7

Bioenergy

Contents

Strategic insight

1. Introduction

The supply of sustainable energy is one of the main challenges that mankind will face over the coming decades, particularly because of the need to address climate change. Biomass can make a substantial contribution to supplying future energy demand in a sustainable way. It is presently the largest global contributor of renewable energy, and has significant potential to expand in the production of heat, electricity, and fuels for transport. Further deployment of bioenergy, if carefully managed, could provide:

- an even larger contribution to global primary energy supply;
- significant reductions in greenhouse gas emissions and potentially other environmental benefits;
- improvements in energy security and trade balances, by substituting imported fossil fuels with domestic biomass;
- opportunities for economic and social development in rural communities;
- scope for using wastes and residues, reducing waste disposal problems and making better use of resources.

This commentary provides an overview of the potential for bioenergy and the challenges associated with its increased deployment. It discusses opportunities and risks in relation to resources, technologies, practices, markets and policy. The aim is to provide insights into the opportunities and required actions for the development of a sustainable bioenergy industry. at present, forestry, agricultural and municipal residues, and wastes are the main feedstocks for the generation of electricity and heat from biomass. In addition, very small shares of sugar, grain, and vegetable oil crops are used as feedstocks for the production of liquid biofuels. Today, biomass supplies some 50 EJ globally, which represents 10% of global annual primary energy consumption.

This is mostly traditional biomass used for cooking and heating

There is significant potential to expand biomass use by tapping the large volumes of unused residues and wastes. The use of conventional crops for energy use can also be expanded, with careful consideration of land availability and food demand. In the medium term, lignocellulosic crops (both herbaceous and woody) could be produced on marginal, degraded and surplus agricultural lands and provide the bulk of the biomass resource. In the longer term, aquatic biomass (algae) could also make a significant contribution. Based on this diverse range of feedstocks, the technical potential for biomass is estimated in the literature to be possibly as high as 1 500 EJ/yr by 2050, although most biomass supply scenarios that take into account sustainability constraints indicate an annual potential of between 200 and 500 EJ/yr (excluding aquatic biomass). Forestry and agricultural residues and other organic wastes (including municipal solid waste) would provide between 50 and 150 EJ/yr, while the remainder would come from energy crops, surplus forest growth, and increased agricultural productivity.

Projected world primary energy demand by 2050 is expected to be in the range of 600 to 1 000 EJ (compared to about 500 EJ in 2008). Scenarios looking at the penetration of different

Figure 9.1
Share of bioenergy in the world primary energy mix
Source: based on IEA, 2006; IPCC, 2007

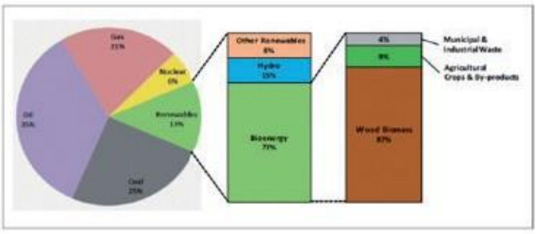
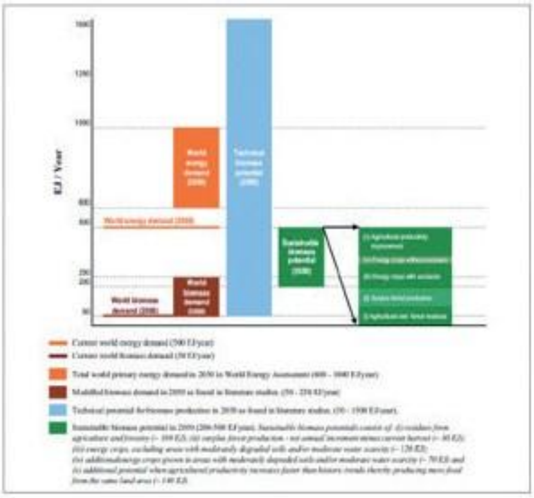


Figure 9.2
Technical and sustainable biomass supply potentials and expected demand
Source: adapted from Dornburg, et al. [2008], based on several review studies



low-carbon energy sources indicate that future demand for bioenergy could be up to 250 EJ/yr. This projected demand falls well within the sustainable supply potential estimate, so it is reasonable to assume that biomass could sustainably contribute between a quarter and a third of the future global energy mix (Fig. 9.2).

Whatever is actually realised will depend on the cost competitiveness of bioenergy and on future policy frameworks, such as greenhouse gas emission reduction targets. Growth in the use of biomass resources in the mid-term period to 2030 will depend on many demand and supply side factors. Strong renewable energy targets being set at regional and national level (e.g. the European Renewable Energy Directive) are likely to lead to a significant increase in demand. This demand is likely to be met through increased use of residues and wastes, sugar, starch and oil crops, and increasingly, lignocellulosic crops. The contribution of energy crops depends on the choice of crop and planting rates, which are influenced by productivity increases in agriculture, environmental constraints, water availability and logistical constraints. Under favourable conditions substantial growth is possible over the next 20 years. However, estimates of the potential increase in production do vary widely. For example, the biomass potential from residues and energy crops in the EU to 2030 is estimated to range between 4.4 and 24 EJ. The long-term potential for energy crops depends largely on:

- land availability, which depends on food sector development (growth in food demand, population diet, and increased crop productivity) and factors limiting access to land, such as water and nature protection;
- the choice of energy crops, which defines the biomass yield levels that can be obtained on the

Other factors that may affect biomass potential include the impact of biotechnology, such as genetically modified organisms, water availability, and the effects of climate change on productivity.

The uptake of biomass depends on several factors:

- biomass production costs – US$ 4/GJ is often regarded as an upper limit if bioenergy is to be widely deployed today in all sectors;

- logistics – as with all agricultural commodities, energy crops and residues all require appropriate supply chain infrastructure;
- resource and environmental issues – biomass feedstock production can have both positive and negative effects on the environment (water availability and quality, soil quality and these will result in regulations restricting or incentivising particular practices (e.g. environmental regulations, sustainability standards, etc.).

Drivers for increased bioenergy use (e.g. policy targets for renewables) can lead to increased demand for biomass, leading to competition for land currently used for food production, and possibly (indirectly) causing sensitive areas to be taken into production. This will require intervention by policy makers, in the form of regulation of bioenergy chains and/or regulation of land use, to ensure sustainable demand and production. Development of appropriate policy requires an understanding of the complex issues involved and international cooperation on measures to promote global sustainable biomass production systems and practices. To achieve the bioenergy potential targets in the longer term, government policies and industrial efforts need to be directed at increasing biomass yield levels and modernising agriculture in regions such as Africa, the Far East and Latin America, directly increasing global food production and thus the resources available for biomass. This can be achieved by technology development and by the diffusion of best sustainable agricultural practices. The sustainable use of residues and wastes for bioenergy, which present limited or zero environmental risks, needs to be encouraged and promoted globally.

Biomass Conversion Technologies

There are many bioenergy routes which can be used to convert raw biomass feedstock into a final energy product (Fig. 9.3). Several conversion technologies have been developed that are adapted to the different physical nature and chemical composition of the feedstock, and to the energy service required (heat, power, transport fuel). Upgrading technologies for biomass feedstocks (e.g. pelletisation, torrefaction and pyrolysis) are being developed to convert bulky raw biomass into denser and more practical energy carriers for more efficient transport, storage and convenient use in

The production of heat by the direct combustion of biomass is the leading bioenergy application throughout the world, and is often cost-competitive with fossil fuel alternatives. Technologies range from rudimentary stoves to sophisticated modern appliances. For a more energy efficient use of the biomass resource, modern, large-scale heat applications are often combined with electricity production in combined heat and power (CHP) systems.

Different technologies exist or are being developed to produce electricity from biomass. Co-combustion (also called co-firing) in coal-based power plants is the most cost-effective use of biomass for power generation. Dedicated biomass combustion plants, including MSW combustion plants, are also in successful commercial operation and many are industrial or district heating CHP facilities. For sludges, liquids and wet organic materials, anaerobic digestion is currently the best-suited option for producing electricity and/or heat from biomass, although its economic case relies heavily on the availability of low-cost feedstock. All these technologies are well established and commercially available.

