Technology Roadmap

Biofuels for Transport

International Energy Agency

INTERNATIONAL ENERGY AGENCY

The International Energy Agency (IEA), an autonomous agency, was established in November 1974. Its primary mandate was – and is – two-fold: to promote energy security amongst its member countries through collective response to physical disruptions in oil supply, and provide authoritative research and analysis on ways to ensure reliable, affordable and clean energy for its 28 member countries and beyond. The IEA carries out a comprehensive programme of energy co-operation among its member countries, each of which is obliged to hold oil stocks equivalent to 90 days of its net imports. The Agency's aims include the following objectives:

- Secure member countries' access to reliable and ample supplies of all forms of energy; in particular, through maintaining effective emergency response capabilities in case of oil supply disruptions.
- Promote sustainable energy policies that spur economic growth and environmental protection in a global context – particularly in terms of reducing greenhouse-gas emissions that contribute to climate change.
- Improve transparency of international markets through collection and analysis of energy data.
- Support global collaboration on energy technology to secure future energy supplies and mitigate their environmental impact, including through improved energy efficiency and development and deployment of low-carbon technologies.
- Find solutions to global energy challenges through engagement and dialogue with non-member countries, industry, international organisations and other stakeholders.

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Foreword

Current trends in energy supply and use are unsustainable – economically, environmentally and socially. Without decisive action, energy-related greenhouse gas (GHG) emissions will more than double by 2050 and increased oil demand will heighten concerns over the security of supplies. We can and must change the path that we are now on; low-carbon energy technologies will play a crucial role in the energy revolution required to make this change happen. To effectively reduce GHG emissions, energy efficiency, many types of renewable energy, carbon capture and storage (CCS), nuclear power and new transport technologies will all require widespread deployment. Every major country and sector of the economy must be involved and action needs to be taken now, in order to ensure that today's investment decisions do not burden us with sub-optimal technologies in the long term.

There is a growing awareness of the urgent need to turn political statements and analytical work into concrete action. To address these challenges, the International Energy Agency (IEA), at the request of the G8, is developing a series of roadmaps for some of the most important technologies needed to achieve a global energy-related CO_2 target in 2050 of 50% below current levels. Each roadmap develops a growth path for the covered technologies from today to 2050, and identifies technology, financing, policy and public engagement milestones that need to be achieved to realise the technology's full potential. These roadmaps also include a special focus on technology development and diffusion to emerging economies. International collaboration will be critical to achieve these goals.

Biofuels provide only around 2% of total transport fuel today, but new technologies offer considerable potential for growth over the coming decades. This roadmap envisions that by 2050, 32 exajoules of biofuels will be used globally, providing 27% of world transport fuel. In addition to enabling considerable greenhouse-gas reductions in the transport sector, biofuels can contribute substantially to energy security and socio-economic development. To achieve this vision, strong and balanced policy efforts are required that create a stable investment environment and allow commercialisation of advanced biofuel technologies, efficiency improvements and further cost reductions along the production chain of different biofuels. Sound sustainability requirements are vital to ensure that biofuels provide substantial GHG emission reductions without harming food security, biodiversity or society.

This roadmap identifies technology goals and defines key actions that stakeholders must undertake to expand biofuel production and use sustainably. It provides additional focus and urgency to international discussions about the importance of biofuels to a low CO_2 future. As the recommendations of the 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.

Nobuo Tanaka
Executive Director, IEA

This roadmap was prepared in 2011. 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 IEA Renewable Energy Division at: renewables@iea.org

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Key findings

- Biofuels – liquid and gaseous fuels derived from organic matter – can play an important role in reducing CO_2 emissions in the transport sector, and ehancing energy security.

- By 2050, biofuels could provide 27% of total transport fuel and contribute in particular to the replacement of diesel, kerosene and jet fuel. The projected use of biofuels could avoid around 2.1 gigatonnes (Gt) of CO_2 emissions per year when produced sustainably.

- To meet this vision, most conventional biofuel technologies need to improve conversion efficiency, cost and overall sustainability. In addition, advanced biofuels need to be commercially deployed, which requires substantial further investment in research, development and demonstration (RD&D), and specific support for commercial-scale advanced biofuel plants.

- Support policies should incentivise the most efficient biofuels in terms of life-cycle greenhouse-gas performance, and be backed by a strong policy framework which ensures that food security and biodiversity are not compromised, and that social impacts are positive. This includes sustainable land-use management and certification schemes, as well as support measures that promote "low-risk" feedstocks and efficient processing technologies.

- Meeting the biofuel demand in this roadmap would require around 65 exajoules (EJ)[1] of biofuel feedstock, occupying around 100 million hectares (Mha) in 2050. This poses a considerable challenge given competition for land and feedstocks from rapidly growing demand for food and fibre, and for additional 80 EJ[1] of biomass for generating heat and power.[2] However, with a sound policy framework in place, it should be possible to provide the required 145 EJ of total biomass for biofuels, heat and electricity from residues and wastes, along with sustainably grown energy crops.

- Trade in biomass and biofuels will become increasingly important to supply biomass to areas with high production and/or consumption levels, and can help trigger investments and mobilise biomass potentials in certain regions.

- Scale and efficiency improvements will reduce biofuel production costs over time. In a low-cost scenario, most biofuels could be competitive with fossil fuels by 2030. In a scenario in which production costs are strongly coupled to oil prices, they would remain slightly more expensive than fossil fuels.

- While total biofuel production costs from 2010 to 2050 in this roadmap range between USD 11 trillion to USD 13 trillion, the marginal savings or additional costs compared to use of gasoline/diesel are in the range of only +/-1% of total costs for all transport fuels.

Key actions in the next 10 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 realise the deployment of sustainable biofuels envisioned in this roadmap, governments must take the lead role in creating a favourable climate for industry investments. In particular governments should:

- Create a stable, long-term policy framework for biofuels to increase investor confidence and allow for the sustainable expansion of biofuel production.
- Ensure sustained funding and support mechanisms at the level required to enable promising advanced biofuel technologies to reach commercial production within the next 10 years and to prove their ability to achieve cost and sustainability targets.
- Continue to develop internationally agreed sustainability criteria as the basis for implemention of sound certification schemes for biofuels and related land-use policies on a national level – without creating unwanted trade barriers, especially for developing countries.
- Link financial support schemes to the sustainable performance of biofuels to ensure >50% life-cycle GHG emission savings for all biofuels, and to incentivise use of wastes and residues as feedstock.

1 This is primary energy content of the biomass feedstock before conversion to final energy.

2 A roadmap looking specifically at the use of bioenergy for heat and power will be produced early in 2012.

- Increase research efforts on feedstocks and land availability mapping to identify the most promising feedstock types and locations for future scale-up.
- Reduce and eventually abolish tariffs and other trade barriers to enhance sustainable biomass and biofuel trade, and tap new feedstock sources.
- Support international collaboration on capacity building and technology transfer to promote the adoption of sustainable biofuel production globally.
- Promote the alignment of biofuel policies with those in related sectors, such as agriculture, forestry and rural development.
- Adopt an overall sustainable land-use management system that aims to ensure all agricultural and forestry land is comprehensively managed in a balanced manner to avoid negative indirect land-use change and support the wide range of demands in different sectors.

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, 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 recognise 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 biofuel roadmap is one of a set of technology roadmaps being developed by the IEA.

The overall aim is to advance global development and uptake of key technologies to reach a 50% CO_2 equivalent emission reduction by 2050 over 2005 levels. The roadmaps will enable governments and industry and financial partners to identify steps needed and implement measures to accelerate required technology development and uptake.

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 roadmap 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 biofuels

To reduce dependency on oil and to contribute to growing efforts to decarbonise the transport sector, biofuels provide a way of shifting to low-carbon, non-petroleum fuels, often with minimal changes to vehicle stocks and distribution infrastructure. While improving vehicle efficiency is by far the most important low-cost way of reducing CO_2 emissions in the transport sector, biofuels will need to play a significant role in replacing liquid fossil fuels suitable for planes, marine vessels and other heavy transport modes that cannot be electrified. Production and use of biofuels can also provide benefits such as increased energy security, by reducing dependency on oil imports, and reducing oil price volatility. In addition, biofuels can support economic development by creating new sources of income in rural areas.

This roadmap is based on the IEA's *Energy Technology Perspectives 2010* (*ETP 2010*) (IEA, 2010c) BLUE Map Scenario, which sets out cost effective strategies for reducing greenhouse-gas emissions by half by 2050.[3] The BLUE Map Scenario envisages that biofuels could contribute significantly to reducing emissions by increasing from 2% of total transport energy today to 27% by 2050. The scenario suggests that a considerable share of the required volume will come from advanced biofuel technologies that are not yet commercially deployed.

Achieving this roadmap's vision of sustainable biofuel supply – and the associated environmental, economic and societal benefits – will require concerted policy support. Sustained, effective and flexible incentive schemes are needed to

3 The primary tool used for the analysis of the BLUE scenarios is the IEA ETP model, a global 15-region model that permits the analysis of fuel and technology choices throughout the energy system. The ETP model belongs to the MARKAL family of bottom-up modelling tools and uses optimisation to identify least-cost mixes of energy technologies and fuels to meet the demand for energy services, given constraints such as the availability of natural resources. The ETP model has been supplemented with detailed demand-side models for all major end-uses in the industry, buildings and transport sectors. These models were developed to assess the effects of policies that do not primarily act on price. For more details: www.iea.org/publications/free_new_Desc.asp?PUBS_ID=2100

help biofuels reach full competitiveness. This will require a long-term focus on technology development of those biofuel technologies that prove to be sustainable with regard to their social, environmental and economic impact. At the same time, the supply of biomass feedstocks needs to be addressed. A sound policy framework is needed to address the growing feedstock demand for biofuel, heat and power, and to ensure sustainability of biomass production throughout all these uses.

Box 1: Biofuels: definitions

In this report the term biofuel refers to liquid and gaseous fuels produced from biomass – organic matter derived from plants or animals.

There is considerable debate on how to classify biofuels. Biofuels are commonly divided into first-, second- and third-generation biofuels, but the same fuel might be classified differently depending on whether technology maturity, GHG emission balance or the feedstock is used to guide the distinction. This roadmap uses a definition based on the maturity of a technology, and the terms "conventional" and "advanced" for classification (see also IEA, 2010f). The GHG emission balance depends on the feedstock and processes used, and it is important to realise that advanced biofuels performance is not always superior to that of conventional biofuels.

Conventional biofuel technologies include well-established processes that are already producing biofuels on a commercial scale. These biofuels, commonly referred to as first-generation, include sugar- and starch-based ethanol, oil-crop based biodiesel and straight vegetable oil, as well as biogas derived through anaerobic digestion. Typical feedstocks used in these processes include sugarcane and sugar beet, starch-bearing grains like corn and wheat, oil crops like rape (canola), soybean and oil palm, and in some cases animal fats and used cooking oils.

Advanced biofuel technologies are conversion technologies which are still in the research and development (R&D), pilot or demonstration phase, commonly referred to as second- or third-generation. This category includes hydrotreated vegetable oil (HVO), which is based on animal fat and plant oil, as well as biofuels based on lignocellulosic biomass, such as cellulosic-ethanol, biomass-to-liquids (BtL)-diesel and bio-synthetic gas (bio-SG). The category also includes novel technologies that are mainly in the R&D and pilot stage, such as algae-based biofuels and the conversion of sugar into diesel-type biofuels using biological or chemical catalysts.

Roadmap purpose

IEA analysis presented in *ETP 2010* and its BLUE Map Scenario, shows that, inter alia, to stabilise atmospheric greenhouse gases around 450 parts per million (ppm) to limit global temperature rise to below 2°C, a significant increase in use of low-carbon biofuels will be required by 2050. However, the scenario does not include a detailed analysis on how to reach these targets. This roadmap aims to identify the primary tasks that must be undertaken globally to accelerate the sustainable deployment of biofuels to reach the BLUE Map projections. The roadmap discusses barriers and challenges to large-scale biofuel deployment such as the need for commercialisation of advanced biofuel technologies, relatively high production costs and supply chain logistics, as well as broader issues governing sustainable feedstock production and biofuel market structures.

In some markets, certain steps described here have already been taken or are under way; but many countries, particularly those in developing regions, are only just beginning to develop biofuels, with some not undertaking any particular action yet. 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 biofuel conversion technology and deployment, since more detailed IEA reports on these topics have recently been published. Conversion technologies are covered in ***From 1st- to 2nd-Generation Biofuel Technologies***.[4] The IEA paper ***Sustainable Production of Second-Generation Biofuels***[5] provides a more detailed analysis of the potential use of residues for biofuel production, including an analysis of current status and perspectives for introduction of advanced biofuels in developing countries. Further analysis of the role of biofuels in the transport sector in different scenarios to 2035 is presented in the IEA ***World Energy Outlook 2010***. In addition, while citations are provided throughout this report, a list with relevant websites and literature can be found in Appendix II. Bioenergy use for heat and power generation will be covered in the forthcoming IEA ***Bioenergy Roadmap***.[6]

This roadmap should be regarded as 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 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 biofuel industry, the automotive sector, R&D institutions and government institutions. The roadmap includes the results of in-depth IEA analysis and two project workshops held at the IEA headquarters. The first workshop considered biofuel technology development, infrastructure requirements and end-use, while the second addressed biomass potentials, sustainability issues and biomass markets relevant to both biofuel and bioenergy heat and power production. Workshop summaries that were circulated among participants provided important input to this roadmap. In addition, a draft roadmap was circulated to participants and a wide range of additional reviewers (see Appendix II).

