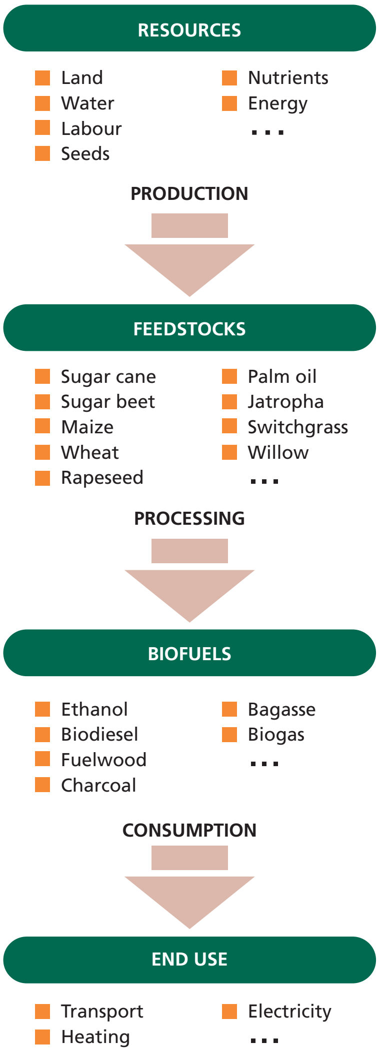
2. Biofuels and agriculture – a technical overview

Traditional biomass, including fuelwood, charcoal and animal dung, continues to provide important sources of energy in many parts of the world. Bioenergy is the dominant energy source for most of the world's population who live in extreme poverty and who use this energy mainly for cooking. More advanced and efficient conversion technologies now allow the extraction of biofuels – in solid, liquid and gaseous forms – from materials such as wood, crops and waste material. This chapter provides an overview of biofuels. What are they, what is their potential and what are their implications for agriculture? The main focus, however, is on liquid biofuels for transport, which are now gaining in prominence as a result of the rapid increase in their use.

FIGURE 4
Biofuels – from feedstock to end use



Source: FAO.

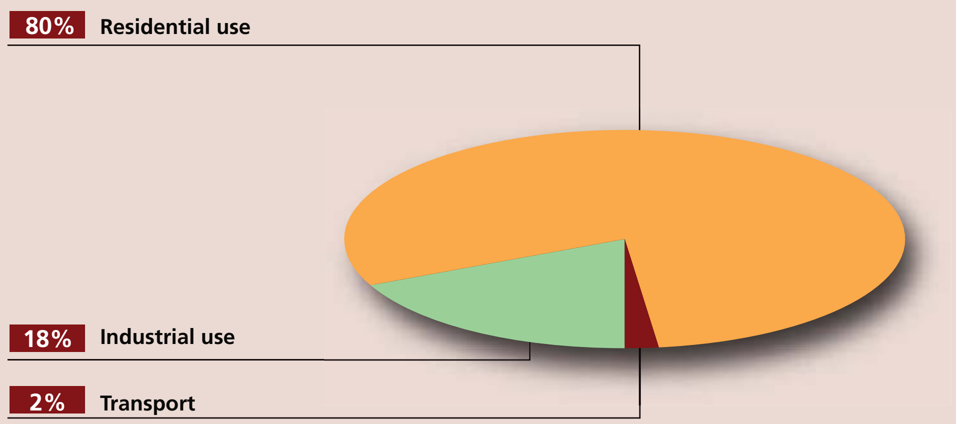
Types of biofuels

Biofuels are energy carriers that store the energy derived from biomass.[2] A wide range of biomass sources can be used to produce bioenergy in a variety of forms. For example, food, fibre and wood process residues from the industrial sector; energy crops, short-rotation crops and agricultural wastes from the agriculture sector; and residues from the forestry sector can all be used to generate electricity, heat, combined heat and power, and other forms of bioenergy. Biofuels may be referred to as *renewable* energy because they are a form of transformed solar energy.

Biofuels can be classified according to source and type. They may be derived from forest, agricultural or fishery products or municipal wastes, as well as from agro-industry, food industry and food service by-products and wastes. They may be *solid*, such as fuelwood, charcoal and wood pellets; *liquid*, such as ethanol, biodiesel and pyrolysis oils; or *gaseous*, such as biogas.

[2] For a review of terminology relating to biofuels, see FAO (2004a).

FIGURE 5
Uses of biomass for energy



Source: IEA, 2007.

A basic distinction is also made between *primary* (unprocessed) and *secondary* (processed) biofuels:

- **Primary biofuels**, such as firewood, wood chips and pellets, are those where the organic material is used essentially in its natural form (as harvested). Such fuels are directly combusted, usually to supply cooking fuel, heating or electricity production needs in small- and large-scale industrial applications.
- **Secondary biofuels** in the form of solids (e.g. charcoal), liquids (e.g. ethanol, biodiesel and bio-oil), or gases (e.g. biogas, synthesis gas and hydrogen) can be used for a wider range of applications, including transport and high-temperature industrial processes.

Liquid biofuels for transport[3]

In spite of their limited overall volume (see Figure 5), the strongest growth in recent years has been in liquid biofuels for transport, mostly produced using agricultural and food commodities as feedstocks. The most significant are ethanol and biodiesel.