There are few examples of commercial gasification plants, and the deployment of this technology is affected by its complexity and cost. In the longer term, if reliable and cost-effective operation can be more widely demonstrated, gasification promises greater efficiency, better economics at both smalland large-scale and lower emissions compared with other bio- mass-based power generation options. Other technologies (such as Organic Rankin Cycle and Stirling engines) are currently in the demonstration stage and could prove economically viable in a range of small-scale.

In the transport sector, first-generation biofuels are widely deployed in several countries, mainly bioethanol from starch and sugar crops and biodiesel from oil crops and residual oils and fats. Production costs of current biofuels vary significantly depending on the feedstock used (and their volatile prices) and on the scale of the plant. The potential for further deploying these first-generation technologies is high, subject to sustainable land-use criteria being met.

First-generation biofuels face both social and environmental challenges, largely because they use food crops which could lead to food price increases and possibly indirect land-use change. While such risks can be mitigated by regulation and sustainability assurance and certification, technology development is also advancing for next-generation processes that rely on non-food biomass (e.g. lignocellulosic feedstocks such as organic wastes, forestry residues, high-yielding woody or grass energy crops and algae). The use of these feedstocks for second-generation biofuel production would significantly decrease the potential pressure on land use, improve greenhouse gas emission reductions when compared to some first-generation biofuels, and result in lower environmental and social risk. Second-generation technologies, mainly using lignocellulosic feedstocks for the production of ethanol, synthetic diesel and aviation fuels, are still immature and need further development and investment to demonstrate reliable operation at commercial scale and to achieve cost reductions through scale-up and replication. The current level of activity in the area indicates that these routes are likely to become commercial over the next decade. Future generations of biofuels, such as oils produced from algae, are at the applied R&D stage, and require considerable development before they can become competitive contributors to the energy markets).

Further development of bioenergy technologies is needed, mainly to improve the efficiency, reliability and sustainability of bioenergy chains. In the heat sector, improvement would lead to cleaner, more reliable systems linked to higher-quality fuel supplies. In the electricity sector, the development of smaller and more cost-effective electricity or CHP systems could better match local resource availability. In the transport sector, improvements could lead to higher quality and more sustainable biofuels.

Ultimately, bioenergy production may increasingly occur in bio-refineries where transport biofuels, power, heat, chemicals and other marketable products could all be co-produced from a mix of biomass feedstocks. The link between producing energy and other materials deserves further attention technically and commercially.

The predominant use of biomass today consists of fuel wood used in non-commercial applications, in simple inefficient stoves for domestic heating and cooking in developing countries, where biomass contributes some 22% to the total primary energy mix. This traditional use of biomass is expected to grow with increasing world population. However, there is significant scope to improve its efficiency and environmental performance and thereby help reduce biomass consumption and related impacts.

In industrialised countries, the total contribution of modern biomass is on average only about 3% of total primary energy, and consists mostly of heat only and heat and power applications. Many countries have targets to significantly increase biomass use, as it is seen as a key contributor to meeting energy and environmental policy objectives. Current markets, growing as a result of attractive economics, mostly involve domestic heat supply (e.g. pellet boilers), large-scale industrial and community CHP generation (particularly where low-cost feedstocks from forest residues, bagasse, MSW etc. are available), and co-firing in large coalbased power plants. The deployment of dedicated electricity plants has been mainly confined to lowcost feedstocks in relatively small-scale applications, such as the use of biogas and landfill gas from waste treatment. Globally, the use of biomass in heat and industrial energy applications is expected to double by 2050 under business-as usual scenarios, while electricity production from biomass is projected to increase, from its current share of 1.3% in total power production to 2.4 – 3.3% by 2030 (corresponding to a 5 - 6% average annual growth rate).

Transport biofuels are currently the fastest growing bioenergy sector, receiving a great deal of public attention. However, today they represent only 1.5% of total road transport fuel consumption and only 2% of total bioenergy. They are, however, expected to play an increasing role in meeting the demand for road transport fuel, with second generation biofuels increasing in importance over the next two decades. Even under business-as usual scenarios, biofuel production is expected to increase by a factor of 10 to 20 relative to current levels by 2030 (corresponding to a 6 - 8% average annual growth rate).

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

The quest for a sustainable energy system will require more bioenergy than the growth projected under the business-as-usual scenarios. A number of biomass supply chain issues and market risks and barriers will need to be addressed and mitigated to enable stronger sustained growth of the bioenergy sector. These include:

- ***Security of the feedstock supply*** - this is susceptible to the inherent volatility of biological production (due to weather and seasonal variations), which can lead to significant variations in feedstock supply quantity, quality and price. Risk mitigation strategies already common in food and energy markets include having a larger, more fluid, global biomass sector and the creation of buffer stocks.
- ***Economies of scale and logistics*** – many commercially available technologies suffer from poor economics at a small scale, but conversely larger scales require improved and more complex feedstock supply logistics. Efforts are required to develop technologies at appropriate scales and with appropriate supply chains to meet different application requirements.
- ***Competition*** - bioenergy technologies compete with other renewable and non-renewable energy sources and may compete for feedstock with other sectors such as food, chemicals and materials. Also, the development of second-generation biofuel technologies could lead to competition for biomass resources between bioenergy applications, and potentially with other industry sectors. Support needs to be directed at developing cost-effective bioenergy routes and at deploying larger quantities of biomass feedstocks from sustainable sources.
- ***Public and NGO acceptance*** - this is a major risk factor facing alternative energy sources and bioenergy in particular. The public needs to be informed and confident that bioenergy is environmentally and socially beneficial and does not result in significant negative environmental and social trade-offs. However, the industry is confident such challenges can be met as similar challenges have been addressed in other sectors and appropriate technologies and practices are being developed and deployed.

Interactions with Other Markets

Developments in the bioenergy sector can influence markets for agricultural products (e.g. food and feed products, straw) and forest products (e.g. paper, board). However, this impact is not straightforward, owing to:

- other factors, such as biomass yield variations and fossil fuel price volatilities influencing markets just as much or more than biomass;
- other policy domains, including forestry, agriculture, environment, transport, health and trade, also having influence on bioenergy policies;
- a lack of transparency in many product and commodity markets, especially in forest products, making it difficult to assess the impact of bioenergy development.

While all forms of bioenergy interrelate with agriculture and/or forest markets through their feedstock demand, the impact of first-generation liquid biofuels on food prices has been a topic of strong debate in recent years. Although different studies reveal a wide variety of opinions on the magnitude of these impacts, most model-based demand scenarios indicate a relatively limited risk of biofuels significantly affecting the price of food crops. In general, markets can work to dampen these effects.

Markets will need access to monetary and physical resources, and will need to function efficiently and transparently in order to counteract the pressure of increasing demand. There is therefore an important role for policy in providing support to an increasingly efficient industry, for example in terms of yields, use of residues and wastes, and land use, while providing regulation to avoid negative impacts associated with the exploitation of physical resources. This requires active coordination between energy, agriculture and forestry, trade and environmental policies.

Bioenergy can significantly increase its existing contribution to policy objectives, such as CO_2 emission reductions and energy security, as well as to social and economic development objectives.

Appreciating where bioenergy can have the greatest impact on GHG emissions reduction relies on both an understanding of the emissions resulting from different bioenergy routes and the importance of bioenergy in reducing emissions in a particular sector. Bioenergy chains can perform very differently with regard to GHG emissions. Substituting biomass for fossil fuels in heat and electricity generation is generally less costly and provides larger emission reductions per unit of biomass than substituting biomass for gasoline or diesel used for transport. However, the stationary bioenergy sector can rely on a range of different low-carbon options while biofuels are the primary option for decarbonising road transport until allelectric and/or hydrogen fuel cell powered vehicles become widely deployed, which is unlikely to be the case for some decades. In the long term, biofuels might remain the only option for decarbonising aviation transport, a sector for which it will be difficult to find an alternative to liquid fuels.

