Technology Roadmap

Bioenergy for Heat and Power

International Energy Agency

INTERNATIONAL ENERGY AGENCY

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Foreword

Current trends in energy supply and use are patently unsustainable – economically, environmentally and socially. Without decisive action, energy-related emissions of carbon dioxide (CO_2) will more than double by 2050 and increased oil demand will heighten concerns over the security of supplies. We can and must change our current path, but this will take an energy revolution and low-carbon energy technologies will have a crucial role to play. Energy efficiency, many types of renewable energy, carbon capture and storage (CCS), nuclear power and new transport technologies will all require widespread deployment if we are to reach our greenhouse gas (GHG) emission goals. Every major country and sector of the economy must be involved. The task is also urgent if we are to make sure that investment decisions taken now do not saddle us with sub-optimal technologies in the long term.

Awareness is growing of the urgent need to turn political statements and analytical work into concrete action. To spark this movement, at the request of the G8, the International Energy Agency (IEA) is leading the development of a series of roadmaps for some of the most important technologies. By identifying the steps needed to accelerate the implementation of radical technology changes, these roadmaps will enable governments, industry and financial partners to make the right choices. This will in turn help societies make the right decisions.

Bioenergy is the largest single renewable energy source today, providing 10% of global primary energy supply. It plays a crucial role in many developing countries, where it provides basic energy for cooking and space heating, but often at the price of severe health and environmental impacts. The deployment of advanced biomass cookstoves and clean fuels, and additional off-grid biomass electricity supply in developing countries, are key measures to improve the current situation and achieve universal access to clean energy facilities by 2030. In addition, this roadmap envisages a strong increase in bioenergy electricity supply to 2050. Bioenergy would then provide 3 100 Terawatt-hours (TWh) of dispatchable and in many cases flexible electricity, meeting 7.5% of world electricity demand, and contributing considerably to better energy security. A significant increase in bioenergy demand is also envisaged in industry, where it can provide high temperature heat and replace CO_2-intensive coke and coal. As discussed in a separate IEA roadmap, rapidly growing demand for biofuels also needs to be considered as it adds to the total biomass demand for energy today and in the future.

This roadmap identifies technology goals and defines key actions that governments and other stakeholders must undertake to expand the sustainable production and use of bioenergy. It provides additional focus and urgency to international discussions about the importance of bioenergy to a low CO_2 future. To achieve this vision, strong and balanced policy efforts are needed to create a stable investment environment and allow commercialisation of new bioenergy conversion technologies, efficiency improvements and further cost reductions along the whole supply chain. Internationally aligned sustainability requirements will be vital to ensure that production and use of bioenergy heat and power provide the envisaged emission reductions, and have a positive impact on socio-economic development and the environment.

As the recommendations of this roadmap are implemented, and as technology and policy frameworks evolve, the potential for different technologies may increase. In response, the IEA will continue to update its analysis of future potentials, and welcomes stakeholder input as these roadmaps are developed.

Maria van der Hoeven
Executive Director

This roadmap was prepared in 2012. It was drafted by the IEA Renewable Energy Division. This paper reflects the views of the International Energy Agency (IEA) Secretariat, but does not necessarily reflect those of individual IEA member countries. For further information, please contact the authors at: Anselm.Eisentraut@iea.org and Adam.Brown@iea.org.

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Acknowledgements

This publication was prepared by the International Energy Agency's Renewable Energy Division (RED). Anselm Eisentraut and Adam Brown were the coordinators and primary authors of this report. IEA colleague Milou Beerepoot provided valuable input to the sections focussing on bioenergy for heat. Paolo Frankl, head of the Renewable Energy Division, provided valuable guidance and input to this work. Didier Houssin, Director of Energy Markets and Security, and Bo Diczfalusy, Director of Sustainable Energy Policy and Technology, provided additional guidance and input.

Several other IEA colleagues have also provided important contributions to the work on this roadmap, in particular: Prasoon Agarawal, Dennis Best, Zuzana Dobrotkova, Lew Fulton, Cédric Philibert, Uwe Remme, Cecilia Tam, Nathalie Trudeau, and other colleagues in the Renewable Energy Division and other divisions within the IEA.

This work was guided by the IEA Committee on Energy Research and Technology. Its members provided important review and comments that helped to improve the document.

Several members from the IEA's Bioenergy Implementing Agreement and its Renewable Energy Working Party provided valuable data, comments and suggestions.

The authors would also like to thank Peter Chambers for skilfully editing the manuscript, as well as the IEA's publication unit, in particular Jane Barbière, Muriel Custodio, Astrid Dumond, Rebecca Gaghen, Angela Gosmann, Cheryl Haines, Bertrand Sadin, Marilyn Smith and Kathleen Sullivan, for their assistance.

This roadmap has benefitted from a wide range of comments and other input received from industry, government and non-government experts and the members of the IEA Bioenergy Implementing Agreement, who attended the roadmap workshops, reviewed and commented on earlier drafts of the roadmap, and provided overall guidance and support. The authors wish to thank all of those who participated in the meetings and commented on the drafts. The resulting roadmap is the IEA's interpretation of the workshops, with additional information to provide a more complete picture, and does not necessarily fully represent the views of the workshop participants and reviewers. A full list of workshop participants and reviewers is included in Appendix II.

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Key findings

Bioenergy is the largest source of renewable energy today and can provide heat, electricity, as well as transport fuels. This roadmap envisages world total primary bioenergy supply increasing from 50 EJ today to 160 EJ in 2050, with 100 EJ of this for generation of heat and power.

In line with analysis in the IEA *World Energy Outlook 2011*, this roadmap aims at the deployment of advanced biomass cookstoves and biogas systems to 320 million households in developing countries by 2030. This deployment is essential as part of a sustained effort to provide universal access to clean energy.

By 2050 bioenergy could provide 3 100 TWh of electricity, *i.e.* 7.5% of world electricity generation. In addition heat from bioenergy could provide 22 EJ (15% of total) of final energy consumption in industry and 24 EJ (20% of total) in the buildings sector in 2050.

Bioenergy electricity could bring 1.3 Gt CO_2-equivalent (CO_2-eq.) emission savings per year in 2050, in addition to 0.7 Gt per year from biomass heat in industry and buildings, if the feedstock can be produced sustainably and used efficiently, with very low life-cycle GHG emissions.

Large-scale (>50 MW) biomass power plants will be important to achieve this roadmap's vision, since they allow for electricity generation at high efficiencies and relatively low costs. Co-firing biomass in coal-fired plants provides an opportunity for short-term and direct reduction of emissions, so avoiding the "carbon lock-in effect" (the inertia that tends to perpetuate fossil-fuel based energy systems).

Smaller-scale (<10 MW) plants have lower electric efficiencies and higher generation costs, and are best deployed in combined heat and power mode, when a sustained heat demand from processes or district heating is available.

Biomass heat and electricity can already be competitive with fossil fuels under favourable circumstances today. Through standardising optimised plant designs, and improving electricity generation efficiencies, bioenergy electricity generation costs could become generally competitive with fossil fuels under a CO_2 price regime.

Enhanced research, development and demonstration (RD&D) efforts will bring new technologies such as small-scale, high efficiency conversion technologies to the market. Development of biomass conversion to biomethane for injection into the natural gas grid could become one very interesting option, since it could exploit existing investments in gas infrastructure and provide flexible electricity.

Around 100 EJ (5 billion to 7 billion dry tonnes) of biomass will be required in 2050, in addition to 60 EJ (3 billion to 4 billion dry tonnes) for production of biofuels. Studies suggest such supply could be sourced in a sustainable way from wastes, residues and purpose grown energy crops.

International trade in biomass and biomass intermediates (pellets, pyrolysis oil, biomethane) will be vital to match supply and demand in different regions and will require large-scale development of biomass and its intermediates.

To achieve the targets in this roadmap, total investment needs in bioenergy electricity generation plants globally are around USD 290 billion between 2012 and 2030, and USD 200 billion between 2031 and 2050. In addition, considerable investments in bioenergy heating installations in industry and buildings are required. Total expenditures on feedstocks are in the range of USD 7 trillion to USD 14 trillion in 2012-2050, depending heavily on feedstock prices.

In the next 10 years to 20 years, cost differences between bioenergy and fossil derived heat and power will remain a challenge. Economic support measures specific to different markets will be needed as transitional measures, leading to cost competitiveness in the medium term. Such support is justified when environmental, energy security, and socio-economic benefits result.

Key actions in the next ten years

Concerted action by all stakeholders is critical to realising the vision laid out in this roadmap. In order to stimulate investment on the scale required to achieve the levels of sustainable bioenergy envisioned, governments must take the lead role in creating a favourable climate for industry investments by taking action on policy, markets and international co-operation. In particular governments should:

- **Create a stable, long-term policy framework for bioenergy** to increase investor confidence and allow for private sector investments in the sustainable expansion of bioenergy production.
- **Introduce efficient support mechanisms** for bioenergy that effectively address the specifics of both electricity and heat markets.
- **Increase research efforts on development of bioenergy feedstocks and land suitability mapping** to identify the most promising feedstock types and locations for future scaling up.
- **Replace traditional biomass use through more efficient stoves and clean fuels** (*e.g.* biogas) by the creation of viable supply chains for advanced biomass cookstoves and household biogas systems.
- **Support the installation of more pilot and demonstration projects**, including innovative concepts for small-scale co-generation power plants, including their complete supply chains.
- **Set medium-term targets for bioenergy** that will eventually lead to a doubling of current primary bioenergy supply (*i.e.* to 100 EJ) by 2030. This will help to establish supply chains, assess the impact on sustainability and identify viable options for effective integration of bioenergy in biomass value chains.
- **Implement internationally agreed sustainability criteria, indicators and assessment methods** for bioenergy. These should provide a basis for the development of integrated land-use management schemes that aim for a more resource efficient and sustainable production of food, feed, bioenergy and other services.
- **Introduce internationally aligned technical standards for biomass and biomass intermediates**, in order to reduce and eventually abolish trade barriers, enhance sustainable biomass trade and tap new feedstock sources.
- **Support international collaboration on capacity building and technology transfer** to promote the adoption of best practices in sustainable agriculture, forestry and bioenergy production.

Introduction

There is a pressing need to accelerate the development of advanced energy technologies in order to address the global challenges of clean energy, climate change and sustainable development. This challenge was acknowledged by the energy ministers from G8 countries, China, India and Korea, in their meeting in June 2008 in Aomori for G8 Hokkaido Toyako Summit in July 2008, Japan, where they declared the wish to have IEA prepare roadmaps to advance innovative energy technology:

> *We will **establish an international initiative with the support of the IEA** to develop roadmaps for innovative technologies and cooperate upon existing and new partnerships [...] Reaffirming our Heiligendamm commitment to urgently develop, deploy and foster clean energy technologies, we recognize and encourage a wide range of policy instruments such as transparent regulatory frameworks, economic and fiscal incentives, and public/private partnerships to foster private sector investments in new technologies...*

To achieve this ambitious goal, the IEA has undertaken an effort to develop a series of global technology roadmaps covering 19 technologies, under international guidance and in close consultation with industry. These technologies are evenly divided among demand side and supply side technologies. This bioenergy roadmap is part of this effort.

The overall aim is to advance global development and uptake of key technologies to reach a 50% CO_2-eq. emission reduction in the energy sector by 2050 compared to 2005 levels. The roadmaps will enable governments, industry and financial partners, in conjunction with civil society, to identify steps needed and implement measures to accelerate the required technology development and uptake and public acceptance.

This process starts with a clear definition of what constitutes a "roadmap" in the energy context, and the specific elements it should comprise. Accordingly, the IEA has defined its global technology roadmaps as:

> *... a dynamic set of technical, policy, legal, financial, market and organisational requirements identified by the stakeholders involved in its development. The effort shall lead to improved and enhanced sharing and collaboration of all related technology-specific research, design, development and deployment (RDD&D) information among participants. The goal is to accelerate the overall RDD&D process in order to deliver an earlier uptake of the specific technology into the marketplace.*

Rationale for bioenergy

Biomass-based energy is the oldest source of consumer energy known to mankind, and is still today the largest source of renewable energy,[1] accounting for roughly 10% of world total primary energy supply (TPES) (IEA, 2011a). Most of this is traditional biomass, which plays an important role in providing energy for cooking and heating, in particular to poor households in developing countries.

Biomass is a unique source of renewable energy as it can be provided as solid, gaseous or liquid fuel and can be used for generating electricity, transport fuels, as well as heat – in particular, high-temperature heat for industry purposes. Bioenergy can be stored[2] at times of low demand and provide dispatchable energy when needed. Depending on the type of conversion plant, bioenergy can thus play a role in balancing the rising share of variable renewable electricity from wind and solar in the power system. In addition, the possibility to store biomass allows for generation of biomass-derived heat to meet seasonal demand, as is commonly done for instance in Nordic countries.

Since bioenergy can be generated from energy crops and biomass residues, as well as organic wastes, there is considerable potential for new sources of income along the whole value chain, from cultivation to harvest, processing and conversion into energy. This can potentially benefit farmers and forest owners and support rural development. Biomass feedstocks in the form of wood chips, pellets, pyrolysis oil orn biomethane can be traded globally. Regions with good biomass supply and those with insufficient supply of cost-competitive biomass can be connected within an international market to meet supply and demand patterns.

However, there are some sensitive aspects to be considered in the sustainable development of bioenergy for heat and power. The large-scale deployment of bioenergy can create competition

1 It should be noted, however, that not all biomass used for bioenergy production today is sourced on a renewable basis.

2 Some biomass feedstocks can be stored for weeks or months in the field or forest, and up to years under dry conditions protected from the weather. Other feedstocks such as organic waste and manure are less suited for storage as over time they decay and lose their energy content.

Box 1: Definitions

Biomass: Any organic, *i.e.* decomposing, matter derived from plants or animals available on a renewable basis. Biomass includes wood and agricultural crops, herbaceous and woody energy crops, municipal organic wastes as well as manure.

Bioenergy is energy derived from the conversion of biomass where biomass may be used directly as fuel, or processed into liquids and gases.

Traditional biomass use in this roadmap refers to the use of wood, charcoal, agricultural residues and animal dung for cooking and heating in the residential sector. It tends to have very low conversion efficiency (10% to 20%) and often unsustainable biomass supply.

Primary bioenergy supply refers to the energy content of biomass feedstocks before conversion.

Final bioenergy consumption refers to the use of biomass in different end-use sectors. In some cases (*e.g.* buildings, industry) this category is equal to the biomass input.

Useful bioenergy refers to the net-energy generation (*i.e.* electricity, heat) excluding transformation losses.

Biofuels refers to liquid and gaseous fuels produced from biomass and used in the transport sector.

with existing uses of biomass such as for food and feed, or forest products, or can compete for land used for their production. This competition can create upward pressure on agricultural and forestry commodity prices and thus affect food security. In some cases bioenergy may also lead to direct and indirect land-use changes resulting in release of GHG emissions, more intensive land use, pressure on water resources and loss of biodiversity. Not all of the mentioned aspects are necessarily negative, however. Production of bioenergy feedstocks can create additional income sources and help stabilise prices for agricultural and forestry products, creating new opportunities for farmers to invest in more efficient production and related socio-economic benefits for rural communities. A sound policy framework will be vital to minimise the potential negative aspects and maximise social, environmental and economic benefits of bioenergy production and use. Only then can bioenergy contribute to meeting energy demand and reducing GHG emissions in a sustainable way, as envisioned in this roadmap.

While several technologies for generating bioenergy heat and power already exist, there is a need to extend the use of the most efficient technologies available today, and to complete the development and deployment of a number of new technology options. Routes for producing and pre-treating biomass feedstocks need to be demonstrated within a sound internationally agreed framework that sets clear principles and evaluation methods to ensure that the fuels are produced and used sustainably. A policy framework will also need to provide support for the efficient use of bioenergy to allow the technologies and fuel supply chains to mature and produce energy competitive with fossil fuels, taking environmental and energy security benefits fully into account.

Roadmap purpose

This roadmap further develops past IEA analysis in line with the forthcoming *Energy Technology Perspectives 2012* (IEA, 2012a; to be published in June 2012). The *ETP 2012* 2°C Scenario (*ETP* 2DS) sets out cost effective strategies for reducing greenhouse gas emissions in the energy sector by 50% in 2050 compared to 2005 levels. This is intended to stabilise atmospheric greenhouse gases around 450 parts per million (ppm) and to limit global temperature rise to 2°C by the end of this century. The analysis in the 2DS and this roadmap shows that bioenergy could make an important contribution to reducing emissions and enhancing energy access. It would involve increasing bioenergy from around 10% of world primary energy supply today to 24% by 2050. An important transition required to achieve this vision is to use biomass more efficiently, for example by deploying more efficient conversion technologies, some of which are still in the demonstration phase, and better integrating bioenergy production into biomass value chains in other industries.

This roadmap aims to identify the primary tasks that must be undertaken globally to accelerate the sustainable deployment of bioenergy to reach the 2DS projections. The roadmap also discusses barriers and challenges to large-scale bioenergy deployment. These include the need for commercialisation of new bioenergy conversion technologies, the establishment of viable, large-scale supply chains for biomass, and broader issues governing sustainable feedstock production and bioenergy market structures. In some markets, certain steps described here have already been taken or are under way; but many countries are only just beginning to develop modern bioenergy supply. Therefore, milestone dates set in this roadmap should be considered as indicative of urgency, rather than as absolutes.

The roadmap does not attempt to cover every aspect of bioenergy conversion technology and deployment, since more detailed reports on these topics have recently been published. The use of biomass as transport fuels, for instance, has been covered in the IEA Technology Roadmap *Biofuels for Transport* (IEA, 2011b),[3] and a more detailed analysis on the role of bioenergy in providing universal energy access has been undertaken in the IEA's *World Energy Outlook 2011* (IEA, 2011c).

So this roadmap should be regarded as part of a longer work in progress. As global analysis moves forward, new data will emerge, which may provide the basis for updated scenarios and assumptions. More important, as the technology, market and regulatory environments continue to evolve, additional insights, opportunities, and tasks will come to light.

Roadmap process, content and structure

This roadmap was compiled with the help of contributions from a wide range of experts in the bioenergy industry, the power sector, R&D institutions and government institutions. It includes the results of in-depth IEA analysis and three project workshops held at the IEA headquarters in 2010 and 2011. During the workshops key topics relevant to bioenergy for heat and power production were addressed, including relevant conversion technologies, RD&D priorities, biomass potential, sustainability issues, biomass markets and the role of developing countries. In addition, a draft roadmap was circulated to workshop participants and a considerable number of external reviewers (see Appendix II) for their comments.

This roadmap builds on a number of previous roadmaps by other organisations, including:

- Biomass Research and Development Technical Advisory Committee: *Roadmap for Bioenergy and Biobased Products in the United States;*[4]
- Clean Energy Council: *Australian Bioenergy Roadmap;*[5]
- European Commission: *Energy Roadmap 2050;*[6]
- European Technology Platform on Renewable Heating & Cooling: *Biomass for Heating and Cooling;*[7]
- Major Economies Forum: *Technology Action Plan: Bioenergy.*[8]

This roadmap is organised into six sections. The first discusses current bioenergy supply, bioenergy heat and electricity generation, the status of different conversion technologies, relevant sustainability issues and recent policy developments to ensure the sustainable production of bioenergy. The next section describes the vision for bioenergy heat and power deployment and CO_2 abatement based on *ETP 2012* 2DS. Then the roadmap addresses the importance of land and biomass resources and the role of international trade in achieving this vision. The following section discusses the current and future economics of generating bioenergy heat and power, including generation costs and total investment needs required to meet the targets described in this roadmap. The roadmap concludes with technology actions and milestones, required policy action and the next steps to support the necessary RD&D and achieve the vision of sustainable bioenergy deployment.

3 www.iea.org/papers/2011/biofuels_roadmap.pdf

4 www.usbiomassboard.gov/pdfs/obp_roadmapv2_webkw.pdf

5 www.cleanenergycouncil.org.au/cec/resourcecentre/reports/bioenergyroadmap.html

6 ec.europa.eu/energy/energy2020/roadmap/doc/com_2011_8852_en.pdf

7 www.rhc-platform.org

8 www.majoreconomiesforum.org

Bioenergy status today

Overview

Bioenergy accounted for roughly 10% (50 EJ)[9] of world total primary energy supply (TPES) in 2009 (Figure 1), with most of this being traditional biomass in non-OECD countries. In OECD countries, bioenergy supply mainly uses modern technologies and overall plays a considerably smaller role than in developing regions (Figure 1). Although bioenergy can be competitive with fossil fuels today under favourable circumstances (with high fossil fuel prices and/or very low feedstock costs) in most cases of commercial use, support policies are needed to offset cost differences with fossil fuels.

Most bioenergy is currently consumed in the buildings sector. The major part of this occurs in developing countries in Asia and Africa (Figure 2), where the traditional use of biomass in basic cookstoves or three-stone fires is still the main source of energy in the residential sector. Traditional biomass, including wood, charcoal, agricultural residues and animal dung, is mostly used for cooking and water heating; in colder climates biomass stoves also provide space heating. The traditional use of biomass is associated with very low efficiencies (10% to 20%) and significant health impairment through smoke pollution (IEA, 2011c). In addition, the biomass often comes from unsustainable sources, leading to deforestation and soil degradation. Nonetheless population growth in developing countries means that traditional biomass use is expected to continue to grow in the next decades, potentially creating considerable environmental and health problems unless more efficient stoves and fuels (biogas, ethanol) are deployed to reduce pollutants and improve efficiency.