Ethanol

Any feedstock containing significant amounts of sugar, or materials that can be converted into sugar such as starch or cellulose, can be used to produce ethanol. Ethanol available in the biofuel market today is based on either sugar or starch. Common sugar crops used as feedstocks are sugar cane, sugar beet and, to a lesser extent, sweet sorghum. Common starchy feedstocks include maize, wheat and cassava. The use of biomass containing sugars that can be fermented directly to ethanol is the simplest way of producing ethanol. In Brazil and other tropical countries currently producing ethanol, sugar cane is the most widely used feedstock. In OECD countries, most ethanol is produced from the starchy component of cereals (although sugar beet is also used), which can be converted fairly easily into sugar. However, these starchy products represent only a small percentage of the total plant mass. Most plant matter is composed of cellulose, hemicellulose and lignin; the first two can be converted into alcohol after they have first been converted into sugar, but the process is more difficult than the one for starch. Today, there is virtually no commercial production of ethanol from cellulosic biomass, but substantial research continues in this area (see the section on second-generation biofuels on pp. 18–19).

[3] This section is based on GBEP (2007, pp. 2–10) and IEA (2004).

BOX 1
Other types of biomass for heat, power and transport

Biomass for heat and power

A range of biomass resources are used to generate electricity and heat through combustion. Sources include various forms of waste, such as residues from agro-industries, post-harvest residues left on the fields, animal manure, wood wastes from forestry and industry, residues from food and paper industries, municipal solid wastes, sewage sludge and biogas from the digestion of agricultural and other organic wastes. Dedicated energy crops, such as short-rotation perennials (eucalyptus, poplar, willow) and grasses (miscanthus and switchgrass), are also used.

Several processes can be used for power generation. Most biomass-derived electricity is produced using a steam-cycle process: biomass is burned in a boiler to generate high-pressure steam that flows over a series of aerodynamic blades causing a turbine to rotate, which in response turns a connected electric generator to produce electricity. Compacted forms of biomass such as wood pellets and briquettes can also be used for combustion, and biomass can also be burned with coal in the boiler of a conventional power plant to yield steam and electricity. The latter is currently the most cost-efficient method for incorporating renewable technology into conventional power production because much of the existing power plant infrastructure can be used without major modifications.

Biogas for heat, power and transport

Anaerobic digestion

Biogas can be created through the *anaerobic digestion* of food or animal waste by bacteria in an oxygen-starved environment. The resulting biogas contains a high volume of methane along with carbon dioxide, which can be used for heating or for electricity generation in a modified internal combustion engine. The conversion of animal wastes and manure to methane/biogas can bring significant environmental and health benefits. Methane is a greenhouse gas that has a global-warming potential that is 22–24 times more powerful than that of carbon dioxide. By trapping and utilizing the methane, its greenhouse gas impacts are avoided. In addition, heat generated during the biodigestion process kills the pathogens present in manure, and the material left at the end of the process provides a valuable fertilizer.

Gasification

Through the process of *gasification*, solid biomass can be converted into a fuel gas or biogas. Biomass gasifiers operate by heating biomass in a low-oxygen, high-temperature environment that breaks it down to release a flammable, energy-rich synthesis gas or "syngas". This gas can be burned in a conventional boiler, or used instead of natural gas in a gas turbine to turn electric generators. Biogas formed through gasification can be filtered to remove unwanted chemical compounds and can be used in efficient "combined-cycle" power-generation systems that combine steam and gas turbines to generate electricity.

Biogas for transport

Untreated biogas is unsuitable as a transport fuel owing to its low methane content (60–70 percent) and high concentration of contaminants. However, it can be treated to remove carbon dioxide, water and corrosive hydrogen sulphide and to enhance its methane content (to over 95 percent). When compressed, treated biogas has properties similar to those of compressed natural gas, making it suitable for use in transport.

Source: based on GBEP, 2007.

Ethanol can be blended with petrol or burned in its pure form in slightly modified spark-ignition engines. A litre of ethanol contains approximately 66 percent of the energy provided by a litre of petrol, but has a higher octane level and when mixed with petrol for transportation it improves the performance of the latter. It also improves fuel combustion in vehicles, thereby reducing the emission of carbon monoxide, unburned hydrocarbons and carcinogens. However, the combustion of ethanol also causes a heightened reaction with nitrogen in the atmosphere, which can result in a marginal increase in nitrogen oxide gases. In comparison with petrol, ethanol contains only a trace amount of sulphur. Mixing ethanol with petrol, therefore, helps to reduce the fuel's sulphur content and thereby lowers the emissions of sulphur oxide, a component of acid rain and a carcinogen.

Biodiesel

Biodiesel is produced by combining vegetable oil or animal fat with an alcohol and a catalyst through a chemical process known as *transesterification*. Oil for biodiesel production can be extracted from almost any oilseed crop; globally, the most popular sources are rapeseed in Europe and soybean in Brazil and the United States of America. In tropical and subtropical countries, biodiesel is produced from palm, coconut and jatropha oils. Small amounts of animal fat, from fish- and animal-processing operations, are also used for biodiesel production. The production process typically yields additional by-products such as crushed bean "cake" (an animal feed) and glycerine. Because biodiesel can be based on a wide range of oils, the resulting fuels can display a greater variety of physical properties, such as viscosity and combustibility, than ethanol.