4 www.iea.org/papers/2008/2nd_Biofuel_Gen.pdf

5 www.iea.org/papers/2010/second_generation_biofuels.pdf

6 www.iea.org/roadmaps

This roadmap builds on previous roadmaps by several other organisations, including:

- Agence de l'environnement et de la maîtrise de l'energie (Ademe), France: *Road Map for Second-Generation Biofuels*[7];
- European Biofuels Technology Platform: *Strategic Research Agenda Update 2010*[8];
- REFUEL: *A European Road Map for Biofuels*[9];
- US Department of Energy: *National Algal Biofuel Technology Roadmap*.[10]

This roadmap is organised into six sections. First, current biofuel production and the status of different conversion technologies are discussed, followed by a section that discusses relevant sustainability issues and recent policy measures to ensure the sustainable production of biofuels. The next section describes the vision for large-scale biofuel deployment and CO_2 abatement based on the *ETP 2010* BLUE Map Scenario. The roadmap next addresses the importance of land and biomass resources, and in the following section analyses the economics of production of different biofuels, including production costs and total expenditure requirements 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 biofuel deployment outlined in this roadmap.

7 www2.ademe.fr

8 www.biofuelstp.eu

9 www.refuel.eu

10 www1.eere.energy.gov/biomass/pdfs/algal_biofuels_roadmap.pdf

Biofuels status today

Overview

Biofuels began to be produced in the late 19th century, when ethanol was derived from corn and Rudolf Diesel's first engine ran on peanut oil. Until the 1940s, biofuels were seen as viable transport fuels, but falling fossil fuel prices stopped their further development. Interest in commercial production of biofuels for transport rose again in the mid-1970s, when ethanol began to be produced from sugarcane in Brazil and then from corn in the United States. In most parts of the world, the fastest growth in biofuel production has taken place over the last 10 years, supported by ambitious government policies.

Support policies for biofuels are often driven by energy security concerns, coupled with the desire to sustain the agricultural sector and revitalise the rural economy. More recently, the reduction of CO_2 emissions in the transport sector has become an important driver for biofuel development, particularly in countries belonging to the Organisation for Economic Cooperation and Development (OECD). One of the most common support measures is a blending mandate – which defines the proportion of biofuel that must be used in (road-) transport fuel – often combined with other measures such as tax incentives. More than 50 countries, including several non-OECD countries, have adopted blending targets or mandates and several more have announced biofuel quotas for future years (Table 1).

Table 1: Overview of biofuel blending targets and mandates

Country / Region	*Current mandate/ target*	*Future mandate/target*	*Current status (mandate [M]/ target [T])*
Argentina	E5, B7	n.a.	M
Australia: New South Wales (NSW), Queensland (QL)	NSW: E4, B2	NSW: E6 (2011), B5 (2012); QL: E5 (on hold until autumn 2011)	M
Bolivia	E10, B2.5	B20 (2015)	T
Brazil	E20-25, B5	n.a.	M
Canada	E5 (up to E8.5 in 4 provinces), B2-B3 (in 3 provinces)	B2 (nationwide) (2012)	M
Chile	E5, B5	n.a.	T
China (9 provinces)	E10 (9 provinces)	n.a.	M
Colombia	E10, B10	B20 (2012)	M
Costa Rica	E7, B20	n.a.	M
Dominican Republic	n.a	E15, B2 (2015)	n.a.
European Union	5.75% biofuels*	10% renewable energy in transport**	T
India	E5	E20, B20 (2017)	M
Indonesia	E3, B2.5	E5, B5 (2015); E15, B20 (2025)	M

B = biodiesel (B2 = 2% biodiesel blend); E = ethanol (E2 = 2% ethanol blend); Ml/d = million litres per day. *Currently, each member state has set up different targets and mandates. **Lignocellulosic-biofuels, as well as biofuels made from wastes and residues, count twice and renewable electricity 2.5-times towards the target.

Source: IEA analysis based on various governmental sources. For more information see also: http://renewables.iea.org.

Table 1: Overview of biofuel blending targets and mandates (continued)

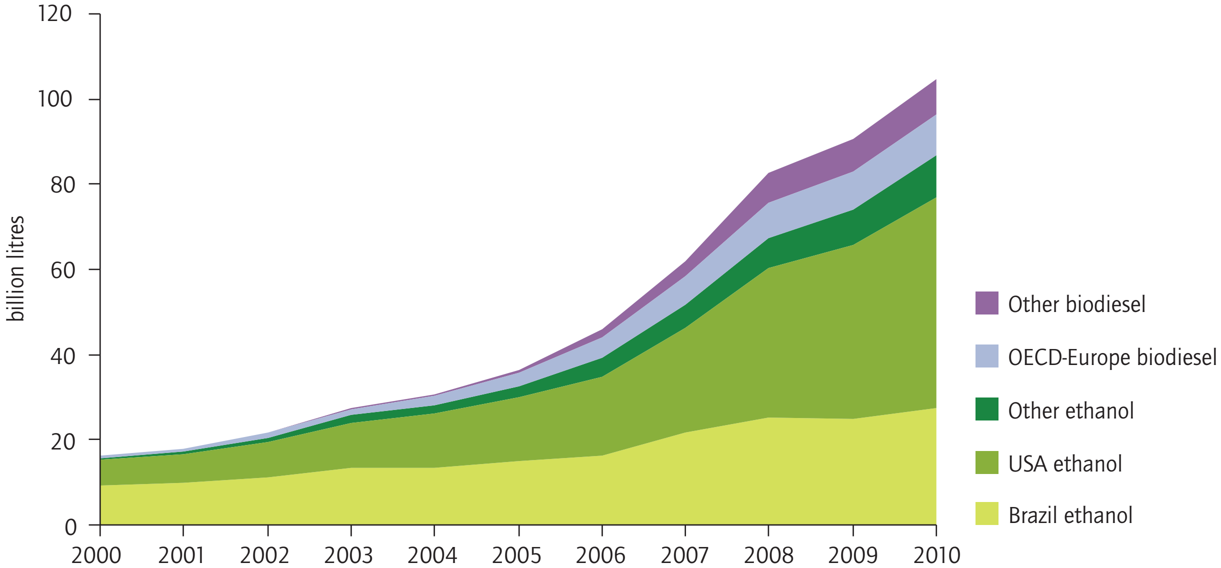
Country / Region	Current mandate/ target	Future mandate/target	Current status (mandate [M]/ target [T])
Jamaica	E10	Renewable energy in transport: 11% (2012); 12.5% (2015); 20% (2030)	M
Japan	500 Ml/y (oil equivalent)	800 Ml/y (2018)	T
Kenya	E10 (in Kisumu)	n.a.	M
Korea	B2	B2.5 (2011); B3 (2012)	M
Malaysia	B5	n.a.	M
Mexico	E2 (in Guadalajara)	E2 (in Monterrey and Mexico City; 2012)	M
Mozambique	n.a.	E10, B5 (2015)	n.a.
Norway	3.5% biofuels	5% proposed for 2011; possible alignment with EU mandate	M
Nigeria	E10	n.a.	T
Paraguay	E24, B1	n.a.	M
Peru	E7.8, B2	B5 (2011)	M
Philippines	E5, B2	B5 (2011), E10 (Feb. 2012)	M
South Africa	n.a.	2% (2013)	n.a.
Taiwan	B2, E3	n.a.	M
Thailand	B3	3 Ml/d ethanol, B5 (2011); 9 Ml/d ethanol (2017)	M
Uruguay	B2	E5 (2015), B5 (2012)	M
United States	48 billion litres of which 0.02 bln. cellulosic-ethanol	136 billion litres, of which 60 bln. cellulosic-ethanol (2022)	M
Venezuela	E10	n.a.	T
Vietnam	n.a.	50 Ml biodiesel, 500 Ml ethanol (2020)	n.a.
Zambia	n.a.	E5, B10 (2011)	n.a.

B = biodiesel (B2 = 2% biodiesel blend); E = ethanol (E2 = 2% ethanol blend); Ml/d = million litres per day. *Currently, each member state has set up different targets and mandates. **Lignocellulosic-biofuels, as well as biofuels made from wastes and residues, count twice and renewable electricity 2.5-times towards the target.

Source: IEA analysis based on various governmental sources. For more information see also: http://renewables.iea.org.

As a result, global biofuel production grew from 16 billion litres in 2000 to more than 100 billion litres (volumetric) in 2010 (Figure 1). Today, biofuels provide around 3% of total road transport fuel globally (on an energy basis) and considerably higher shares are achieved in certain countries. Brazil, for instance, met about 21% of its road transport fuel demand in 2008 with biofuels. In the United States, the share was 4% of road transport fuel and in the European Union (EU) around 3% in 2008.

Figure 1: Global biofuel production 2000-10

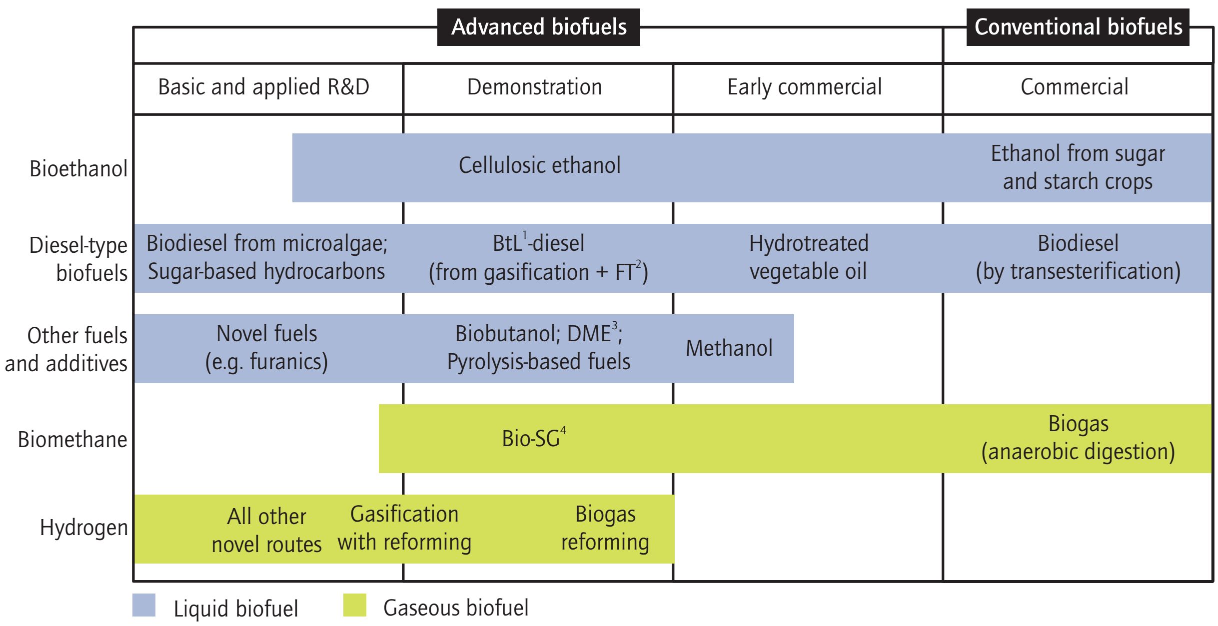


Source: IEA, 2010a.

Conventional and advanced biofuel conversion technologies

A wide variety of conventional and advanced biofuel conversion technologies exists today. The current status of the various technologies and approaches to biofuel production is summarised in Figure 2 and below. A more detailed description of some emerging technologies is provided in Appendix I. Conventional biofuel processes, though already commercially available, continue to improve in efficiency and economics. Advanced conversion routes are moving to the demonstration stage or are already there.

Figure 2: Commercialisation status of main biofuel technologies



1. Biomass-to-liquids; 2. Fischer-Tropsch; 3. Dimethylether; 4. Bio-synthetic gas.

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

Conventional biofuels

Sugar- and starch-based ethanol

In the sugar-to-ethanol process, sucrose is obtained from sugar crops such as sugarcane, sugar beet and sweet sorghum, and is subsequently fermented to ethanol. The ethanol is then recovered and concentrated by a variety of processes.

The conversion process of starch crops requires an additional step, the hydrolysis of starch into glucose, which requires more energy than the sugar-to-ethanol route. The overall economic and environmental efficiency of starch-based processes are heavily influenced by the value of co-products such as dried distiller's grains with solubles (DDGS) and fructose.

The costs of production from sugar and starch are very sensitive to feedstock prices, which – in particular during recent years - are volatile. Efficiency could be improved and costs lowered through use of more effective amylase enzymes, decreased ethanol concentration costs and enhanced use of co-products.

Conventional biodiesel

Biodiesel is produced from raw vegetable oils derived from soybean, canola, oil palm or sunflower, as well as animal fats and used cooking oil. These oils and fats are converted to biodiesel using methanol or ethanol. Vegetable oils are sometimes used as untreated raw oils, but this is not recommended due to the risks of engine damage and gelling of the lubricating oil. Co-products of biodiesel production, mainly protein meal and glycerine, are important to the overall economics of the process. The profitability of conventional biodiesel production is also sensitive to feedstock prices.

Biogas

Biogas can be produced through anaerobic digestion of feedstocks such as organic waste, animal manure and sewage sludge, or from dedicated green energy crops such as maize, grass and crop wheat. Biogas is often used to generate heat and electricity, but it can be also upgraded to biomethane by removing CO_2 and hydrogen sulfide (H_2S), and injected into the natural gas grid. Biomethane can also be used as fuel in natural gas vehicles.

Advanced biofuels

Cellulosic ethanol

Bioethanol can be produced from ligno-cellulosic feedstocks through the biochemical conversion of the cellulose and hemicellulose components of biomass feedstocks into fermentable sugars (IEA, 2008a). The sugars are then fermented to ethanol, following the same conversion steps as conventional biofuels. Cellulosic ethanol has the potential to perform better in terms of energy balance, GHG emissions and land-use requirements than starch-based biofuels (IEA, 2008a). The first large-scale plants demonstrating this technology are now coming into production.