In most OECD countries bioenergy plays only a minor role in buildings and has been growing at small rates (Figure 2). Pellet stoves are gaining some momentum in certain countries, where government support is available and/or direct cost benefits compared to fossil fuels make such stoves profitable. Commercial bioenergy heat production, on the other hand, has been growing more rapidly. It has doubled over the last decade as a result of increased co-firing in coal plants and installation of dedicated biomass co-generation power plants. Use of biomass for district heating is particularly advanced in Sweden, Finland, and Austria, but other countries are now following this path.

Electricity supply from bioenergy has been rising steadily since 2000; in 2010 bioenergy provided some 280 TWh of electricity globally, equivalent to 1.5% of world electricity production. Power generation from biomass is still concentrated in OECD countries, but China and Brazil are also becoming increasingly important producers thanks to support programmes for biomass electricity generation, in particular from agricultural residues (Figure 3). Models established in China and Brazil could also become a viable way to promote bioenergy electricity generation in other non-OECD countries with high energy demand growth rates and high availability of biomass residues in agro-processing industries such as sugar or rice. Currently, bioenergy electricity is principally derived through combustion and power generation via steam turbines, including through co-firing of biomass with coal.

In several emerging and industrialised countries (including Brazil, Canada, China, the European Union, South Africa, and the United States), support policies are an important driver for the development of modern bioenergy supply (IEA, 2012b). Some regions have experienced strong growth rates for bioenergy electricity and commercial heat over the last decade. In some countries this growth has recently slowed, due to constrained government support in combination with rising feedstock costs and resulting lack of competitiveness of bioenergy with other energy sources. Concerns over the sustainability of bioenergy – mainly related to biofuels for transport – have also had an impact. Addressing these economic and non-economic barriers will be vital to ensure sustained growth of bioenergy.

9 This figure is subject to some uncertainties, since no accurate data on the actual use of different biomass feedstocks in the residential sector exist, in particular in developing countries. According to the IPCC (2011) an estimated 6-12 EJ/year of biomass for the informal sector is not included in official energy balances.

Figure 1: Global primary bioenergy supply

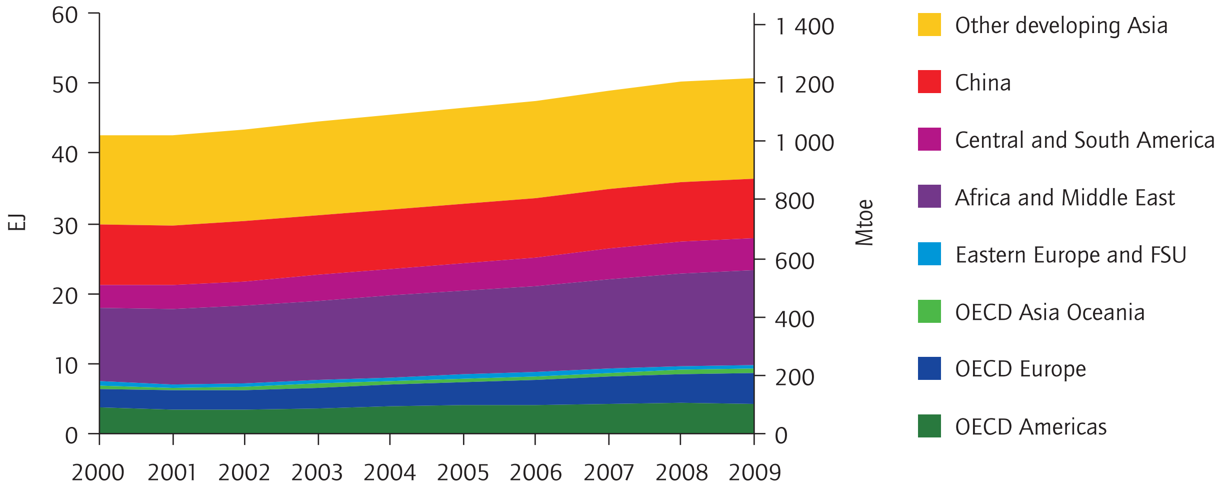


Figure 2: Total final bioenergy consumption in buildings

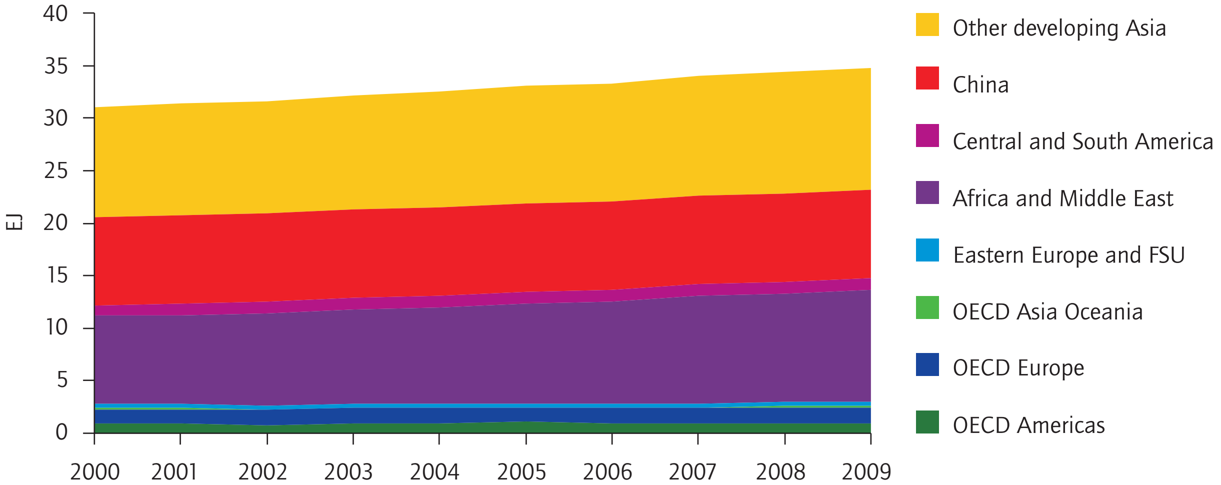
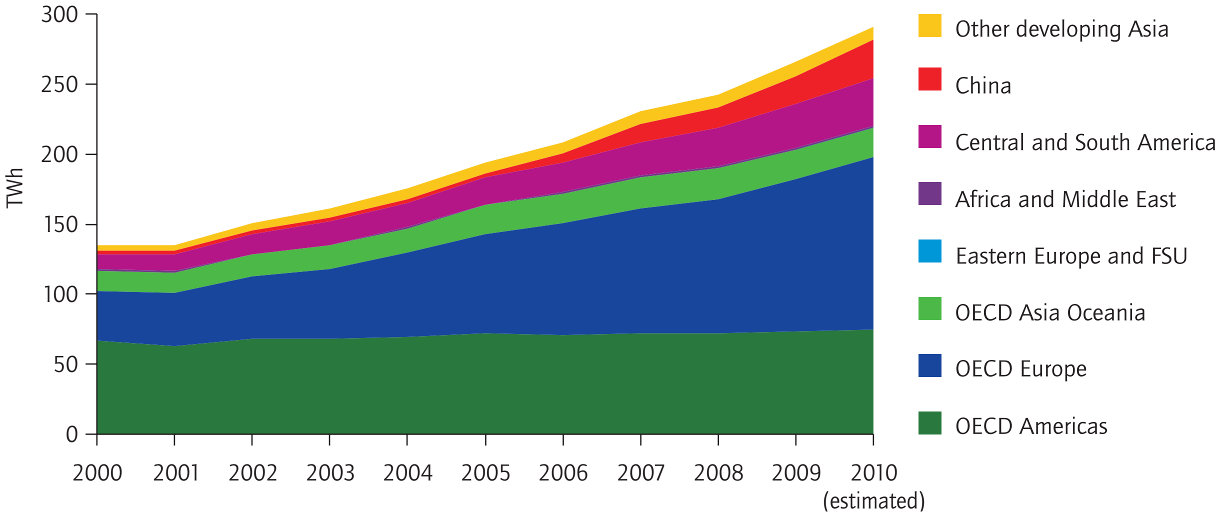


Figure 3: Global bioenergy electricity generation 2000-10



Technologies for producing heat and power from biomass

Biomass characteristics

A wide range of biomass feedstocks can be used for heat and/or power production. These include wet organic wastes such as sewage sludge, animal wastes and organic liquid effluents, the organic fraction of municipal solid waste, residues from agriculture and forestry, and purpose grown energy crops, including perennial lignocellulosic plants. As a feedstock for producing electricity or heat, biomass has a number of advantages over fossil fuels. It is widely distributed, relatively easy to collect and use and can produce less net CO_2 emissions than fossil fuels per unit of useful energy delivered, if sourced sustainably (see sustainability section for further discussion). In addition, biomass usually contains less sulphur than coal or oil.

On the other hand the combustion characteristics of biomass feedstocks differ markedly from those of fossil fuels like oil, coal and gas, posing some technical and economic challenges:

- The bulk density and calorific value are lower, which means that transporting untreated feedstocks can be more difficult and costly. This can limit the area within which it is possible to source biomass and limit the economic scale of operation.
- Some biomass resources are generated seasonally, *e.g.* during a specific harvesting period, so storage is needed to provide energy all year round.
- Systems for storing and handling and for feeding raw biomass into combustion or conversion systems have to be bigger and therefore more expensive than the fossil fuel equivalents.
- Untreated biomass often contains high levels of moisture, which reduces the net calorific value and affects handling and storage properties. Dry biomass also absorbs water and under-cover storage is often necessary to keep the fuels dry and avoid degradation.
- The thermochemical characteristics and chemical composition of biomass feedstocks differ markedly from solid fossil fuels due to typically higher oxygen, chlorine and alkaline content. Combustion systems (including the feed systems, furnace, particle and emission abatement systems, and ash management) have to be designed specifically with the feedstock in mind, to ensure clean and efficient combustion and to avoid fouling, and corrosion problems.

This means that systems for using biomass have to be specifically designed to match the feedstock properties, and that pre-treatment of biomass before conversion to energy is often necessary. Further efforts to introduce international technical standards for different types of (pre-treated)

Figure 4: Examples of different biomass feedstocks, typical feedstock costs, and plant capacities

Biomass feedstocks

	Wastes	Processing residues	Locally collected feedstocks	Internationally traded feedstocks
	■ Organic waste (MSW) ■ Sewage sludge ■ Manure/dung	■ Timber residues ■ Black liquor ■ Bagasse ■ Rice husks ■ Food processing wastes	■ Agricultural residues (*e.g.* straw) ■ Forestry residues ■ Roundwood and thinnings ■ Energy crops	■ Roundwood ■ Wood chips ■ Biomass pellets (wood, torrefied) ■ Biomethane ■ Pyrolysis oil
Typical feedstock costs (USD/GJ)	negative to 0	0 - 4	4 - 8	8 - 12
Typical plant capacity (MW electric)	0.5 - 50	0.5 - 50	10 - 50	> 50

biomass feedstocks would help to reduce technical challenges and costs related to conversion of biomass to energy (for further discussion see section on international trade below).

Fuel options and costs

In addition to the physical and chemical characteristics of biomass feedstocks listed above, the wide range of potential feedstocks also poses logistical challenges, with widely varying supply costs. To simplify discussion and analysis here, potential feedstocks are divided into four main categories (Figure 4) based on their spatial availability and logistics, which have an impact on feedstock costs and the economically feasible scale of conversion plants. A more detailed discussion of different feedstock options can be found in Appendix I.

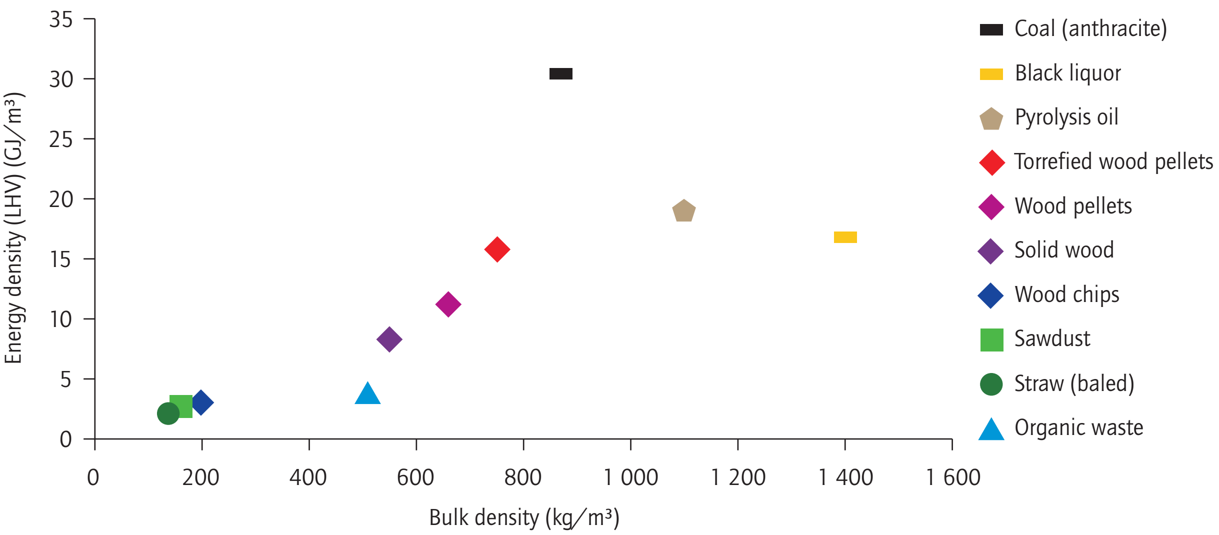
Biomass pre-treatment/ upgrading technologies

A range of pre-treatment and upgrading technologies have been developed in order to improve biomass characteristics, in particular to enhance the energy density of bulky feedstocks (as shown in Figure 5), to make the handling and transport, and the conversion processes more efficient and reduce associated costs. A more detailed description of different pre-treatment options can be found in Appendix I.

Common forms of pre-treatment include the most basic, **drying**, which aims to reduce transport costs by reducing the high initial moisture content of many biomass feedstocks, while also improving combustion efficiency and thus the overall economics of the process. **Pelletisation** and **briquetting** are commercially available, relatively simple technologies used to mechanically compact bulky biomass such as sawdust or agricultural residues. In **torrefaction**, a process somewhat similar to traditional charcoal production, biomass is heated up in the absence of oxygen to between 200°C and 300°C and turned into char. The torrefied wood is typically pelletised and has a higher bulk density and 25% to 30% higher energy density than conventional wood pellets (see Figure 5), and properties closer to those of coal. Another thermochemical pre-treatment process is **pyrolysis** and **hydrothermal upgrading**, during which biomass is heated to temperatures between 400-600°C in absence of oxygen to produce liquid pyrolysis oil (also referred to as bio-oil), solid charcoal, and a product gas. Pyrolysis oil has about twice the energy density of wood pellets, making it viable for long-distance transport.

Biomethane is a methane rich gas, similar to natural gas, which can be produced by **anaerobic digestion** of biomass to biogas with subsequent upgrading, or through **thermochemical conversion** of biomass to a methane rich gas called bio-synthetic natural gas (bio-SNG). Its properties

Figure 5: Comparison of bulk density and energy density of different biomass feedstocks



Source: IEA analysis based on DENA, 2011; FNR, 2011a; IEA Bioenergy, 2011; Kankkunen and Miikkulainen, 2003. For detailed data see Table 6 in Appendix I.

are identical to those of natural gas, allowing for biomethane to be injected in the natural gas grid, and used in commercial-scale gas power plants, or alternatively in buildings and the transport sector.

Biomass for heat

Traditional biomass for domestic cooking and heating

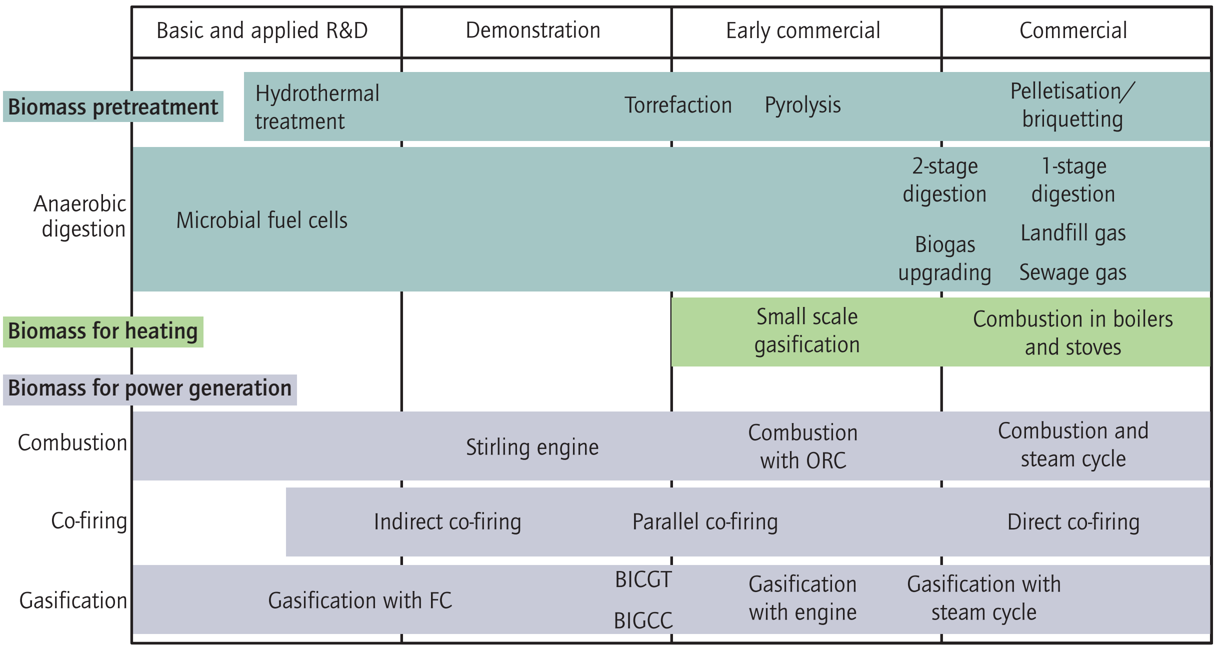
The most common form of bioenergy, still used as the principal source of heat and for cooking and space heating in many less developed countries, involves the use of an open fire or a simple stove – commonly referred to as traditional biomass use. The key problem of this type of bioenergy is that the biomass is often sourced unsustainably, leading to forest degradation. In addition, open fires or simple stoves show very low conversion efficiency – often in the range of 10% to 20% – and can cause severe problems of smoke pollution, as well as black carbon emissions with considerable global warming potential (see sustainability section below).

Comparatively small investments in new, more efficient biomass stoves for cooking or heating, in the cost range of a few USD up to USD 100, can lead to significantly improved efficiencies. They reduce fuel use and improve indoor air quality, while providing employment in the stoves supply chain stove (IEA, 2011c). Initiatives such as The Global Alliance for Clean Cookstoves, which aims for 100 million homes to adopt clean and efficient stoves and fuels by 2020 (Global Alliance for Clean Cookstoves, 2012) will be critical to achieve the envisaged level of energy access, and reduce the environmental and health problems associated with traditional biomass use.

Commercial-scale modern biomass combustion for heat

Large-scale biomass combustion plants to produce heat are a mature technology; in many cases the heat generated is competitive with that produced from fossil fuels. Modern on-site biomass technologies include efficient wood log, chips, and pellet burning stoves, municipal solid waste (MSW) incineration, and use of biogas. Bioenergy heat can also be produced in co-generation power plants, when there is a steady heat demand, for instance from industry or a district heating network. In such cases overall efficiencies of around 70% to 90% are possible (see discussion in the power section below).

Figure 6: Overview of conversion technologies and their current development status



Note: ORC = Organic Rankine Cycle; FC = fuel cell; BICGT = biomass internal combustion gas turbine; BIGCC = biomass internal gasification combined cycle

Source: Modified from Bauen *et al.*, 2009

Commercially available systems range from very large boilers with a capacity between 1 MW and 10 MW commonly used in the paper and timber industry, to small installations that provide heat for individual houses from logs, wood chips or wood pellets. Heat can also be provided from biogas or biomethane, and small-scale (10 kW_{th} to 500 kW_{th}) biomass gasifier systems for heating purposes are entering the market in China, India and South-East Asia, although their reliability of operation still needs to be improved (Bauen *et al.*, 2009).

Biomass for power generation

Steam turbine plant

In **biomass-based power plants**, the heat produced by direct biomass combustion in a boiler can be used to generate electricity via a steam turbine. This technology is currently the most established route to produce power from biomass in stand-alone applications. The efficiency of power generation depends on the scale of the plant. At a scale compatible with the availability of local biomass feedstocks (10 MW to 50 MW), power generation efficiencies using steam turbines tend to be in the range of 18% to 33%, somewhat lower than those of conventional fossil-fuelled plants of similar scale.

The **co-firing** of biomass with coal in existing large power station boilers has proved to be one of the most cost-effective large-scale means of converting biomass to electricity (and where suitable networks exist, to heat). This approach makes use of the existing infrastructure of the coal plant and thus requires only relatively minor investment in biomass pre-treatment and feed-in systems. It also profits from the comparatively higher conversion efficiencies of these large-scale coal plants. This option provides an opportunity for direct carbon savings by directly reducing the volumes of coal used.