Biodiesel can be blended with traditional diesel fuel or burned in its pure form in compression ignition engines. Its energy content is 88–95 percent of that of diesel, but it improves the lubricity of diesel and raises the cetane value, making the fuel economy of both generally comparable. The higher oxygen content of biodiesel aids in the completion of fuel combustion, reducing emissions of particulate air pollutants, carbon monoxide and hydrocarbons. As with ethanol, diesel also contains only a negligible amount of sulphur, thus reducing sulphur oxide emissions from vehicles.

Straight vegetable oil

Straight vegetable oil (SVO)[4] is a potential fuel for diesel engines that can be produced from a variety of sources, including oilseed crops such as rapeseed, sunflower, soybean and palm. Used cooking oil from restaurants and animal fat from meat-processing industries can also be used as fuel for diesel vehicles.

Biofuel feedstocks

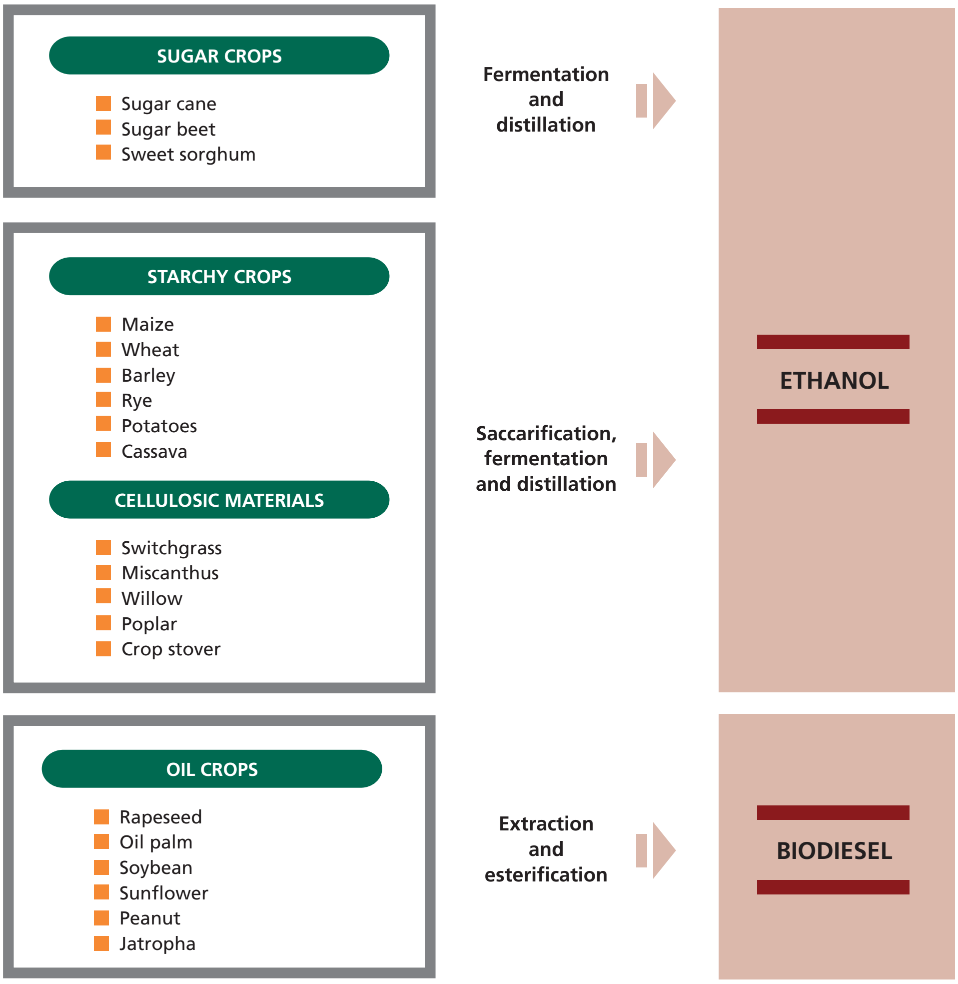
There are many supply sources of biomass for energy purposes, scattered across large and diverse geographical areas. Even today, most energy derived from biomass used as fuel originates from by-products or co-products of food, fodder and fibre production. For instance, the main by-products of forest industries are used to produce fuelwood and charcoal, and black liquor (a by-product of pulp mills) is a major fuel source for bioelectricity generation in countries such as Brazil, Canada, Finland, Sweden and the United States of America. A considerable amount of heat and power is derived from recovered and/or recycled woody biomass and increasing amounts of energy are recovered from biomass derived from cropland (straw and cotton stalks) and forest land (wood chips and pellets). In sugar- and coffee-producing countries, bagasse and coffee husks are used for direct combustion and to produce heat energy and steam.

In terms of bioenergy, however, the big growth area in recent years has been in the production of liquid biofuels for transport using agricultural crops as feedstocks. The bulk of this has taken the form of ethanol, based on either sugar crops or starchy crops, or biodiesel based on oil crops.

As shown in Figure 6, a range of different crops can be used as feedstock for ethanol and biodiesel production. However, most global ethanol production is derived from sugar cane or maize; in Brazil, the bulk of ethanol is produced from sugar cane and in the United States of America from maize.

4 Also referred to as pure plant oil (PPO).

FIGURE 6
Conversion of agricultural feedstocks into liquid biofuels



Source: FAO.