Land suitable for producing biomass for energy can also be used for the creation of biospheric carbon sinks. Several factors determine the relative attractiveness of these two options, in particular land productivity, including co-products, and fossil fuel replacement efficiency. Also, possible direct and indirect emissions from converting land to another use can substantially reduce the climate benefit of both bioenergy and carbon sink projects, and need to be taken into careful consideration. A further influencing factor is the time scale that is used for the evaluation of the carbon reduction potential: a short time scale tends to favour the sink option, while a longer time scale offers larger savings as biomass production is not limited by saturation but can repeatedly (from harvest to harvest) deliver greenhouse gas emission reductions by substituting for fossil fuels. Mature forests that have ceased to serve as carbon sinks can in principle be managed in a conventional manner to produce timber and other forest products, offering a relatively low GHG reduction per hectare. Alternatively, they could be converted to higher yielding energy plantations (or to food production) but this would involve the release of at least part of the carbon store created.

The use of domestic biomass resources can make a contribution to energy security, depending on which energy source it is replacing. Biomass imports from widely distributed international sources generally also contribute to the diversification of the energy mix. However, supply security can be affected by natural variations in biomass outputs and by supply-demand imbalances in the food and forest product sectors, potentially leading to shortages.

The production of bioenergy can also result in other (positive and negative) environmental and socioeconomic effects. Most of the environmental effects are linked to biomass feedstock production, many of which can be mitigated through best practices and appropriate regulation. Technical solutions are available for mitigating most environmental impacts from bioenergy conversion facilities and their vehicle fleets such as city buses have historically been diesel powered but are very suitable for the introduction of new fuels, e.g. biogas or ethanol. The performance and sustainability of liquid biofuels is a current RD&D focus. Their use is largely a question of appropriate environmental regulations and their enforcement. The use of organic waste and agricultural/forestry residues, and of lignocellulosic crops that could be grown on a wider spectrum of land types, may mitigate land and water demand and reduce competition with food.

Feedstock production systems can also provide several benefits. For instance, forest residue harvesting improves forest site conditions for planting, thinning generally improves the growth and productivity of the remaining stand, and removal of biomass from over-dense stands can reduce the risk of wildfire. In agriculture, biomass can be cultivated in so-called multifunctional plantations that – through well-chosen locations, design, management, and system integration – offer extra environmental services that, in turn, create added value for the systems.

Policy around bioenergy needs to be designed so that it is consistent with meeting environmental and social objectives. Bioenergy needs to be regulated so that environmental and social issues are taken into consideration, environmental services provided by bioenergy systems are recognised and valued, and so that it contributes to rural development objectives.

The deployment of many bioenergy options depends on government support, at least in the short and medium term, the design and implementation of appropriate policies and support mechanisms is vital, and defensible, particularly given the associated environmental benefits and existing government support for fossil fuels. These policies should also ensure that bioenergy contributes to economic, environmental and social goals. Experience over the last couple of decades has taught us the following:

A policy initiative for bioenergy is most effective when it is part of a long-term vision that builds on specific national or regional characteristics and strengths, e.g. in terms of existing or potential biomass feedstocks available, specific features of the industrial and energy sector, and the infrastructure and trade context.

Policies should take into account the development stage of a specific bioenergy technology, and provide incentives consistent with the barriers that an option is facing. Factors such as technology maturity, characteristics of incumbent technologies and price volatilities all need to be taken into consideration. In each development stage, there may be a specific trade-off between incentives being technology-neutral and closely relating to the policy drivers and on the other hand creating a sufficiently protected environment for technologies to evolve and mature.

There are two classes of currently preferred policy instruments for bio-electricity and renewable electricity in general. These are technology-specific feed-in tariffs and more generic incentives such as renewable energy quotas and tax differentiation between bioenergy and fossil-based energy. Each approach has its pros and cons, with neither being clearly more effective.

Access to markets is a critical factor for almost all bioenergy technologies, so that policies need to pay attention to grid access, and standardisation of feedstocks and biofuels.

As all bioenergy options depend on feedstock availability, a policy strategy for bioenergy should pay attention to the sectors that will provide the biomass. For the agricultural and forestry sectors, this includes consideration of aspects such as productivity improvement, availability of agricultural and forest land and access to and extractability of primary residues. For other feedstocks, such as residues from wood processing and municipal solid waste, important aspects are mobilisation and responsible use.

A long-term successful bioenergy strategy needs to take into account sustainability issues. Policies and standards safeguarding biomass sustainability are currently in rapid development. Due to the complexity of the sustainability issue, future policy making and the development of standards will need to focus on integrated approaches, in which the complex interactions with aspects such as land use, agriculture and forestry, and social development are taken into account.

Long-term continuity and predictability of policy support is also important. This does not mean that all policies need to be long-term, but policies conducive to the growth of a sector should have a duration that is clearly stated and in line with meeting certain objectives, such as cost reduction to competitive levels with conventional technologies.

The successful development of bioenergy does not only depend on specific policies which provide incentives for its uptake, but on the broader energy and environment legal and planning framework. This requires coordination amongst policies and other government actions, as well as working with industry and other stakeholders to establish a framework conducive to investment in bioenergy.

Climate change and energy security are problems for which solutions need to be developed and implemented urgently. The scale of the challenge is such that it will require contributions from disparate sources of energy. Bioenergy already contributes significantly to addressing these problems and can contribute much further through existing and new conversion technologies and feedstocks.

Furthermore, bioenergy can contribute to other environmental and social objectives, such as waste treatment and rural development. However, policy makers and the public at large will need to be comfortable that this expansion is sustainable. Bioenergy can result in many external benefits but also entails risks. A development and deployment strategy needs to be based on careful consideration of the strengths and weaknesses, as well as the opportunities and threats that characterise it.

Current bioenergy routes that generate heat and electricity from the sustainable use of residues and wastes should be strongly stimulated. These rely on commercial technologies, lead to a better use of raw materials, and result in clear GHG savings and possibly other emission reductions compared to fossil fuels. The development of infrastructure and logistics, quality standards and trading platforms will be crucial to growth and may require policy support.

Further increasing the deployment of bioenergy, and in particular of biofuels for transport in the short term, should be pursued by

- paying specific attention to sustainability issues directly related to the biomass-to energy production chain, and avoiding or mitigating negative impacts through the development and implementation of sustainability assurance schemes;
- incentivising biofuels based on their potential greenhouse gas benefits;
- considering potential impacts of biomass demand for energy applications on commodity markets and on indirect land use change;
- defining growth rates that result in feedstock demands that the sector can cope with on a sustainable basis.

Development of new and improved biomass conversion technologies will be essential for widespread deployment and long-term success. Public and private funding needs to be devoted to research, development and deployment as follows:

for liquid biofuels - advanced technologies that allow for a broader feedstock base using non-food crops with fewer (direct and indirect) environmental and social risks, and higher greenhouse gas benefits;

for power and heat production – more efficient advanced technologies, such as gasification and advanced steam cycles, and technologies with improved economics at a smaller scale to allow for more distributed use of biomass;

for novel biomass - upgrading technologies and multiproduct bio-refineries, which could contribute to the deployment and overall cost-competitiveness of bioenergy.

As the availability of residues and wastes will limit bioenergy deployment in the long term, policies stimulating increased productivity in agriculture and forestry, and public and private efforts aimed at development of novel energy crops, such as perennial lignocellulosic crops and other forms of biomass, such as algae, are essential for a sustained growth of the bio-energy industry. These efforts need to be integrated with sustainable land-use policies which also consider making efficient and environmentally sound use of marginal and degraded lands.

Acknowledgement

This paper is based on the Executive Summary of a report prepared for the IEA Bioenergy Agreement by a consortium led by the Energy Research Centre of the Netherlands (ECN), and including E4tech, Chalmers University of Technology and the Copernicus Institute of the University of Utrecht.