The proportion of biomass that can be co-fired by simply mixing solid biomass and coal and injecting them together into the boiler is between 5% to 10%, while higher co-firing rates require modifications, such as to the fuel pre-treatment (milling). The alternative options of indirect and parallel co-firing, in which the fuel is fed separately into the boiler via separate burners, are designed to avoid these issues, but are more capital intensive than direct co-firing (Fernando, 2009). While solid biomass feedstocks such as pellets are most commonly used, liquid and gaseous biomass fuels such as tall oil (a by-product of pulp production) and biomethane can also be used in this way. The latter presents a particularly interesting option, as it can be blended with natural gas in any proportion and allows the use of existing natural gas infrastructure and high co-firing proportions.

A complementary approach currently being developed within Europe is the conversion of coal-fired power plants nearing the end of their lifetime to operate entirely on biomass. This involves some down-rating of capacity, but indications are that this can be achieved at low costs, with generation costs similar to those achieved through co-firing (Committee on Climate Change, 2011).

Co-generation power plants allow for an economic use of the heat produced in biomass power generation, and are an effective way to significantly increase the overall efficiency of a power plant (and hence its competitiveness) from either co-firing or stand-alone biomass plants. When a good match exists between heat production and demand, such co-generation plants have typical overall (thermal + electric) efficiencies in the range of 80% to 90%. At a smaller scale the power generation efficiency is lower, and co-generation operation is best led by the heat demand, which tends to determine the competitiveness of the plants.

Thermal gasification

Gasification is a thermochemical process in which biomass is transformed into fuel gas, a mixture of several combustible gases. Gasification is a highly versatile process, because virtually any (dry) biomass feedstock can be efficiently converted to fuel gas. The produced gas can, in principle, be used to produce electricity directly via engines or by using gas turbines at higher efficiency than via a steam cycle, particularly in small-scale plants (<5 MWe to 10 MWe).

At larger scales (>30 MWe), gasification-based systems can be coupled with combined gas and steam turbines, again providing efficiency advantages compared to combustion. The efficiency and reliability of such plants still need to be fully established. Although several projects based on advanced concepts such as biomass integrated gasification combined cycle (BIGCC) are in the pipeline in northern Europe, United States, Japan, and India, it is not yet clear what the future holds for large-scale biomass gasification for power generation (Bauen *et al.*, 2009). Developments and pilots in IGCC, for instance in China, will likely also contribute to key technology learning that may help development of BIGCC technologies, including in developing countries where related pilot projects and R&D are underway.

Engines

Gas from thermal gasification or anaerobic digestion processes can be used to produce electricity via engines, with a higher potential efficiency than with steam cycle systems operating at a similar scale. At a smaller scale, the use of vegetable oil or biodiesel in blends with conventional diesel for use in diesel generators would also be feasible and could provide an important option for off-grid electricity generation, in particular in rural areas to reduce dependency on imported fossil fuels.

Biorefineries

The **biorefinery** concept is analogous to the basic concept of conventional oil refineries: to produce a variety of fuels and other products from a certain feedstock. The economic competitiveness of the operation is based on the production of high-value co-products[10] in addition to comparably low-value bioenergy, including biofuels. Biorefineries can process different biomass feedstocks into energy and a spectrum of both intermediate and final marketable products such as food, feed, materials and chemicals (Jong and Ree, 2009). A biorefinery can consist of a single unit, but can also be formed by a cluster of single-purpose facilities that process by-products or wastes of neighbouring facilities. Examples of energy-driven biorefineries include cellulosic ethanol plants that are being deployed at pre-commercial scales now (IEA, 2011b). Several innovative biorefinery concepts are currently being developed, an overview of which can be found in a recent report of the IEA Bioenergy Task 42.[11] Biorefineries may contribute significantly to the sustainable and efficient use of biomass resources, by providing a variety of products to different markets and sectors. The biorefinery concept also has the potential to reduce conflicts and competition over land and feedstock, but it is necessary to measure and compare the benefits of biorefineries with other possible solutions to define the most sustainable option.

Combining bioenergy with carbon capture and storage

So far CCS has mainly been discussed in the context of avoiding CO_2 emissions from fossil fuels, but the technology could also be deployed in bioenergy conversion plants. The idea behind bioenergy with CCS (BECCS) is that capturing the CO_2 emitted during bioenergy generation and injecting it into a long-term geological storage provides the possibility to remove "neutral" CO_2 from the atmosphere, thus providing negative emissions. Liquid biofuel production plants or biomass gasification plants are particularly suited for BECCS, since relatively pure CO_2 streams occur in many cases that make the CO_2 capturing relatively simple and lowers the costs of transport and storage infrastructure. With increasing shares of biomass co-firing in coal-fired plants equipped with CCS, the amount of CO_2 captured from bioenergy will increase and could contribute to achieving emission reductions envisaged in the 2DS (see section on roadmap vision below). In addition, large biomass-only plants will come on-line and could be equipped with CCS technology, although the decreased efficiency for capturing CO_2 might render the combination less profitable than for coal-fired plants. As shown in Figure 11 industry is expected to begin switching from fossil fuels to biomass for energy-intensive production processes when a CO_2 pricing mechanism is introduced. This will open the possibility for BECCS and negative emissions also here once CCS deployment is commenced for those industries.

Economics today

The economic viability of bioenergy derived electricity and/or heat depends on which of the wide variety of feedstocks and technologies are deployed, and critically on the scale of operation and availability of heat sinks (district heating network, demand in industry). This is particularly important as far as electricity generation is concerned, as with increasing scale efficiency increases and the capital costs per unit of generation decline sharply.

Electricity generation can in some cases be competitive today where low cost fuels such as wastes or process residues are used, the scale of generation is high or there is also a good heat load enabling effective co-generation operation. However in most cases generation currently requires some level of financial support, particularly where the external costs of fossil fuel based generation are not fully taken into account.

Heat generated from biomass can also be a cost-competitive option today, again depending on feedstock and scale of operation, and on the fuel source being replaced (see below for a fuller discussion of current economic and future trends).

10 For examples see for instance ICCA, 2011

11 www.biorefinery.nl/fileadmin/biorefinery/docs/Brochure_Totaal_definitief_HR_opt.pdf

Sustainability of biomass for energy

A variety of different environmental, social and economic issues need to be addressed to ensure the overall impact of bioenergy is positive compared to that of fossil fuels. The debate about potential negative environmental, social, and economic impacts of bioenergy has been principally associated with biofuels for transport, where the main feedstocks today (starch, sugar and oil crops) are also used as feed and food (for more details see IEA, 2011b). However the same sustainability issues are also relevant for heat and power generated from biomass, and the whole life-cycle impact of bioenergy production needs to be carefully considered.

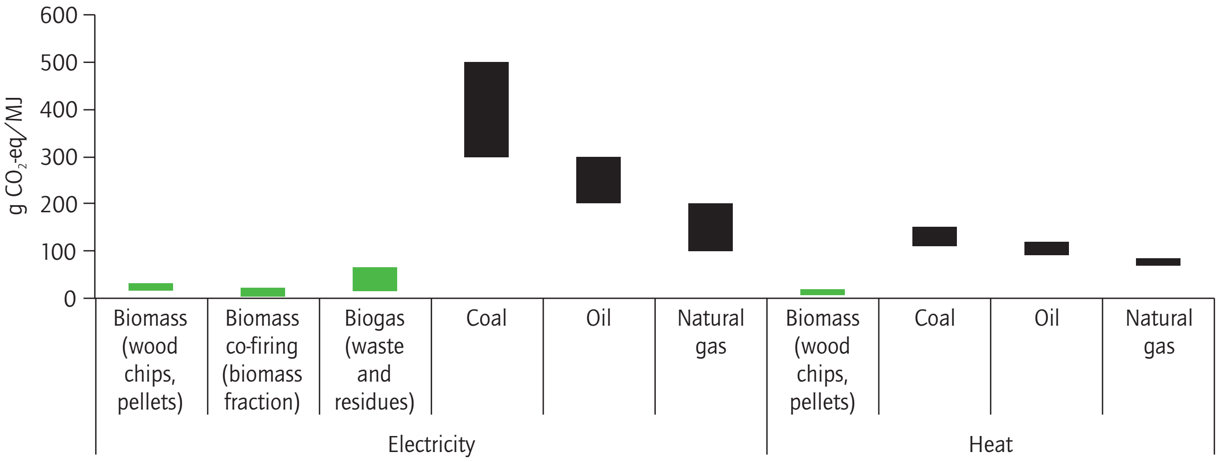
Lifecycle GHG savings of bioenergy heat and power

One of the key issues for heat and power generated from biomass is the reduction of lifecycle GHG emissions compared to the use of fossil fuels, as this is one of the key drivers to promote bioenergy use. GHG benefits of bioenergy systems can be evaluated by comparing them with the energy system they replace through a lifecycle assessment (LCA) (see Bird *et al.*, 2011 for more details). In most LCA and emission accounting guidelines, the CO_2 released during the conversion of biomass is considered "neutral" as it has been absorbed from the atmosphere during its growth, and will be absorbed again by plant regrowth (provided the biomass is sourced sustainably). This assumption is recently being questioned, however (Cherubini *et al.*, 2011; EEA, 2011).

As for all renewable energy sources, actual emissions and potential GHG savings can only be estimated by looking at the whole life cycle compared to fossil fuels. For bioenergy the GHG reduction potential depends on the biomass feedstock, cultivation methodology, transport distance and mode as well as conversion technology and process efficiency among other factors. Good agricultural and forestry management practices ensure sustainable biomass extraction rates, reduce the use of energy-intensive fertiliser, and mitigate soil degradation. These are important measures to enhance the GHG-reduction potential of bioenergy and help ensure a sustainable use of the biomass resources.

Bioenergy for heat and power can provide considerable emission reductions compared to coal, oil, and natural gas generated heat and power, when no additional GHG emissions from changes in land use occur (Figure 7, and see section below). The lowest life-cycle GHG emissions can be achieved through use of residues and wastes on site, for instance in pulp and paper mills. When use of wastes and residues avoids methane (CH_4) emissions that occur through decay of organic waste, emission savings of more than 100% compared to fossil fuels can be achieved. For co-firing and other utility-scale bioenergy

Figure 7: Lifecycle GHG emissions (excluding land use change) per unit of output for a range of bioenergy (green) and fossil (black) options



Note: Based on current state of technologies. Ranges reflect variations in performance as reported in literature. Possible emissions from land-use change are not included here.

Source: Based on Cherubini *et al.*, 2009; IPCC, 2011.

generation from wood chips and pellets, GHG reduction potential is somewhat lower, depending on the supply chain, but still considerable compared to fossil fuels. As discussed above, one option to achieve "negative emissions" from large-scale bioenergy plants is to combine bioenergy and CCS (for life-cycle emissions values see IPCC, 2011).

Bioenergy and land-use change

While lifecycle GHG emissions of bioenergy heat and power shown in Figure 7 can be significantly lower than those of reference fossil fuels, concerns have been raised that the GHG benefits of bioenergy can be reduced or negated by CO_2 emissions caused by land-use change (LUC).[12] The level of emissions released by changes in land use depends on when and where the changes take place, and how the respective carbon stocks (in form of standing biomass as well as soil carbon) and emission cycles are modified when managed for bioenergy feedstocks as compared to a business-as-usual scenario. Depending on the pace of plant regrowth, it might take several decades to remove the atmospheric CO_2 that is released in the early stage of a bioenergy scheme (for instance if a forest is clear-cut) (Bird *et al.*, 2011; Cherubini *et al.*, 2011).

For this reason, and also to avoid forest and woodland degradation and subsequent soil degradation, it is generally preferable to establish land use management that reduces large initial releases of GHG, and leads to additional biomass growth and thus carbon sequestration compared to the previous land use. In some cases, however, it can make sense to put large bioenergy schemes in place that cause a temporary decline in carbon stocks, if the scale of GHG savings by replacing fossil fuels still allows for longer term emission reductions in the energy sector. Such an approach should then lead to a stabilisation of atmospheric CO_2 levels, as envisioned in the *ETP 2012* 2DS underlying this roadmap.

While some data on emissions from direct land-use change are available (see for instance Fritsche *et al.*, 2010), the exact order of magnitude of emissions related to indirect land-use change (ILUC) is still subject to intensive research efforts. Results from studies on ILUC related emissions caused by conventional biofuels[13] for transport indicate that GHG emissions can in some cases be very high (E4Tech, 2010; Edwards *et al.*, 2010; Tyner *et al.*, 2010), but results vary between different studies and no consensus has yet been reached.

In general the same risk of ILUC exists for biomass feedstocks used for heat and power generation, in particular when energy crop plantations are established on agricultural land. However, less attention has so far been given to bioenergy, which is in part due to the broader feedstock base that can be used for heat and power generation, and the considerably more complex modelling requirements (resulting for instance from the importance of the forestry sector for biomass provision, which is less relevant for conventional biofuels). The initial emissions resulting from changes in land-use – be it direct or indirect – are similar for biofuel feedstocks as for energy crops used for heat and power generation. However, the amortisation period until the initial emissions are offset by reduced fossil fuel emissions is typically shorter for bioenergy, since emission savings compared to fossil fuels are higher than for biofuels. For instance, if pasture land is converted into a corn field used for ethanol production, it might take considerably longer to provide net emission savings than if the same pasture were converted into a short rotation wood plantation used for heat generation.

Measures to address ILUC are discussed in the milestones section below and more information can also be found in a recent IEA bioenergy publication (Berndes *et al.*, 2010), which discusses the issues surrounding land-use change and its impact on GHG balances of bioenergy in a comprehensive and up-to-date manner.

Other sustainability issues

While GHG life-cycle emission savings are an important environmental aspect of bioenergy use, there are several other issues to be considered: biodiversity, impact on soil fertility and soil degradation, the use of water and impact on water quality, employment, and potential health impacts, among others. These aspects are covered briefly below, and have been discussed in more detail elsewhere (Eisentraut, 2010; IEA, 2011b; GBEP, 2011; FAO and UNEP, 2010, Global Bio Pact, 2011; UNEP, Oeko Institut and IEA Bioenergy Task 43, 2011).

12 The land-use change can be either direct, as when energy crops are grown on land that was previously used for a different purpose, or was previously not managed at all; or indirect, when energy crop production in one place displaces the production of other crops or increases the overall demand for biomass, which is then produced on other land (perhaps in another region or country).

13 Produced mainly from sugar, starch and oil bearing crops.

Key environmental concerns include the overuse of natural resources through deforestation or increased extraction rates of forest biomass, with negative impact on soil quality, carbon stocks and biodiversity. For agricultural biomass, the issues include unsustainable intensification associated with excessive residue removal, excessive use of fertiliser and pesticides, and overuse of irrigation water. Most of these issues can be addressed by sound land-use planning, strict application of good management practices, and the use of well-adapted indigenous energy crops (*e.g.* use of perennial instead of annual species).

Social and economic impacts are also important factors in the overall impact of bioenergy production. Bioenergy deployment has considerable potential to create employment in the agricultural and forestry sector and along the supply chain, and thus to benefit rural communities. This aspect is particularly important in developing countries, where much of the population depends on agriculture for their livelihood. In these countries, bioenergy often provides energy in rural areas, and there is considerable potential to enhance this role by improving the efficiency of bioenergy use and creating new, sustainable supply systems for biomass feedstocks (GBEP, 2011). Poorly managed bioenergy expansion, however, can trigger negative effects such as compromising smallholders' access to land, so reducing employment and local food security. A strong policy framework is therefore needed, with legal requirements for investors and project developers that ensure good project management. Capacity building, establishment of smallholder co-operatives and development of integrated production systems for food, fibre and bioenergy will all be important to ensure rural communities can profit from bioenergy development.

One critical issue is the health impact of pollution by black carbon – a component of particulate matter – through biomass combustion in traditional biomass stoves. This is a major health problem in many developing countries, and has a considerable regional and global climate impact (UNEP, 2011). Without significant improvements in the efficiency of biomass cookstoves, over 1.5 million people could die every year by 2030 from the effects of indoor smoke (IEA, 2011c). These health implications underline the importance of deploying advanced stoves and cooking fuels, such as bio-ethanol or biogas. In addition, modernisation would lead to more efficient use of biomass resulting in fuel cost savings, and would reduce the time people spend on gathering wood that they could use for other productive, learning or recreational activities. Employment opportunities in the stove manufacturing and distribution chain are another important socio-economic benefit.

Serious impacts on health can also arise outside buildings, through fine particles (<2.5 micro meter diameter) from biomass combustion. The filters and scrubbers that remove particulate matter and are commonly installed in utility-scale power plants are rarely applied to smaller scale biomass combustion units. However, small scale particle removal technologies are becoming available, and electrostatic precipitators seem to be quite suitable for this purpose, but of course require a source of electricity (IEA Bioenergy Task 32, 2011).

It is important to recognise that many of the environmental and social aspects mentioned above are related to the entire agricultural and forestry sector, and would most effectively be addressed through a holistic approach. Until such a holistic approach is implemented at global level, each country or region needs to ensure – for instance through sustainability certification – that the net effect of bioenergy use and production is positive.

Criteria and certification schemes

A considerable number of certification schemes that deal specifically with the sustainability of biofuels for transport exist or are currently under development (IEA, 2011b). Fewer schemes include biomass used for heat and power generation, which reflects the lack of specific legislation, among other factors. However, there are several well established schemes that certify forestry and agricultural products, and these could provide a basis for certification schemes for bioenergy for heat and power. It is not possible to include all relevant standards and certification schemes here, but an overview of some key initiatives is included in Appendix I, and more information can be found in IEA (2011b); Dam *et al.* (2010); Scarlat and Dallemand (2010).

Some policies adopted in recent years include binding sustainability standards for biofuels. One such policy is in the European Union, where the Renewable Energy Directive (RED) lays down mandatory sustainability criteria and requires sustainability certification for biofuels used in transport (EC, 2009).[14] For solid and gaseous biomass used for electricity and heat generation, the European Commission has published a report proposing sustainability criteria similar to those for liquid biofuels, for plants of a minimum 1 MW electric or thermal capacity (EC, 2010). The EC will publish a decision on the adoption of mandatory sustainability criteria for solid and gaseous fuels in early summer 2012, and meanwhile encourages its member states to set up voluntary certification schemes.

Some EU member states, including Belgium, Germany and the UK, have already adopted sustainability requirements for certain types of biomass used for electricity and/or heat generation. Finland, France, Hungary and Slovenia have introduced regulations to ensure wood biomass used for electricity and heat complies with sustainable forest management practices. Some countries, including Austria, France and Italy, specifically promote the use of locally sourced biomass, or aim at protection of other economic sectors; in Belgium, for example, woody resources suitable for the wood processing industry are not eligible for Flemish Green Power Certificates (for more information see SolidStandards, 2011).

In the **United States**, sustainability requirements for liquid biofuels have been in place for a few years (for more details see IEA, 2011b). However, there are no specific requirements for biomass used for heating, cooling or power generation in place yet.

So progress in development and implementation of sustainability requirements for bioenergy is promising. However, a potential dampener on further growth is increasingly seen to be the lack of legal certainty about quality and sustainability requirements for biomass used for heat and power generation. Several groups, including bioenergy producer associations, have published proposals calling for adoption of a sound, standardised policy framework for sustainability certification of bioenergy as an important element of an effective international bioenergy market (EURELECTRIC, 2011; AEBIOM and EBA, 2011; IWPB, 2011).

International harmonisation between sustainability schemes and quality standards would help reduce the potential for confusion and inefficiencies in the market. All schemes need to include comprehensive cover of sustainability requirements, to avoid abuses such as “shopping” for standards that suit the user but meet only particular criteria. Local information and expertise will be needed to implement internationally agreed sustainability standards, criteria and indicators, especially in developing countries. It will be vital to provide substantial support in capacity building, to measure these indicators and achieve minimum standards from production to policy level.

Inevitably, large-scale bioenergy expansion as envisioned in this roadmap will require substantial changes to current land-use patterns and production systems in the forestry and agricultural sector – not all of which will be positive. With a sound policy framework in place and concerted public and private stakeholder engagement along the supply chain it should, however, be possible to ensure bioenergy has a net positive impact in terms of sustainability, compared to a reference fossil-based energy system. Certain elements of sustainability can be dealt with by individual producers or processors through careful management and appropriate project design, and thus effectively be addressed by certification. Other aspects such as indirect land-use change, food security, and land rights, however, cannot be entirely controlled by individual producers. They will require action at a national or regional level, addressing the whole agricultural and forestry sector.

14 In order to count towards the RED target, biofuels must provide a 35% GHG emissions saving compared to fossil fuels. This threshold will rise to 50% in 2017 and to 60% in 2018 for new plants. In addition the criteria include provisions against deforestation and use of land with high carbon stocks, and/or high biodiversity.