Other significant crops include cassava, rice, sugar beet and wheat. For biodiesel, the most popular feedstocks are rapeseed in the EU, soybean in the United States of America and Brazil, and palm, coconut and castor oils in tropical and subtropical countries, with a growing interest in jatropha.

Biofuels and agriculture

The current expansion and growth of energy markets, as a result of new energy and environment policies enacted over the past decade in most developed countries and in several developing countries, is reshaping the role of agriculture. Most significant is the sector's increasing role as a provider of feedstock for the production of liquid biofuels for transport – ethanol and biodiesel. Modern bioenergy represents a new source of demand for farmers' products. It thus holds promise for the creation of income and employment. At the same time, it generates increasing competition for natural resources, notably land and water, especially in the short run, although yield increases may mitigate such competition in the longer run. Competition for land becomes an issue especially when some of the crops (e.g. maize, oil palm and soybean) that are currently cultivated for food and feed are redirected towards the production of biofuels, or when food-oriented agricultural land is converted to biofuel production.

Currently, around 85 percent of the global production of liquid biofuels is in the form of ethanol (Table 1). The two largest ethanol producers, Brazil and the United States of America, account for almost 90 percent of total production, with the remainder accounted for mostly by Canada, China, the EU (mainly France and Germany) and India. Biodiesel production is principally concentrated in the EU (with around 60 percent of the total), with a significantly smaller contribution coming from the United States of America. In Brazil, biodiesel production is a more recent phenomenon and production volume remains limited. Other significant biodiesel producers include China, India, Indonesia and Malaysia.

Different crops vary widely in terms of biofuel yield per hectare, both across feedstocks and across countries and production systems, as illustrated in Table 2. Variations are due both to differences in crop yields per hectare across crops and countries and to differences in conversion efficiency across crops. This implies vastly different land requirements for increased biofuel production depending on the crop and location. Currently, ethanol production from sugar cane and sugar beet has the highest yields, with sugar-cane-based production in Brazil topping the list of in terms of biofuel output per hectare and India not far behind. Yields per hectare are somewhat lower for maize, but with marked differences between yields, for example, in China and in the United States of America. The data reported in Table 2 refer only to technical yields. The cost of producing biofuels based on different crops in different countries may show very different patterns. This is discussed further in Chapter 3.

The biofuels life cycle: energy balances and greenhouse gas emissions

Two of the main driving forces behind policies promoting biofuel development have been concerns over energy security and a desire to reduce greenhouse gas emissions. Just as different crops have different yields in terms of biofuel per hectare, wide variations also occur in terms of energy balance and greenhouse gas emission reductions across feedstocks, locations and technologies.

The contribution of a biofuel to energy supply depends both on the energy content of the biofuel and on the energy going into its production. The latter includes the energy required to cultivate and harvest the feedstock, to process the feedstock into biofuel and to transport the feedstock and

TABLE 1
Biofuel production by country, 2007

COUNTRY/COUNTRY GROUPING	ETHANOL		BIODIESEL		TOTAL	
	(Million litres)	*(Mtoe)*	*(Million litres)*	*(Mtoe)*	*(Million litres)*	*(Mtoe)*
Brazil	19 000	10.44	227	0.17	19 227	10.60
Canada	1 000	0.55	97	0.07	1 097	0.62
China	1 840	1.01	114	0.08	1 954	1.09
India	400	0.22	45	0.03	445	0.25
Indonesia	0	0.00	409	0.30	409	0.30
Malaysia	0	0.00	330	0.24	330	0.24
United States of America	26 500	14.55	1 688	1.25	28 188	15.80
European Union	2 253	1.24	6 109	4.52	8 361	5.76
Others	1 017	0.56	1 186	0.88	2 203	1.44
World	**52 009**	**28.57**	**10 204**	**7.56**	**62 213**	**36.12**

Note: Data presented are subject to rounding.
Source: based on F.O. Licht, 2007, data from the OECD–FAO AgLink-Cosimo database.

TABLE 2
Biofuel yields for different feedstocks and countries

CROP	GLOBAL/NATIONAL ESTIMATES	BIOFUEL	CROP YIELD	CONVERSION EFFICIENCY	BIOFUEL YIELD
			(Tonnes/ha)	*(Litres/tonne)*	*(Litres/ha)*
Sugar beet	Global	Ethanol	46.0	110	5 060
Sugar cane	Global	Ethanol	65.0	70	4 550
Cassava	Global	Ethanol	12.0	180	2 070
Maize	Global	Ethanol	4.9	400	1 960
Rice	Global	Ethanol	4.2	430	1 806
Wheat	Global	Ethanol	2.8	340	952
Sorghum	Global	Ethanol	1.3	380	494
Sugar cane	Brazil	Ethanol	73.5	74.5	5 476
Sugar cane	India	Ethanol	60.7	74.5	4 522
Oil palm	Malaysia	Biodiesel	20.6	230	4 736
Oil palm	Indonesia	Biodiesel	17.8	230	4 092
Maize	United States of America	Ethanol	9.4	399	3 751
Maize	China	Ethanol	5.0	399	1 995
Cassava	Brazil	Ethanol	13.6	137	1 863
Cassava	Nigeria	Ethanol	10.8	137	1 480
Soybean	United States of America	Biodiesel	2.7	205	552
Soybean	Brazil	Biodiesel	2.4	205	491