Bioenergy is produced from wide variety of feedstocks of biological origin and by numer-ous conversion technologies to produce heat, power, liquid biofuels, and gaseous biofuels. The “traditional domestic” use of fuelwood, charcoal, and agricultural residues in develop-ing countries for household cooking, lighting and space-heating is the dominant source of world’s bioenergy. The industrial use of biomass for production of pulp, paper, tobacco, pig iron, etc. produces side streams (i.e. bark, wood chips, black liquor, agricultural residues, etc.), which may be converted to bioenergy. Chemical conversion technologies (i.e. Fish- er-Tropsh synthesis and other chemical routes) are used to produce liquid and gaseous fuels, and biological conversion technologies to produce biogas (i.e. anaerobic digestion) and alcohols (i.e. fermentation). In the long term, also bio-photochemical routes (i.e. algae, hydrogen, etc.) may offer new bioenergy resources.

According to the IEA Statistics, the share of bioenergy has been about 10% of Total Primary Energy Supply (TPES) since 1990 even though TPES has been increasing at an average annual rate of 2.0%. Between 1990 and 2010 bioenergy supply has increased from 38 to 52 EJ as a result of increasing energy demand in non-OECD countries and, on the other hand, new policies to increase the share of renewable and indigenous energy sources especially in many OECD and but also in non-OECD-countries. Solid biofuels, mainly wood, are the largest renewable energy source, representing 69% of world renewable energy supply. Solid biofuels are mainly used in developing countries, especially in South Asia and sub-saharan Africa. Liquid biofuels for transport provide about 4% of world renewable energy supply and 0.5% of global TPES. The share of biogases in world renewable energy supply is only 1.5% but it had the highest growth rate since 1990 (about 15% per year) compared to other biofu-els. Liquid biofuels also had remarkable growth rate (11% per year) while the growth rate of solid biofuels was moderate (1% per year) (IEA 2012).

In 2010, the largest bioenergy producers were China and India, who produced 20% and 17% of the world's bioenergy respectively (IEA 2012). In China, the share of bioenergy is less than 10% of its TPES while in India it is almost 25%. In the third and fourth largest bioenergy producers, Nigeria and United States, the share of bioenergy of TPES was above 80% and below 4% respectively in 2010, which clearly shows the difference between developing and industrialized countries: in developing non-OECD countries bioenergy is typically the major energy source while in the OECD-countries bioenergy typically covers minor share of TPES.

Recently, the European Union (EU) has set binding targets to increase the share of renew-ables by 2020 to 20% from its energy consumption. Many non-EU countries have also set renewable targets, and bioenergy is expected to be the major contributor to reach these targets with the help of national supports schemes, like feed-in tariffs, tax incentives and investment subsidies. At the same time there is increasing concern on sustainable and relia-ble supply of biofuels due to its complex environmental implications and due to competition on land area between bioenergy feedstocks, food, feed, and biomaterial production. On the other hand, there is considerable potential to increase the efficiency of bioenergy produc-tion, which lies between 5% to 15% to power and heat production in the old traditional use of biomass up to 60-90% in modern applications, like combined heat and power applications, fuel cells, stirling engines, and 2nd generation biofuel concepts. Taken into account the above uncertainties, there are greatly differing estimates of the contribution of bioenergy to the TPES, from below 100 EJ/yr to above 400 EJ/yr in 2050. Unlike today, the largest bioenergy resource is expected be agricultural bioenergy resources. Sustainable forest products and wood fuel production should not cause any deforestation and thereby decrease of net car-bon sinks, which limits its use. On the other hand, there are higher expectations to expand agricultural land area to produce bioenergy resources and better utilisation of agricultural residues.

Resource availability and location

Bioenergy is mainly produced from local wood resources. According to FAO statistics (2013) the world's total forest area is more than 4 billion hectares (ha), corresponding to about 30% of total land area. More than half of the world's total forest area is located in five forest-rich countries with large total land area – Russian Federation (809 million ha), Brazil (520 million ha), Canada (310 million ha), the United States (304 million ha), and China (207 million ha). In 2011, the largest woodfuel producers were India, China, Brazil, Ethiopia, and Nigeria. On the other hand, the US, Russia, and Canada were the largest producers of industrial roundwood. Both China and Brazil were included in the top five industrial roundwood producers as well.

Biofuel and bioenergy production form crops and agricultural resources has become increasingly important, as production of bioethanol and other biofuels for transportation has been promoted by several countries' energy, climate, and agricultural policies. Bioethanol production form cereals have also raised strong criticism due to concerns on its possible impacts on food security and price and due to little scope of easy expansion of agricultural land. Also, net greenhouse gas savings by crop based transportation fuels has raised concern. To limit the uncertainties related to net GHG emissions and food security, the EU has set a renewable energy directive, which calls for GHG reduction a minimum of 35% and in new plants in 2018 by 60 %.

According to the FAO Statistics (2013), about 1.5 billion ha, corresponding to about 12% of the world's land area is used for crop production (arable land plus land under permanent crops). If we also take into account permanent meadows and pastures, the total agricultural land area increases close to 5 billion ha. The accessible agricultural land is very unevenly distributed among regions and countries – about 90% is in Latin America and Sub-Saharan Africa, and there is practically no possibilities for agricultural expansion in Southern and Western Asia as well as in Northern Africa. Therefore expansion of agricultural land for producing biofuels has to take into account factors such as food supplies for increasing population, water use, biodiversity, and agro-economics, which affect the future bioenergy potentials. However, the share of agricultural land to produce biofuels is currently less than 0.01% (0,05 million ha) even though it has more than doubled since 2005 mainly due to increase of land area under oil crops, maize, as well as sugar cane and root to produce biofuels (FAO 2012). The use of sugar for biofuels is the highest (15% of total use) while the use of vegetable oils (5% of total use) and cereals (3% of total use) are still relatively low.

In the most optimistic scenarios, where bioenergy is expected to be produced annually also by photosynthesis, bioenergy meets more than the current global energy demand without competing with food production, forest product production, and biodiversity. In total, the expected contribution to the world's primary energy supply could be in the range of 250–500 EJ/yr. Based on recent literature, even with strict criteria and excluding areas with water stress or high biodiversity value, a minimum of 250 EJ/yr is likely available. The largest biomass production potential lies in large-scale energy plantations in areas with a favourable climate for maximising the production of biomass. Latin America, Sub-Saharan Africa, and Eastern Europe, along with Oceania and East and North-East Asia, have the most promises to become important producers of biofuels in the long term. However, there are still great uncertainties even with the lower range potentials, due to the impacts of climate change, speed of deforestration and erosion, and increased land use because of increased share of livestock products in protein supply, and added value of ecosystem services. Also, the technoeconomical limitations will limit the reliable and cost competitive biomass raw material supply for heat, power and transportation fuel production in future bioeconomy. On the other hand, higher improvements in biomass harvesting and logistics (both woodfuels and agrobiomass), well-functioning biofuel and food markets, increased expenditures to increase biomass yelds per ha, and changes in our habits to favour vegetarian diets and to minimize food waste could result in higher bioenergy resource potentials.

Overview of existing and emerging technologies

Traditional large scale applications on bioenergy has in most cases based on utilization and existing residues from agricultural and forest-based industries or utilization of waste streams from municipalities or industry. Another option has been replacing of a limited share or all of the use of fossil fuels with biomass in existing plants.

Choices of the technological development and implementation of new technologies are to a great extent based on existing market conditions, possible local incentives and regulations on bioenergy. Effects can be seen as different choices of feedstocks, energy carriers, capacities and technologies of energy production facilities in different countries.

Most of biomass is used locally, with limited transportation distances, but the increased use of energy carriers, such as pellets and briquettes, allow overseas transportation and replacement of fossil oil, gas and coal in many capacity scales. Variety of energy carriers from wood will increase: production of torrefied wood, fast pyrolysis oil, synthetic natural gas, and several types of transportation fuels have been demonstrated already, and several full-scale plants are planned to be demonstrated, especially in North America and European countries. Energy carriers from lignocellulosic feedstocks are typically produced by thermochemical processes, final product being solid for torrefied wood, liquid for fast pyrolysis oil or gaseous. Complexity of processes, and thus investment and operation costs depend largely on the quality specifications of final products. Highest costs are connected to products that can be mixed without blending wall to existing high-quality transportation fuels or natural gas.