Vision for bioenergy deployment and CO_2 abatement

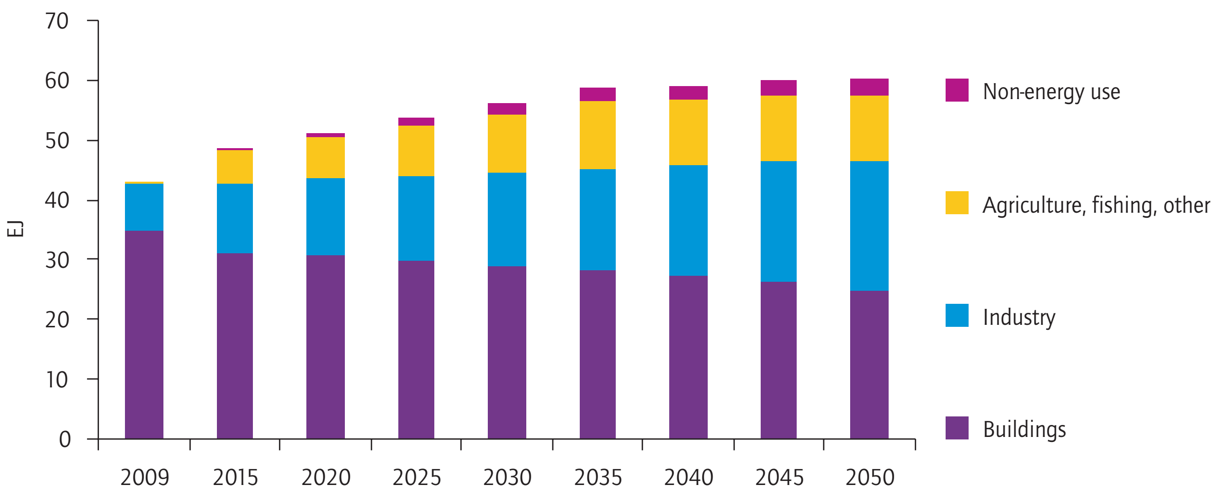
Bioenergy deployment

In the 2DS of *ETP 2012* that serves as the basis for this roadmap, the contribution of bioenergy to global primary energy supply increases from around 50 EJ in 2009 to roughly 160 EJ in 2050. Bioenergy would then provide around 24% of TPES in 2050 compared to 10% today. Around 60 EJ of this primary bioenergy supply is needed for production of transport fuels, which have been covered in a previous roadmap (IEA, 2011b). A total of 100 EJ, *i.e.* 5 billion to 7 billion dry tonnes of biomass, will be needed to provide electricity as well as heat for the residential sector, in industry and in other sectors.

Total final bioenergy consumption in this roadmap vision increases from 43 EJ today to 60 EJ in 2050 (Figure 8). Achieving this vision, and the associated CO_2 reductions, will require the deployment of a set of efficient bioenergy conversion technologies at different scales. Small-scale systems (<1 MW), including efficient biomass stoves, are best suited to provide heat only, since capital costs per unit for co-generation systems are significantly higher, and electric efficiencies relatively low, compared to utility-scale plants (see economics section below). Such systems play a key role in replacing inefficient traditional use of biomass for cooking and heating in developing countries, and to a lesser extent in replacing fossil fuel-fired domestic heating systems, including in industrialised countries. In the medium to long term, thanks to enhanced RD&D efforts, more efficient small-scale co-generation options such as fuel cells run on biomethane will eventually emerge and play an increasing role in providing both heat and electricity.

While small-scale options are important in the residential sector, this roadmap's vision can be achieved only with a significant contribution of bioenergy production in large-scale (>50 MW) plants. In the short term, replacing coal in existing assets by means of co-firing will be an important way of achieving emission reductions with comparatively small additional investments. Nonetheless, since efficiencies in old coal-fired plants are considerably lower than in state-of the art installations, dedicated biomass plants at similar scales will increasingly be needed to replace to provide additional capacity in order to achieve the supply of bioenergy electricity and heat envisioned in this roadmap. In the medium term, a transition towards more efficient (in terms of electric efficiency) technologies including biomass gasification, and biomethane production for use in natural gas-fired combined-cycle plants, will be needed to reach this roadmap's targets. Biomethane in particular could benefit from the rapidly expanding production and use of unconventional gas, which in certain regions is leading to new infrastructure investments (including gas storage). In regions where coal-fired electricity and heat generation is dominant (*e.g.* China, India, Indonesia), co-firing will likely remain an important option for emission reductions

Figure 8: Roadmap vision of world final bioenergy consumption in different sectors



Note: Bioenergy use in the buildings sector is for both heating and cooking. Demand for transport fuels is not shown here since this has been discussed in a previous roadmap (IEA, 2011b).

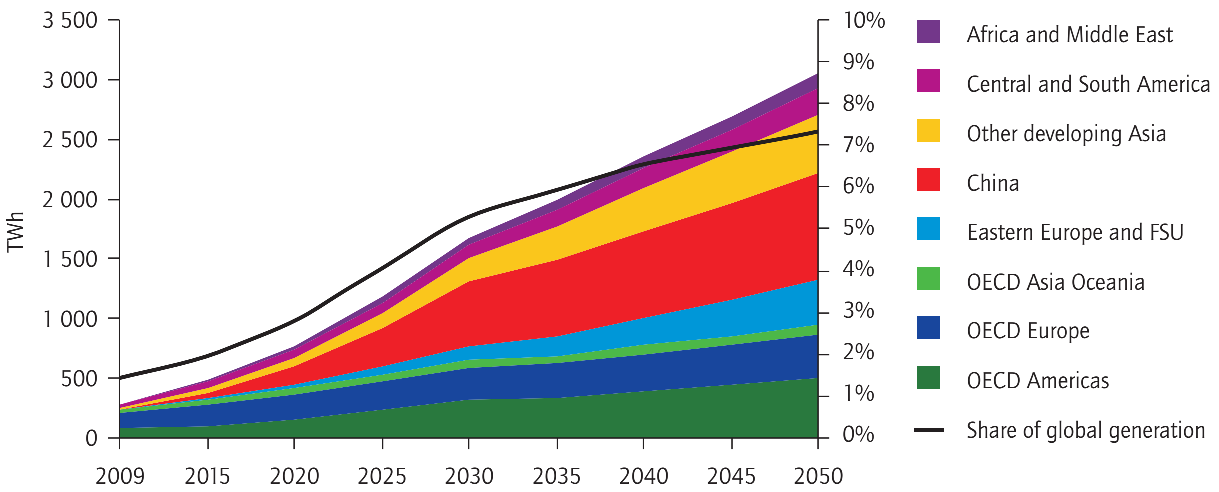
even in the longer term, but only if boilers are refurbished to accept higher shares of biomass or if torrefied wood pellets are used.

Bioenergy electricity

With increasing economic growth, world electricity demand in the *ETP 2012* 2DS will grow rapidly from about 20 000 TWh in 2009 to 42 000 TWh in 2050. The share of renewable electricity will increase from 19% in 2009 to almost 60% in 2050, with the remaining 40% coming from nuclear as well as coal, natural gas and other fossil sources. Bioenergy generally provides dispatchable electricity: this will play a vital role as rapidly rising shares of variable renewable electricity are deployed over time in the *ETP* 2DS. The flexibility of bioenergy electricity depends on the type of power plant: co-firing or dedicated biomass plants with steam turbines are in some cases able only to provide baseload power, but several plant types can react to predictable changes in demand by ramping up and down (to a minimum operating level). These mid-merit plants give the power system very important flexibility (IEA, 2011d). Biogas and biomethane, if stored and converted into electricity when demand peaks, or if fed into the natural gas grid for use in open-cycle natural gas plants, can respond quickly to short-term variability in the power system and thus even provide peak-load electricity.

Global bioenergy electricity generation capacity in this roadmap grows from around 50 GW in 2009 to 560 GW in 2050, 50 GW of which are equipped with carbon capture and storage (CCS) technology. World bioenergy electricity generation increases more than tenfold from around 290 TWh in 2009 to 3 100 TWh in 2050, around 300 TWh of this comes from plants equipped with CCS. Total bioenergy electricity generation could provide around 7.5% of world electricity generation, compared to 1.5% today. The use of biomass for power generation varies between regions, depending on biomass availability, conversion costs, and the availability of alternative low-carbon energy sources. China accounts for the largest share (920 TWh) of total bioenergy electricity generation in 2050, followed by OECD Americas (520 TWh). Other regions also have considerable generation level in 2050 such as OECD Europe (370 TWh), Other Developing Asia (570 TWh, of which 250 TWh in India), Eastern Europe and former Soviet Union (FSU) (280 TWh, of which 170 TWh in Russia) and Central and South America (240 TWh, of which 190 TWh in Brazil), some (*e.g.* Eastern Europe and FSU, China) starting from a very low basis (Figure 9).

Figure 9: Roadmap vision of bioenergy electricity generation by region



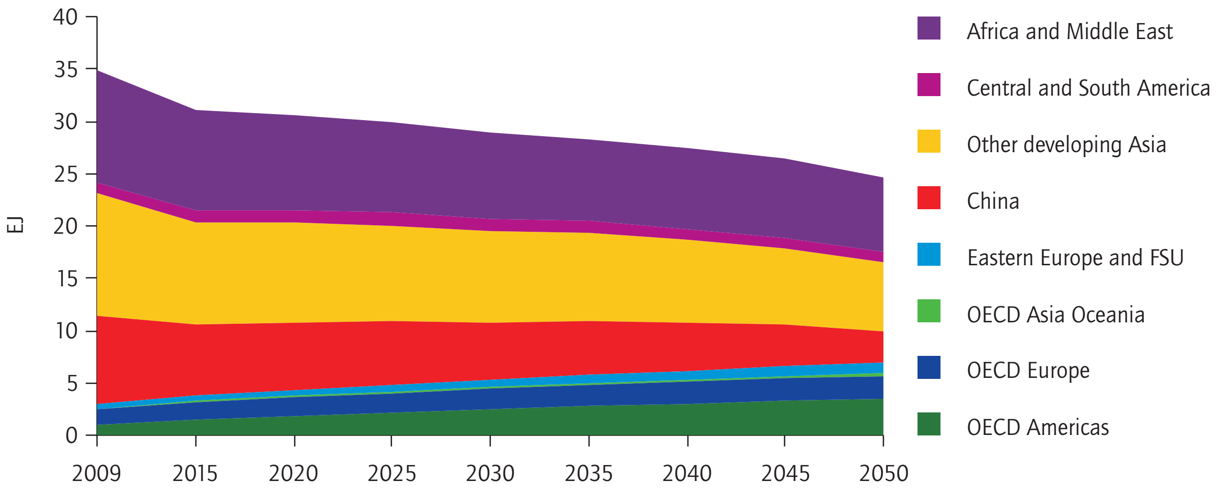
Bioenergy in buildings

The buildings sector is expected to remain the largest consumer of biomass throughout the projection period, although total bioenergy demand to provide heat in this sector is expected to decrease significantly over time (Figure 10). Driven by fast growing population, biomass use for cooking and heating will remain an important source of energy, particularly in rural areas of many developing countries in Africa and Asia. Given the associated negative environmental and health impacts, widespread deployment of efficient biomass stoves and household biogas systems, as well as alternative technologies (*e.g.* solar cooker, solar-heating installations) will be crucial to meet the growing energy demand in the buildings sector. Having more efficient stoves also reduces the biomass needed to provide a unit of heat and, together with energy efficiency measures, can thus lead to a considerable reduction in the amount of primary biomass needed in the buildings sector. These improvements can be achieved at comparably small costs, and could lead to a reduction of final bioenergy consumption in the residential sector of non-OECD countries from 32 EJ in 2009 to 18 EJ in 2050.

In OECD countries, bioenergy demand in the residential sector will roughly double from 3 EJ in 2009 to 6 EJ in 2050 (Figure 10), driven by space heating demand. Obligations for use of renewable energy for heating public and/or new and refurbished private buildings, which usually come along with energy efficiency regulations, are one driver for deploying small biomass boilers such as pellet stoves (Beerepoot and Marmion, forthcoming). These are taking effect in a number of OECD countries, including many European countries.

One relatively new issue that has not yet been addressed in great detail is the potential use of heat for cooling in the buildings sector, for which demand is increasing rapidly in many regions of the world. Meeting this cooling demand would create new opportunities for use of surplus heat from co-generation or heat plants during summer season. Depending on the development, demand for bioenergy heat in the longer term might even be larger than anticipated today, so it merits greater attention.

Figure 10: Final bioenergy consumption in the buildings sector in different world regions



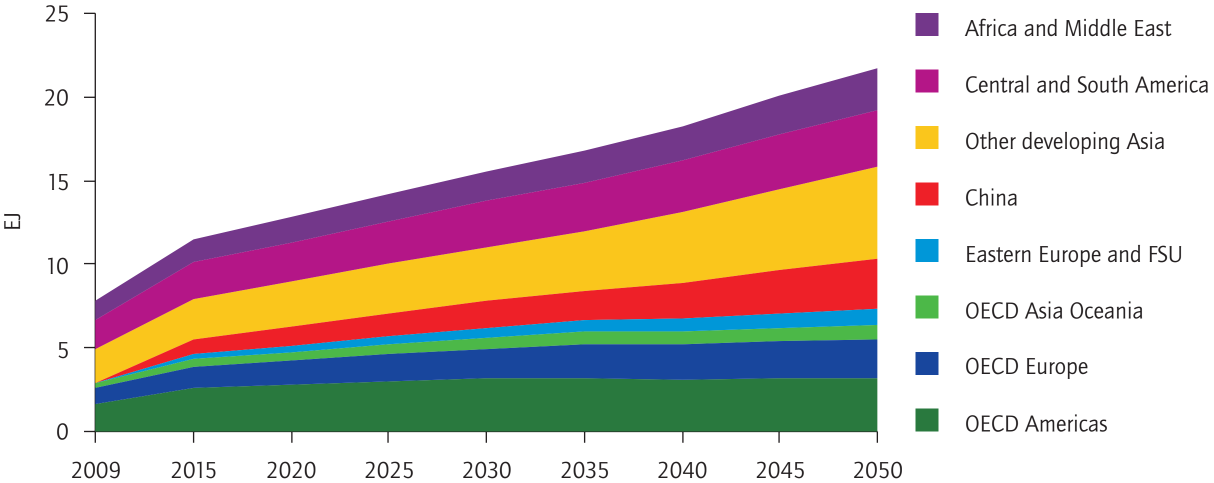
Bioenergy in industry

One of the fastest growing sectors in terms of bioenergy demand is the industry sector, where this roadmap sees final bioenergy demand increasing from 8 EJ in 2009 to 22 EJ in 2050 (Figure 11), providing 15% of the sector's total final energy demand. Biomass is a particularly important potential source of low-carbon energy in the industry sector as it can provide high temperature heat that is currently mainly provided by coal or coke. Biomass can also be used as feedstock for materials and chemicals, but this use is not discussed here (for more information see ICCA, 2011).

Biomass is already used today to provide process heat in the wood processing and pulp and paper industry, mainly from process residues. Considerable amounts of charcoal are also used to provide high temperature heat in the iron and cement industry in Brazil, where biomass accounts for more than a third of final energy consumption (UNIDO, 2011). To achieve this roadmap's vision, bioenergy consumption in these sectors needs to increase, and become more efficient. In addition, other energy intensive sectors such as cement, chemicals and petrochemicals could use considerable shares of bioenergy but more concerted efforts are required since these sectors are not currently involved in biomass and bioenergy value chains. As the price for CO_2 emissions rises over the projection period, bioenergy demand in industry will grow considerably. In the medium term, demand growth in OECD countries slows down, but strong growth persists throughout the projection period in non-OECD countries. Other Developing Asia (5 EJ), Central and South America (4 EJ) and China (3 EJ) will eventually be the largest consumers of bioenergy in industry in 2050 (Figure 11).

Final bioenergy consumption in other sectors such as agriculture and fisheries as well as nonenergy use of biomass sum up to roughly 14 EJ in 2050 (Figure 8). This reflects a strong increase in bioenergy demand over the 40-year projection period in this roadmap, given that bioenergy demand today is less than 0.5 EJ in these sectors.

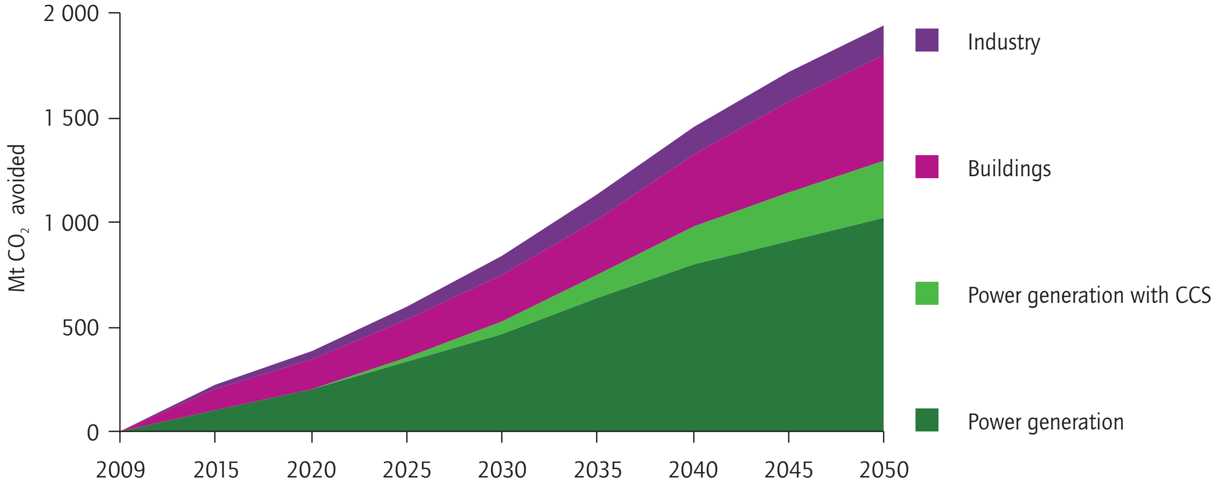
Figure 11: Roadmap vision of final bioenergy consumption in industry



CO_2 abatement through bioenergy

The use of bioenergy as outlined above can contribute to overall CO_2 abatement in the *ETP 2012* 2DS, if the biomass is sourced sustainably and provides very low lifecycle-GHG emissions. Under these conditions, the use of bioenergy for heat could provide 150 Mt CO_2-eq. in buildings (9% of total emission savings in this sector) and 500 Mt CO_2-eq. in industry (7.5% of total emission savings in this sector) in 2050 compared to the *ETP* 6°C Scenario (business as usual) (Figure 12). Bioenergy electricity generation could provide an additional 1.0 Gt CO_2-eq. of emission savings, which together with around 300 Mt CO_2-eq. of emission reductions through combining bioenergy electricity generation with carbon capture and storage (CCS) could provide 6% of total emission savings in the power sector in 2050. Although the decreased efficiency for capturing CO_2 might render the combination less profitable than for coal-fired plants, this would allow for "negative emissions" through removal of "neutral" CO_2 (see sustainability section above for discussion) from the atmosphere. As shown in Figure 11, different industries will increasingly switch from fossil fuels to biomass for energy-intensive production processes, opening the possibility for bio-CCS and negative emissions once CCS deployment is initiated for those industries (IEA, 2011e).

Figure 12: CO_2 emission reductions from bioenergy electricity and bioenergy use in industry and buildings compared to a business as usual scenario (6°C Scenario)



Note: This assumes that biomass is sourced sustainably with very low life-cycle GHG emissions.

Economic perspective and cost reduction targets

Basis for analysis

The cost estimates presented hereinafter reflect average generation costs, and it needs to be noted that not all scales and technologies are covered here. Future cost estimates are presented to 2030. Beyond this development of generation costs is increasingly uncertain since improvements in mature technologies might only lead to marginal cost reductions, and feedstock costs will likely see some upward development that might offset such cost improvements. A range of technologies currently in the RD&D stage have not been covered here, since very little cost information on these technologies is currently available. It should be noted that these technologies might nonetheless play an important role in providing bioenergy electricity and heat in the future, but more reliable cost information is needed to assess their potential contribution.

Feedstock costs

As discussed above, the biomass used for heat or power generation can be classified under four categories: wastes, processing residues, locally collected feedstocks and internationally traded feedstocks. Indicative cost ranges for each of these categories, along with the scales of power generation that are most likely to be compatible with the availability of the fuels, are shown in Figure 5 above and used in the analysis here.

Electricity generation technology options and costs

Currently most biomass electricity generation is based on conventional steam turbines, at a range of scales of operation, and this is the basis for the analysis that follows. A further set of generation technologies is becoming available, including gasification and use of the resulting gases in an engine or a fuel cell to produce power. Such systems potentially offer better generation efficiency and lower capital costs, but as the systems are so far not deployed on a commercial scale it is difficult to find reliable cost and operating data for inclusion in the analysis. However the demonstration of such systems may well open up opportunities for reduced costs and improved efficiencies, particularly at lower scales, and these technologies are expected to play an increasing role in the longer term.

Impact of scale

For most systems producing heat or power from biomass, scale of operation is a very important factor, with capital and operating costs per unit of output increasing markedly as scale reduces. This is particularly true of power generation, where the efficiency rises sharply with increasing scale: from 8% to 12% in systems producing around 1 MW, to 20% to 25% in condensing plants producing 5 MW to 10 MW, and 35% to 40% in large scale plant (>100 MW) (Loo and Koppejan, 2008). On the other hand, it is easier to find markets for the heat produced in smaller scale operations, so improving their overall economics. It may also be possible to match the scale of operation to the availability of low cost biomass raw materials, or to use a smaller catchment area, so reducing the logistical issues and costs of supplying feedstock.

Table 1: Overview of bioenergy power plant conversion efficiencies and cost components

Capacity	*<10 MW*	*10-50 MW*	*>50 MW*	*Co-firing**
Typical power generation efficiency (%)	14-18	18-33	28-40	35-39
Capital costs (USD/kW)	6 000-9 800	3 900-5 800	2 400-4 200	300-700
Operating costs (% of capital costs)	5.5-6.5	5-6	3-5	2.5-3.5

*Co-firing costs relate only to the investment in additional systems needed for handling the biomass fuels, with no contribution to the costs of the coal-fired plant itself. Efficiencies refer to a plant without CCS.

Source: IEA analysis based on DECC (2011), IPCC (2011), Mott MacDonald (2011), Uslu *et al.* (2012).

Given the wide range of fuels, technologies and scales of operation, it is difficult to provide definitive costs for power generation from the wide range of available biomass resources. However, using the classification of biomass opportunities suggested earlier, the table below shows typical ranges for capital costs and operating parameters for steam turbine based systems. The figures are based on data, information and advice from a variety of industry and other sources.