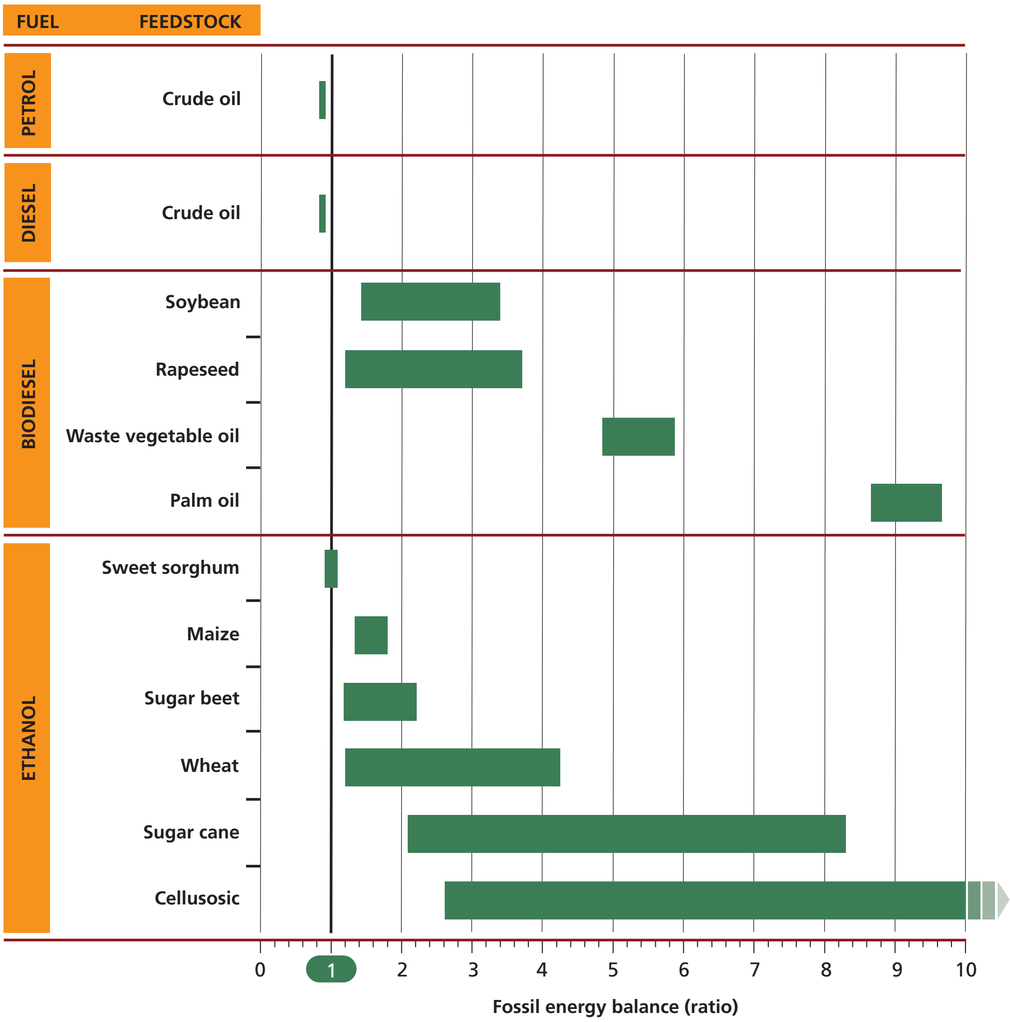
Sources: Rajagopal *et al*., 2007, for global data; Naylor *et al*., 2007, for national data.

the resulting biofuel at the various phases of its production and distribution. The fossil energy balance expresses the ratio of energy contained in the biofuel relative to the fossil energy used in its production. A fossil energy balance of 1.0 means that it requires as much energy to produce a litre of biofuel as it contains; in other words, the biofuel provides no net energy gain or loss. A fossil fuel energy balance of 2.0 means that a litre of biofuel contains twice the amount of energy as that required in its production. Problems in assessing energy balances accurately derive from the difficulty of clearly defining the system boundary for the analysis.

Figure 7 summarizes the results of several studies on fossil energy balances for different types of fuel, as reported by the Worldwatch Institute (2006). The figure reveals wide variations in the estimated fossil energy balances across feedstocks and fuels and, sometimes, for a feedstock/fuel combination, depending on factors such as feedstock productivity, agricultural practices and conversion technologies.

Conventional petrol and diesel have fossil energy balances of around 0.8–0.9, because some energy is consumed in refining crude oil into usable fuel and transporting it to markets. If a biofuel has a fossil energy balance exceeding these numbers, it contributes to reducing dependence on fossil fuels. All biofuels appear to make a positive contribution in this regard, albeit to widely varying degrees. Estimated fossil fuel balances for biodiesel range from around 1 to 4 for rapeseed and soybean feedstocks. Estimated balances for palm oil are higher, around 9, because other oilseeds must be crushed before the oil can be extracted, an additional processing step that requires energy. For crop-based ethanol, the estimated

FIGURE 7
Estimated ranges of fossil energy balances of selected fuel types



Note: The ratios for cellulosic biofuels are theoretical.