Large scale heat and power production
Electricity from wood fuels is mainly produced in

- Combined heat and power (CHP) plants in municipalities and industry producing district heat, process steam and power (1-200 MWe) ,
- co-firing in large coal boilers (typically under 30% share of woodfuel),
- and medium sized electricity-only biomass power plants (1-50 MWe).

Figure 9.3
Options for large scale biomass-based heat and/or power production with variable share of biomass (20-100%) of the total fuel use in a power plant.

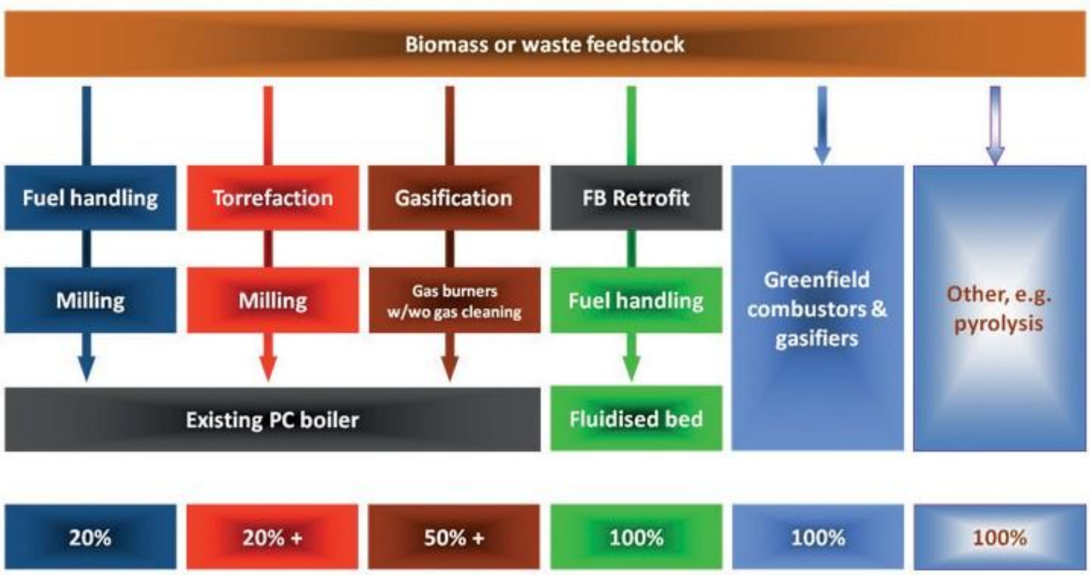
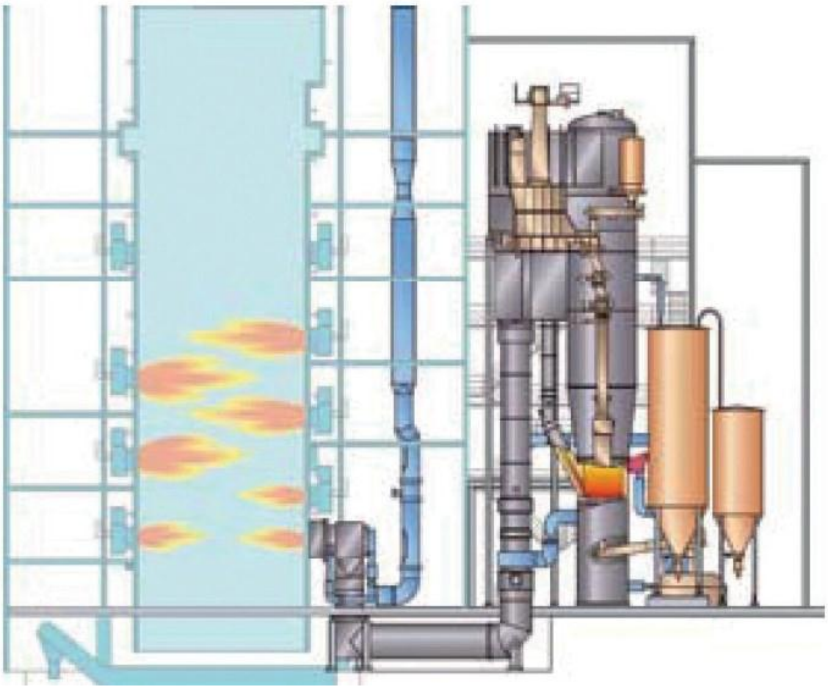


Figure 9.4
Good-quality solid recovered fuel (SRF) is gasified in the atmospheric fluidized bed gasifier and fed up to 15-20 % to the coal-fired boiler at the Kymijärvi Power Plant in Lahti, Finland.



Choice of technology and plant size depends on local conditions and quality of the fuels. Fluidized bed technology for combustion and gasification allows variable mixtures of biomass with high efficiency; also co-firing with coal is feasible. Introduction of liquid and gaseous energy carriers from solid biomass-based fuels will allow the use of high efficiency technologies, such as combustion engines, combined cycle plants, and fuel cells, and use of biomass for small-scale power production replacing fossil fuels.

Transition to low carbon economies requires 80-95% reduction in greenhouse gas emissions (GHG), which means that CO2 emissions form energy production, should be close to zero, or even negative. Capturing CO2 of biogenic origin from flue and process gases results in negative net emissions, which could offer cost-effective solutions for GHG emission reductions. This bio-CCS (carbon capture and storage) could be an option both in large scale co-firing and biomass-only plants as well as in pulp and paper industries, when the value of avoided CO2 emission is high, in the level of 100 €/t

Transportation fuels
The main transport biofuels on the market today are bioethanol, different fatty acid methyl (or ethyl) esters (biodiesel), and to a lesser extent also methane (biogas). Bioethanol has, by far, the largest market.

The main two technologies of advanced biofuels are producing biofuels from solid biomass by a so-called gasification route or sugar route. In the first process type, biomass is first gasified, the gasification product gas is cleaned and processed to form a synthesis gas, which is then used in a commercial chemical synthesis process to produce liquid biofuels like Fischer-Tropsch diesel, methanol, ethanol, MTBE/ETBE, dimethylether (DME) or gaseous biofuels like methane or hydrogen. Ethanol can be produced by biotechnical processes based on hydrolysis of lignocellulosic raw materials and fermentation of the extracted sugars.

Hydrogenation of oils and fats is a process that has entered in the market very fast with high volumes. In the process vegetable oils and animal fats are converted to renewable diesel fuel. The produced synthetic diesel fuels can be used as a blending component or as such.

Next generation biofuels can be used without blending wall in existing and future power trains. Fuel consumption will be lowered with dedicated tail pipe cleaning requirements. Ethanol can be used up to E85 blends and modern paraffinic bio diesel can be used up to 100 % in current engines. In a short perspective, hybrid vehicles are often considered as the most promising alternative vehicle technology. Advantage of this technology is the possibility to save fuel by smoothing out the operation of the internal combustion engine and by recovering braking energy. Compared to other alternative vehicle technologies, the hybrid technology provides possibilities to reduce energy consumption and exhaust emissions without the need for a new infrastructure. This is why these vehicles are often seen a step towards plug in hybrid vehicles, fuel cell vehicles and a full electric propulsion.

Environmental implications

Bioenergy production can have various and complex environmental impacts which can be positive or negative depending on the biomass type used for bioenergy production, local conditions, intensity and efficiency of biomass use, and the auxiliary inputs used in bioenergy production. The impacts can occur in a local or global scale, and can be classified as direct or indirect. The positive environmental impacts of bioenergy production are often considered to be the renewability of the raw material used and its carbon neutrality over the biomass growth cycle. The main environmental challenges due to intensified bioenergy production are mostly related to the feedstock production, such as impacts on land use, soil carbon and nutrient stocks, biodiversity, and on water use. Also the end use of bioenergy can have negative environmental impacts, especially in the developing countries, where traditional open fires and low-efficiency stoves produce large amounts of incomplete combustion products with negative consequences for climate change and local air pollution (Chum et al. 2011). Furthermore, the foreseen climate warming can have significant but currently uncertain effects to biomass production and its sustainability.