Potential for cost reductions

There is scope for reduction in the costs of conversion plants. For radical reductions in the costs of the principal plant components this scope is limited, since they are well developed systems having much in common with coal and other solid fuel systems. There is however scope for cost reduction if the market volume for plants rises, and more standard "off the shelf" designs can be developed, instead of the current situation where plants are usually purpose engineered individually. This cost trend would also be helped by the development of tight specifications for fuels. These factors coupled with scope for evolving improved generation efficiencies mean that, overall, solid cost reductions could be expected by 2030 – estimated by industry sources to be around 20% reduction in capital costs, with a 5% improvement in generation efficiency.

In addition to reductions in capital costs for conversion plants, there might be potential to further reduce feedstock processing and transportation costs. For feedstocks the largest potential for cost reduction lies with internationally transported biomass. There is scope here for the introduction of processes such as torrefaction, currently at the pre-commercial stage, to allow the energy density of fuels to be increased, bringing down transport and logistic costs. Such quality improvements would reduce the need for specific feedstock handling systems, and also allow furnace and boiler costs to be reduced as fuel properties become more favourable for combustion. The same effect can be achieved through biomethane, which has the same properties as natural gas. Reduction in procurement costs might also be possible, if an international market for biomass feedstocks develops. However, growing international demand will likely create upward price pressure that could well offset such cost reductions. Overall, it is expected that feedstock costs will become more stable through international trading.

Beyond 2030, given potential pressure on feedstock prices as demand rises, and the limited scope for further improvements in these well established technologies, further significant cost reductions are likely to be limited. However additional technologies, particularly associated with thermal gasification of biomass, are likely to become commercially available and play an important role in future generation portfolios. The possible costs and operating parameters resulting from these changes are shown in Table 2.

Table 2: Overview of possible operating parameters and generating costs for bioenergy electricity by 2030

Capacity	*<10 MW*	*10-50 MW*	*>50 MW*	*Co-firing**
Typical power generation efficiency (%)	16-20	23-38	33-45	33-45
Capital costs (USD/kW)	4 800-7 800	3 100-4 600	1 900-3 400	300-700
Operating costs (% capital costs)	5.5-6.5	5-6	3-5	2.5-3.5

*Co-firing costs relate only to the investment in additional systems needed for handling the biomass fuels, with no contribution to the costs of the coal-fired plant itself. Efficiencies refer to a plant without CCS.

Source: IEA analysis based on DECC (2011), IPCC (2011), Mott MacDonald (2011), Uslu *et al.* (2012).

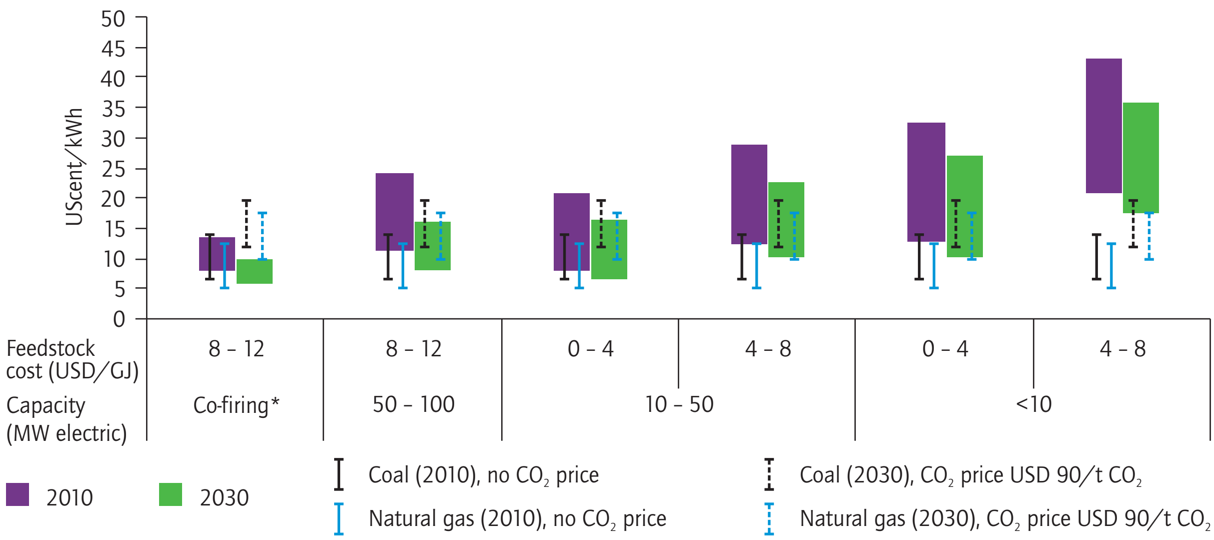
Current and future generation costs

Estimates of generation costs for electricity today and in 2030 are based on a wide range of sources. Generation costs for different scales of operation and different biomass feedstock compared to levelised cost of electricity generated from coal and natural gas (with and without CO_2 price) are shown in Figure 13.

The analysis indicates that there is a strong scale effect, but the lower capital costs and higher power generation efficiencies are to some extent offset by increased fuel prices likely to be required for large scale operation. In favourable circumstances, co-firing of internationally traded fuels can be close to competitive with coal-based electricity generation. Electricity generation in dedicated biomass plants is currently competitive with fossil-based electricity only at a higher carbon price, meaning that at present financial support is needed to make these options commercially attractive. The use of low-cost (0-4 USD/GJ) process residues in the 10-50 MW range can be financially attractive, particularly at the higher end of the scale. For collected feedstocks the conversion at low scale appears unattractive, even at very high carbon prices, as high unit capital costs and low efficiencies push up generation costs.

With the envisaged cost reductions through standardising the design of future bioenergy power plants, electricity generation from biomass will come closer to competitiveness with electricity from coal or natural gas. This would certainly be the case with a carbon price of USD 90/t CO_2 assumed in the 2DS (Figure 13).

Figure 13: Bioenergy electricity generation costs 2010 and 2030, compared to coal and natural gas based power generation



*Co-firing costs relate only to the investment in additional systems needed for handling the biomass fuels, with no contribution to the costs of the coal-fired plant itself. Fossil electricity generation costs are not capacity specific.

Source: IEA analysis based on DECC (2011), IPCC (2011), Mott MacDonald (2011), Uslu *et al.* (2012).

Co-generation operation

Overall costs could be reduced and energy generation efficiencies enhanced with combined heat and power operation. This is particularly evident for the smaller scale systems, where electricity generation efficiencies are low. The overall economics in these cases will be determined by the availability of a steady heat load, and operation is likely to be determined by the pattern of heat demand rather than the desire to produce electricity at high load factors. For larger scale systems, finding steady heat loads capable of taking all the potentially generated heat is more problematic. Such plants are best suited in a situation where a steady industrial heat load, or a network with a regular heat demand (*e.g.* district heating) is available. As discussed earlier, using heat to meet cooling demand might become a valid option in the future: it could create a year-round heat demand and thus enhance the viability of large-scale co-generation operation.

Heat production options and costs

Producing heat from biomass is well established. Commercially available systems include small scale systems for domestic use through to very large industrial systems. The capital and operating costs for heat generating systems vary with scale in a similar manner to those for electricity generation, although efficiency is less sensitive to scale of operation.

Current costs

As examples of typical costs of heat generation, this analysis has considered the use of solid biomass to produce heat at: a domestic scale; for use at a commercial institutional level or for district heating (largely for space and water heating); and in industry. The critical difference between these applications is the constancy of the heat load, which is much lower for smaller space heating applications than for industrial purposes. For the purposes of this analysis it is assumed that the smaller scale applications use wood pellets as feedstock, and the larger applications wood chips. Indicative capital and operating costs for heat production are shown in Table 3.

It should be noted that the capital costs are much lower than the equivalent electricity producing plant. For example a 10 MW_e plant, operating at 18% efficiency, has a capital cost of 5 800 USD/MW_e. Such a plant has a thermal capacity equivalent to 55 MW_{th}, so the cost is some 1 050 USD/MW_{th}, around twice the equivalent cost for a heat only plant.

Table 3: Overview of bioenergy heat plant scales and cost components

	Domestic ($12\ kW_{th}$)	Small commercial ($100\text{-}200\ kW_{th}$)	Large commercial ($350\text{-}1\ 500\ kW_{th}$)	Small industry ($100\text{-}1\ 000\ kW_{th}$)	Large industry ($350\text{-}5\ 000\ kW_{th}$)
Feedstock	pellets	pellets	wood chips	wood chips	wood chips
Typical full load hours per year	700-1 500	1 400-1 750	1 800-4 000	4 000-8 000	4 000-8 000
Capital cost (USD/kW)	950-1 350	550-1 200	550-800	600-700	550-600
Feedstock costs (USD/GJ)	10-20	8-15	5-12	5-12	5-12

Source: IEA analysis based on AEA (2011), DECC (2011), IPCC (2011), Mott MacDonald (2011), Uslu *et al.* (2012).

Future costs

Like bioenergy power generation, technologies for heat production are very well established and based on mass produced components. The scope for cost reduction by process improvement is therefore limited. However there is scope for optimising costs and overall system design, which vary widely between installations and countries. The Carbon Trust estimated that considerable cost reductions should be possible in the UK through optimising the overall system design including the storage systems. There is also scope for cost reduction through package designs and through scaling up of manufacturing processes and increased levels of competition as the markets grow. It is estimated that together these could lead to total cost reductions in the order of 25% by 2030.

Table 4: Overview of future bioenergy heat plant capital costs

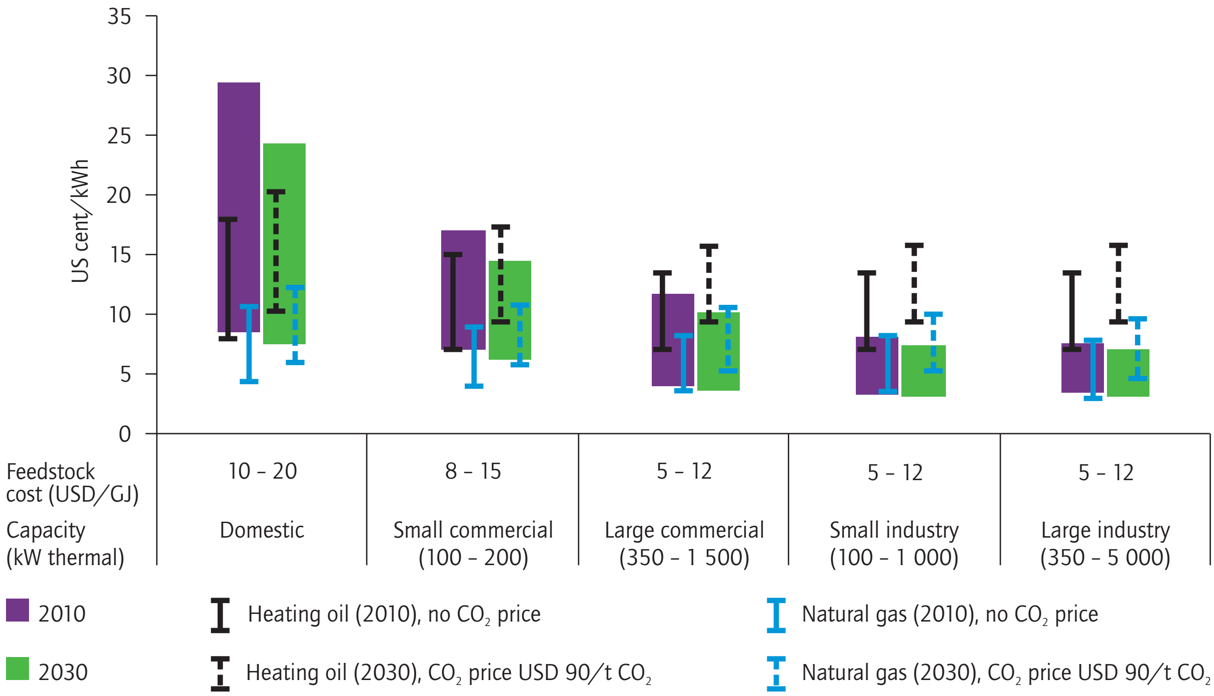
	***Domestic* (12 kW$_{th}$)**	***Small commercial* (100-200 kW$_{th}$)**	***Large commercial* (350-1 500 kW$_{th}$)**	***Small industry* (100-1 000 kW$_{th}$)**	***Large industry* (350-5 000 kW$_{th}$)**
Capital cost (USD/kW)	700-1 000	400-900	400-600	450-600	350-450

Source: IEA analysis based on AEA (2011), DECC (2011), IPCC (2011), Mott MacDonald (2011), Uslu *et al.* (2012).

The analysis indicates that in favourable circumstances, where the load factor is high, and feedstock costs are low bioenergy heat can already compete with oil derived heat in each of the sectors, and with gas where prices are high. Comparative costs of bioenergy heat and that generated from heating oil and natural gas in the different sectors are shown in Figure 14.

Benchmarking possible future costs for bioenergy heat against that derived from heating oil and natural gas with a carbon price equivalent to 90 USD/t CO_2 shows that bioenergy heat can be competitive with these fossil sources in many circumstances, if the assumed cost reductions can be achieved. It is thus not surprising that bioenergy for heat in industry plays an important role in this roadmap's vision.

Figure 14: Bioenergy heat production costs 2010 and 2030, compared to heating oil and natural gas based heat production



Source: IEA analysis based on AEA (2011), DECC (2011), IPCC (2011), Mott MacDonald (2011), Uslu *et al.* (2012).

Overall perspective

If the ambitious cost reduction and efficiency improvement targets for electricity generation systems can be achieved over the coming years, it is likely that larger scale uses of bioenergy including co-firing and large dedicated biomass power plants will become competitive. At that point there would no longer be a need for high levels of continuing financial support, which would reduce the policy costs of stimulating further bioenergy deployment.

The same trends will also make the use of process residues and collected fuels competitive, at least at larger scales of operation, and particularly where there are opportunities for using the heat produced, for processes or for heating. Power generation is less competitive at a smaller scale because of higher capital costs and lower efficiencies, except in cases where there is good match with a heat load.

The emergence of other new technologies – such as gasification and the use of the produced gas via a gas engine – may provide low cost and more efficient routes to power generation from biomass at a smaller scale. Demonstrating the costs and reliability of such systems, while also meeting stringent environmental criteria, is a key technical challenge for the coming five years to ten years.

Similarly, at a larger scale there is potential for higher generation efficiencies from BIGCC plants similar to those now being developed principally for use at a large scale for coal. Developing cost-effective designs for such plant at scales matching biomass availability may prove challenging, however, and multi-fuelling with a mixture of biomass fuels and coal may be more productive.

The use of biomass in co-generation systems often gives cost and overall efficiency advantages, if a suitable heat load can be found. However this is often not cost competitive at a small scale, because of low electrical efficiencies and high capital costs. By contrast, using biomass for heating is already a cost competitive option across a range of scales of operation, particularly when oil is being replaced by biomass derived heat. The range of cost effective opportunities will increase further if costs can be reduced by optimising and standardising plant designs.

Investments in bioenergy electricity generation

Investments in different forms will be needed to achieve a total bioenergy electricity capacity of 575 GW in 2050 as envisaged in this roadmap. Refurbishing of existing coal-fired plants to allow for higher biomass co-firing rates or use of biomass only will be critical, in particular in the first half of the projection period. In regions with high reliance on coal-fired electricity and thus large amounts of standing assets (China, India) these investments will also be needed in the longer term. In addition, investments in new dedicated biomass electricity generation capacity will be needed. These include utility-scale plants, as well as smaller-scale (<50 MW) plants for regional electricity supply, with off-grid solutions to provide energy access for rural populations in developing countries.

Worldwide, investment needs in power generation in the 2DS sum up to USD 25.4 trillion between 2010 and 2050, USD 7.7 trillion more than in the 6DS. Global investment volumes in bioenergy electricity generation sum up to USD 290 billion during 2010-30. This will be used primarily to refit coal-fired plants and build dedicated biomass power plants. The highest absolute investments during this period will be required in China, OECD Europe, Other developing Asia and OECD Americas (Table 5). In the second half of the projection period global required investments in bioenergy electricity generation are around USD 200 billion (Table 5). Most of these investments will come from public and privately owned utilities, with some from smaller power suppliers. Private investment, for instance in agricultural biogas digesters, will play a smaller role in terms of total investments, but may have a strong local importance.

To ensure the required investments in mini-grid and off-grid electricity generation for rural areas in developing countries will require strong governance and regulatory reforms, among other things, to attract private sector investment. Investments will depend on bilateral and multilateral development sources, the governments of developing countries, and a broad range of actors from the private sector (for more information on this see IEA, 2011c).

Table 5: Investment needs (billion USD) in bioenergy electricity generation capacity, including co-firing, in different world regions in this roadmap

Region	*2010-20*	*2021-30*	*2031-50*
OECD Europe	21	8	22
OECD Americas	13	11	20
OECD Asia Oceania	4	6	6
Africa and Middle East	7	3	7
China	39	99	54
India	14	8	10
Central and South America	16	5	17
Other developing Asia	12	15	52
Eastern Europe and FSU	3	6	15
World	130	160	202

Note: Numbers might not add up due to rounding.

Investments in bioenergy heat production

Assessing the investment needs in heat production capacities in industry, and particularly in buildings, is a very difficult task. This is due to the variety of different technologies needed in different industry sectors, and the lack of data on future scales of operation. The variety of scales and technologies is equally diverse in the buildings sector and possible technologies for bioenergy heat cover a range of scales, from individual household size solutions, campus size heating plants, as well as district heating fed by large co-generation plants. Given this variety, only a rough estimate of investment needs for bioenergy heating installations in OECD countries is presented here. Based on typical boiler sizes, reaching this roadmap's vision might require an accumulated USD 5001 000 billion of investment in biomass heating installations in the buildings sector of OECD countries over the projection period.

An analysis of investment needs in advanced biomass cookstoves has been undertaken in the IEA *World Energy Outlook 2011*. The analysis suggests that in order to achieve modern energy access in developing countries in line with the UN Millenium Development Goals, a total of 250 million people need access to clean cookstoves by 2030, requiring cumulative investments in the range of USD 17 billion. In addition, around 70 million households will need to be equipped with biogas systems, requiring an additional USD 37 billion of investments 2012-30 (IEA, 2011c).

An indicative assessment of total investment needs in industry in this roadmap suggests that between 2010 and 2050 USD 100-300 billion would be required for biomass furnaces, and other installations. The exact figures will depend, however, on the technologies and scales used, and the share of co-combustion of biomass with coal and coke, amongst others.

Expenditure on biomass feedstocks

Assessing the exact expenditures on biomass feedstocks that are required to meet the bioenergy demand in this roadmap is very challenging, given the various feedstock sources and the uncertainties around future feedstock costs. The figures indicated below should thus be taken as very rough estimates only, given the scarce reliable information on feedstock supply costs in different world regions. Based on the four feedstock categories and related costs presented earlier, accumulated expenditure from 2010 to 2030 could reach between USD 3 trillion and USD 6 trillion. In the last half of the projection period, the total expenditure on feedstocks would sum up to USD 4 trillion to USD 8 trillion, if this roadmap target is to be met. Just as investments in bioenergy generation capacity, feedstock-related expenditures need to be compared to expenditures that would have occurred if the projected energy demand would have been met with fossil fuels instead. These net spending on bioenergy heat and power compared to fossil fuel-based generation are much smaller than the total expenditure. In some cases, where biomass-based generation is cheaper than the fossil reference, fuel cost savings can even be achieved.

Biomass supply

The availability of sufficient amounts of biomass as feedstock for production of heat, power and transport fuels is one of the key factors determining the role of bioenergy in the future energy mix. The question of land and biomass availability for bioenergy generation needs to be carefully addressed. The steadily growing world population – estimated to reach 9.1 billion in 2050 – together with economic growth in many emerging economies is projected to lead to 70% increase in global food demand and a net demand of additional 70 Mha arable land[15] in 2050 (FAO, 2009a). In addition biomass demand in other non-energy sectors such as timber, and pulp and paper needs to be met, and growing interest in other industries (*e.g.* chemicals) will likely further increase the overall demand for biomass in the future.

Overview on bioenergy potentials

The potential supply of biomass for energy purposes is the subject of many assessments with national, regional and global focus, some of which are rather optimistic. These estimates need to be carefully evaluated, as they do not always fully consider all factors involved in mobilising the indicated biomass potential. This is particularly true for the economics of biomass production and transport, which are inevitably subject to uncertainties. Although some cost-supply curves for different types of biomass are available for certain regions, they often have limitations with regard to the feedstock sources considered. Cost information on biomass supply in developing countries is particularly scarce as they have no large-scale commercial bioenergy sector yet. Some energy crops that might play a role in certain regions in the longer term, such as marine biomass, are generally not included in most studies. Other varying assumptions that lead to inconsistent results between studies include assumed future intensity and productivity of agricultural production and global food demand (in particular in terms of diet). Both of these are crucial in determining how much suitable land could potentially be available for cultivation of energy crops.

In addition, most estimates give little attention to the availability of water and soil nutrients, and the potential impact of climate change on biomass production in different world regions. Some work on this has been undertaken, but more research is still needed to better understand potential limitations. The same is true for the impact of energy prices on agricultural production costs, *e.g.* through fertiliser prices and tractor fuel. More work on these important interactions is needed to better understand constraints and potential scope for symbiosis between the two sectors (FAO, 2011a).