Sources: based on Worldwatch Institute, 2006, Table 10.1; Rajagopal and Zilberman, 2007.

balances range from less than 2 for maize to around 2–8 for sugar cane. The favourable fossil energy balance of sugar-cane-based ethanol, as produced in Brazil, depends not only on feedstock productivity, but also on the fact that it is processed using biomass residues from the sugar cane (bagasse) as energy input. The range of estimated fossil fuel balances for cellulosic feedstocks is even wider, reflecting the uncertainty regarding this technology and the diversity of potential feedstocks and production systems.

Similarly, the net effect of biofuels on greenhouse gas emissions may differ widely. Biofuels are produced from biomass; in theory, therefore, they should be carbon neutral, as their combustion only returns to the atmosphere the carbon that was sequestered from the atmosphere by the plant during its growth – unlike fossil fuels, which release carbon that has been stored for millions of years under the surface of the earth. However, assessing the net effect of a biofuel on greenhouse gas emissions requires analysis of emissions throughout the life cycle of the biofuel: planting and harvesting the crop; processing the feedstock into biofuel; transporting the feedstock and the final fuel; and storing, distributing and retailing the biofuel – including the impacts of fuelling a vehicle and the emissions caused by combustion. In addition, any possible co-products that may reduce emissions need to be considered. Clearly, therefore, fossil energy balances are only one of several determinants of the emissions impact of biofuels. Critical factors related to the agricultural production process include fertilizing, pesticide use, irrigation technology and soil treatment. Land-use changes associated with expanded biofuel production can have a major impact. For example, converting forest land to the production of biofuel crops or agricultural crops displaced by biofuel feedstocks elsewhere can release large quantities of carbon that would take years to recover through the emission reductions achieved by substituting biofuels for fossil fuels. Chapter 5 discusses further the relationship between biofuels and greenhouse gas emissions and reviews the evidence that the impact of biofuels on climate change may vary and may not necessarily be positive – or as positive as is often initially assumed.

Second-generation liquid biofuels[5]

Current liquid biofuel production based on sugar and starch crops (for ethanol) and oilseed crops (for biodiesel) is generally referred to as first-generation biofuels. A second generation of technologies under development may also make it possible to use lignocellulosic biomass. Cellulosic biomass is more resistant to being broken down than starch, sugar and oils. The difficulty of converting it into liquid fuels makes the conversion technology more expensive, although the cost of the cellulosic feedstock itself is lower than for current, first-generation feedstocks. Conversion of cellulose to ethanol involves two steps: the cellulose and hemicellulose components of the biomass are first broken down into sugars, which are then fermented to obtain ethanol. The first step is technically challenging, although research continues on developing efficient and cost-effective ways of carrying out the process. The lack of commercial viability has so far inhibited significant production of cellulose-based second-generation biofuels.

As cellulosic biomass is the most abundant biological material on earth, the successful development of commercially viable second-generation cellulose-based biofuels could significantly expand the volume and variety of feedstocks that can be used for production. Cellulosic wastes, including waste products from agriculture (straw, stalks, leaves) and forestry, wastes generated from processing (nut shells, sugar-cane bagasse, sawdust) and organic parts of municipal waste, could all be potential sources. However, it is also important to consider the crucial role that decomposing biomass plays in maintaining soil fertility and texture; excessive withdrawals for bioenergy use could have negative effects.

Dedicated cellulosic energy crops hold promise as a source of feedstock for second-generation technologies. Potential crops include short-rotation woody crops such as willow, hybrid poplars and eucalyptus or grassy species such as miscanthus, switchgrass and reed canary grass. These crops present major advantages over first-generation crops in terms of environmental sustainability. Compared with conventional starch and oilseed crops, they can produce more biomass per hectare of land because the entire crop is available as feedstock for conversion to fuel. Furthermore, some fast-growing perennials such as short-rotation woody crops and tall grasses can sometimes grow on poor, degraded soils where food-crop production is not optimal because of erosion or other limitations. Both these factors may reduce competition for land with food and feed production. On the downside, several of these species are considered invasive or potentially invasive and may have negative impacts on water resources, biodiversity and agriculture.

Second-generation feedstocks and biofuels could also offer advantages in terms of reducing greenhouse gas emissions. Most studies project that future, advanced fuels from perennial crops and woody and agricultural residues could dramatically reduce life-cycle greenhouse gas emissions

[5] This section is based on GBEP (2007), IEA (2004) and Rutz and Janssen (2007).

relative to petroleum fuels and first-generation biofuels. This stems from both the higher energy yields per hectare and the different choice of fuel used in the conversion process. In the current production process for ethanol, the energy used in processing is almost universally supplied by fossil fuels (with the exception of sugar-cane-based ethanol in Brazil, where most of the energy for conversion is provided by sugar-cane bagasse). For second-generation biofuels, process energy could be provided by left-over parts of the plants (mainly lignin).

While cellulosic biomass is harder to break down for conversion to liquid fuels, it is also more robust for handling, thus helping to reduce its handling costs and maintain its quality compared with food crops. It is also easier to store, especially in comparison with sugar-based crops, as it resists deterioration. On the other hand, cellulosic biomass can often be bulky and would require a well-developed transportation infrastructure for delivery to processing plants after harvest.