Advanced biodiesel

Several processes are under development that aim to produce fuels with properties very similar to diesel and kerosene. These fuels will be blendable with fossil fuels in any proportion, can use the same infrastructure and should be fully compatible with engines in heavy duty vehicles. Advanced biodiesel and bio-kerosene will become increasingly important to reach this roadmap's targets since demand for low-carbon fuels with high energy density is expected to increase significantly in the long term. Advanced biodiesel includes:

- **Hydrotreated vegetable oil (HVO)** is produced by hydrogenating vegetable oils or animal fats. The first large-scale plants have been opened in Finland and Singapore, but the process has not yet been fully commercialised (Bacovsky *et al.*, 2010).
- **Biomass-to-liquids (BtL)** diesel, also referred to as Fischer-Tropsch diesel, is produced by a two-step process in which biomass is converted to a syngas rich in hydrogen and carbon monoxide. After cleaning, the syngas is catalytically converted through Fischer-Tropsch (FT) synthesis into a broad range hydrocarbon liquids, including synthetic diesel and bio-kerosene.

Advanced biodiesel is not widely available at present, but could become fully commercialised in the near future, since a number of producers have pilot and demonstration projects underway (USDOE, 2009).

Other biomass-/sugar-based biofuels

In recent years, several novel biofuel conversion routes have been announced, such as the conversion of sugars into synthetic diesel fuels.

These include:

- The use of a micro-organisms such as yeast, heterotrophic algae or cyanobacteria that turn sugar into alkanes, the basic hydrocarbons for gasoline, diesel and jet fuel.
- The transformation of a variety of water-soluble sugars into hydrogen and chemical intermediates using aqueous phase reforming, and then into alkanes via a catalytic process (Blommel *et al.*, 2008).
- The use of modified yeasts to convert sugars into hydrocarbons that can be hydrogenated to synthetic diesel.

So far, none of the above processes has been demonstrated on a commercial scale.

Bio-synthetic gas

Bio-SG is biomethane derived from biomass via thermal processes. The first demonstration plant producing biomethane thermochemically out of solid biomass started operation in late 2008 in Güssing, Austria, and a plant is planned in Gothenburg, Sweden (DBFZ, 2009).

The deployment of natural gas vehicles (NGV) has started to grow rapidly, particularly during the last decade, reaching shares of 25% and more of the total vehicle fleet in countries including Bangladesh, Armenia and Pakistan (IEA, 2010d). These vehicles can also be run on biomethane derived from anaerobic digestion or gasification of biomass.

Other fuels and additives

Several routes to fuels and additives at different commercialisation stages are described in Appendix I, including hydrothermal processing, pyrolysis oil, dimethylether (DME), biobutanol, and solar fuels.

Algae as biofuel feedstock

Algae have been cultivated commercially since the 1950s, mainly for the pharmaceutical industry, but only recently gained attention as a potential source of biomass. Algae promise a potentially high productivity per hectare, could be grown on non-arable land, can utilise a wide variety of water sources (fresh, brackish, saline and wastewater), and potentially recycle CO_2 and other nutrient waste streams (Darzins *et al.*, 2010). However, algae cultivation faces several challenges, related to availability of locations with sufficient sunshine and water, required nutrient inputs, and oil extraction (Darzins *et al.*, 2010; USDOE, 2010).

The most anticipated biofuel products appear to be high-quality diesel and jet fuel analogues, since few alternatives exist to replace these fuels. However, cultivation of algae and extraction of the oil is currently expensive. Production cost estimates for the raw oil vary between USD 0.75/l to more than USD 5.00/l, excluding costs for conversion to biofuel (Darzins *et al.*, 2010). Optimisation of algal strains, concerns over unwanted or adverse effects due to contamination, and scaling up production remain significant challenges to the development and commercialisation of algae-based biofuels, and require more basic R&D efforts than other advanced biofuel routes. Commercially viable production of biofuel from algae will depend on effective strategies to generate high-volume, low-value biofuel along with high-value co-products.

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, low-volume co-products in addition to comparably low-value 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). Two main categories can be defined: energy-driven biorefineries, which include biofuel plants, and product-driven biorefineries, which focus on producing food, feed, chemicals and other materials and might create power or heat as a co-product (Jong and Ree, 2009).

A biorefinery can consist of a single unit, for instance a paper mill that produces pulp and paper and generates electricity from processing residues. It can also be formed by a cluster of single facilities that process by-products or wastes of neighbouring facilities. Biorefineries can potentially make use of a broader variety of biomass feedstocks and allow for a more efficient use of resources than current biofuel production units, and reduce competition among different uses of biomass. Several innovative biorefinery concepts are currently being developed. An overview of some operating biorefineries can be found in a recent report of the IEA Bioenergy Task 42.[11]

Biorefineries will contribute significantly to the sustainable and efficient use of biomass resources, by providing a variety of products to different markets and sectors. They also have the potential to reduce conflicts and competiton over land and feedstock.

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

Sustainability of biofuel production

The growth of biofuels is being stimulated by concerns about global emission levels and energy security. Over the last few years, there has been a vigorous debate about the extent to which biofuels lead to GHG reductions, particularly given new research about the emissions associated with direct and indirect land-use changes (ILUC) caused by biofuel production (Edwards *et al.*, 2010; Tyner *et al.*, 2010; E4Tech, 2010). There has also been a public debate over whether conventional biofuels can harm food security, following a peak in agricultural commodity prices in 2007-08. Although the latest analyses suggest that a combination of high oil prices, poor harvests and use of commodities by financial investors probably had a considerably higher impact on food prices than biofuel production (World Bank, 2010), food security remains a critical topic for the design of sound biofuel policies. There is also some controversy over the potential environmental, economic and social impacts of biofuel production and use.

Greenhouse-gas emissions

The role of bioenergy systems in reducing GHG emissions needs to be evaluated by comparison with the energy systems they replace using life-cycle assessment (LCA) methodology. A number of such analysis methodologies have been developed, including those by the IEA Bioenergy Agreement's Task 38[12] and by the Global Bioenergy Partnership.[13]

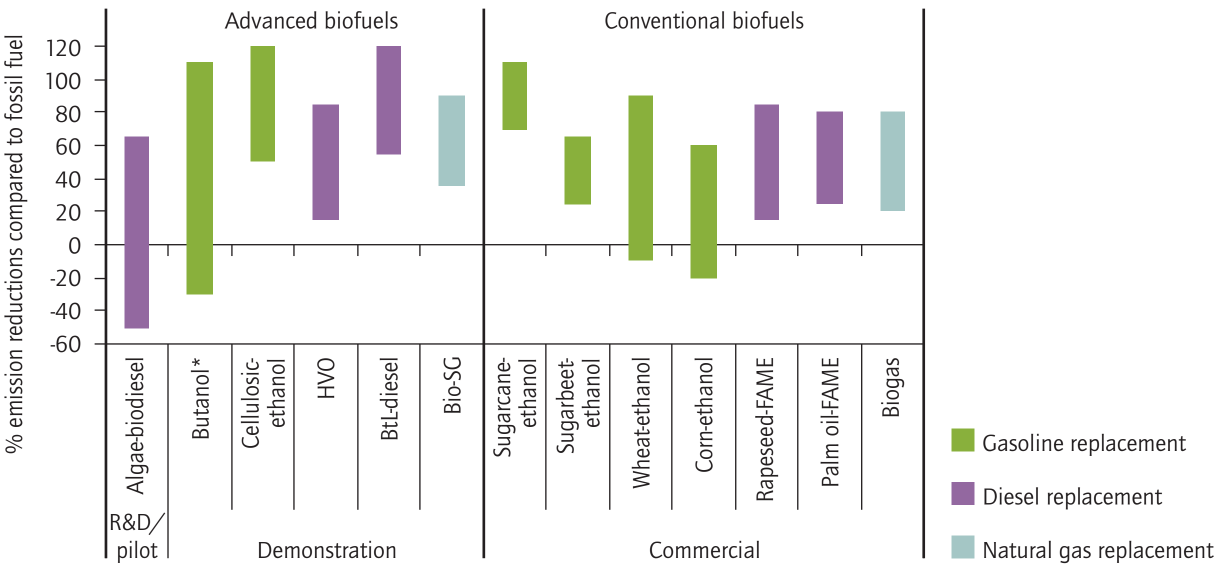
Figure 3 is based on a number of "well-to-wheel" LCA studies that compare the GHG emissions associated with different biofuels against the replaced fossil fuel. The figure covers mature, emerging and innovative processes. The data show a large range for each biofuel, depending on the details of the process and way the feedstock is produced, including the amount of fertilisers used. In general, producing ethanol from sugar cane (*e.g.* in Brazil or Thailand) shows significant potential for GHG mitigation, if no indirect land-use change occurs. The levels of mitigation associated with other conventional biofuels are more modest, but could be improved through better use of co-products and use of process energy from renewable sources rather than from fossil fuels.

Some emerging and novel technologies for producing ethanol or diesel from ligno-cellulosic feedstocks look more promising. In some cases they can reduce emissions by more than 100%

12 www.ieabioenergy-task38.org

13 www.globalbioenergy.org/programmeofwork/sustainability/en/

Figure 3: Life-cycle GHG balance of different conventional and advanced biofuels, and current state of technology



Note: The assessments exclude emissions from indirect land-use change. Emission savings of more than 100% are possible through use of co-products. Bio-SG = bio-synthetic gas; BtL = biomass-to-liquids; FAME = fatty acid methyl esthers; HVO = hydrotreated vegetable oil.

Source: IEA analysis based on UNEP and IEA review of 60 LCA studies, published in OECD, 2008; IEA, 2009; DBFZ, 2009.

when co-products are used to produce heat and power, replacing fossil fuels for example. However, estimates for these processes are theoretical or based on pilot plants and the uncertainties are higher, since such plants are not yet operating at a commercial scale.

Biofuels and land-use change

Concerns have been raised that the GHG benefits of producing and using biofuels can be reduced or negated by carbon emissions associated with land-use change (LUC). A comprehensive and up-to-date analysis of the issues involved has recently been published by IEA Bioenergy (Berndes *et al.*, 2010).

When biofuel production involves a change in land use then there may be additional emission impacts – positive or negative – that must be taken into account in calculating the GHG balance. The land-use change can be:

- direct, as when biofuels feedstocks are grown on land that was previously forest;
- indirect, when biofuel production displaces the production of other commodities, which are then produced on land converted elsewhere (perhaps in another region or country).

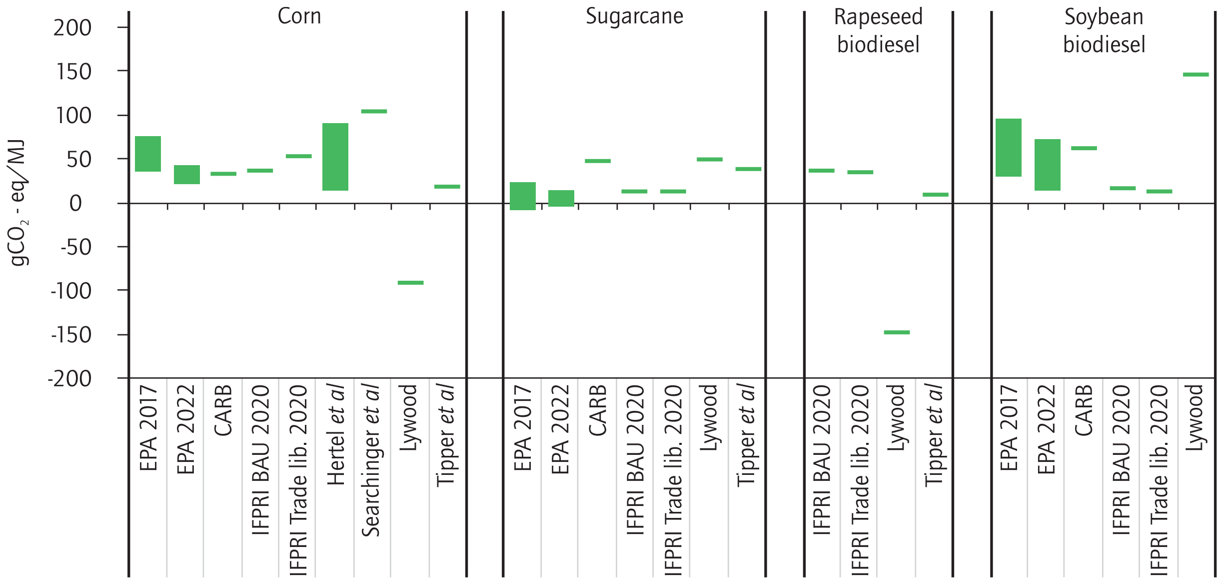
For biofuels to provide the envisaged emission reductions in the transport sector, it is essential to avoid large releases of GHG caused by land-use changes. However, emissions related to current biofuel production generate only around 1% of the total emissions caused by land-use change globally (Berndes *et al.*, 2010), most of which are produced by changes in land use for food and fodder production, or other reasons.

Accounting for land-use change

Direct land-use change and associated GHG emissions need to be accounted for when assessing the environmental balance of biofuels, and conversion of land with high carbon stocks must be avoided. Indirect land-use changes, however, are more difficult to identify and model explicitly in GHG balances. Several modelling approaches are being developed to allow for accounting of such indirect effects.

Figure 4 shows the wide ranges of model-based quantifications of emissions from direct and indirect land-use change. The range of estimates is such that in the most extreme cases the emission savings shown in Figure 3 could in some cases be more than off-set by the emissions caused by land use change.

Figure 4: Ranges of model-based quantifications of land-use change emissions (amortised over 30 years) associated with the expansion of selected biofuel/crop combinations



Source: Provided by IEA Bioenergy and sourced from Berndes *et al.*, 2010.

In some government programs and standards schemes (*e.g.* the California Low Carbon Fuel Standard[14]) a specific GHG penalty is added into calculations of overall GHG balances to account for indirect land-use change. Reaching consensus on what the penalties should be is difficult given the high uncertainty in the calculations.