One important and relatively new topic is the impact of sustainability requirements for biofuels and biomass used for heat and power generation (see sustainability section above). Since these sustainability requirements are not only new but so far limited to certain regions, assessments of bioenergy potential have generally not considered these requirements. First efforts in the European Union have been undertaken in the Biomass Futures project, whose final results in form of an *Atlas of EU biomass potentials* were published in March 2012 (Elbersen *et al.*, 2012).

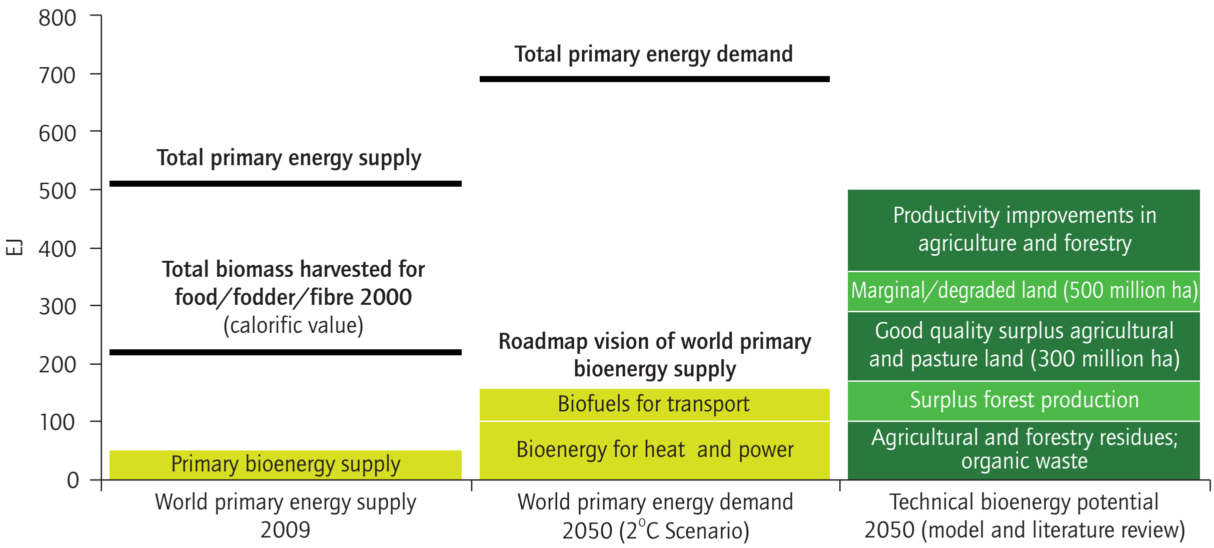
Taking into account these uncertainties in long-term assessments, the range of bioenergy potential estimates can be narrowed down to a more solid 100 EJ to 300 EJ, with some more optimistic estimates pointing to a technical potential of up to 500 EJ in 2050 (Slade *et al.*, 2011; IPCC, 2011; Dornburg *et al.*, 2010).

Meeting the roadmap targets

Analysing biomass potentials over a 40-year horizon inevitably includes some assumptions on a number of uncertain factors, which will always be subject to debate. This is particularly true for bioenergy, since its development is influenced by trends not only in the energy sector, but also in the agricultural and forestry sectors. In light of these uncertainties, rather than debating whether the size of the global bioenergy potential in 2050 could reach 100 EJ or 500 EJ, a more pragmatic approach in form of an intermediate target for biomass supply is needed to plan the sector's development in the short and medium term.

15 FAO projects that around 120 Mha of additional land will be brought into cultivation, mainly in developing countries in Latin America and Africa, whereas such land use in developed regions is expected to decrease by 50 Mha.

Figure 15: Comparison of primary bioenergy demand in this roadmap and global technical bioenergy potential estimate in 2050



Note: The technical potential for 2050 indicates the upper bound of biomass technical potential based on integrated global assessment studies using five resource categories indicated on the stacked bar chart, and limitations and criteria with respect to biodiversity protection, water limitations, and soil degradation, assuming policy frameworks that secure good governance of land use (Dornburg *et al.*, 2010). Expert estimates undertaken by the IPCC (2011) indicate potential deployment levels of terrestrial biomass for energy by 2050 in the range of 100 to 300 EJ, with a most likely range of 80-190 EJ/yr, with upper levels in the range of 265-300 EJ/yr.

Source: Adapted from IPCC, 2011, and supplemented with data from IEA, 2011a and IEA, 2012a.

In this roadmap vision, a total of 100 EJ (*i.e.* roughly 5 billion to 7 billion dry tonnes) of biomass will be required to provide enough feedstock for the production of heat and power, in addition to 60 EJ needed for production of transport fuels in 2050 (IEA, 2011a). This is a considerable increase on the estimated 50 EJ of biomass used for energy today. Since much of this biomass is used at rather low efficiencies, the key priority should be to improve the efficiency of existing biomass to energy production. In parallel it is critical to find ways to validate, demonstrate, and mobilise another 50 EJ of biomass (*i.e.* doubling current primary bioenergy supply) in a sustainable manner by 2030. This should be done with a primary focus on "available" feedstocks such as residues and wastes, but will also need to include energy crops. Achieving this intermediate step will provide important lessons on the logistical, technical, ecological and economic feasibility of large-scale biomass supply, and a better understanding of positive and negative environmental, social and economic effects including on related sectors. This field experience should then allow more accurate expectations of the role of bioenergy in the future energy system (see also Slade *et. al*, 2011 for further discussion).

Realistic options to increase bioenergy supply in the short and medium term with little sustainability concerns include the use of **wastes and residues** that are in several cases just discarded or used in an inefficient manner. Based on a thorough review of bioenergy potential estimates undertaken by the IPCC, up to 100 EJ could be provided from wastes and residues (Figure 15). Organic waste and renewable MSW is often discarded in landfills today, in particular in emerging economies and developing countries. Making better use of this resource, for instance through digestion to biogas, could provide considerable amounts of bioenergy at a relatively low cost and play an increasing role in these countries, as well as in several OECD countries. Furthermore, vast amounts of agricultural residues are produced in North America, Eastern and South-Eastern Asia, as well as in South America that could be used for bioenergy production; and considerable amounts of forestry residues are produced in North America, and to a smaller extent in South America, Eastern and Northern Europe (for more details see Eisentraut, 2010). Most of the current and future residue potential will be used domestically, as residues are typically bulky and thus costly to collect and transport over long distances. The same is true for organic waste, which will play a role only locally and is unlikely to be traded, unless it is converted into biomethane. Using these resources could help to create new sources of income and employment in the agricultural and forestry sector, but good practice needs to be applied in order not to compromise productivity, given the role of residues for nutrient cycling, soil carbon sequestration and biodiversity.

A large share of bioenergy today is provided from **forest biomass**. The traditional use of biomass relies to a large extent on fuelwood, which is often sourced in an unsustainable manner. Many recent studies exclude mature forests from their potential assessment due to uncertainties related to the impact of increased extraction rates on biodiversity, and the carbon pay-back time of this forest biomass (Slade *et al.*, 2011). Some studies indicate a future potential of forest biomass – other than residues – for bioenergy production in the range of 10 EJ to 100 EJ in 2050. Based on a review of several studies IPCC (2011) analysis indicates that it seems technically feasible to extract between 60 EJ to 100 EJ of additional wood from existing managed forests without reducing the re-growth potential. Although economic considerations, environmental concerns and the forest-owner structure with many smallholders in certain regions might limit this potential, forest biomass could be particularly important to supply bioenergy feedstocks in forest-rich regions such as North America, Russia and Scandinavia. These regions can also profit from their large timber industry that has extensive experience with mobilising and processing large amounts of biomass.

Although wastes and residues, and also forest biomass can play an important role in supplying feedstocks for bioenergy production in the short and medium term, dedicated **energy crop plantations**, mainly woody and herbaceous perennial energy crops (willow, poplar, eucalyptus, miscanthus, switchgrass) will be required to meet the projected bioenergy demand in this roadmap. Such plantations can provide relatively high biomass yields on a regular basis (rotation periods range from annual up to a few years) and are a key element in supplying considerable amounts of biomass from a limited area. However, with growing demand for food and feed, the use of arable land for bioenergy needs to be restricted to avoid negative impacts on food security.

There are various options to expand energy crop plantations with limited risk of negative side-effects. Using land not suitable to food production (*e.g.* contaminated or degraded land) can be an option, but availability of such soils with sufficient productivity is limited. The use of pastures and surplus arable land, on the other hand, will play a key role for the establishment of energy crop plantations. In Brazil, for instance, vast areas of pasture land have been identified in which sugarcane expansion can take place without compromising domestic cattle production. Such an approach could be replicated in other regions, where pasture land is used with cattle densities lower than the grazing capacity.

Based on indications in existing studies, the potential for energy crops may lie between 30 EJ and 200 EJ in 2050, with a more solid estimate of around 120 EJ indicated by the IPCC review (Figure 15). IEA analysis matching IIASA land-suitability analysis (Fischer *et al.*, 2010) with FAO data (not yet published)[16] on future land demand for agriculture suggests that considerable amounts (about 300 million hectares [Mha]) of pasture land and unprotected grassland and woodland with good suitability for (energy) crop cultivation could be available in 2050, in particular in Eastern Africa, South America and Eastern Europe. In addition 500-900 Mha of unprotected marginal land could be available. These estimates need to be heavily qualified, however, since the data quality on land suitability and existing uses is not always sufficient, and lack of infrastructure as well as low yields attainable on marginal land might often make energy crop plantations economically unattractive. Furthermore, biodiversity impacts as well as changes in carbon stock might prohibit cultivation of certain areas.

Assuming that one-third of the potentially available residues and wastes were available for production of bioenergy for heat and power in 2050, an additional 2.5 billion tonnes to 4.5 billion tons of biomass from lignocellulosic energy crops would be required to meet this roadmap's targets. With an average yield of 15 dry tonnes/ha/year, roughly between 170 Mha and 300 Mha – corresponding to 4% and 6%, respectively, of current agricultural land – would be required. With higher energy crop yields, or enhanced use of residues and wastes, total land demand would be significantly lower.

16 FAO kindly provided data from the forthcoming study "World agriculture: towards 2050/80".

Future land demand for agriculture and bioenergy might also be influenced by efficiency improvements in the agricultural sector. According to FAO estimates around one-third of global food production is wasted during harvest and transport (mainly in developing countries), or at consumer level (mostly in developed countries) (FAO, 2011b). Reducing these losses could allow farmers to dedicate some of their land to production of bioenergy feedstocks and diversify their income streams without negative impact on local food security. Furthermore, yield improvements in the agricultural sector can lead to higher land-use efficiency and reduce land demand. There is still considerable room for improving yields, in particular in developing countries (Fischer *et al.*, 2010), but it is not clear to which extent these "yield gaps" between current and realistically achievable yields can be closed, and at what cost (economically and environmentally). Higher yields could lead to considerable surplus of arable land available for bioenergy production in certain regions.

New feedstocks such as algae, halophytes (that are adapted to saline environments) and others that are currently in an early stage of RD&D are usually not considered at all in most studies. While the potential of these feedstocks might in fact be more limited than that of conventional energy crops, they could nonetheless make a contribution to bioenergy supply in the longer term, and could become an important biomass source in certain regions. A review of algae biomass for energy production has been undertaken by FAO (2009c) and IEA Bioenergy Task 39 (2011).

Biomass trade

International trade will play an increasing role in meeting this roadmap's targets, by balancing bioenergy supply and demand between different regions. This section focuses on the trade of primary and refined biomass (pellets, torrefied pellets, biomethane), although electricity from biomass can also be traded between neighbouring countries. Detailed information on the development of sustainable bioenergy trade is also provided by the IEA Bioenergy Task 40.[17]

Today both agricultural and forestry products are traded internationally and increasing amounts of solid and liquid biomass for energy purposes are shipped around the world. Trade in fuel wood amounted to 4.4 million tons (Mt) in 2009. Trade in wood pellets used for energy generation has also gained considerable momentum, with an estimated 3 Mt of wood pellets traded internationally in 2010 (Cocchi *et al.*, 2011). In addition, considerable amounts of ethanol, vegetable oils, and biodiesel are traded, for use mainly in the transport sector.

Wood pellets are mainly shipped from North America, Eastern Europe, and Australia to consumption centres in Central Europe, the United States and Asia. According to analysis undertaken by IEA Bioenergy Task 40 (Cocchi *et al.*, 2011), global wood pellet production to 2020 is likely to increase considerably, with Canada, the United States, and Russia all expected to markedly increase their production capacity. In addition, Brazil might become an important producer if announced investments in pellet production materialise. On the demand side China, Japan and Korea are expected to use increasing tonnages of pellets over the next decade. The actual demand will depend on policy support measures, in particular for co-firing, as well as the price of reference fossil fuels (coal for industrial use, heating oil in the domestic sector). IEA Bioenergy Task 40 analysis suggests that depending on actual demand for pellets, between 16 Mt (low trade scenario) and 33 Mt (high trade scenario) of wood pellets per year could be traded internationally in 2020.

The outlined scenarios show that international biomass trade will play a critical role in connecting regions with considerable biomass feedstock potential with those regions that have limited biomass resources but growing demand for bioenergy production. In addition to wood pellets, torrefied pellets, biomethane and pyrolysis oil are likely to be increasingly traded over long distances. The envisaged scale for pyrolysis or torrefaction units is considerably smaller than that of large power plants; the technologies will thus become an important way to mobilise local biomass potential that could otherwise not be traded economically over long distances.

Biomass and biofuel markets have been developing in a promising direction over the last decade, but they are still immature and trade barriers threaten to limit their development. Key barriers include import and export tariffs, which mainly apply to biofuels. For solid biomass and biomass intermediates, lack of handling

17 www.bioenergytrade.org

and port infrastructure and resulting inefficient logistics are one barrier to enhanced international trade of these products. In addition, technical standards will be an important prerequisite to allow for commoditisation of biomass and biomass intermediates and create a truly robust market for international trade (Junginger *et al.*, 2010). Sustainability certification might also act as trade barrier when different schemes are not properly aligned internationally. Important work on sustainability certification schemes and enhanced uptake of technical standards for solid biomass by industry is being undertaken, for instance by the SolidStandards project.[18]

Based on the potential biomass availability and projected future bioenergy demand, international biomass trade will be vital to meet this roadmap's vision of global bioenergy use. In the short term, trade will include conventional biofuels and certain types of lignocellulosic feedstocks (mainly wood pellets). After 2020, trade in refined biomass (pyrolysis oil, torrefied wood pellets), as well as lignocellulosic feedstock, is likely to grow rapidly and to supply large bioenergy power and/or heat plants in regions with limited feedstock availability. Certain biomass trade routes will exist only for a limited period, for instance until domestic supply in the importing region is sufficiently developed or demand in the exporting region increases. Likely trade routes that are already being established today include Eastern Europe to Central Europe; Latin America to the United States, the European Union and Japan. Australia may become a supplier to China; and other developing Asian and African countries could play an increasing role in the longer term in exporting feedstocks to Asian, European and North American markets.

18 www.solidstandards.eu

Milestones for technology improvements

Technology	*Timing*
Develop low-cost, efficient biomass cookstoves, suited to customer needs	2012-2015
1st commercial-scale torrefaction and pyrolysis plant	2015
1st commercial-scale bio-SNG and BIGCC plant	2015
Develop "off the shelf" plant design to reduce capital costs	2012-2020
Better feedstock flexibility for pre-treatment technologies to allow for broader feedstock base	2012-2020
1st commercial-scale BECCS project	2020-2025
Increase average electricity generation efficiency by 5 percentage points	2030

Most technologies used for generation of bioenergy for heat and power have been deployed on commercial scale for decades and no steep learning curves with significant cost and efficiency improvements can be expected. The main exception is power plant components that have only recently been brought to the market as a result of increased use of biomass. The most important cost-reduction measure for commercial technologies will be to standardise plant design and produce "off the shelf" plants of specified capacities. Some efficiency improvements can still be realised, in particular for plants that have been operating for some decades with efficiencies much lower than the "state of the art" plants. Replacing or refurbishing these outdated plants will increase efficiencies and bring down generation costs; a 5 percentage point increase in electricity generation efficiency of new plants by 2030 is deemed a realistic target.

Stronger cost and efficiency improvements can be expected for technologies that are currently in a pre-commercial stage and still face technical challenges. This includes technologies such as torrefaction, pyrolysis and thermochemical gasification. Tar-removal from the product gas is an issue for torrefaction and especially gasification of biomass. Enhanced feedstock flexibility is also an important R&D field, as it would allow for use of a broader feedstock base and thus allow for choice of most economical feedstocks. For both torrefaction and pyrolysis, issues related to the quality of the end product require further R&D. Stability of pyrolysis oil is another important aspect that needs to be improved to enable storage and long-distance transport. For all of these pre-commercial technologies, reaching economy of scale will also be an important step towards reductions in capital and overall generation costs. Experience from operating commercial-scale plants will then allow further process optimisation and efficiency improvements.

There is also potential for improvements of small-scale (<5 MW) co-generation systems. These are currently rather capital intensive per unit of electricity produced and thus often not competitive with large-scale options (see economics section above). Reducing the capital costs and improving the electric efficiency of small-scale co-generation and trigeneration (power and heat for heating and cooling) technologies will be important to make small-scale options more competitive. Technologies in the early stage of development such as fuel cells run on biomethane could potentially become valid options, but more RD&D efforts are still needed.

The interest in combining bioenergy and biofuel production with CCS is growing, but a number of key issues need to be addressed to better understand the potential of BECCS in the future. This includes more research into the overall storage potential for CO_2, and the development of comprehensive maps showing potential storage capacities and identifying transport and storage infrastructure needs. In addition, more pilot and demonstration projects are needed to better understand the feasibility of applying CCS to different bioenergy and biofuel plants.

Feedstock and sustainability

Milestones for feedstocks and sustainability	*Timing*
Adopt sound sustainability certification schemes for biomass.	2012-20
Reduce and eventually abolish tariffs and other trade barriers (*e.g.* logistical) and adopt international technical standards to promote biomass trade.	2012-20
Continue alignment of LCA methodology with regard to direct and indirect land-use change, to provide a basis for sound support policies.	2012-20
Increase bioenergy production based on “low-risk” feedstocks (*e.g.* wastes and residues) and through yield improvements.	2012-30
Improve biomass potential analysis with better regional and economic data, including from large-scale energy crop field trials.	2012-30
Enhance biomass cascading and use of co-products through integration of bioenergy production in biorefineries.	2012-50

Meeting this roadmap’s targets will require a substantial amount of biomass as feedstock. In total around 5-7 billion tons (dry) per year of biomass will be needed for heat and power generation in 2050, with a considerable share of this coming from dedicated energy crops. The assessment of available land that could be brought into cultivation for energy crop production in a sustainable way is thus a key priority for further development of the bioenergy sector. While a number of estimates are available on current and future land use and the potential land availability for bioenergy, more efforts are needed to match local, national and global data. Top-down approaches such as remote sensing should be combined with participatory bottom-up approaches such as verification on the ground by consulting local stakeholders. This should also help to improve the economic analysis of biomass availability through cost supply curves.

Bioenergy feedstocks such as fast growing wood species and other lignocellulosic energy crops have been used for energy production for some time, but there is still scope to further increase yields and develop crop varieties with favourable characteristics for energy conversion. In addition, there is still considerable scope for RD&D on breeding of new crops and improved cultivation practices. Large-scale field trials are needed in different regions to assess the suitability of indigenous energy crops that suit local conditions. The field trials will improve data on economics of cultivation, harvesting and transport. Experience gained in these field trials will help to develop efficient feedstock supply chains and draw a realistic picture of the future role of bioenergy.

Towards sustainable feedstock production and use

Strategies for exploring and developing short and medium term bioenergy potential should focus on options that support the sustainability of bioenergy production, as has been discussed. Residues and waste are one obvious source for bioenergy with considerable potential. But changes in waste treatment will be required. Landfill can be used either by extracting the methane-rich gas, or by deploying waste separation systems to recover the organic waste for anaerobic digestion to biogas. While the latter poses logistical challenges, there are obvious sustainability benefits such as the avoidance of methane emissions. Using harvesting residues that are typically left in the field will require efficient collection systems, and good soil management practices to ensure the residue removal does not lead to degradation of the soil.

Efficiency improvements in both land use (*i.e.* productivity) and energy conversion, including through biomass cascading, will also be necessary to increase the supply of bioenergy feedstocks. Yield improvements could play a considerable role in raising the land productivity of energy crops (including perennial lignocellulosic crops) and the forestry and agricultural sectors' experience with crop breeding and cultivation techniques should be used extensively. Yields in developing countries could increase considerably, but adoption of best practices is required. This must include ensuring that the use of fertilisers and irrigation does not lead to negative impacts such as eutrophication, salination, or depletion of water reserves. The cultivation of perennial feedstocks could help to maintain the quality of agricultural land and so benefit the whole agricultural sector. However, the scope might be limited in degraded and contaminated land because of poor yield potential.

New plantation concepts for fast growing wood species need to be established and managed based on best practice experiences from industry, governments and other stakeholders. Such plantations will allow for efficient and sustainable production of biomass for material and energy use, create new employment and reduce environmental degradation (for more information see WWF, 2011). Innovative cultivation methods that take advantage of multi-season planting and intercropping, such as integrated food and energy systems (IFES), can help to minimise the amount of land needed to meet fuel, food and feed needs, and reduce the risk of competition between food and energy crops (Bogdanski *et al.*, 2010).