The effects on land use occur due to competition on land area between bioenergy feedstocks, food, feed, and biomaterial production. The indirect land use change (iLUC) occurs, when the cultivation of bioenergy raw material forces for example food production to other locations with land use impacts. The iLUC impacts are generally related to the oil crops and to other agricultural feedstocks, and can significantly reduce the greenhouse gas (GHG) emission reduction potential of the bioenergy products (e.g. Searchinger et al. 2008). Another environmental impact related to agricultural feedstocks is the water use, which can be a critical issue for water intensive crops and for locations with water shortage. Impacts on biodiversity and soil resources and habitat loss can occur due to intensified agro- or forest bioenergy production (Chum et al. 2011). Currently, a widely discussed issue related to the forest bioenergy is the carbon and climate neutrality of forest biomass (Cherubini et al. 2011; Helin et al. 2012). Bioenergy can be considered as carbon neutral, if the carbon emitted in biomass combustion is re-absorbed to the re-growing biomass. However, bioenergy might not be climate neutral, if the period for re-absorption of carbon is very long (e.g. 80 years for Boreal forests), as the carbon released in the combustion has a warming impact during its stay in the atmosphere (Cherubini et al. 2011). If the climate impacts are studied for a shorter period of time due to tight schedule for the needed emission reductions (e.g. 20-30 year), forest biomass may not be considered carbon neutral, nor climate neutral over this time scale. Generally, the environmental impacts are considered to be less relevant for bioenergy systems using waste and residue materials as input, as they do not compete on land and other auxiliary resources. However, intensified use of residues can have an effect on soil carbon and nutrient stocks. Currently, also the waste hierarchy, and the definitions of which type of materials can be defined as wastes or residues are discussed. Recently, also a question on whether and how efficiently bioenergy replaces fossil fuels has been raised, affecting the emission reduction potential of bioenergy (Rajagopal et al. 2011; York 2012). There are still many uncertainties related to the lifecycle-GHG emission assessments of bioenergy, which should be studied by the scientific communities in coming years.

There are several initiatives established in order to evaluate and control the environmental sustainability of bioenergy products, most of which are specified on the production of liquid biofuels for transportation. For example, the European Union (EU) has established the environmental sustainability criteria for liquid biofuels and other bioliquids in its Renewable Energy Directive (RED, 2009/28/EC) (EU 2009). A biofuel product must comply with these criteria, in order to be accounted to national targets for renewable energy and to benefit from subsidies. The RED sets the emission saving limits that biofuels have to gain compared to fossil fuels (first 35 % and later 60% emission reduction), and introduces a first-ever life cycle analysis (LCA) based mandate methodology to calculate the GHG emission balances of biofuels and other bioliquids. EU is also planning to take the iLUC impacts into consideration in the RED sustainability criteria (EC 2012). A strong incentive is given for the use of waste and residues, as biofuels produced from these raw materials can be counted as double towards the national targets for renewable energy in transportation (EU 2009). European Commission has also accepted some voluntary schemes, such as ISCC, RED Cert and Biograce GHG calculation tool to be suitable for GHG assessment according to the RED (EC 2013). EU is planning to establish similar criteria for bioenergy from solid and gaseous biomass (EC 2010).

Also in the USA sustainability criteria have been established for biofuels, such as the Renewable fuel standard in the USA, included in the 2007 Energy Independence and Security Act (EISA 2007), and the Low carbon fuel standard in California (CARB 2009). The Renewable Fuel Standard demands for minimum GHG reductions from renewable fuels, discourages use of food and fodder crops as feedstocks, and estimates the (i)LUC effects. The California Low Carbon Fuel Standard sets an absolute carbon intensity reduction standard for biofuels, and demands for periodical evaluation of new information, e.g. on iLUC impacts (Chum et al. 2011).There are also several voluntary schemes to evaluate the sustainability of specific bioenergy feedstocks (e.g. Roundtable on Sustainable Palm Oil, and Round Table on Responsible Soy EU RED, Better Sugarcane Initiative) (EC 2013; Chum et al. 2011).

Bioenergy markets

Global trade in biomass feedstocks (e.g. wood chips, vegetable oils and agricultural residues) and processed bioenergy carriers (e.g. ethanol, biodiesel, wood pellets) is growing rapidly boosted by national policies, like feed-in tariffs, in some European countries. Present estimates indicate that bioenergy trade is modest – around 1.1 EJ (about 2% of current bioenergy use even though the volume of energy biomass trade has been increasing. Especially the direct trade of biofuels has grown rapidly but the indirect trade through the trading of industrial roundwood and material by-products has been relatively stable over the past years. The global economic recession caused the indirect trade to decrease between 2008 and 2009; a time span during which the direct trade continued to grow. The importance of the direct trade has increased remarkably. In 2004, the direct trade covered less than a fourth of the total global bioenergy trade. In 2011, the proportion of direct trade had increased to 45%.

The international trade of biomass and biofuels for energy production is much smaller than the international trade of biomass for other industrial purposes. Most of the biomass products are mainly consumed locally in the countries of production, but in the case of products such as sawn timber, paper and paperboard, palm oil, and wood pellets, a considerable proportion of the total production is exported.

Table 1 gives an estimate of the scope of international trade of biomass for energy purposes in 2004–2011. In the case of ethanol and palm oil (and other vegetable oils), the final use is not always clear, and some assumptions had to be made, as to how much of the total trade is earmarked for fuel use. The figures in Table 1 should therefore be considered as indicative showing the scales of various energy biomass trade streams.

Table 1

Estimated scope of international biomass fuel trade between 2004 – 2011 in PJ (excluding tall oil, ETBE, and waste)

Source: Heinimö et al 2013

Year/product	2004	2005	2006	2007	2008	2009	2010	2011
Indirect trade	585	640	636	671	606	493	598	648
industrial roundwood	450	488	488	507	431	341	404	444
wood chips and particles	136	152	149	165	175	152	194	204
Direct trade	203	230	292	337	467	449	438	500
Charcoal	27	31	35		38	39	44	46
Fuel wood	33	35	39	38	38	51	51	60
Wood pellets	26	42	55	50	53	84	120	135
Biodiesel	0	2	4	33	89	83	97	112
Ethanol	91	85	120	126	178	122	60	69
Palm oil (and other vegetable oils for biodiesel)	26	34	39	56	71	70	66	78
Total	**788**	**870**	**929**	**1 009**	**1 072**	**942**	**1 036**	**1 277**

Trade in *wood chips for energy* (virgin and/or tertiary residues) is practically limited to Europe, Turkey, and Japan, being less than 20 PJ annually. The direct trade of wood chips for energy purposes is thus about 10% of the indirectly traded volume (in terms of calorific value).

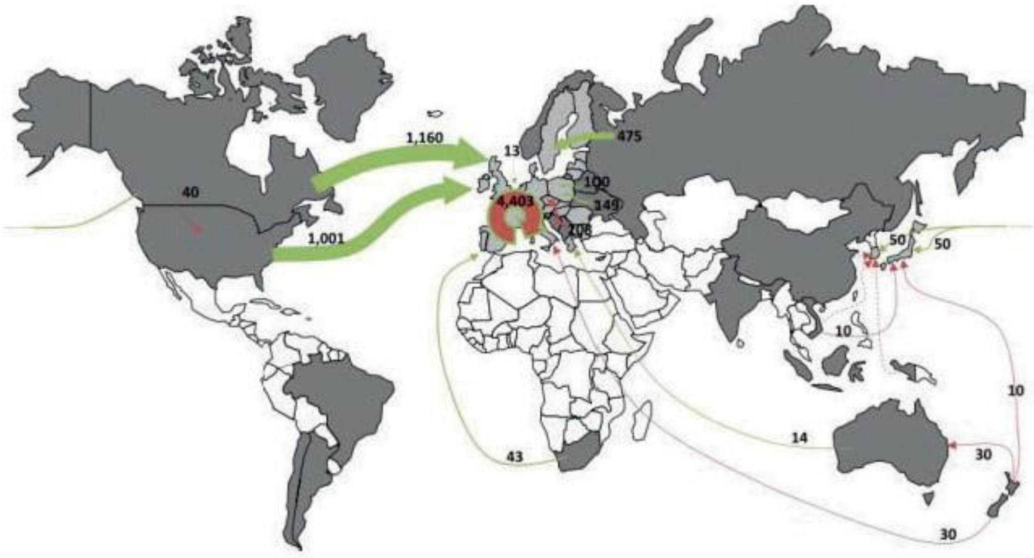
Apart from heating and cooking (including barbeque in industrial countries), *charcoal* is applied in the chemical (as active coal) and in the iron and steel industry (as a reducing agent and energy source). The largest producer between 2000 and 2010 was Brazil (13%), where most charcoal is used in pig iron production. The international trade with charcoal has been dominated by Germany (10%), Japan (9%), and South Korea (8%) in terms of imports. Total world exports have been led by Somalia over the past four years. Up to now there has been no direct and large scale trade for modern energy conversion, and the current trade for energy purposes is limited to heating, cooking, and barbeque. During 2004–2011, the charcoal trade volumes have almost doubled.