Significant technological challenges still need to be overcome to make the production of ethanol from lignocellulosic feedstocks commercially competitive. It is still uncertain when conversion of cellulosic biomass into advanced fuels may be able to contribute a significant proportion of the world's liquid fuels. Currently, there are a number of pilot and demonstration plants either operating or under development around the world. The speed of expansion of biochemical and thermochemical conversion pathways will depend upon the development and success of pilot projects currently under way and sustained research funding, as well as world oil prices and private-sector investment.

In summary, second-generation biofuels based on lignocellulosic feedstocks present a completely different picture in terms of their implications for agriculture and food security. A much wider variety of feedstocks could be used, beyond the agricultural crops currently used for first-generation technologies, and with higher energy yields per hectare. Their effects on commodity markets, land-use change and the environment will also differ – as will their influence over future production and transformation technologies (see Box 2).

Potential for bioenergy

What is the potential for bioenergy production? The technical and economic potential for bioenergy should be discussed in the context of the increasing shocks and stress on the global agriculture sector and the growing demand for food and agricultural products that is a consequence of continuing population and income growth worldwide. What is technically feasible to produce may not be economically feasible or environmentally sustainable. This section discusses in more detail the technical and economic potential of bioenergy.

Because bioenergy is derived from biomass, global bioenergy potential is ultimately limited by the total amount of energy produced by global photosynthesis. Plants collect a total energy equivalent of about 75 000 Mtoe (3 150 Exajoule) per year (Kapur, 2004) – or six to seven times the current global energy demand. However, this includes vast amounts of biomass that cannot be harvested. In purely physical terms, biomass represents a relatively poor way of harvesting solar energy, particularly when compared with increasingly efficient solar panels (FAO, 2006a).

A number of studies have gauged the volume of biomass that can technically contribute to global energy supplies. Their estimates differ widely owing to different scopes, assumptions and methodologies, underscoring the high degree of uncertainty surrounding the possible contribution of bioenergy to future global energy supply. The last major study of bioenergy conducted by the International Energy Agency (IEA) assessed, on the basis of existing studies, the range of potential bioenergy supply in 2050 from a low of 1 000 Mtoe to an extreme of 26 200 Mtoe (IEA, 2006, pp. 412–16). The latter figure was based on an assumption of very rapid technological progress; however, the IEA indicates that a more realistic assessment based on slower yield improvements would be 6 000–12 000 Mtoe. A mid-range estimate of around 9 500 Mtoe would, according to the IEA, require about one-fifth of the world's agricultural land to be dedicated to biomass production.

BOX 2
Biotechnology applications for biofuels

Many existing biotechnologies can be applied to improve bioenergy production, for example, in developing better biomass feedstocks and improving the efficiency of converting the biomass to biofuels.

Biotechnologies for first-generation biofuels

The plant varieties currently used for first-generation biofuel production have been selected for agronomic traits relevant for food and/or feed production and not for characteristics that favour their use as feedstocks for biofuel production. Biotechnology can help to speed up the selection of varieties that are more suited to biofuel production – with increased biomass per hectare, increased content of oils (biodiesel crops) or fermentable sugars (ethanol crops), or improved processing characteristics that facilitate their conversion to biofuels. The field of genomics – the study of all the genetic material of an organism (its genome) – is likely to play an increasingly important role. Genome sequences of several first-generation feedstocks, such as maize, sorghum and soybean, are in the pipeline or have already been published. Apart from genomics, other biotechnologies that can be applied include marker-assisted selection and genetic modification.

Fermentation of sugars is central to the production of ethanol from biomass. However, the most commonly used industrial fermentation micro-organism, the yeast *Saccharomyces cerevisiae*, cannot directly ferment starchy material, such as maize starch. The biomass must first be broken down (hydrolysed) to fermentable sugars using enzymes called amylases. Many of the current commercially available enzymes, including amylases, are produced using genetically modified micro-organisms. Research continues on developing efficient genetic yeast strains that can produce the amylases themselves, so that the hydrolysis and fermentation steps can be combined.

Application of biotechnologies for second-generation biofuels

Lignocellulosic biomass consists mainly of lignin and the polysaccharides cellulose (consisting of hexose sugars) and hemicellulose (containing a mix of hexose and pentose sugars). Compared with the production of ethanol from first-generation feedstocks, the use of lignocellulosic biomass is more complicated because the polysaccharides are more stable and the pentose sugars are not readily fermentable by *Saccharomyces cerevisiae.* In order to convert lignocellulosic biomass to biofuels the polysaccharides must first be hydrolysed, or broken down, into simple sugars using either acid or enzymes. Several biotechnology-based approaches are being used to overcome such problems, including the development of strains of *Saccharomyces cerevisiae* that can ferment pentose sugars, the use of alternative yeast species that naturally ferment pentose sugars, and the engineering of enzymes that are able to break down cellulose and hemicellulose into simple sugars.

Apart from agricultural, forestry and other by-products, the main source of lignocellulosic biomass for second-generation biofuels is likely to be from "dedicated biomass feedstocks", such as certain perennial grass and forest tree species. Genomics, genetic modification and other biotechnologies are all being investigated as tools to produce plants with desirable characteristics for second-generation biofuel production, for example plants that produce less lignin (a compound that cannot be fermented into liquid biofuel), that produce enzymes themselves for cellulose and/or lignin degradation, or that produce increased cellulose or overall biomass yields.