The great uncertainty and lack of standardised methodology to quantify indirect land-use change impacts are also highlighted in a report by the European Commission (EC, 2010). The report concludes that there are several remaining deficiencies and uncertainties associated with the modelling of indirect land-use effects. The Commission will continue to conduct work in this area to ensure that policy decisions are based on the best available science and to meet its future reporting obligations. By July 2011, the Commission plans to finalise its impact assessment, assessing the following policy options:

- taking no action for the time being, while continuing to monitor impacts;
- increasing the minimum GHG saving threshold for biofuels;
- introducing additional sustainability requirements on certain categories of biofuels;
- attributing a quantity of GHG emissions to biofuels reflecting the estimated indirect land-use impact (EC, 2010).

While primarily affecting EU member states, the decisions may serve as a basis for new biofuel sustainability requirements in countries outside the European Union.

14 www.arb.ca.gov/fuels/lcfs/lcfs.htm

One interesting approach to reducing the risk of land-use change is a zoning programme that has been developed in Brazil. The Agro-Ecological Sugarcane Zoning constrains the areas in which sugar cane production can be expanded by increasing cattle density, without 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.

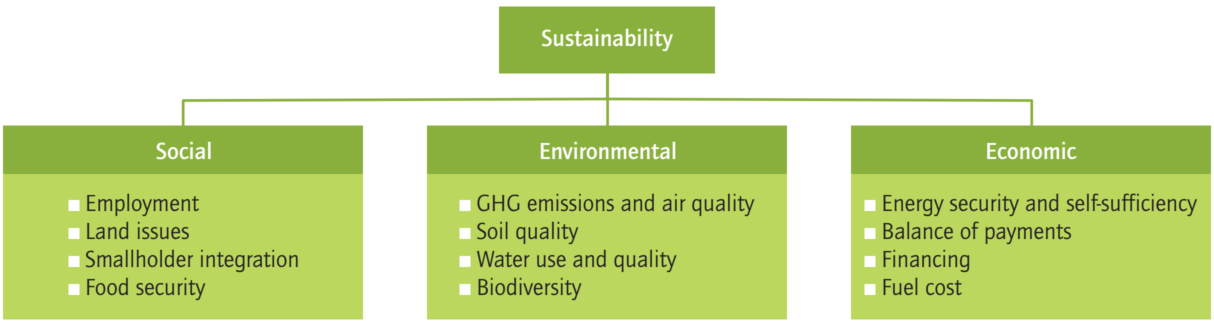
While there are some remaining uncertainties about the quantification of emissions from indirect land use change, it is possible to identify routes where the risks of land-use change and resulting emissions can be minimised and in some cases be negative. These include:

- focus on wastes and residues as feedstock;
- maximising land-use efficiency by sustainably increasing productivity and intensity and chosing high-yielding feedstocks;
- using perennial energy crops, particularly on unproductive or low-carbon soils;
- maximising the efficiency of feedstock use in the conversion processes;
- cascade utilisation of biomass, *i.e.* linking industrial and subsequent energetic use of biomass;
- co-production of energy and food crops.

Other sustainability issues

The GHG performance of biofuels is a key to achieving a low-carbon transport sector and meeting this roadmap's vision. However, given the extensive nature of the potential supply and use of biofuels, and their interaction with the

Figure 5: Environmental, social and economic aspects of biofuel and bioenergy production



agricultural and forestry sectors, all three pillars of sustainability (Figure 5) – environment, economic and social – need to be fully considered and appropriately addressed on policy level.

Sustainability issues of biofuel production have been discussed in more detail by IEA (2010b); FAO and UNEP (2010) and in other publications (see Appendix II). They also form the core of the work on sustainability criteria undertaken by the Global Bioenergy Partnership, the Roundtable for Sustainable Biofuels and other international and national efforts that aim to establish criteria, standards and certification schemes to prevent or limit negative impacts from biofuel production. Through careful management and appropriate project choice and design, negative impacts can be minimised or avoided, and biofuel projects can in fact have positive impacts. For example, planting perennial energy crops on degraded soil can reduce erosion, increase carbon stocks and water retention capacity, enhance biodiversity and provide additional income to rural economies.

Criteria and standards

Many efforts are under way to develop sustainability criteria and standards that aim to provide assurance about overall sustainability of biofuels. These include efforts to co-ordinate activities at the global level, as well as national and regional initiatives. Task 40 of the IEA Bioenergy Implementing Agreement has assessed that there are 67 such initiatives worldwide, covering different aspects of the supply chain (Dam, 2010).

International initiatives include:

- The **Global Bioenergy Partnership** (GBEP)[15] is an intergovernmental initiative with partners from 23 member countries and 12 international organisations (along with 32 observers). The partners are endeavouring, via task forces, to develop a methodological framework that policy makers and stakeholders can use to assess GHG emissions associated with bioenergy. The GBEP aims to develop a set of relevant, practical, science-based, voluntary criteria and indicators as well as examples of best practice regarding the sustainability of bioenergy. GBEP's work on sustainability indicators is quite advanced, with a final agreement expected in May 2011.

15 www.globalbioenergy.org

- The **Roundtable on Sustainable Biofuels** (RSB)[16] is a voluntary international initiative that brings together farmers, companies, non-governmental organisations (NGO), experts, governments and inter-governmental agencies concerned with ensuring the sustainability of biofuel production and processing. Through an open, transparent and multi-stakeholder process, the RSB has developed a third-party certification system for biofuel sustainability, criteria that has been launched in March 2011, and encompasses environmental, social and economic production principles.
- The **International Organization for Standardization** (ISO)[17] will develop an international standard via a new ISO project committee (ISO/PC 248, Sustainability Criteria for Bioenergy). The project will gather international expertise and best practice, and identify criteria that could prevent bioenergy from being harmful to the environment or leading to negative social impacts. In addition, the standard aims at making bioenergy more competitive, to the benefit of both national and international markets.
- The **International Sustainability and Carbon Certification System** (ISCC) 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.

There are also initiatives looking at standards for the sustainable production of specific agricultural products, such as the Roundtable for Sustainable Palm Oil, the Roundtable for Responsible Soy and the Better Sugarcane Initiative. The standards aim at ensuring sustainable production of feedstocks, regardless of their final uses (be it for food, material or biofuel production), and can thus help to ensure sustainable production throughout the whole sector, rather than for the feedstock specifically dedicated to biofuel production.

Some policies have been adopted during recent years that include binding sustainability standards for biofuels, including:

- The **European Union** has introduced regulations under the Renewable Energy Directive (RED) that lay down sustainability criteria that biofuels must meet before being

16 http://rsb.epfl.ch/

17 www.iso.org

eligible to contribute to the binding national targets that each member state must attain by 2020 (EC, 2009). In order to count towards the RED target, biofuels must provide 35% GHG emissions saving compared to fossil fuels. This threshold will rise to 50% as of 2017, and to 60% as of 2018 for new plants.

- In the **United States**, the Environmental Protection Agency (EPA) is responsible for the Renewable Fuel Standard II program.[18] This establishes specific annual volume requirements for renewable fuels, which rise to 36 billion gallons by 2022. These regulatory requirements apply to domestic and foreign producers and importers of renewable fuel used in the US. Advanced biofuels[19] and cellulosic biofuels must demonstrate that they meet minimum GHG reduction standards of 50% and 60% respectively, based on a life-cycle assessment (including indirect land-use change) in comparison with the petroleum fuels they displace.

- In **Switzerland** the Federal Act on Mineral Oil mandates a 40% GHG reduction of biofuels in order to qualify for tax benefits. In addition, feedstock must not be grown on land that was recently deforested or that is important for maintaining biodiversity. Biofuel producers must also comply with social standards in the countries in which feedstock production and biofuel conversion take place.

Some aspects, such as indirect land-use change, are out of the control of individual producers, and have to be dealt with at a national or regional level, while other aspects can be managed by individual producers or processors. Nonetheless, the overview shows a proliferation of standards, increasing the potential for confusion, inefficiencies in the market and abuses such as "shopping" for standards that meet particular criteria. Such disparities may act as a discouragement for producers to make the necessary investments to meet high standards. To develop the local information and expertise required to implement internationally agreed sustainability standards, criteria and indicators in practice, especially in developing countries, it will be vital to provide substantial support in capacity building, from production to policy level.

18 www.epa.gov/otaq/fuels/renewablefuels/index.htm

19 "Advanced biofuels" under the RFS II comprise any biofuel other than corn-ethanol, with life-cycle GHG emission savings of >50%.

Vision for technology deployment and CO_2 abatement

Biofuel deployment

The *ETP 2010* BLUE Map Scenario sets a target of 50% reduction in energy-related CO_2 emissions by 2050 from 2005 levels. This requires the rapid development and deployment of low-carbon energy measures and technologies, such as improved energy efficiency, greater use of renewable energy sources, and deployment of CCS (IEA, 2010c). To achieve the projected emission savings in the transport sector, *ETP 2010* projects that sustainably produced biofuels will eventually provide 27% of total transport fuel (Figure 6).

Based on the BLUE Map Scenario, by 2050 biofuel demand will reach 32 EJ, or 760 million tonne of oil equivalent (Mtoe). As advanced biofuels are commercialised, they will eventually provide the major share of biofuel, whereas most oil- and starch-based conventional biofuels are expected to be phased out because of rising and increasingly volatile feedstock prices. Diesel and kerosene replacements will play an important role in decarbonising heavy transport modes that have limited low-carbon fuel alternatives.

Reductions in transport emissions contribute considerably to achieving overall BLUE Map targets, accounting for 23% (10 Gt CO_2-equivalent[20]) of total energy-related emissions reduction by 2050 (IEA, 2010c). The highest reductions are achieved in OECD countries, while some non-OECD countries, including India and China, show significant increases because of rapidly growing vehicle fleets. Vehicle efficiency improvements account for one-third of emissions reduction in the transport sector; the use of biofuels is the second-largest contributor, together with electrification of the fleet,[21] accounting for 20% (2.1 Gt CO_2-equivalent) of emissions saving (Figure 7).

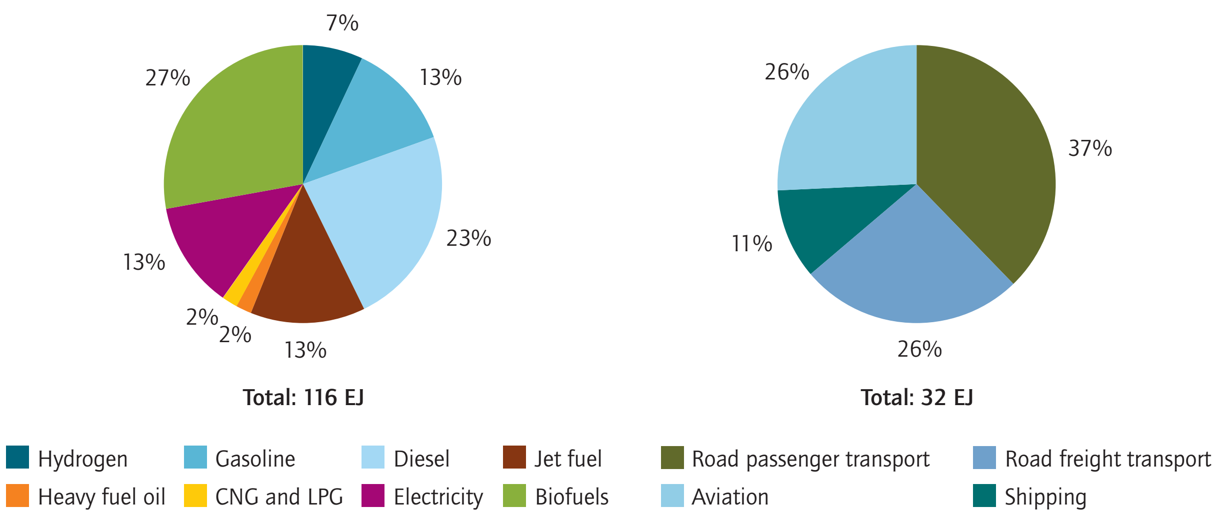
To reach the reduction targets, all available options need to be pursued vigorously, along with the evaluation of new technological developments, such as production of low-carbon fuels combined with CCS (see Box 2).

In this roadmap, biofuel demand over the next decade is expected to be highest in OECD countries, but non-OECD countries will account for 60% of global biofuel demand by 2030 and roughly 70% by 2050, with strongest demand projected in China, India and Latin America (Figure 8). Conventional biofuels are expected to play a role in ramping up production in many developing countries because the technology is less costly and less complex than for advanced biofuels. The first commercial advanced biofuel projects will be set up in the United States and

20 This includes 1.8 Gt emission savings through modal shifts

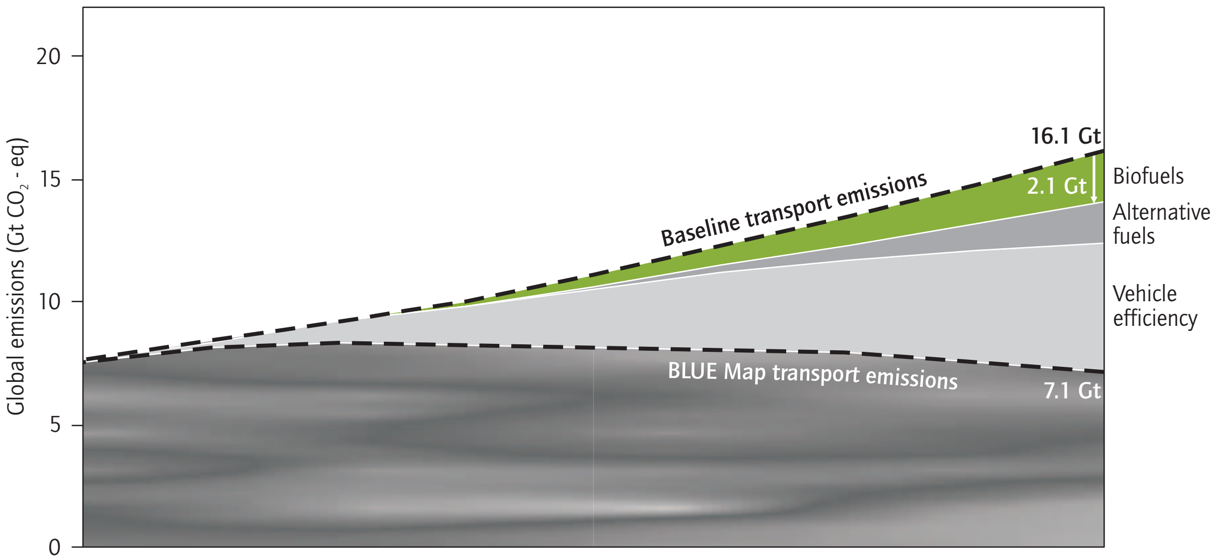
21 More information on the development of electric and plug-in hybrid electric vehicles can be found in the IEA technology roadmap released in 2009 (www.iea.org/roadmaps).