Fuel wood use for heat generation in high performance boilers and stoves has been heavily driven across the EU over the last years. Its share in the global trade increased from 50% (2000–2004) to over 80% (2007–2011). Most of this trade is cross-border trade: short- or mid-range in bagged form, conglomerated in nets, or stacked on pallets. Recorded trade

Figure 9.5

Major global wood pellet trade streams in 2011 (in kilotonnes).

Source: Heinimö et al 2013.



streams outside Europe are between South Africa and its neighbouring countries (Swaziland and Namibia), Canada and the USA, and across South East Asia. By 2010, half of the total fuel wood production was centred in India (17%), China (10%), Brazil (8%), Ethiopia (5%), Congo (4%), Nigeria (3%), and Indonesia (3%) [15]. Similarly to the charcoal trade, the volumes of fuel wood had almost doubled compared to the figures of 2004.

Wood pellets have become one of the most important energy biomass commodity. International trade volumes of pellets have constantly been increasing since 2004: the trade has increased fivefold from 2004 to 2010. Around 60% of the global wood pellet production was concentrated in the EU, Figure 9.5. Since 2000, EU production, demand, and imports have increased more than tenfold [7]. Until 2010, most pellets were combusted in residential heating (dominated by Italy, Germany, and Austria), followed by district heating (Sweden and Denmark), and large scale power production (concentrated in Belgium, the Netherlands, and the UK). While being relatively self-sufficient in the residential pellet market segment, the EU has become heavily import-dependent in the industrial pellet market. This is largely due to the strong increase in demand (predominantly from the Netherlands and the UK), but also linked to a limited mobilisation and production (within the EU and its border countries), competitive to overseas pellet export prices. In 2009, approximately 1.7 Mtonnes were imported from outside the EU. By 2012, this volume had risen to 4.6 Mtonnes, Figure 9.5). By 2020, EU wood pellet imports are expected to be in the range of 15–30 Mtonnes. While the majority of this volume will be industrial pellets, wood pellet imports for the domestic market are also expected to increase.

To overcome barriers in biomass and biofuel trade for energy, technical standards are a perquisite to allow for commoditisation of biomass and biofuels. ISO is currently preparing almost 60 standards for solid biofuels. Pellet standards under development will specify general requirements, graded pellets and non-woody graded pellets, and quality for industrial pellets. ISO standards under development also consist of classification of raw material, which is based on their origin and source, and specifications for woody biomass, herbaceous biomass, fruit biomass, aquatic biomass, blends and mixtures, and thermally treated biomass (e.g. torrefied biomass)(see Alakangas 2013). Threshold values for new standards have been agreed, and they will be published in 2014.

Figure 9.6
Example of an A-frame silo for the large-scale storage of solid biofuel.
Source: Raumaster

Lessons learnt and key actions for the future

Several scenario studies for the transition low carbon society by 2050 has indicated that globally the transport and industrial sectors are the most challenging sectors to decarbonize. Both of these sectors could replace the use of fossil fuels by biofuels to a certain extent, but the limiting factor would be the availability and price of sustainable biofuels. In addition, the role of biomass as a resource for material use is increasing as new processes and products are being developed in chemical and other industries in future bioeconomy. Therefore it is important to use bioenergy resources on those sectors, where the special properties of biomass may be utilized, and on the other hand, where the deepest, cost effective greenhouse gas emissions reductions may best achieved. As an example, heavy road transport and aviation could hardly be decarbonized without biofuels.

As a storable form of renewable energy, biofuels will have a vital role in hybrid renewable energy solutions in future low carbon energy systems. Recently, the investments on variable wind and solar power have increased the need for balancing power and energy storages. In those countries, where natural gas infrastructures and gas storages already exist, synthetic methane (SME) and biogas may offer cost-effective solution to balance electricity supply and demand. Liquid biofuels may replace mineral oils to produce peak power and heat, and on the other hand, solid biofuels could replace coal and other solid fossil fuels as a balancing energy source during seasonal high energy demands and/or low renewable energy production.

As current energy systems are largely based on fossil fuels, hybrid systems offer short term solutions to increase the share of bioenergy of TPES. The hybrid systems are cost-effective solutions in many countries already today, even though market prices of both fossil fuels and emissions allowances have experienced downward trend. Advanced new combustion technologies, like multifuel fired fluidized bed combustion, allow for using wide range of renewable wastes and other low grade renewable materials for energy production, and investing in new high efficiency technologies offer better cost-efficiency and reduced environmental impacts, both direct and indirect.

In the long term, transition to “bioeconomy” could offer pathway for a low carbon society, where the basic building blocks for industry and the raw materials for energy are derived from plant or crop-based sources as well as from municipal and livestock wastes. Today, it is not known, which new technologies and new products will emerge into the markets, and which bio-based products (i.e. energy, transport fuels, or industrial products) will have the best paying ability against competing energy technologies, fuels, or industrial products. For example, the IEA Roadmaps for transport and biofuels (IEA 2011) and for heat and power (IEA 2012b) expect that biofuels could provide up to 65 EJ transport fuels and additional 80 EJ for electricity and heat. Producing such amount of biofuels requires around 170-300 million ha land area in 2050, which is about 4-6% of existing agricultural land area (IEA 2012). For comparison, it is estimated that by 2050 global agricultural production will have to increase by 60% from its 2005-2007 level to feed the increasing population, which will require expansion of arable land by about 70 million ha (FAO 2013).

The way forward

The bioenergy success stories in industrialized countries with the highest share of bioenergy of their TEPS has usually based on the sustainable use of local residues and resources and long-term policy framework to support RD&D of the whole bioenergy value chain to develop and deploy high efficiency bioenergy technologies and to ensure reliable and low cost fuel supply. In addition, national energy, climate, employment, education, agriculture, and/or forestry policies have promoted bioenergy in many ways in these countries.

Today’s cost-effective bioenergy concepts use often renewable biogenic waste or industrial side streams, like black liquor, agricultural and municipal solid wastes, to produce combined heat and power or heat for industries and communities. Co-firing of bioenergy feedstock with fossil fuels is also a cost-effective solution in many applications. In addition, the lowest life-cycle GHG emissions can be achieved through use of residues and wastes on site.

It can be expected that the traditional use of woodfuel will have a major role in the future small scale applications as well. Therefore it is important to develop technologies and catalyse investments in new, more efficient biomass stoves in developing countries to increase the energy efficiency and to decrease environmental impacts.

Due to limited availability of sustainable biomass resources, biofuels and biomaterials should be used in those sectors, which have limited options for deep greenhouse gas emission reduction (i.e. transport and process industries), which have high cost-effectiveness (i.e. usage as balancing power and energy storage), and where the special properties of biomass may be utilized (i.e. new bio-based products which cannot be produced from mineral oil).