Sources: based on FAO, 2007a, and The Royal Society, 2008.

More important than the purely technical viability is the question of how much of the technically available bioenergy potential would be economically viable. The long-term economic potential depends crucially on assumptions concerning the prices of fossil energy, the development of agricultural feedstocks and future technological innovations in harvesting, converting and using biofuels. These aspects are discussed in further detail in Chapter 3.

A different way of looking at the potential for biofuel production is to consider the relative land-use requirements. In its "Reference Scenario" for 2030 in *World Energy Outlook 2006*, the IEA projects an increase in the share of the world's arable land devoted to growing biomass for liquid biofuels from 1 percent in 2004 to 2.5 percent in 2030. Under its "Alternative Policy Scenario", the share in 2030 increases to 3.8 percent. In both cases, the projections are based on the assumption that liquid biofuels will be produced using conventional crops. Should second-generation liquid biofuels become widely commercialized before 2030, the IEA projects the global share of biofuels in transport demand to increase to 10 percent rather than 3 percent in its Reference Scenario and 5 percent in the Alternative Policy Scenario. Land-use requirements would go up only slightly, to 4.2 percent of arable land, because of higher energy yields per hectare and the use of waste biomass for fuel production. Nevertheless, this illustrates that, even under a second-generation scenario, a hypothetical large-scale substitution of liquid biofuels for fossil-fuel-based petrol would require major conversion of land. See also Chapter 4 for a further discussion, including regional impacts.

The potential for current biofuel technologies to replace fossil fuels is also illustrated by a hypothetical calculation by Rajagopal *et al.* (2007). They report theoretical estimates for global ethanol production from the main cereal and sugar crops based on global average yields and commonly reported conversion efficiencies. The results of their estimates are summarized in Table 3. The crops shown account for 42 percent of total cropland today. Conversion of the entire crop production to ethanol would correspond to 57 percent of total petrol consumption. Under a more realistic assumption of 25 percent of each of these crops being diverted to ethanol production, only 14 percent of petrol consumption could be replaced by ethanol. The various hypothetical calculations underline that, in view of their significant land requirements, biofuels can only be expected to lead to a very limited displacement of fossil fuels. Nevertheless, even a very modest contribution of biofuels to overall energy supply may yet have a strong impact on agriculture and on agricultural markets.

TABLE 3
Hypothetical potential for ethanol from principal cereal and sugar crops

CROP	GLOBAL AREA	GLOBAL PRODUCTION	BIOFUEL YIELD	MAXIMUM ETHANOL	PETROL EQUIVALENT	SUPPLY AS SHARE OF 2003 GLOBAL PETROL USE[1]
	(Million ha)	*(Million tonnes)*	*(Litres/ha)*	*(Billion litres)*	*(Billion litres)*	*(Percentage)*
Wheat	215	602	952	205	137	12
Rice	150	630	1 806	271	182	16
Maize	145	711	1 960	284	190	17
Sorghum	45	59	494	22	15	1
Sugar cane	20	1 300	4 550	91	61	6
Cassava	19	219	2 070	39	26	2
Sugar beet	5.4	248	5 060	27	18	2
Total	**599**	**...**	**...**	**940**	**630**	**57**

Note: **...** = not applicable. Data presented are subject to rounding.
[1] Global petrol use in 2003 = 1 100 billion litres (Kim and Dale, 2004).
Source: Rajapogal *et al.*, 2007.

Key messages of the chapter

- Bioenergy covers approximately 10 percent of total world energy supply. Traditional unprocessed biomass accounts for most of this, but commercial bioenergy is assuming greater importance.
- Liquid biofuels for transport are generating the most attention and have seen a rapid expansion in production. However, quantitatively their role is only marginal: they cover 1 percent of total transport fuel consumption and 0.2–0.3 percent of total energy consumption worldwide.
- The main liquid biofuels are ethanol and biodiesel. Both can be produced from a wide range of different feedstocks. The most important producers are Brazil and the United States of America for ethanol and the EU for biodiesel.
- Current technologies for liquid biofuels rely on agricultural commodities as feedstock. Ethanol is based on sugar or starchy crops, with sugar cane in Brazil and maize in the United States of America being the most significant in terms of volume. Biodiesel is produced using a range of different oil crops.
- Large-scale production of biofuels implies large land requirements for feedstock production. Liquid biofuels can therefore be expected to displace fossil fuels for transport to only a very limited extent.
- Even though liquid biofuels supply only a small share of global energy needs, they still have the potential to have a significant effect on global agriculture and agricultural markets because of the volume of feedstocks and the relative land areas needed for their production.
- The contribution of different biofuels to reducing fossil-fuel consumption varies widely when the fossil energy used as an input in their production is also taken into account. The fossil energy balance of a biofuel depends on factors such as feedstock characteristics, production location, agricultural practices and the source of energy used for the conversion process. Different biofuels also perform very differently in terms of their contribution to reducing greenhouse gas emissions.
- Second-generation biofuels currently under development would use lignocellulosic feedstocks such as wood, tall grasses, and forestry and crop residues. This would increase the quantitative potential for biofuel generation per hectare of land and could also improve the fossil energy and greenhouse gas balances of biofuels. However, it is not known when such technologies will enter production on a significant commercial scale.