One issue that is emerging with the growing demand for biomass from the energy sector is the "best use" of biomass. Pulpwood, for instance, can be used for production of pulp, paper and particle boards, as well as for energy generation, which is likely to lead to upward price pressure on this raw material. Although forest owners might welcome this, the respective industries might suffer from lower profitability as a result of rising prices. Encouraging the cascading use of biomass might help to mitigate this price pressure. The idea of biomass cascading is a hierarchical use of biomass, starting with those uses that require high quality biomass (*e.g.* construction sector) and subsequent use of the material in applications where lower quality is acceptable. Energy conversion would typically be the last step in this hierarchy, making use of residues along the production chain and the discarded material. Implementing biomass cascading will require changes in logistics such as efficient waste separation, as well as changes in consumer behaviour. It is unlikely that biomass cascading will emerge without initial policy support. Some countries have started to introduce regulations that aim at protecting existing sectors and allow for biomass use for energy purposes only if these sectors are not affected negatively (SolidStandards, 2011). These policies will likely encourage cascading use of biomass streams, but additional measures might also be required. It needs to be noted that the "best use" of biomass always depends on the point of view. What is best in terms of resource efficiency might not always be best in terms of economics, or lead to the lowest cost CO_2 abatement. The best use of biomass is therefore defined by a number of variables that emerge from specific national and regional contexts.

Improving GHG performance

Most bioenergy systems can provide considerable GHG emission reductions compared to fossil fuels in the medium to long term, if the feedstock is sourced without negative effects on land use, as discussed earlier. The overall GHG balance of bioenergy heat and power can be optimised further by choice of feedstock and cultivation technique and by improving the conversion efficiency of the process. High GHG savings can typically be achieved by using waste and residue feedstocks; perennial energy crops that require little fertilisation and improve soil carbon sequestration can also lead to high GHG savings. Other measures include minimising process-based emissions through energy efficiency measures, use of renewable energy in the process, and the cascaded utilisation of biomass. Some of these measures will also lead to cost reductions and should thus be pursued vigorously.

Addressing land use change

Default values for emissions related to ILUC have been introduced in the United States biofuel regulations, and discussions are taking place in the European Union. Until now the discussions have focussed on biofuels only, but ILUC accounting rules are likely to be introduced for biomass used for heat and power generation at some point. While the implementation of ILUC default values in GHG emission accounting – also referred to as *ILUC factor* – for bioenergy is relatively simple, defining solid default values is a complicated task, given the uncertainties around actual emissions described above. For this reason, ILUC factors are controversial as they could impose a GHG penalty regardless of the actual feedstock cultivation practice and without directly encouraging improved land management practices. Default ILUC emission values should thus only be introduced, if there is a possibility for producers to have their specific production chain audited as part of sustainability certification, to define the actual ILUC-related emissions of their product.

While ILUC modelling is inevitably subject to considerable uncertainties, studies are required to identify management systems that minimise negative impacts on land use triggered by energy crop plantations, which can then inform sound support policies for bioenergy. Despite the current uncertainties about the impact of LUC and ILUC, there are practical measures that should be stringently pursued to reduce the risk of ILUC associated with the production of biomass for fuels, heat and power (see for instance Ecofys, 2010). Focussing on wastes and residues as feedstock will not induce additional land demand, if the residues are not currently used. Maximising land use efficiency by sustainably increasing productivity and intensity and choosing high-yielding feedstocks, such as perennial energy crops, particularly on unproductive or low carbon soils, will also reduce the risk of negative ILUC. The integration of energy production within biomass value chains, including the deployment of biorefineries, and better cascade use of biomass, is another important measure that requires more attention. In the longer term, aquatic biomass feedstocks such as micro and macro algae might also play a role in producing biomass for heat, power and biofuels without large additional land demand. Policy action can be taken by providing incentives for bioenergy production from residues and wastes, use of high productive feedstocks, and more efficient use of co-products (*e.g.* waste heat).

One interesting approach to reducing the risk of land-use change is a zoning programme that has been developed in Brazil. The so-called *Agro-Ecological Sugarcane Zoning* (AEZ Cana) constrains the areas in which sugar cane production can be expanded on existing pastures by increasing cattle density on the remaining pasture, so avoiding the need to convert new land to pasture. The programme is enforced by limiting access to development funds for sugar cane growers and sugar mill/ethanol plant owners that do not comply with the regulations. A similar approach should also be implemented in other countries and regions, and for other types of energy crops used for heat and power production.

Ultimately, sustainable land-use management schemes will be needed to address the outlined risks effectively and ensure that bioenergy delivers the envisaged emission savings in a cost optimal way compared to other low-carbon technologies.

Enhancing biomass trade

Dismantling trade barriers such as lack of technical standards is a key task to support the development of international trade between biomass-rich regions and bioenergy production and consumption centres. International standards for biomass and intermediate products (biomethane, pyrolysis oil, pellets) will help to enhance trade and simplify logistics of handling and storage, many stakeholders in the sector see such standards as a key to enhanced biomass trade (Junginger *et al.*, 2010). Sustainability certification for bioenergy will be needed as a supporting tool to create international markets. It is therefore imperative that certification schemes are aligned internationally so that they do not act as a trade barrier and exclude participation of smallholders. Trade agreements can also help stimulate production of biomass feedstocks for export, especially in developing countries, and lead towards the creation of an international market for biomass and biomass intermediates.

Policy framework: roadmap actions and milestones

Overcoming economic barriers

This roadmap recommends the following actions	*Timing*
Create a stable, long-term policy framework for bioenergy, to increase investor confidence and allow for the sustainable expansion of bioenergy production.	2012-30
Phase out inefficient fossil fuel subsidies and introduce CO_2 emission pricing schemes to ensure a level playing field for bioenergy.	2012-30
Introduce mandatory sustainability requirements and quality standards based on credible, internationally aligned certification schemes.	2012-15
Analyse and introduce appropriate accounting in CO_2 pricing schemes for negative emissions related to CCS on biomass-based installations.	2012-30
Adjust economic incentives over time, as bioenergy moves towards competitiveness with fossil counterparts.	2020-40

Bioenergy heat and power can, under favourable circumstances, be competitive with fossil fuels today. In many countries, however, the cost difference between biomass and coal is currently too big to allow for cost-competitive bioenergy generation. A favourable framework is thus needed to promote the sustainable use of bioenergy for heat and power generation.

One of the first steps policymaker can undertake is to remove inefficient fossil fuel subsidies, which in many cases encourage a wasteful use of energy. Only 8% of the USD 409 billion spent globally in 2010 was distributed to the poorest parts of the population (IEA, 2011c). In order to provide access to energy, direct measures such as financing schemes for advanced biomass cookstoves, biogas systems etc. would be more effective and less costly, and help promote low-carbon energy.

Introducing a price for CO_2 is another important measure to reduce energy-related GHG emissions by promoting the more efficient use of fossil energy and supporting the use of renewable and other low-carbon energy sources. There are various ways to introduce a price on CO_2, some of which have been established under the Kyoto Protocol, such as international emission trading which has been introduced in the European Union and is envisaged for Australia from 2015. Another example is joint implementation of GHG mitigation projects between developed countries, and Clean Development Mechanism (CDM) for joint projects by developed countries in developing countries. The CDM is particularly relevant for attracting investments in bioenergy projects in developing countries: 12% of all CDM projects are related to bioenergy (UNEP, 2012). With the recent (2011) inclusion of CCS in the CDM, accounting for negative emissions is possible (as opposed to current provisions in the EU Emissions Trading Scheme), and BECCS projects could thus also be eligible. Another measure that has proved quite successful is a so-called "carbon tax", which has been introduced for instance in Sweden, Denmark, Finland, and Australia (starting in July 2012).

These measures can put a monetary (penalty) value on CO_2 emissions, but the resulting price level has not always been enough to lead to significant emission reductions or to a greater uptake of new low-carbon technologies. To enhance the use of bioenergy, a CO_2 price would need to offset the cost difference between conventional coal and biomass, and encourage investments in refurbishing of existing assets and dedicated biomass plants. One question that is yet to be addressed is how to encourage "negative emissions" from BECCS; different policy options are possible (IEA, 2012c). A logical approach would be to provide an incentive for each net ton of CO_2 from biomass that is stored below ground. Such an incentive could well be integrated into an existing carbon market and could stimulate the enhanced use of biomass in (fossil fuel) plants equipped with CCS technology.

Another way to promote bioenergy is to use mandates. Mandates in place today typically define a certain share of renewable energy in total energy supply (*e.g.* 20% renewable energy by 2020 in the

European Union and Australia), rather than referring to specific technologies. This approach encourages emission reduction in a cost-optimal way, using a portfolio of different technologies suited to local conditions. Past experience has shown that ensuring the sustainability of feedstock supply should be a prerequisite for any mandate on bioenergy.

Mandates and CO_2 pricing might, however, not always be enough: more specific support measures for bioenergy heat and electricity might be needed. Such measures will be particularly important to promote technologies that are not yet fully commercial, and so are subject to higher investment and generation costs. Common measures to promote deployment of renewable energy include:[19]

- **Feed-in tariffs**, which ensure a certain price per kilowatt-hour of electricity/heat that is fed into the grid. The level might be adjusted depending on the specific technology and the size of conversion plants.
- **Tradable green certificates**, which are issued for each kilowatt-hour of heat/electricity generated. The certificates can then be traded on a separate market and sold to large consumers or retailers that are obliged to buy a certain number of certificates.
- **Tenders** in which project developers name the price for which they will build a certain project that is needed to comply with the government's quota. Tenders typically are combined with long-term power-purchasing agreements.
- **Tax incentives or credits** are commonly used, for instance in the United States. They allow the producer of renewable electricity to sell generated tax credits to companies, which can deduct them from their taxes.
- **Direct cash grants/rebates** are measures to directly reduce the investment costs associated with a specific project. These measures are particularly valuable for commercial-scale plants that are the first of their kind, and often associated with considerable investment risks. They have also been successful in promoting small-scale renewable heat installations in countries such as Germany and Austria.

In general, the heat market is very heterogeneous in terms of stakeholders and investors, climate conditions and heat energy infrastructures (Beerepoot and Marmion, forthcoming). Bioenergy heat policies will thus need to be customised for local heat market conditions. Policies designed for end-users such as the building sector or industry will be faced by similar challenges as energy efficiency policies, such as diverging investment decision criteria and "split-incentive" problems. Heat policies may thus have more in common with energy efficiency policies than with renewable electricity policies. However, when bioenergy supplies commercial heat through a district heating network, there will be similarities with the electricity market: heat output is measured and a grid is available for surplus production. In these cases, successful policies based on support of bioenergy heat output (such as a feed-in tariff) may be a good strategy.

Which specific policy incentive, or combination of support measures, is most suitable to promote sustainable bioenergy depends on a variety of factors that are typically country-specific. This is particularly true for bioenergy, since biomass resources are not equally distributed between different regions. The maturity of the sector and the cost-competitiveness of the generated bioenergy compared to fossil fuels and other renewable energy sources are important factors, as well as the structure of the energy market. It is thus important that governments evaluate carefully which support mechanisms will achieve envisaged bioenergy deployment targets in a cost optimal way. This includes taking into account the different market characteristics for electricity and heat.

Bioenergy can play a role in balancing rising shares of variable renewable electricity within a power system. Depending on the plant design, some large-scale biomass plants are able to react to predictable changes in demand and provide very important flexibility to the power system (IEA, 2011d). The most flexible options are biogas and biomethane that is fed into the gas grid, and converted in open-cycle gas plants that can respond quickly to short-term variability in the power system when demand peaks. However, wear and tear, such as corrosion and fouling in solid biomass plants, caused by ramping production up and down entails additional investments or higher operation and maintenance costs. For biomass to unleash its full potential as a dispatchable, flexible electricity source, these additional costs need to be covered in some way. The German *Renewable Energy Sources Act*, for instance, provides a "flexibility premium" for biogas plants capable of storing biogas and providing additional electricity at times of peak demand. In

19 For more information on different policy measures and their efficiency see IEA, 2011f.

addition, a premium for biogas upgrading and injection into the natural gas grid is provided under the law, a mechanism that has also been introduced in Luxemburg as of January 2012.

Sound policies to promote bioenergy also need to take into account that investment risks are spread out along the whole supply chain. Most of the measures described above fail to address upstream investments in feedstock cultivation and biomass refining. Such investments in form of infrastructure, land lease/purchases, and plantation establishment occur mainly in the forestry and agricultural sectors. Especially in developing countries, these sectors suffer from a severe lack of investment (FAO, 2009b). This financing gap needs to be addressed to strengthen the sectors, enable infrastructure investments, and raise overall productivity to enable the feeding of 9 billion people in 2050. A comprehensive agricultural and rural development strategy that includes bioenergy and biofuel projects is therefore needed to increase the potential for symbioses between investments in bioenergy and those into agricultural production. This can enhance the overall benefits for rural economies such as creation of additional income, access to modern energy services, and increased productivity.

Addressing non-economic barriers

Logistics

Large bioenergy plants have a biomass demand of several 100 000 tonnes of biomass per year, requiring well developed supply chains to mobilise sufficient amounts of feedstocks at reasonable costs and with minimal transport GHG emissions. Poor infrastructure can become a critical non-economic barrier, in particular in undeveloped rural areas, and should be tackled as part of a rural development strategy that benefits the agricultural and forestry sector as a whole. Lessons learned in the agricultural and forestry sector – which have developed well functioning supply chains for biomass over decades – should be used to develop new supply chains for other bioenergy feedstocks.

One particular challenge is the ownership structure in the agricultural and forestry sector in certain regions (not only in developing countries). In Europe, for instance, three-quarters of forests are owned by small-scale (less than 3 ha) private forest owners (Hirsch *et al.*, 2007); in many developing countries, the same is true for the agricultural sector with the important difference that these smallholders often do not have formal land ownership, so their situation is more precarious. Capacity building, awareness-raising, and the introduction of co-operatives are vital measures to integrate small landowners into the bioenergy supply chain and mobilise currently untapped potential.

Sustainability and public acceptance

Governments should adopt sustainability requirements for bioenergy, following internationally agreed sustainability criteria and evaluation methods, and making use of existing schemes for biomass in the forestry and biofuels sectors. International harmonisation of certification schemes is important, to provide credible certification schemes and avoid market disturbance or creation of trade barriers. Specific attention must be paid to integrating smallholders in certification schemes, since these producers often cannot handle the additional costs of complying with certification. If these concerns are addressed adequately, sustainability certification will likely become a driver for the development of an international bioenergy market. However, additional measures are also needed to address the unsustainable use of land and water resources and the issues related to (indirect) land-use changes. Sustainable land-use planning will be a key towards tackling these issues, but to be effective it will sooner or later have to include the whole agricultural and forestry sectors.

The importance of deploying advanced biomass cookstoves and clean fuels to replace traditional biomass use has been highlighted in this roadmap. Past experience shows, however, that clean cookstove programmes have not always been successful in triggering a sustainable transition. This is due to a number of barriers that need to be addressed carefully. Lack of awareness of the health and economic benefits (through fuel savings) of efficient biomass stoves and clean fuels forms one of the most important non-economic barriers. Furthermore, consumer needs must be addressed through providing different designs that meet customers' economic and cultural requirements. This will require a well functioning market for efficient cookstoves, as well as rigorous quality standards that help increase consumer acceptance (Global Alliance for Clean Cookstoves, 2011).

Support for RD&D

In 2010, global corporate and government expenditures on R&D in bioenergy for heat and power summed up to USD 600 million, up 18% from the year before (UNEP and BNEF, 2011) – but this is small compared to other technologies such as solar and biofuels. This reflects to some extent the maturity of many technologies for heat and/or power generation from biomass that are already commercialised and have less potential for major technological breakthroughs through R&D. Nonetheless, there are technologies that still require R&D effort in order to improve conversion efficiencies and achieve production costs competitive with existing technologies. In addition there is scope for R&D along the whole supply chain to make bioenergy more efficient, and reduce costs of feedstocks, transport and the final product.

Government support for RD&D will be needed in the short term to accelerate the development of technologies currently in the early stages of development. Private sector investments will also be crucial, and could be achieved by, for example, innovative public-private partnerships. It is crucial that RD&D efforts focus on all parts of the supply chain, from crop breeding to cultivation techniques to harvesting, pre-treatment and transport and finally conversion to energy, to achieve all the potential efficiency improvements and cost reductions.

Downstream R&D needs, such as in conversion technologies and end-use applications for bioenergy heat and power, are often addressed through energy-related research funds and initiatives. R&D efforts in the upstream part of the supply chain, including crop breeding, cultivation techniques and feedstock storage, are often also relevant to agriculture and forestry in general, and could help boost productivity and avoid losses in these sectors. This means that public funds to support such R&D might come from different, non-energy related sources, and should be used in a way that improves bioenergy supply and at the same time benefits agricultural and forestry supply chains.

International collaboration

This roadmap recommends the following actions	***Timing***
Enhance efforts to introduce internationally aligned certification schemes for biomass feedstocks based on commonly agreed sustainability indicators.	2012-20
Increase efforts to align technical standards for biomass intermediates to reduce trade barriers and infrastructure compatibility problems.	2012-20
Expand international RD&D collaboration, making best use of national competencies.	2012-30
Enhance exchange of technology and deployment, including best practices for sustainable bioenergy production.	2012-30

International collaboration will be required in many fields to create a sustainable global bioenergy sector. Joint international efforts in the mapping of bioenergy potential, such as the international Clean Energy Ministerial Bioenergy Working Group's Bioenergy Atlas, will be crucial to provide better land-use data and will help to improve the analysis of global biomass potential. Crop-breeding efforts and large-scale field trials should also be undertaken jointly, combining existing technical knowledge with local expertise on indigenous crop species. Best practices for sustainable feedstock cultivation need to be transferred to regions with lack of capacity in this field. This will be particularly important to help small feedstock producers comply with sustainability certification schemes and gain access to international markets. In addition it will have positive spill-over effects on agricultural production in general.

Joint RD&D efforts to develop bioenergy conversion processes have already been successfully established but need to be enhanced to ensure capacity building and technology transfer. Involving developing countries in the technology development is a key issue to establish viable bioenergy concepts in different regional contexts. Co-operation will be needed between industrialised and developing countries, and among developing countries. Knowledge gained in publicly funded projects should be shared in a manner that promotes both horizontal and vertical transfer and access to technologies and know-how for sustainable bioenergy production.

International collaboration to develop sound sustainability criteria for bioenergy has already been fruitful, as the launch and field testing of indicators developed by the Global Bioenergy Partnership (GBEP) in pilot projects in Columbia, Ghana and Indonesia shows. Further collaboration is now needed to ensure certification schemes for bioenergy are aligned internationally to ensure the marketability of biomass feedstocks in different markets. Global alignment of technical standards – including in particular intermediates such as pyrolysis oil and torrefied wood – will improve biomass tradability and help to overcome non-economic barriers related to infrastructure and consumer acceptance. Exchange of experiences between emerging markets and large bioenergy-producing countries and regions (such as North America, the European Union, Brazil and China) will help spur the development of bioenergy in new markets.

Many international organisations and initiatives are working on development of sustainable bioenergy and biofuels. The IEA Bioenergy Implementing Agreement,[20] for instance, is working on RD&D issues and emphasising large-scale global deployment of bioenergy. The agreement includes 12 tasks that focus on different technologies and aspects of bioenergy development along the whole supply chain. It provides a good platform for greater collaboration among OECD and non-OECD countries, focusing on sustainable large-scale bioenergy deployment and the commercialisation of new technologies in this field.

20 www.ieabioenergy.com

Bioenergy in developing countries

Bioenergy today plays a key role in the energy supply of many developing countries, in particular in Sub-Saharan Africa. Given that a large share of world primary bioenergy supply is consumed in these countries and that their energy demand is expected to grow in the future, it will be crucial to consider the particular needs of developing countries and develop specific policy frameworks to achieve the level of bioenergy deployment envisaged in this roadmap.

Most of the biomass consumed in non-OECD countries is often used for domestic heating (including cooking) at very low efficiencies. The high reliance on biomass as a primary source of energy also leads to environmental problems such as forest degradation, a problem that is likely to increase with population growth. Improving the efficiency of current traditional biomass use and deploying alternative fuels for cooking such as biogas and ethanol will thus be crucial elements in a more sustainable bioenergy supply in developing countries (for further discussion see IEA, 2011c).

Several small-scale bioenergy projects in developing countries have already been shown to lead to greater access to energy and to offer new opportunities in rural areas, by creating new employment and revenues along the supply chain. Bioenergy can also help reduce spending on fossil fuels, for instance when diesel generators are run on locally produced vegetable oil, or when biogas is used to generate electricity instead. In addition, such developments can increase the reliability of fuel supply and enable higher productivity due to more reliable access to electricity. One of the key challenges to overcome is the initial investment needed for a diesel generator or biogas system with engine, since local communities often lack the required capital. Government support and innovative private sector schemes will therefore be needed to overcome this initial economic hurdle. Overviews of some case studies are given, for instance, by Janssen and Rutz (2012) and Practical Action Consulting (2009).

Commercial-scale options to generate bioenergy electricity and heat are another option to increase supply while making use of domestic resources. Several countries outside the OECD are already generating bioenergy on a commercial scale, with Brazil and China among the largest producers of electricity from biomass. Some of the technology options deployed for instance in Brazil, where sugarcane mills are using bagasse for electricity and heat generation, could be replicated in other sugar-producing countries in Africa and Asia. Given the lack of access to electricity in many developing countries, such options should be pursued vigorously.

Many developing countries face particular challenges in developing a viable, sustainable bioenergy industry. Limited financial resources, poor infrastructure, lack of skilled labour and lack of formal land ownership structures are among the most significant barriers. Most of these challenges are aggravated by unstable policy frameworks, which can pose considerable risks for private sector investments. Bioenergy development will therefore also depend on public investment. In order to make such investments worthwhile, it will be essential to make the fullest use of synergies with existing industries such as crop and timber production. The benefits of infrastructure investments (*e.g.* road/rail, electricity access) can be maximised when undertaken as part of an overall rural development strategy that promotes rural development.

