize the negative impacts by imposing environmental constraints on development. They are optimistic in the sense that they try to describe sustainable paths as opposed to unsustainable ones. What they are *not* is forecasts extrapolated from empirical observations or any practical experience of trying to achieve these sorts of transitions at a global scale. They therefore provide limited insight into how biomass supply would actually develop if demand was to increase.

In a special report on renewable energy sources for climate change mitigation published in 2011, the view of the Intergovernmental Panel on Climate Change (IPCC) was that the global biomass technical potential could reach 100–300 EJ by 2050. However, the authors of this report also concluded that the technical potential cannot be determined precisely because it depends on 'factors that are inherently uncertain' while societal preferences are unclear. Moreover, increased biomass consumption could evolve in a sustainable or unsustainable way and this could present a challenge for effective governance (IPCC, 2011).

17.6 The sustainability and governance challenge

In the 1990s bioenergy was generally regarded as an uncontroversial and environmentally benign alternative to fossil fuels. At this time food and energy prices were comparatively low. Resource scarcity was not high on the agenda, and agricultural land had been taken out of production in Europe and North America to limit food surpluses. Bioenergy was seen by policymakers and politicians as an attractive and low-risk option, and one that could help meet a wide range of policy goals. This favourable view, however, was largely untempered by experience. Outside of a small number of industrial sectors such as pulp and paper, and countries such as Brazil which had been an early adopter of ethanol for transport, there was very limited practical understanding of deploying bioenergy technologies at scale.

By 2015, this situation had to a large extent reversed. Companies and policymakers had accumulated a wealth of knowledge from real projects, but the sustainability of biomass supply had become highly controversial as an increasingly complex and contested picture of the potential impacts and benefits emerged.

By far the most heated debate has been around the production of transport biofuels from commodity food crops. The principal argument against using food crops in this way is that it will increase competition for land, thereby driving up the price of food and setting in motion a cascade of undesirable indirect effects. For example, it is argued that increased demand will not only cause the poor to suffer but will lead to increased conversion of pasture and forested land to arable production. This land conversion may be associated with greenhouse gas emissions if, for instance, newly exposed carbon-rich soils begin to oxidize, and these emissions could negate many of the environmental benefits that provided the rationale for supporting biofuels in the first place. Similarly, agricultural intensification could lead to greater fertilizer use and emissions of nitrous oxides which are also a potent greenhouse gas. Some of the more vociferous opponents claim that biofuels will lead to famine, deplete water resources, destroy biodiversity and soils, as well as being primarily responsible for the food price spikes that occurred in 2008 (Eide, 2008; Mitchell, 2008).

Those seeking to counter these arguments acknowledge the potential for competition but question both the *scale of the effect* and the *direction of travel*. In 2012/13 roughly 137 Mt of cereals (~14 per cent of global production) was used to produce bioethanol, but because one of the co-products of ethanol production is a protein-rich animal feed, the net additional demand for cereals would have been somewhat less (around 9 per cent of global production)[8] (F. O. Lichts, 2013). It is also argued that the 2008 price spikes could better be attributed to a multitude of factors *in addition to biofuels*. These include: the depreciation of the US dollar, increased oil prices, export restrictions on rice, weather shocks leading to poor harvests in some regions, commodity speculation, and increased meat consumption in China and India (Headey and Fan, 2008). The direction of travel is also important because bioenergy proponents do not advocate that an ever larger proportion of good quality farmland should be used to produce biofuels from sugar, starch, and vegetable oil. Rather, they envisage that technological advances will lead to a new generation of conversion technologies able to convert residues and waste products into fuels. A number of researchers have also suggested that there may be beneficial synergies from co-producing food and energy crops. Perennial energy crops, for instance, may also be used to mitigate some of the environmental impacts of intensive agriculture—such as nitrate run-off and soil erosion (Wicke et al., 2011; Berndes, 2008). Using biomass to provide energy services in developing countries might even help prevent wastage in food supply-chains and provide a route for the introduction of sorely needed agricultural infrastructure and knowhow (Lynd and Woods, 2011).

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[8] Net additional demand for cereals is ~2/3rds gross input to biofuels (Keller, 2010).

Arguments about sustainability, however, are not restricted to the use of food crops and agricultural land. The rapid increase in wood pellet imports from North America to Europe has attracted opprobrium from non-governmental organizations including Greenpeace and Friends of the Earth (RSPB, 2012). In this case the principal objection is that producing wood pellets could directly (or indirectly through market-mediated changes in demand) reduce the standing stock of forest biomass. Their fear is that this could result in carbon emissions increasing in the short term generating a *carbon debt* that would only be repaid over a much longer timescale as the trees regrow and reabsorb the carbon. Whether a debt arises has been reasonably well examined in the academic literature and depends on how a forest is managed and the balance of impacts between natural disturbance (wind, fire, pests) and human disturbance (harvesting). A debt is most likely to occur when unmanaged forest is brought into management, but this also depends on assumptions about what, if anything, is done to increase the productivity of the forest, such as accelerating the rate of re-establishment after harvesting. If, alternatively, you consider a forest with a population of different age trees that is already under management, and each year only the annual growth increment is harvested, no debt arises (Matthews et al., 2014). Carbon debt has only recently entered the public consciousness and has gained salience because of the rapid growth of the wood pellet market and because the timeframes for policy and forest management decisions are so dramatically different. It has yet to be seen how this heightened concern will affect political support for co-firing projects in the UK and Europe.