One of the most viable sectors for bioenergy is transport sector, where the share of biofuels should be increased from the current 3% to above 25% by 2050. To reach this target, advanced 2nd generation biofuel technologies should be commercially deployed. The current use of cereals based transportation biofuels have clear blending wall like E10 or B7, which must have complimentary solutions by next generation dropping (“no blending wall”) biofuels produced form sustainable cellulosic resources, as much as possible.

The deployment of maximum sustainable bioenergy potential will require well-functioning markets for biofuels, food and other bio-products, to ensure both food security and reliable biofuel supply. Development of biofuel markets requires also internationally agreed sustainability criteria and certification schemes to abolish trade barriers, now and in the future.

Development of novel biomass conversion technologies and integrated concepts as well as new bioenergy resources, like algae-based biofuels, could offer new solutions for increased use of bioenergy. Investments on bio-CCS could also offer cost effective solution for achieving low carbon societies, but the implementation requires new policies to take into account "net negative emissions".

Acknowledgements

This chapter is written by experts on bioenergy, energy systems, and sustainablity from VTT Technical Research Centre of Finland. The following persons have contributed in writing: Tiina Koljonen, Kai Sipilä, Satu Helynen, Kati Koponen, and Eija Alakangas.

References

Alakangas, E. Towards international standards – industrial wood pellet standards under development, 21st European Biomass Conference and Exhibition 2013, Copenhagen, 3 – 6 June 2013, paper, 3 p.

CARB (2009) Proposed Regulation to Implement the Low Carbon Fuel Standard. California Environmental Protection Agency, Air Resources Board, Stationary Source Division, Sacramento, California, 374 pp.

Cherubini F, Peters GP, Berntsen T, Stromman AH, Hertwich E (2011) CO(2) emissions from biomass combustion for bioenergy: atmospheric decay and contribution to global warming. *Global Change Biology Bioenergy, 3,* 413-426.

Chum H, Faaij A, Moreira J *et al*. (2011) Bioenergy. In IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. In: (ed O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth,P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, C. von Stechow).

EC (2013) Biofuels - Sustainability schemes. Available: http://ec.europa.eu/energy/renewables/biofuels/sustainability_schemes_en.htm. 2013.

EC (2012) Proposal for a directive of the European parliament and of the council amending directive 98/70/EC relating to the quality of petrol and diesel fuels and amending Directive 2009/28/EC on the promotion of the use of energy from renewable sources. Brussels, 17.10.2012. COM(2012) 595 final. 2012/0288 (COD). Available: http://ec.europa.eu/energy/renewables/biofuels/doc/biofuels/com_2012_0595_en.pdf.

EC (2010) Report from the Comission to the Council and the European Parliament on sustainability requirements for the use of solid and gaseous biomass sources in electricity, heating and cooling.

EISA (2007) Public Law 110 - 140 - Energy Independence and Security Act of 2007. The United States

EU (2009) Directive of the European Parliament and of the Council on the promotion of the use of energy from renewable sources. 2009/28/EC. The Official Journal of the European Union 05/06/2009.

FAO 2013. FAO Statistical Yearbook 2013. World food and agriculture.

Heinimö, J., Lamers, P. & Ranta, J. International trade of energy biomass – an overview of the past development. 21st European Biomass Conference and Exhibition 2013, Copenhagen, 3 – 6 June 2013, paper, 9 p.

Helin T, Sokka L, Soimakallio S, Pingoud K, Pajula T (2012) Approaches for inclusion of forest carbon cycle in life cycle assessment ? A review. *GCB Bioenergy*, In press.

IEA 2012. IEA Statistics 2012. Renewables Information. OECD, Paris.

ISO (2006) 14040:2006. Environmental management -- Life cycle assessment -- Principles and framework. International Organization for Standardization (ISO). 20 p.

Rajagopal D, Hochman G, Zilberman D (2011) Indirect fuel use change (IFUC) and the lifecycle environmental impact of biofuel policies. *Energy Policy*, 39, 228-233.

Searchinger T, Heimlich R, Houghton RA *et al*. (2008) Use of US croplands for biofuels increases greenhouse gases through emissions from land-use change. *Science*, 319, 1238.

York R (2012) Do alternative energy sources displace fossil fuels? *Nature Clim.Change*, 2, 441-443.

Country notes

Argentina

Biodiesel produced in 2011, tonnes	2 376.297
Biodiesel production capacity in 2011, tonnes per year	3 100
Ethanol produced in 2011, tonnes	131 389

Austria

Electricity: installed capacity in 2011, MW	300
Electricity: actual generation in 2011, TJ	11 500
Ethanol production, installed capacity in 2011, TJ/year	5 000
Ethanol energy produced in 2011, TJ	2 210
Biodiesel installed capacity in 2011, TJ/year	17 000
Biodiesel energy produced in 2011, TJ	6 618

Brazil

Electricity: installed capacity in 2011, MW	1 178 869
Electricity: actual generation in 2011, TJ	25 913
Ethanol installed capacity in 2011, TJ/year	572 477
Ethanol production in 2011, TJ	358 025
Biodiesel installed capacity in 2011, TJ/year	213 666
Biodiesel production in 2011, TJ	78 710

Canada

Ethanol installed capacity in 2011, TJ	41 906
Ethanol production in 2011, TJ	40 060

Croatia

Electricity: installed capacity in 2011, MW	6 500
Electricity: actual generation in 2011, TJ	128.53
Biodiesel installed capacity in 2011, TJ/year	2 361.6
Biodiesel production in 2011, TJ	283
Biogas installed capacity in 2011, TJ/year	423.45
Biogas production in 2011, TJ	128.53

Czech Republic

Ethanol installed capacity in 2011, TJ/year	4 320
Ethanol production in 2011, TJ	1 469
Biodiesel installed capacity in 2011, TJ/year	15 540
Biodiesel production in 2011, TJ	7 773

Estonia

Electricity: installed capacity in 2011, MW	120
Electricity actual generation in 2011, TJ	2 664

Finland

Solid fuel production installed capacity in 2011, TJ/year	12 600
Solid fuel production in 2011, TJ	3 200
Ethanol installed capacity in 2011, TJ/year	293
Ethanol production in 2011, TJ	210
Biodiesel installed capacity in 2011, TJ/year	15 910
Biodiesel production in 2011, TJ	12 100
Biogas installed capacity in 2011, TJ/year	2156.5
Biogas production in 2011, TJ	53

Germany

Electricity installed capacity in 2011, MW	3 099
Electricity production in 2011, TJ	68 040
Ethanol installed capacity in 2011, TJ/year	24 680
Ethanol production in 2011, tonnes	577 000
Biodiesel installed capacity in 2011, TJ/year	177 930
Biodiesel production in 2011, tonnes	2 870 000

Italy

Electricity installed capapcity in 2011, MW	2 824
Electricity actual generation in 2011, TJ	38 996.64
Biodiesel installed capacity in 2011, tonnes/year	2 395 240
Biodiesel production in 2011, tonnes	620 000

Japan

Electricity installed capacity in 2011, MW	319
Electricity actual generation in 2011, TJ	15 128

Latvia

Electricity installed capacity in 2011, MW	12
Electricity actual generation in 2011, TJ	400

Mexico

Electricity installed capacity in 2011, MW	89.9
Electricity actual generation in 2011, TJ	49 199
Solid fuel production installed capacity in 2011, TJ/year	47 929.76
Solid fuel production energy produced in 2011	47 929.76
Biodiesel installed capacity in 2011, TJ/year	1 470
Biodiesel production in 2011, TJ	1 470
Biogas installed capacity in 2011, TJ/year	1 470
Biogas production in 2011, TJ	1 470

Romania

Electricity installed capacity in 2011, MW	25
Electricity actual generation in 2011, TJ	659

Serbia

Biodiesel installed capacity in 2011, TJ/year	4
Biodiesel production in 2011, TJ	2 400

Sweden

Electricity installed capacity in 2011, MW	2.9
Electricity actual production in 2011, TJ	43 920

Switzerland

Solid fuel production installed capapcity in 2011, MW	10 584
Solid fuel production in 2011, TJ	39 206