Administrative and governance problems may severely affect large-scale foreign investment in developing countries. Foreign investment in bioenergy projects may also be constrained by the limited size of domestic markets. Export of biomass or biomass intermediates to regions with strong demand can therefore be a viable option to attract new investments. Ensuring access to international markets for biomass exports is likely to increase investor confidence. However, it can create risks, for instance in the form of so-called land-grabbing, *i.e.* (foreign) investors buying or leasing vast amounts of agricultural land for bioenergy production, with negative impact on local farmers. Supporting smallholder participation in bioenergy value chains will be vital to avoid displacement of local populations and maximise benefits for rural development. Another option for financing bioenergy projects, including at village level or for individual households, is through the Clean Development Mechanism (CDM). Around 12% of all projects under the CDM today are bioenergy projects, and there is still considerable scope for developing CDM bioenergy projects in less developed countries.

Sound political frameworks, including land management schemes and sustainability certification based on internationally agreed criteria, will be crucial elements to ensure that foreign investments and CDM projects materialise. A challenge for developing countries is that costs of sustainability certification are typically higher than in industrialised countries; they can reach 20% of total production costs for smallholders (UNCTAD, 2008). There is thus a need to couple certification requirements with financing and technical assistance that allows developing countries to master and apply certification schemes, improve the credibility of their assessment bodies and reduce costs for certification of biomass production.

Capacity building along the whole supply chain will also be crucial to make full use of bioenergy. Building capacity for feedstock cultivation needs to involve best agricultural and forestry practices, which will benefit farmers and can increase productivity and sustainability of the whole agricultural/ forestry sectors. International collaboration and investments through public-private partnerships are needed to couple business models with comprehensive agricultural education and training for farmers. Furthermore, to ensure technology access and transfer, co-operation on RD&D should be enhanced among industrialised and emerging economies, as well as among developing countries. Technologies and biomass supply strategies suited to a country's specific needs should be developed, based on techno-economic analysis and with reference to experience in other countries. The focus in the short term should be on strategies that are technically less complex and do not require large investments.

Near-term actions for stakeholders

This roadmap has responded to requests from the G8 and other government leaders for more detailed analysis of the sustainable growth pathway for bioenergy. It is intended to outline a process that evolves to take into account new technology developments, policies and international collaboration efforts. The roadmap has been designed with milestones that the international community can use to ensure that bioenergy development efforts are on track to achieve reductions in greenhouse-gas emissions that are required by 2050 in a sustainable manner. The IEA, together with government, industry and non-governmental organisation (NGO) stakeholders, will report regularly on the progress achieved toward this roadmap's vision. For more information about the roadmap's actions and implementation, visit **www.iea.org/roadmaps**.

Stakeholder	Action items
National and local governments	• Ensure enhanced deployment of advanced biomass cookstoves and biogas systems, as part of a sustained effort to provide universal access to clean energy in developing countries. • Provide medium and long term targets and support policies that stimulate investment in sustainable bio-energy production and ensure that new, promising conversion technologies reach a commercial stage. • Progressively eliminate subsidies to fossil fuels, and establish a price for CO_2 emissions. • Ensure increased and sustained RD&D funding to promote cost and efficiency gains for existing and emerging technologies. • Implement sound sustainability criteria and evaluation methods for bioenergy, based on internationally agreed indicators, building on existing schemes in the forestry and biofuel sectors. • Set minimum GHG reduction targets and integrate environmental and social criteria for bioenergy heat and power into national support schemes. • Promote good practices in bioenergy production, particularly with regard to feedstock cultivation. • Work towards the development of an international market for bioenergy feedstocks by seeking commoditisation of biomass and biomass intermediates through international technical standards and elimination of trade barriers. • Ensure that bioenergy policies are aligned with related policies for agriculture, forestry and rural development. • Extend sustainability criteria for biofuels and bioenergy to all biomass products (including food and fibre) to ensure sustainable land use.

Stakeholder	Action items
Industry	• Establish commercial-scale plant for torrefaction, pyrolysis and bio-SNG by 2015. • Provide small-scale solutions for efficient bioenergy co-generation and trigeneration (power and heat for heating and cooling) technologies. • Improve feedstock flexibility of processes to allow a broader range of feedstocks and reduce feedstock competition with other sectors. • Implement credible, independent sustainability certification schemes. • Engage in public-private partnerships to support smallholder qualification and participation in bioenergy value chains. • Establish large-scale field trials and vigorously pursue the development of new, productive feedstocks.
Universities and other research institutions	• Further improve life-cycle assessment methodology for bioenergy, in particular accounting for indirect land-use change. • Provide spatial information on land and biomass resources and develop systems to monitor, evaluate and avoid undesired land-use changes. • Improve economic models based on detailed cost curves for feedstock supply in different regions, to improve analysis of bioenergy potentials. • Collaborate with industry on large-scale energy crop field trials. • Develop national bioenergy RD&D roadmaps to identify critical technology breakthroughs needed for sustainable bioenergy production.
Non-governmental organisations	• Monitor progress towards sustainable bioenergy development and policy milestones and publish results regularly to keep governments and industry on track. • Provide objective information on the potential of sustainable bioenergy to mitigate climate change, increase energy security, and provide economic benefits to rural communities. • Engage in capacity building and implementation of good practices.
Intergovernmental organisations and multilateral development agencies	• Provide capacity building/training for regulatory frameworks and business models to help developing countries implement sustainable cultivation techniques, feedstock supply and bioenergy conversion. • Work on development of technical standards for biomass, in particular intermediates, to enhance trade between countries. • Provide technical support to help developing countries devise and implement certification schemes and bioenergy support policies. • Promote and facilitate a structured dialogue between policy makers and the round-tables that are developing standards for the certification of bioenergy or bioenergy feedstocks, in order to ensure coherence between regulatory frameworks and standards.

Appendix I: Feedstocks, pre-treatment technologies and sustainability certification

Bioenergy feedstocks and characteristics

Wastes

Using wastes such as sewage sludge and the organic fraction of MSW as fuel provides an alternative disposal or environmental treatment option that avoids disposal costs. This environmental credit is often necessary to make projects economically viable, because the difficult characteristics of the feedstocks require specific technologies with high capital and operating costs. For example a system for combusting MSW needs to be extremely robust, to handle a very heterogeneous feedstock, be capable of combusting inputs which vary greatly in terms of moisture content and calorific value, and be equipped with sophisticated flue gas cleaning systems to achieve stringent emission standards. This gas cleaning requirement means that small plants are too costly, and larger scale operation may be necessary (5 MW to 50 MW electricity output).

Anaerobic digestion, including landfill gas, is another common technology suitable for using sewage sludge, organic waste or animal waste to produce biogas for upgrading to biomethane, or heat and power generation on site. The scale of operation is constrained by the availability of the raw materials within a certain distance from the conversion plant, and is typically in the range of 0.5 MW to 20 MW electricity generation.

Process residues

Many bio-based industrial processes lead to the collection and concentration of large volumes of residues at the point of production. For example: the timber processing produces large volumes of sawdust and other wood residues; pulp and paper production generates black liquor; the sugarcane industry produces large volumes of bagasse. If there are no existing uses for these materials, they can be available at zero or low costs (typically between USD 0 to USD 4 per Gigajoule [GJ]) and can be used to produce electricity or process heat for the associated industrial processes or as an additional by-product of the process. For example in Brazil, and other countries with sugarcane industries, the use of high pressure boilers has led to a rapid increase in the production of electricity from bagasse, both for use within the sugar and ethanol production and for export to the grid. For process residues the size of bioenergy plant operation is determined by the availability of the raw materials (although this can be supplemented by bringing in additional materials available nearby in some cases). The scale of operation is typically limited to 50 MWe.

Locally collected feedstocks

The third category is feedstocks produced during harvesting operations in agriculture or forestry, and that can be collected and brought to a central point for conversion into energy, as is already the case in Denmark, China and other countries. These residues could be supplemented by purpose grown energy crops such as short rotation or plantation forestry in order to boost the local availability of raw materials and allow for operation at larger scale. Given the cost of collecting, transporting and eventually storing of the biomass, the costs of the delivered feedstock are typically between USD 4 and USD 8/GJ. Increasing the catchment area pushes up the transport costs (and related CO_2 emissions) and will thus limit the economic scale of operation of such plants to a maximum of around 50 MW, except where the feedstocks are particularly abundant.

Internationally traded feedstocks

Finally there is the prospect of pre-treating biomass (see below) to produce solid, liquid and gaseous feedstocks with high energy density, suitable for international long-distance shipping for use in centralised heat (mainly industrial use) and power generation. For example wood pellets are currently produced in several regions including Russia, British Columbia and the Southern United States, and brought in bulk sea carriers to Europe for co-firing with coal or in large scale power generation. Given the attractive incentives in several European countries, many European based utilities are actively developing supply chains all around the world. Currently such fuels are delivered internationally at prices of around USD 8 to USD 12/GJ, with prices influenced to some extent by the incentives provided in European markets. Such fuels are compatible with large scales of operation similar to those of fossil fuel-based generation, so benefitting from enhanced electricity generation efficiencies, and projects considered are typically in the range 50 MW to 200 MW.

Pre-treatment technologies

A good overview of the current state of the art has been provided at a recent workshop of the IEA Bioenergy Implementing Agreement (IEA Bioenergy, 2011).

Drying

Drying is the most crucial form of pre-treatment for all thermal conversion routes of biomass feedstocks into energy. High moisture content needs to be reduced to increase the net calorific value of the biomass, reduce transport costs, and improve combustion efficiency and thus the overall economics of the process. Biomass such as agricultural and forest residues can be left in stacks on the harvesting site for dying, but especially in humid climates, or regions with heavy snow fall, this will not be sufficient to get to very low (<20%) moisture content. Covering biomass piles with waterproof sheets is a common measure that helps achieve low moisture content and avoids decay of the biomass. In some cases, biomass feedstocks need to be actively dried before conversion into pellets, or into useful energy. This can be feasible from an economic and environmental point of view if waste heat is used, but to use fossil energy for drying biomass is questionable from both an economic as well as sustainability point of view.

Pelletisation and briquetting

Both pelletisation and briquetting are commercially available, relatively simple technologies to mechanically compact biomass. Sawdust and low quality wood are the major feedstocks for production of wood pellets, whereas briquetting is commonly used to condense agricultural residues. Wood pellets can be produced in different quality standards depending on the purity of the feedstock material. High quality pellets (EN 14961-2, class A1+2) are used in smaller scale appliances including those for heating single dwellings, allowing easier handling and distribution and minimising the scale of storage required. Pellets are often used for long-haul transport of fuels for large scale use, for example for co-firing in coal fired power generation plants.

Table 6: Typical characteristics of different biomass feedstocks compared to coal

Feedstock	Moisture content (%)	Bulk density (kg/m^3)	Heating value (LHV) (GJ/t)	Energy density (LHV) (GJ/m^3)	Energy content (kWh/t)
Coal (anthracite)	10	870	35	31	9 700
Solid wood	20*	550	15	8	4 200
Wood chips	20*	200	15	3	4 200
Sawdust	10	160	17	3	4 700
Black liquor	25	1 400	12	17	3 400
Wood pellets	10	660	17	11	4 700
Torrefied wood pellets	5	750	21	16	5 800
Pyrolysis oil	25	1 100	17	19	4 700
Straw (baled)	15*	140	15	2	4 200
Organic waste	60	500	7	4	1 200

*air dried.

Notes: LHV = lower heating value. Table indicates average values, which can differ in practice.

Source: Based on DENA, 2011; FNR, 2011a; IEA Bioenergy, 2011; Kankkunen and Miikkulainen, 2003.

Torrefaction

In the torrefaction process biomass (currently mainly wood) is heated to between 200°C and 300°C in the absence of oxygen and turned into char. The process is similar to conventional charcoal production, with the important difference that more volatiles remain in the biomass feedstock. The torrefied wood is typically pelletised and has a higher bulk density and 25% to 30% higher energy density than conventional wood pellets (see Table 6). In addition, the torrefied biomass has properties closer to those of coal and can be handled, stored and processed in existing coal plants without any modification. The first large-scale torrefaction plants, with capacities of 35 kton to 60 kton/year, are now being successfully demonstrated (Kleinschmidt, 2011), but the economics of the process remain somewhat uncertain due to a lack of reliable data from such commercial-scale production. Potentially higher costs per unit delivered energy for torrefied biomass compared to wood pellets could be offset through reductions in capital and operating costs in the combustion plant. One of the critical R&D issues to address is the feedstock flexibility of the process, since this would significantly enhance the feedstock base and the role of torrefaction in mobilising scattered biomass resources such as agricultural residues.

Pyrolysis/hydrothermal upgrading

In this process biomass is heated to temperatures between 400°C and 600°C in the absence of oxygen. The process produces solid charcoal, liquid pyrolysis oil (also referred to as bio-oil), and a product gas. The exact fraction of each component depends on the temperature and residence time (Bauen *et al.*, 2009). Pyrolysis oil has about twice the energy density of wood pellets, which could make it particularly attractive for long-distance transport. So far, however, the technology is in demonstration phase for this application. Challenging technical issues include the quality of the pyrolysis oil (such as relatively high oxygen content) and its long-term stability, as well as the economics of its production and use. Pyrolysis oil could be used in heat and/or power generation units, or upgraded to transport fuel. Research is also under way to explore the possibility of mixing pyrolysis oil with conventional crude oil for use in oil refineries (EBTP, 2010).

Biogas and biomethane

One possible route for biomethane production is **anaerobic digestion** of biomass to a biogas consisting of methane (CH_4), CO_2, H_2O and other gases. The process comprises biomass decay in the absence of oxygen and occurs, for instance, to organic waste in landfills. The process has been commercialised in dedicated biogas digesters fed with sewage sludge, manure, organic waste or energy crops. Biogas digesters of a few kilowatt capacity (household size) have been deployed, in particular in developing countries' rural areas, for domestic cooking and heating. China has an estimated 32 million household biogas digesters (REN21, 2009), but utilisation rates are apparently low and methane leakage is a serious concern. For the commercial production of biogas, digesters of 150 kW up to several megawatt capacity are typically used.

Biogas can also be upgraded to biomethane to meet natural gas standards and fed into the natural gas grid or used as vehicle fuel. Commercial biogas production has been growing rapidly in Sweden, Austria and Germany (the largest producer of biogas in the European Union with total installed capacity of 2 700 MW_{el} and 46 biogas plants upgrading biogas and feeding it into the natural gas grid (FNR, 2011b).

A second process currently under development is the **thermochemical conversion** of biomass to a methane-rich gas synthesis gas. The product is called bio-synthetic natural gas (bio-SNG) and can be used on-site for heat and electricity generation, or upgraded to biomethane and for injection into the natural gas grid or use in transport. A demonstration plant has been running for several years in Austria, and large-scale projects are currently envisaged for Sweden (EBTP, 2012).

Overview of sustainability certification schemes relevant to bioenergy

The **Global Bioenergy Partnership** (GBEP)[21] – an intergovernmental initiative aiming to develop a methodological framework that policy makers and stakeholders can use to assess GHG emissions associated with bioenergy. In May 2011, the GBEP has launched a set of 24 voluntary indicators whose applicability is currently being tested

21 www.globalbioenergy.org

in different countries. A report outlining the indicators and methodology has been launched in December 2011 (GBEP, 2011).

The **International Organization for Standardization** (ISO)[22] is developing an international standard via a new ISO project committee (ISO/PC 248, Sustainability Criteria for Bioenergy). The standard aims to address environmental and social aspects of bioenergy production and use, as well as making bioenergy more competitive, to the benefit of both national and international markets.

The **International Sustainability and Carbon Certification System** (ISCC)[23] has developed the first internationally recognised certification system for biomass. The ISCC certifies the sustainability and GHG savings of all kinds of biomass, including feedstocks for bioenergy and biofuel production.

The **Roundtable on Sustainable Biofuels** (RSB)[24] provides an international standard and certification scheme for socially, environmentally and economically sustainable production of biomass and biofuels. The primary use of the RSB Standard is a certification system involving independent third party certification bodies in a risk management approach that ensures security and robustness while remaining flexible for participating operators.

22 www.iso.org

23 www.iscc-system.org

24 rsb.epfl.ch

The **NTA 8080**[25] is a voluntary certification scheme for biomass used in energy applications, the chemical industry and other sectors. It has been developed by a diverse group of stakeholders, based on Dutch and European sustainability requirements.

The **Forest Stewardship Council** (FSC)[26] is an independent, non-governmental organisation that provides a well established, voluntary, market-based tool to certify wood products from sustainable forest management worldwide. The underlying principles and criteria are developed through a multi-stakeholder process and include managerial aspects as well as environmental and social requirements. So far, GHG savings are not part of the standard, however.

The **Programme for the Endorsement of Forest Certification** (PEFC)[27] is another independent, non-profit, non-governmental organisation dedicated to promoting sustainable forest management and best practice along the whole supply chain, through independent third-party certification. The PEFC endorses national forest certification systems that are developed through multi-stakeholder processes, and ensures consistency with international requirements. So far, GHG savings are not part of the standard, however.

25 www.sustainable-biomass.org

26 www.fsc.org

27 www.pefc.org

Appendix II: Abbreviations, acronyms and units of measure

Acronyms and abbreviations

2DS	*ETP 2012* 2°C Scenario
6DS	*ETP 2012* 6°C Scenario
AD	anaerobic digestion
AEZ	Agro-Ecological Zoning
BECCS	bioenergy with carbon capture and storage
BIGCC	biomass integrated gasification combined cycle
Bio-SNG	bio synthetic natural gas (also referred to as bio synthetic natural gas)
CCS	carbon capture and storage
CDM	Clean Development Mechanism
CO_2	carbon dioxide
ETP 2012	*Energy Technology Perspectives 2012*
EU	European Union
FAO	Food and Agriculture Organisation of the United Nations
FSC	Forest Stewardship Council
GBEP	Global Bioenergy Partnership
GHG	greenhouse gas
IFES	Integrated Food and Energy Systems
IIASA	International Institute for Applied Systems Analysis
ILUC	indirect land-use change
IPCC	Intergovernmental Panel on Climate Change
ISCC	International Sustainability and Carbon Certification
ISO	International Organisation for Standardisation
LCA	life-cycle assessment
LUC	land-use change
MSW	municipal solid waste
NGO	non-governmental organisation
ORC	Organic Rankine Cycle
PEFC	Programme for the Endorsement of Forest Certification
R&D	research and development
RD&D	research, development and demonstration
RED	Renewable Energy Directive
RSB	Roundtable on Sustainable Biofuels
TPES	Total primary energy supply
USD	US dollar, refers to 2010 in this report

Units of measure

EJ	exajoule = 10^{18} joule
Gt	gigatonne
kton	kilotonne (*i.e.* 1000 tonnes)
kW	kilowatt
kWe	kilowatt electric
kWth	kilowatt thermal
kWh	kilowatt-hour
MW	megawatt
Mha	million hectares
MJ	megajoule
Mtoe	million tonnes of oil equivalent
Ppm	parts per million
TWh	Terawatt-hour

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List of selected literature and relevant websites for further reading

Literature for further reading	
IEA (forthcoming), *Energy Technology Perspectives 2012*	www.iea.org
IEA (2011), *Technology Roadmap - Biofuels for Transport*	www.iea.org/roadmaps
IEA (2011), *Energy for all. Financing access for the poor.*	www.worldenergyoutlook.org
IEA (2007), *Bioenergy Project Development & Biomass Supply*	www.iea.org
Bauen et al. (2009), *Biomass - A Sustainable and Reliable Source of Energy*	www.ieabioenergy.com
Berndes et al. (2010), *Bioenergy, Land-Use Change and Climate Change Mitigation*	www.ieabioenergy.com
Cocchi *et al.* (2011), *Global wood pellet industry and market study*	www.bioenergytrade.org
GBEP (2011), *The Global Bioenergy Partnership Sustainability Indicators for Bioenergy*	www.globalbioenergy.org
FAO and UNEP (2010), *A Decision Support Tool for Sustainable Bioenergy*	www.fao.org
FAO (2011), *Energy-smart food for people and climate*	www.fao.org/energy
IPCC (2011), *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation*	www.ipcc.ch
Junginger et al. (2011), *Barriers and Opportunities for Global Bioenergy Trade*	www.bioenergytrade.org
Loo & Koppejan (2008), *The Handbook of Biomass Combustion and Co-firing*	www.ieabcc.nl
UNEP Oeko Institut and IEA Bioenergy Task 43 (2011), *The Bioenergy and Water Nexus*	www.unep.org
UNIDO (2011), *Renewable Energy in Industry Applications*	www.unido.org
WWF (2011), *Next Generation Plantations*	www.panda.org

Websites	
International Energy Agency	www.iea.org
IEA Technology Roadmaps	www.iea.org/roadmaps
IEA Policies and Measures Database	renewables.iea.org
IEA Bioenergy Implementing Agreement	www.ieabioenergy.com
Global Bioenergy Partnership	www.globalbioenergy.org
Global Environmental Fund	www.thegef.org

Note: This list represents a selection of some of the relevant websites, organisations and literature. Given the enormous amount of relevant stakeholders, it does not attempt to present a complete list of all relevant websites and literature in the field of sustainable bioenergy production.

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IEA Publications, 9 rue de la Fédération, 75739 PARIS CEDEX 15
PRINTED IN FRANCE BY CORLET, July 2012 (second edition)

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