Figure 6: Global energy use in the transport sector (left) and use of biofuels in different transport modes (right) in 2050 (BLUE Map Scenario)



Note: CNG= compressed natural gas; LPG= liquefied petroleum gas.
Source: IEA, 2010c.

Figure 7: Contribution of biofuels to GHG emissions reduction in the transport sector

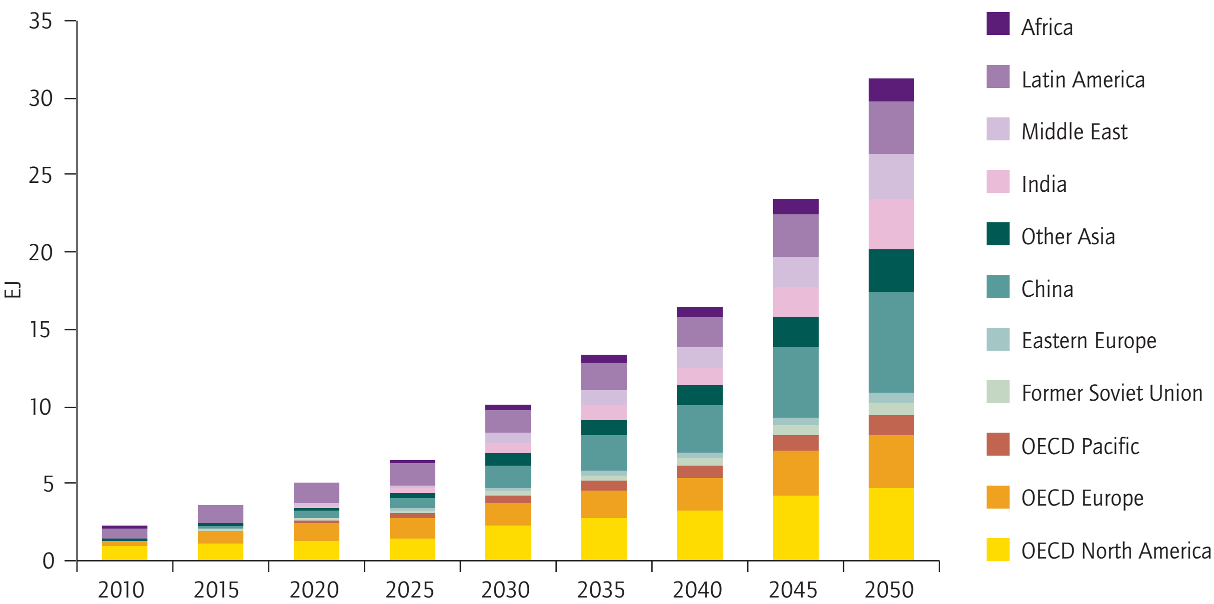


Note: Modal shifts (not included) could contribute an additional 1.8 Gt CO_2-eq. of emission reductions.

Source: IEA, 2010c.

Europe, as well as in Brazil and China, where several pilot and demonstration plants are already operating. Once technologies are proven and feedstock supply concepts have been established, advanced biofuels will be set up in other emerging and developing countries. In regions with limited land and feedstock resources, such as the Middle East and certain Asian countries, feedstock and biofuel trade will play an increasing role (see section on biomass and biofuel trade below).

Figure 8: Biofuel demand by region 2010-50



Note: FSU= Former Soviet Union.

Source: IEA, 2010c.

Box 2: Biofuel production and CCS: towards negative CO_2 emissions

The possibility of using bioenergy in combination with carbon capture and storage (BECCS) is now being actively considered. The idea behind BECCS is that capturing the CO_2 emitted during bioenergy generation and injecting it into a long-term geological storage formation could turn "carbon neutral" emissions into negative emissions (Kraxner *et al.*, 2010).

The CO_2 streams from biofuel production (fermentation or gasification) are relatively pure, making the process less laborious than CCS of flue gases from fossil-fuel power plants. Given the relatively low costs and comparably small energy losses, BECCS projects could be some of the first to implement CCS technology (Lindfeldt & Westermark, 2009).

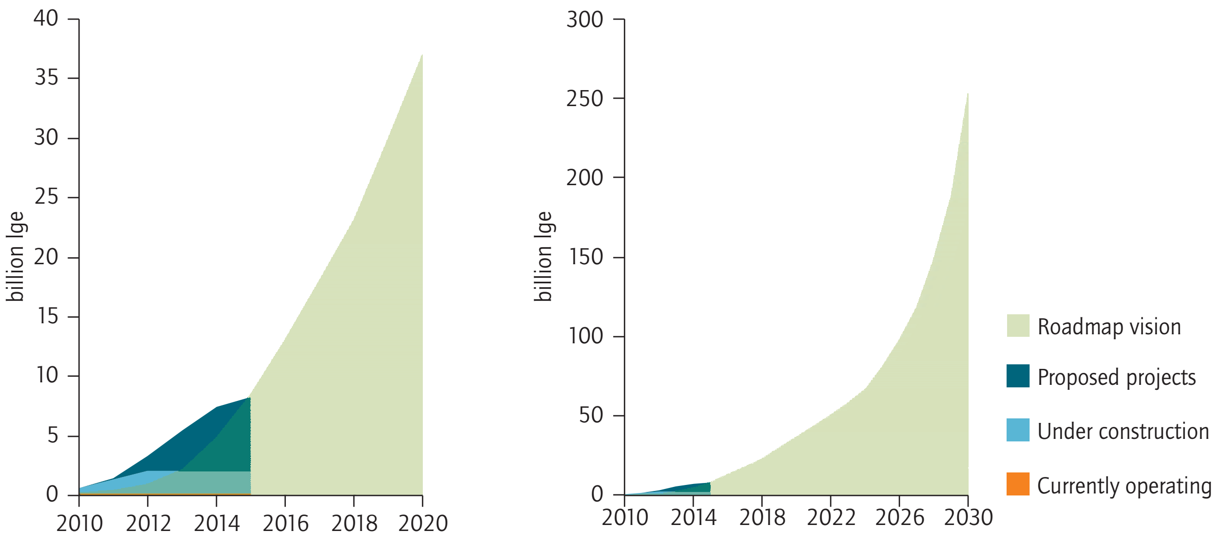
One BECCS demonstration project started operation in Illinois in the beginning of 2010. About 1 000 t CO_2/day emitted from ethanol fermentation in a wet-mill will be stored in sandstone rock 2 400m below ground (MGSC, 2010). However, more RD&D is needed on this important technology solution, as has been outlined in the IEA ***CCS Roadmap*** (IEA, 2010e).

Advanced biofuel deployment: the capacity challenge

This roadmap anticipates the installation of the first commercial-scale advanced biofuel plants within the next decade, followed by rapid growth of advanced biofuel production after 2020. Some novel technologies such as algae biofuels and sugar-based hydrocarbons will also need to be developed, but commercialisation of these will require more substantial RD&D. These novel technologies, once commercially proven, will help meet the roadmap's biofuel demand beyond 2020-30.

Several advanced biofuel pilot and demonstration plants are already operating, and a considerable number have been announced for the next five years. The majority of these plants are in North America and the European Union, but an increasing number are operating or constructed outside the OECD. The installed advanced biofuel capacity today is roughly 175 million litres gasoline

Figure 9: Advanced biofuel production capacity to 2015, 2020 and 2030



Note: A load factor of 70% is assumed for fully operational plants. Actual production volumes may be well below nameplate capacity within the first years of production.

Source: Based on IEA analysis in IEA, 2010a; IEA, 2010c; IEA 2010f.

equivalent (Lge) per year, but most plants are currently operating below nameplate capacity. Production capacity of another 1.9 billion Lge/yr is currently under construction and would be sufficient, if operating with full load, to meet this roadmap's targets for advanced biofuel production until 2013. Project proposals for an additional 6 billion Lge/yr capacity have been announced until 2015 (Figure 9). However, given the number of delays to announced projects during recent years, it remains uncertain if plants will start operating according to proposed schedules.

Given the current development of operating and currently constructed advanced biofuel capacity, this roadmap's targets for the coming years could well be met. After 2015, however, advanced biofuel production will need to ramp up rapidly (Figure 9). This means that all operating, constructed and announced advanced biofuel plants need to operate on full capacity (typically 70% of nameplate capacity). In addition, new plants need to start production after 2015.

The challenge of reaching the vision in this roadmap becomes clear when looking at the required development of advanced biofuel capacity to 2020, and even more so when looking at 2030. A 30fold increase over currently announced advanced biofuel capacity will be required to reach 250 billion Lge/yr operating capacity in 2030 as foreseen in this roadmap (Figure 9). Beyond 2030, a further quadrupling of advanced biofuel capacity will be required until 2050 to reach this roadmap's targets.

The importance of land and biomass resources

The rising levels of biofuel production envisaged in this roadmap will considerably increase demand for biomass feedstocks. Making this feedstock available in a sustainable way, without compromising food security, threatening biodiversity or limiting smallholders' access to land, will require a sound policy framework and involvement of all stakeholders along the production chain.

This is particularly true given that the world's population is estimated to reach 9.1 billion by 2050, leading to a 70% increase in global food demand (FAO, 2009). According to FAO projections, 90% of the additional crop demand could be met with higher yields and increased cropping intensity, but nonetheless a net expansion of arable land[22] by about 70 Mha would be needed. Arable land expansion is expected to take place mainly in developing countries in Sub-Saharan Africa and Latin America (around 120 Mha). In developed regions, land use is expected to decrease by 50 Mha (FAO, 2009) so biofuel production potential in these countries may increase considerably.

Overview on land and bioenergy potential estimates

Because of the many factors involved, assessing the global biomass potential is not a straightforward task. The most ambitious estimates indicate a technical potential for bioenergy of more than 1 500 EJ in 2050. A comprehensive review by Dornburg *et al.* (2008) of sources of feedstock for biofuel and bioenergy estimates the potential of agricultural and forestry residues at 85 EJ and that of surplus forest growth[23] at roughly 60 EJ in 2050. The review also estimates that available surplus arable land could be used to produce around 120 EJ of dedicated energy crops, with little risk of increasing water stress and soil erosion, or compromising areas for nature protection. The study indicates that this "lower-risk" potential[24] could be even bigger when areas with moderate soil degradation and water stress are used (70 EJ), and agricultural productivity is increased faster than has been the case in the past (up to 140 EJ). By 2050, the total bioenergy potential from "low-risk" feedstock sources could thus reach 475 EJ (Figure 10). This is around three times the primary bioenergy demand of 145 EJ projected in the BLUE Map Scenario (65 EJ for biofuels, 80 EJ mainly for heat and power) in 2050 (IEA, 2010c).

Several factors may discourage the use of these "lower-risk" resources, however. Using residues and surplus forest growth, and establishing energy crop plantations on currently unused land, may prove more expensive than creating large-scale energy plantations on arable land. In the case of residues, opportunity costs can occur, and the scattered distribution of residues may render it difficult in some places to recover them (IEA, 2010b). This could also be true for surplus forest growth, and biodiversity concerns may prevent use of the identified surplus forest growth potential in some places. Bringing unused land back into production will require additional investments in infrastructure, while soil fertility, water availability and other factors may compromise yields.

More data on the availability and costs of residues that could be made available sustainably, along with field data on suitability of different energy crops under various geographical and climatic conditions, will help to assess the economics of bringing unused land into cultivation and establishing energy-crop plantations. This information needs to be made available on a regional or country-by-country basis to establish reliable resource cost curves for raw materials that meet specified sustainability criteria.