These examples of on-going debates surrounding sustainability serve to illustrate the complexity of sourcing large quantities of biomass for energy production almost no matter what the ultimate source of the biomass might be. At European level the policy response has been twofold. Firstly, proposals (expected to be adopted in 2014) have been put forward to amend the legislation that mandates increasing quantities of bioenergy in member states (Renewable Energy Directive). These proposals are intended to favour sources of biomass such as residues that are considered less likely to raise sustainability concerns. Other proposed changes include increasing the minimum greenhouse gas saving threshold for new installations, accounting for land use change impacts, and setting limits on the quantities of food-crop-based biofuels. The second element of the policy response has been to place increased reliance on biomass certification schemes that attempt to ensure that biomass entering the energy supply chain meets minimum environmental criteria.

Certification schemes aim to translate broad sustainability principles into decision making criteria that can be evaluated on the basis of detailed and specific indicators. Although the concept of certification is not new—familiar examples include fair-trade coffee and the Forestry Stewardship Council (FSC) standard for wood products—the introduction and design of certification standards for bioenergy as a means to ensure sustainability is not straightforward. Identifying appropriate criteria for certification schemes presents a trade-off between efficacy and ease of adoption.

If criteria are overly detailed and too stringent, compliance may be difficult to demonstrate or they may act as a barrier to trade as reporting costs may become excessive. Conversely, if criteria are too general, they may become meaningless. There is also a risk of leakage if measures are applied to bioenergy production in isolation from the rest of the agricultural and forestry system. For instance, if food and feed crops do not face limitations in land use conversion then areas currently used for food could be diverted to bioenergy and be replaced with newly deforested land elsewhere. Adoption of standards is also essentially a voluntary approach as the implementation of binding requirements is limited by World Trade Organization rules.[9]

A review of bioenergy standards in 2010 identified sixty-seven ongoing certification initiatives (van Dam et al., 2010a). The way these initiatives had approached developing criteria, prescribing calculation methodologies and adopting default values for indicators, was found to be very diverse, reducing transparency and making comparison between schemes difficult (van Dam et al., 2010b). The majority of schemes also focused only on the environmental sustainability of liquid biofuels (and to a lesser extent wood pellets) ignoring social criteria such as peasant farmers' access to land, water, and other natural resources. This proliferation of schemes presents a risk for confusion and potential for a race to the bottom if companies shop around for a standard that can demonstrate regulatory compliance with minimum effort and no change in production methods.

One of the most comprehensive sets of sustainability criteria and indicators has been developed by the Global Bioenergy Partnership—summarized in Table 17.1. These indicators aspire to be value-neutral and do not provide thresholds or limits. Nonetheless they show the breadth of impacts that policymakers might wish to consider in a national or international certification scheme.

The greater the role that bioenergy has in meeting future energy demand, the more important it will become to ensure that biomass production delivers sustainability benefits over the fossil fuel alternatives. Because biomass supply is intertwined with so many different production systems these benefits may be hard to identify. For many biomass resources the economic, social, and environmental impacts are diverse, difficult to quantify, and often contested. Biomass certification is the principal approach to ensuring biomass supply meets public expectations for sustainability, and initiatives have developed and evolved as supply has increased. Sustainability concerns nonetheless present a constraint on the uptake of modern bioenergy technologies and new approaches may be required to reconcile competing demands for food, energy, and environmental protection.

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[9] Although the use of standards is voluntary, conformity to European standards may constitute a presumption of conformity to the legal requirements of European Directives.

Table 17. e Global Bioenergy Partnership's sustainability indicators for bioenergy

	Environmental	Social	Economic
Themes	Greenhouse gas emissions. Productive capacity of the land and ecosystems. Air quality. Water availability, use efficiency and quality. Biological diversity. Land use change, including indirect effects.	Price and supply of a national food basket. Access to land, water, and other natural resources. Labour conditions. Rural and social development. Access to energy. Human health and safety.	Resource availability and use efficiencies in bioenergy production, conversion, distribution and end use. Economic development. Economic viability and competitiveness of bioenergy. Access to technology and technological capabilities. Energy security/diversification of sources and supply. Energy security/ infrastructure and logistics for production and use.
Indicators	• Lifecycle GHG emissions	• Allocation and tenure of land for new bioenergy production	• Productivity
	• Soil quality	• Price and supply of a national food basket	• Net energy balance
	• Harvest levels of wood resources	• Change in income	• Gross added value
	• Emission of non-GHG air pollutants, including air toxics	• Jobs in the bioenergy sector	• Change in consumption of fossil fuels and traditional use of biomass
	• Water use and efficiency	• Change in unpaid time spent by women and children collecting biomass	• Training and requalification of the workforce
	• Water quality	• Bioenergy used to expand access to modern energy services	• Energy diversity • Infrastructure and logistics for distribution of bioenergy
	• Biological diversity in the landscape	• Change in mortality and burden of disease attributable to indoor smoke	• Capacity and flexibility of use of bioenergy
	• Land use and land-use-change related to bioenergy feedstock production	• Incidence of occupational injury, illness and fatalities	

Source: adapted from GBEP (2001

17.7 Summary and conclusions

Biomass can be used to provide the full range of modern energy services—heat, power, and transport fuels—using established and proven technology. Advanced conversion technologies that offer improved performance and the ability to use a broader range of feedstock are also beginning to enter the market. Bioenergy production has grown rapidly over the last ten years and estimates of global biomass potential suggest that there is scope for its role in the energy mix to increase further. Yet as bioenergy production has increased, concerns about the environmental and social impacts of biomass supply have emerged that have resonated with public sentiment and gained significant political traction. These concerns appear increasingly likely to constrain future growth, and it has yet to be seen how rapidly the combination of more advanced conversion technologies together with approaches such as biomass certification will provide a way forward. Thus the future development of the bioenergy sector is uncertain. The efficacy of the conversion technologies is not in doubt, but the sheer complexity of biomass supply chains and the acceptability of their environmental and social impacts could limit its contribution to global energy supply.

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