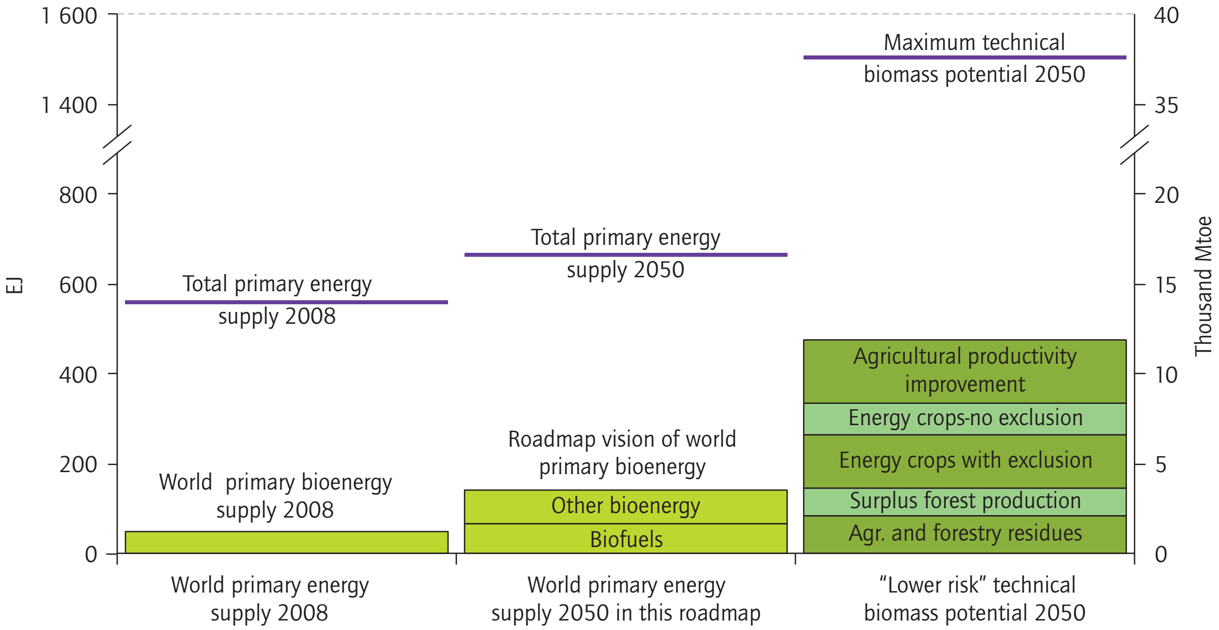
The total feedstock required in 2050 to meet the ambitious goals of this roadmap is around 65 EJ of biomass. It is assumed that 50% of the feedstock for advanced biofuels and biomethane will be obtained from wastes and residues, corresponding to 1 Gt of dry biomass, or 20 EJ. This is a rather conservative estimate, but given the potential constraints regarding collection and transportation of residues, and the potentially enormous feedstock demand of commercial advanced biofuel plants (up to 600 000 t/yr and more), it is not clear if a higher residue share can realistically be mobilised for biofuel production. The location of advanced biofuel plants alongside other industrial facilities producing lignocellulosic residues as by-product,

22 Arable land is the land under temporary agricultural crops, temporary meadows for mowing or pasture, land under market and kitchen gardens and land temporarily fallow (less than five years). Arable land in 2008 accounted for 1.4 Gha of the 4.9 Gha global agricultural area worldwide (source: http://faostat.fao.org).

23 Surplus forest growth is the amount of wood that could be used in addition to current removal without reducing the regrowing forest stock.

24 Referred to as "sustainable potential" in the original study.

Figure 10: Comparison of global biomass supply estimates for 2050



Note: "lower-risk" bioenergy potential consists of: agriculture and forestry residues (85EJ); surplus forest production (60 EJ); energy crops with exclusion of areas with moderately degraded soils and/or moderate water scarcity (120 EJ); additional energy crops grown in areas with moderately degraded soils and/or moderate water scarcity (70 EJ), and additional potential when agricultural productivity improves at faster than historic trends, thereby producing more food from the same land area (140. EJ).

Source: Adapted from Dornburg *et al.*, 2008 and Bauen *et al.*, 2009, and supplemented with data from IEA, 2010c.

such as paper mills and sugar factories, could lead to a considerably higher share of advanced biofuel production from residues and wastes.

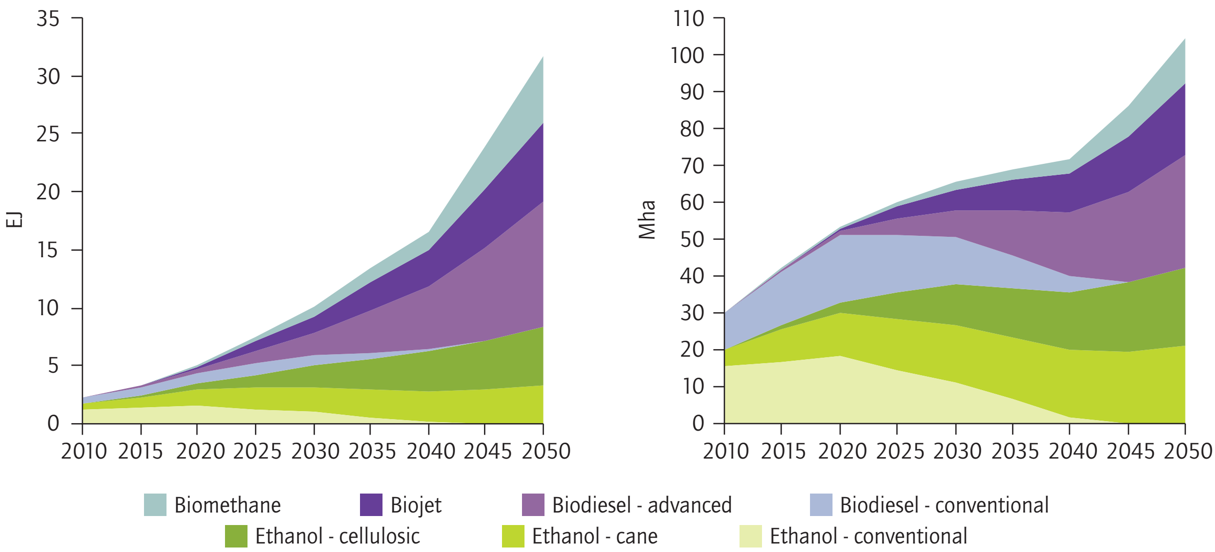
To meet this roadmap's targets, some expansion of energy crops will be necessary. Based on the land-use efficiencies indicated in Table 2, land use for biofuel production would need to increase from 30 Mha today to around 100 Mha in 2050 (Figure 11). This corresponds to an increase from 2% of total arable land today to around 6% in 2050. This expansion would include some cropland, as well as pastures and currently unused land, the latter in particular for production of lignocellulosic biomass.

Meeting the roadmap targets

The current and future land-use efficiency of different biofuels is indicated in Table 2. Based on historic data as well as future projections on yield improvements indicated in literature, land-use efficiency of all biofuels is expected to improve.

The potential for yield improvements is higher for advanced biofuels, thanks to expected increases in conversion efficiency as well as more productive feedstock varieties, many of which have not yet been developed commercially. The estimates below reflect global average values; significant differences between regional yields can exist. The more biofuels are produced from high-yielding feedstocks and in regions with favourable climate conditions, the less total land will be required to produce an equivalent amount of biofuel.

Figure 11: Demand for biofuels (left) and resulting land demand (right) in this roadmap



Note: This is gross land demand excluding land-use reduction potential of biofuel co-products. This assumes 50% of advanced biofuels and biomethane are produced from wastes and residues, requiring 1 Gt of residue biomass. If more residues were used, land demand could be reduced significantly.

Source: IEA analysis based on IEA, 2010c and Table 2 below.

Table 2: Land-use efficiency of different biofuel crops and expected yield improvements (global averages)

Biofuel type	*Yields, 2010 (litres/ha)*		*Average improvement per year, 2010-50*	*Resulting yields in 2050 (Lge or Lde/ha)*	*Main co-product, 2010 values, (Kg/L biofuel)*
	nominal	*Lde or Lge*			
Ethanol - conventional (average yield of feedstocks below)	3 300	2 300	0.7%	3 000	
Sugar beet	4 000	2 800	0.7%	3 700	Beet pulp (0.25)
Corn	2 600	1 800	0.7%	2 400	DDGS (0.3)
Ethanol - cane	4 900	3 400	0.9%	4 800	Bagasse (0.25)
Cellulosic-ethanol - SRC*	3 100	2 200	1.3%	3 700	Lignin (0.4)
Biodiesel - conventional (average yield of feedstocks below)	2 000	1 800	1.0%	2 600	FAME: Glycerine (0.1)
Rapeseed	1 700	1 500	0.9%	2 100	Presscake (0.6)
Soy	700	600	1.0%	900	Soy bean meal (0.8)
Palm	3 600	3 200	1.0%	4 800	Empty fruit bunches (0.25)

Table 2: Land-use efficiency of different biofuel crops and expected yield improvements (global averages) (continued)

Biofuel type	Yields, 2010 (litres/ha) nominal	Lde or Lge	Average improvement per year, 2010-50	Resulting yields in 2050 (Lge or Lde/ha)	Main co-product, 2010 values, (Kg/L biofuel)
BtL - SRC*	3 100	3 100	1.3%	5 200	Low temperature heat; pure CO_2
HVO	2 000	2 000	1.3%	3 400	Same as for conventional biodiesel feedstock above
Biomethane (average of technologies below)	n.a	3 800	1.0%	5 700	
Anaerobic digestion (maize)	n.a	4 000	1.0%	6 000	Organic fertiliser
bio-SG (SRC)*	n.a	3 600	1.0%	5 400	Pure CO_2 (0.6 L)

Note: Biofuel yields are indicated as gross land use efficiency, not taking into account the land demand reduction potential through co-products. 1 litre ethanol = 0.65 Lge; 1 litre biodiesel = 0.90 Lde; 1 litre advanced biodiesel = 1 Lde. *assuming average yield of 15 t/ha for woody crops from short rotation coppice (SRC).

Source: IEA analysis based on Accenture, 2007; BRDI, 2008; Brauer *et al.*, 2008; E4Tech, 2010; ECN, 2009; FAO, 2003; FAO, 2008; GEMIS, 2010; IEA, 2008; Jank *et al.*, 2007; Küsters, 2009; Kurker *et al.*, 2010; and Schmer *et al.*, 2008.

Detailed resource mapping is not available, but a brief qualitative assessment of regional biomass potentials is presented below.

Africa

- Several countries, including Kenya, Mozambique, South Africa and Zambia, plan to expand domestic biofuel production in the coming years. Given the comparably low crop yields achieved today (UNEP, 2009), a considerable potential to increase grain production exists. This could free up land for sustainable biofuel production without compromising food security.
- There may be potential to use currently unused land, but it is difficult to identify "unused" land, since reliable field data is lacking on current land-use through smallholders and rural communities. Complex land tenure structures and lack of infrastructure in rural areas are additional challenges for the expansion of biofuel production in many African countries.

Americas

- A 2005 study from the Oak Ridge National Laboratory suggested that in the US alone, around 22 Mha of cropland could be made available for biomass production by 2050 (Perlack *et al.*, 2005), mainly through yield improvements and changes in land management. Together with residues from agriculture and forestry, a potential biomass supply of 1.3 billion tonne has been assessed.
- Canada's large forestry and agricultural sectors could also provide considerable amounts of residue for bioenergy and biofuel production, in addition to agricultural residues and dedicated energy crops.
- Latin America has been identified as a region with considerable potential to produce bioenergy because of favourable climatic conditions and vast areas suitable for agriculture that are currently fallow, not cultivated or used as extensive pasture (Smeets *et al.*, 2007). Brazil, for instance, plans to expand the area under sugar cane – around 50% of which is used for biofuel production – from the current 4.4 Mha (2008 data) to about 8 Mha in 2017, mainly by cultivating current extensive pasture area (IEA, 2010b).

Asia

- Biofuel production in some Asian countries grew rapidly in recent years and is expected to continue, particularly in China, Thailand, Singapore and Indonesia (IEA, 2010a).
- With quickly growing populations in many Asian countries, and economic growth driving the demand for meat and thus fodder crops and pasture land, it is difficult to estimate potentially available land for biofuel production. Agricultural wastes and residues will become increasingly important as advanced biofuel feedstock (IEA, 2010b). There is also potential for yield improvements of biofuel crops.
- In Eastern Asia, studies have indicated a considerable potential for energy crop cultivation on surplus land (Hoogwijk *et al.*, 2004).

Europe

- Eastern Europe has been identified as region with a considerable amount of underutilised and abandoned agricultural land. Estimates suggest that around 40 Mha could become available for biofuel feedstock cultivation in the new EU member states and the Ukraine (REFUEL, 2008).
- In other parts of Europe, land availability is a potentially limiting factor and more efficient use of waste and residues will play an important role to enable further development of the biofuel sector.

Oceania

- Current biofuel production in Oceania accounts for less than 1% of global production (IEA, 2010a), but vast amounts of pasture land suggest that production levels could increase considerably.
- Research on drought-tolerant energy crop species will play an important role in increasing biofuel production in regions of low rainfall.
- Pilot algae cultivation projects have been established in Australia during recent years; if successful, algae may become another biomass source in the longer term (Geoscience Australia and ABARE, 2010).

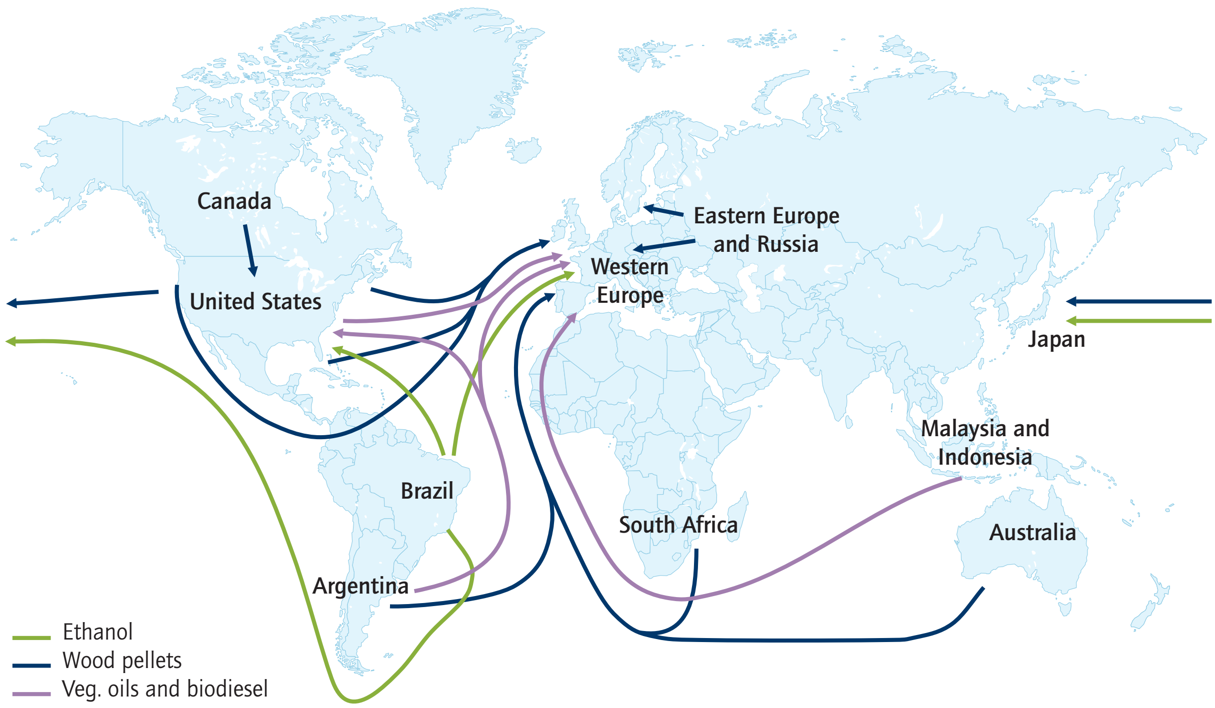
Biomass and biofuel trade

Trade in biomass and biofuels can mobilise currently untapped biomass resources and trigger investments in biomass-rich regions by providing access to international markets. Biomass and biofuel trade has been growing constantly, driven by increasing and volatile oil prices, and by policies promoting use of biomass and biofuel for energy generation (Junginger *et al.*, 2010). Growing biofuel demand in the United States, the European Union and Japan has led to considerable flows of Brazilian ethanol to these markets, as well as vegetable oil and biodiesel from the United States, Latin America and South East Asia (Figure 12). Around 2.8 Mt of bioethanol and 2.9 Mt of biodiesel were traded globally in 2008, in addition to approximately 4 Mt of wood pellets (Junginger *et al.*, 2009).

Biomass and biofuel markets have globalised over the last decades but are still immature and face barriers such as tariffs that need to be reduced to create stable market conditions. In this roadmap's vision, trade will become increasingly important to promote biofuel production and meet blending mandates, as well as to balance demand and supply fluctuations among different regions. In the short term, trade will include conventional biofuels and feedstocks, but after 2020, lignocellulosic feedstock trade is likely to grow rapidly and supply large advanced biofuel plants in coastal locations. Pelletisation, pyrolysis or torrefaction will become increasingly important since they increase the energy density and thus tradability of lignocellulosic feedstocks (*e.g.* residues). These intermediate products are relatively homogeneous and thus more suitable for conversion to biofuels.

Certain biomass and biofuel trade routes will only exist for a limited period, until either domestic supply in the importing region is sufficiently developed or demand in the exporting region increases. In the long term, for example, biofuel demand in non-OECD countries is expected to increase rapidly. Eastern Europe may supply biomass and biofuel to Central Europe; Latin America to the US, the EU and Japan; South East Asia and Australia may become suppliers to China and other developing Asian countries; and African countries could play an increasing role in the longer term in exporting feedstocks and/or biofuels to Asian, European and North American markets.

Figure 12: World biomass shipping today



Source: Based on Bradley *et al.*, 2009.

Economic perspectives

Biofuel production costs

For biofuels to be widely used, they must not only be sustainable with regard to environmental and social impacts, but also with regard to economical aspects. This means that they must eventually become competitive with gasoline and/or diesel fuel. Governments are justified in creating differential tax systems to reflect the differing external costs of different fuels, however, and some fuels successfully co-exist in markets today with fuels that are less expensive. Given that sustainably produced biofuels are justified for environmental reasons or as part of other societal objectives – such as rural economic development – it may make sense to realise these additional values through a differential tax system to promote their use. But there will be limits to how much differential can be justified, so biofuels will need to move toward cost parity with petroleum-based fuels in the longer term. A taxation system based on the environmental and energy performance of individual fuel types, including a carbon tax (as is already the case in Sweden) is one way of placing value on biofuels' environmental and societal contribution, and of reducing gaps in competitiveness with fossil fuels.

Based on the ETP BLUE Map Scenario, the IEA has developed detailed cost estimates for a range of fuels today and in the future, based on a bottom-up analysis of supply-chain components (IEA, 2011 forthcoming). Fuel-cost estimates presented below reflect retail price-equivalents and take into account all the key steps in biofuel production, including feedstock production and transport, conversion to final fuel, and fuel transport and storage, to the point of refuelling. In addition, the analysis considers the cost of biofuel production represented by oil use (such as for shipping) and the effect of changes in oil price on other fuel and commodity prices (such as crops).

Estimated biofuel production costs show significant differences depending on factors such as scale of the plant, technology complexity and feedstock costs. Little detailed data on advanced biofuel production costs are available, because such information is usually confidential and there is as yet no experience from large commercial-scale production plants. Long-term production cost estimates, to 2020-30, are based on the lowest fixed and variable costs of fuels that might be achieved. In the end, learning rates and cumulative production will determine when "long-term" costs are achieved.

For conventional biofuels today, the main cost factor is feedstock, which accounts for 45% to 70% of total production costs, whereas for advanced biofuels the main factor is capital costs (35% to 50%), followed by feedstock (25% to 40%) (IEA, 2009). In the longer term, reduced feedstock cost volatility will be a vital advantage for advanced biofuels that use lignocellulosic biomass sourced from energy crops, waste and residues. Making use of co-products such as DDGS, glycerine, bagasse, lignin or waste heat can reduce biofuel production costs by up to 20% depending on the fuel type and use of co-product.[25] In some cases (*e.g.* soy biodiesel), the biofuel is a by-product rather than the main product.

Figure 13 presents two different cost analyses in order to take into account uncertainties such as the dynamic between rising oil prices and biofuel production costs. The low-cost scenario anticipates minimal impact of rising oil prices on biofuel production costs. Biofuel production costs fall as scale and efficiency increase. The costs (retail price equivalent, untaxed) of advanced biofuels such as cellulosic-ethanol and BtL-diesel reach parity with petroleum gasoline and diesel fuel by about 2030. Sugarcane ethanol remains the lowest-cost biofuel throughout.

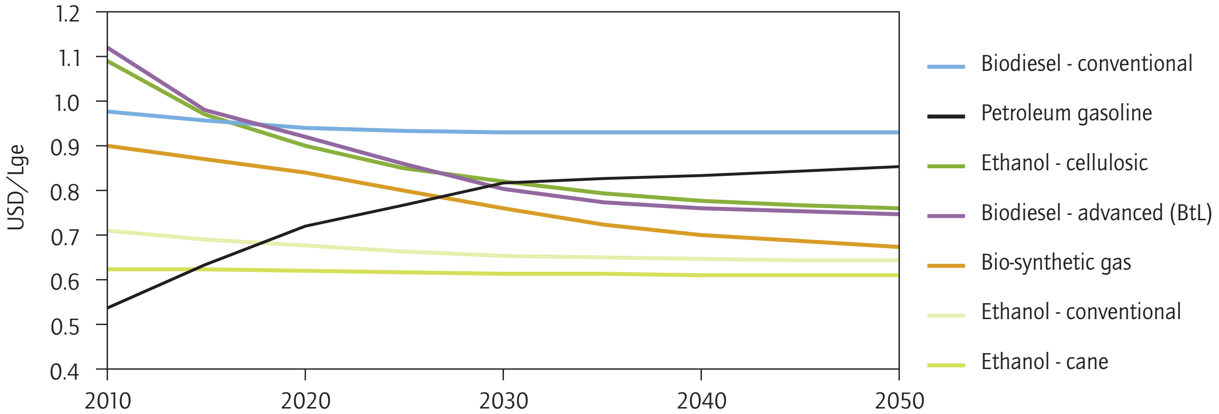
In the high-cost scenario, oil prices have a greater impact on feedstock and production costs and most biofuels remain slightly more expensive than gasoline/diesel, with oil at USD 120/bbl in 2050. Nonetheless, the total cost difference per litre compared with fossil gasoline and diesel is less than USD 0.10 in 2050 (with exemption of conventional biodiesel), and bio-synthetic gas as well as sugarcane ethanol can be produced at lower costs, leading to actual savings in fuel expenditure. Most conventional biofuels are close to cost parity or, in the case of sugarcane ethanol, lie well below reference gasoline and diesel prices (Figure 13).

Whether advanced biofuels can reach the cost of conventional fuels will depend on several factors that are still uncertain. If oil prices rise above USD 120/bbl, advanced biofuels will reach cost-competitiveness even in the high-cost scenario. Valuing CO_2 savings at around USD 50 per tonne would also enable most biofuels to reach reach cost parity or better.

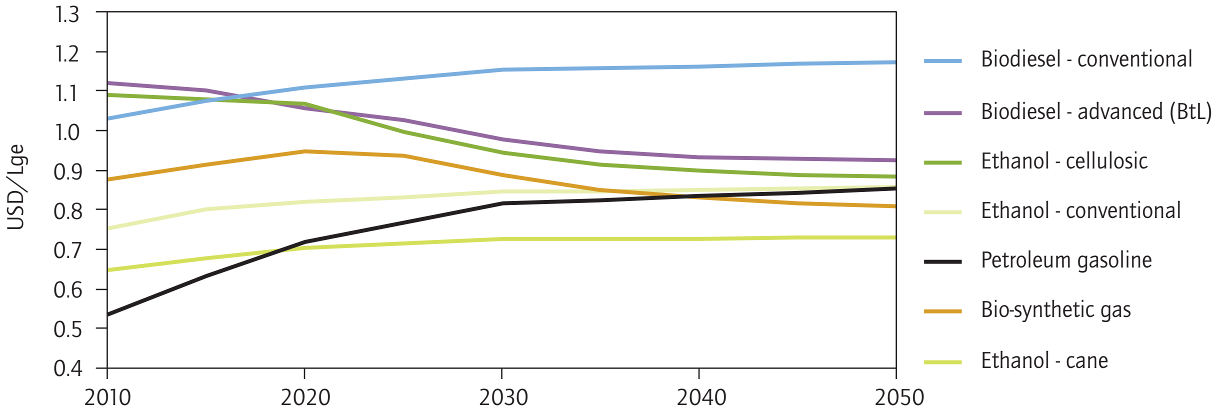
25 In Brazil, for instance, sugarmills can sell bioelectricity produced from bagasse; the revenues represent around 15% of total income of the unit.

Figure 13: Costs of different biofuels compared to gasoline (BLUE Map Scenario)

Low-cost scenario



High-cost scenario



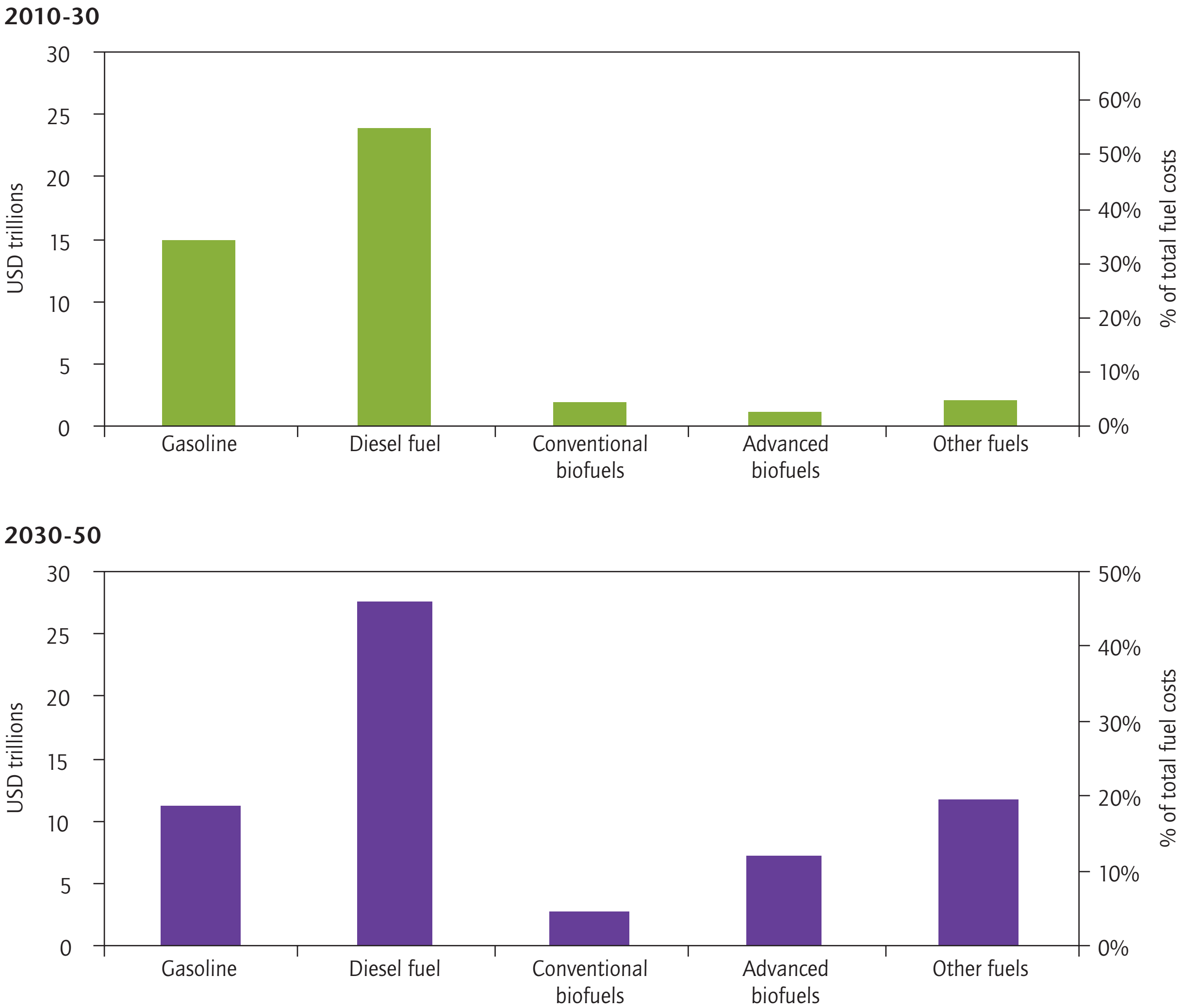
Note: costs reflect global average retail price without taxation. Regional differences can occur depending on feedstock prices and other cost factors.

Total costs for biofuel deployment

The total cost of biofuel use to 2030 is projected to be around USD 2.5 trillion (low-cost scenario) to USD 2.9 trillion (high-cost scenario) in this roadmap's vision. Total expenditures on transport fuels, by contrast, are estimated at USD 43 trillion to 44 trillion between 2010 and 2030 (Figure 14). Thus, the total expenditure on biofuels accounts for roughly 6% to 7% of all transport fuel spending.

After 2030, biofuel production ramps up considerably and the total cost of biofuels from 2030 to 2050 is projected to be about USD 8.2 trillion (low-cost scenario) to USD 9.9 trillion (high-cost scenario) in this roadmap. The total cost of transport fuels is between USD 58 trillion and USD 61 trillion – thus biofuels account for about 14% to 16% of spending on transport fuels (Figure 14).

Figure 14: Total cost for all transport fuels production (high-cost scenario)

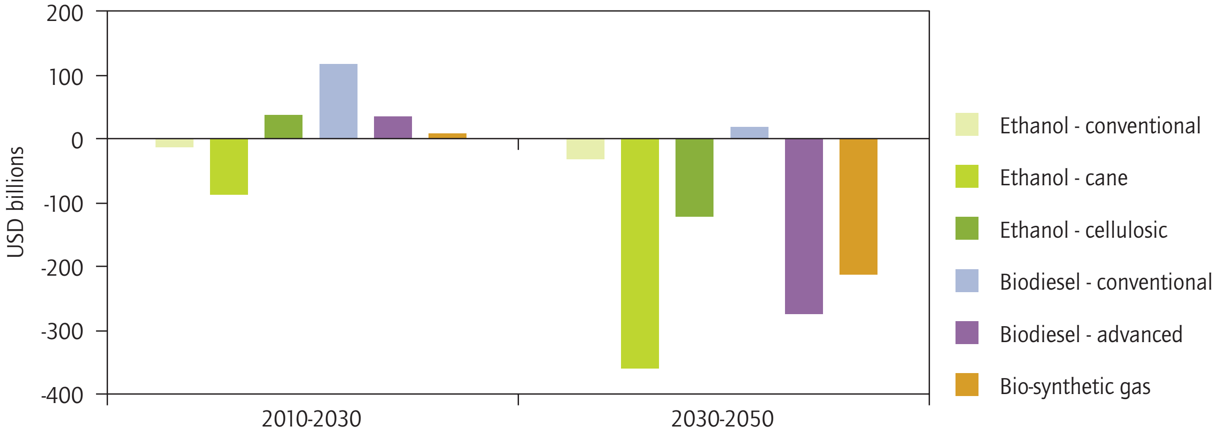


Total global expenditure on biofuels needs to be compared to the expenditure required if diesel and gasoline were used instead. Over the next 20 years, use of biofuels would lead to incremental costs of USD 95 billion in the low-cost scenario and up to USD 480 billion in the high-cost scenario above the cost of gasoline/diesel replaced. This is equivalent to between 0.2% and 1.1% of total fuel costs. Advanced biofuels account for the major share of these costs, given their comparably high production costs in this time frame (Figure 15).

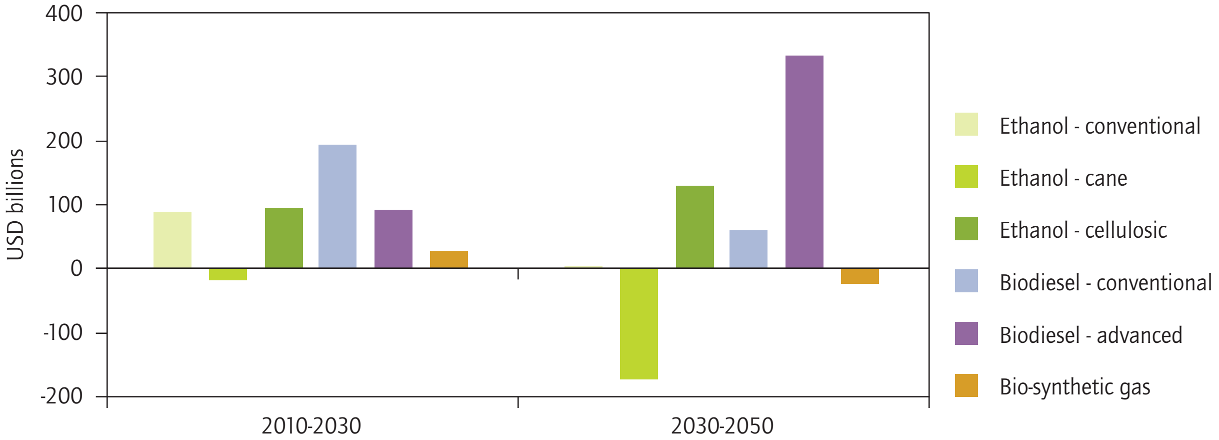
Between 2030 and 2050, total incremental costs for biofuels are around USD 330 billion in the high-cost scenario. This reflects additional expenditure for advanced biofuels of USD 440 billion, together with USD 110 billion of fuel cost savings (compared with use of fossil gasoline/diesel) through use of conventional biofuels. If rising oil prices have a limited impact on feedstock and commodity costs, advanced biofuels could be produced at lower costs than their fossil counterparts. In the low-cost scenario, incremental spending on advanced biofuels is thus USD 610 billion less compared with use of fossil fuel, and total fuel cost savings add up to USD 980 billion (Figure 15).

Figure 15: Incremental costs for biofuels by time frame

Low-cost scenario



High-cost scenario



Overall, in this roadmap's vision, incremental cost differences of all biofuels compared to use of fossil fuels from 2010 to 2050 are estimated to range from a USD 810 billion cost increment to a cost reduction of nearly USD 890 billion. Even in the high-cost scenario, additional expenditure on biofuels is low relative to the total expenditures on all transport fuels over this time frame, and is around 0.8% of total fuel cost expenditure.

Table 3: Total production costs for biofuels in this roadmap and incremental costs over replaced gasoline/diesel fuel

	2010-30	*2030-50*	*Total (2010-50)*
Conventional biofuel	1 650 - 1 920	2 290 - 2 750	3 940 - 4 670
Advanced biofuel	890 - 1 050	5 940 - 7 190	6 830 - 8 240
Total fuel costs	43 200 - 43 800	58 350 - 60 460	101 600 - 104 300
Biofuels incremental costs over replaced gasoline/diesel	95 - 480	-980 - 330	-890 - 810
Incremental cost share of total fuel cost expenditure	0.2 - 1.1%	-1.7 - 0.5%	-0.9 - 0.8%

Milestones for technology improvements

Technology development of conventional and advanced biofuels currently underway promises to boost sustainable biofuel production and reduce costs. The most critical milestones for advanced conversion technologies closest to commercialisation (HVO, cellulosic-ethanol, BtL/FT, bio-SG) are to demonstrate reliable and robust processes within the next five years, and achieve commercial-scale production within the next 10 years. Other important milestones include improving overall environmental performance of conventional biofuels, and the demonstration of algae-based biofuels and other novel conversion routes.

Milestones for technology improvements	*Dates*
Demonstrate reliable, commercial-scale production of cellulosic-ethanol, BtL-diesel, HVO and bio-SG.	2010-2015
All biofuels to reach >50% life-cycle GHG-emission reductions.	2015-2020
Demonstrate economically feasible production of algae-derived biofuel and other novel biofuel routes.	2020-2030
Integrate biofuel production in innovative biorefinery concepts.	2015-2025

Conventional biofuels

Conventional biofuels are relatively mature, but overall sustainability of the technologies could be further improved by reducing economic, environmental and social impacts. Conversion efficiency improvements will not only lead to better economics but also increase land-use efficiency and the environmental performance of conventional biofuels.

For conventional biodiesel, key areas for improvement include more efficient catalyst recovery, improved purification of the co-product glycerine and enhanced feedstock flexibility. For conventional ethanol, new, more efficient enzymes, improvement of DDGS' nutritional value, and better energy efficiency can raise the conversion efficiency and reduce production costs.

Further cost improvements could be achieved by maximising value-added co-product solutions, and by better integrating upstream and downstream processes. Producing conventional and/or advanced biofuels in biorefineries would promote more efficient use of biomass and bring associated cost and environmental benefits.

Advanced biofuels

Several advanced biofuels currently in a critical phase of technology development need to reach commercial scale and be widely deployed. As with conventional biofuels, improvements in conversion efficiency are needed, as well as strategies for reducing capital requirements. These strategies have to include integrating the different process steps along the whole supply chain (*i.e.* from biomass feedstock to transportation biofuel) to demonstrate the effective performance and reliability of the process. This should include the use of core technology components such as tar-free syngas production or (hemi-)cellulose to sugar conversion in other industries (*e.g.* chemical industry).

Specific R&D needs will need to be addressed to prove the industrial reliability as well as technical performance and operability of the conversion routes, in order to achieve economically sound production processes (Table 4). Detailed scientific support, modelling and monitoring of the above fields are required to obtain maximum learning and progress from current pilot and demonstration activities.

Table 4: Advanced biofuels key R&D issues

Technology	Key R&D issues
Cellulosic-ethanol	• Improvement of micro-organisms and enzymes • Use of C5 sugars, either for fermentation or upgrading to valuable co-products • Use of lignin as value-adding energy carrier or material feedstock
HVO	• Feedstock flexibility • Use of renewable hydrogen to improve GHG balance
BtL-diesel	• Catalyst longevity and robustness • Cost reductions for syngas clean-up • Efficient use of low-temperature heat
Other biomass-based diesel/kerosene fuel	• Reliable and robust conversion process in pilot and demonstration plants
Algae-biofuels	• Energy- and cost-efficient cultivation, harvesting and oil extraction • Nutrient and water recycling • Value-adding co-product streams
Bio-SNG	• Feedstock flexibility • Syngas production and clean-up
Pyrolysis oil	• Catalysts improvement to exhibit oil stability over time • Upgrading to fungible biofuel

For all biofuels, there is scope for cost reductions that will help to improve competitiveness with fossil fuels and drive commercial deployment:

- **Capital costs** are expected to come down as a result of scaling up (particularly for advanced biofuels). Co-location with existing biofuel plants, power plants or other industrial facilities reduces capital costs and can bring further benefits such as more efficient use of by-products.

- **Conversion costs** can be brought down through scaling up and technology learning. Further improvement of conversion efficiency (*e.g.* through more efficient enzymes) and energy efficiency should also help to reduce costs.

- **Feedstock costs** cannot be predicted and are subject to agricultural commodity prices, oil prices and other factors. Enhancing feedstock flexibility will create access to a broader range of biomass sources with potentially low costs (such as residues) and reduced price volatility. Improving and creating transport infrastructure could further reduce biomass supply costs.

Feedstock and sustainability

Milestones for feedstocks and sustainability	Dates
Increase biofuel production based on “low-risk” feedstocks (*e.g.* wastes and residues) and through yield improvements.	2010-50
Reduce and eventually abolish tariffs and other trade barriers (*e.g.* logistical) to promote biomass and biofuel trade.	2010-20
Improve biomass potential analysis with better regional and economic data, including from large-scale field trials.	2010-30
Enhance biomass cascading and use of co-products through integration of biofuel production in biorefineries.	2010-30
Continue alignment of LCA methodology to provide a basis for sound support policies.	2010-20

The assessment of available land that could be brought into cultivation for biofuel production in a sustainable way is a key priority for further development of the biofuel sector. To obtain better data on land availability and biomass potentials, land-use mapping and agro-ecological zoning (AEZ)[26] need to be further developed and improved by collecting data at the local, national and global levels. 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. A critical element to improve data on biomass potentials is the economic analysis of biomass availability through cost supply curves.

With the expansion of advanced biofuel production, high-yield lignocellulosic energy crops will be needed. Lignocellulosic energy crops have not been subject to intensive crop-breeding efforts in most parts of the world, so substantially more R&D is required to improve yields and develop varieties with characteristics that favour conversion to biofuel. Large-scale field trials are needed in different regions to assess the suitability of indigenous energy crops that are adapted to local conditions. The field trials will improve data on economics of cultivation, harvesting and transport that can be used for biomass potential analysis. In addition, experiences gained in these field trials will help to develop efficient feedstock supply chains.

National and local supply analyses need to be integrated into a global analysis on biomass and bioenergy potentials, to provide a holistic picture of biomass and land availability, and allow a smooth and sustainable expansion of biofuel production and trade.

Towards sustainable feedstock production and use

Despite uncertainty over long-term land and feedstock potential, it is critical to identify and mobilise sustainable biomass sources in the short- and medium-term to avoid bottlenecks for the expanding biofuel industry.

The focus should be on options that can be mobilised with little risk of compromising the sustainability of biofuel production. Enhanced use of wastes and residues as feedstocks, for instance through biomass cascading, is vital to increase the efficiency of biomass use and to avoid potential competition for land with agriculture or forestry.

Another proven measure that does not require additional land to be cultivated and has been proven effective is the improvement of crop yields (*e.g.* USDA, 2010). Experiences with crop breeding and cultivation techniques from other sectors (*e.g.* sugarcane sector) should be used to improve yields for new energy crops, such as switchgrass. Developing countries, in particular, show a considerable potential for improving yields. Greater adoption of management practices used in industrialised countries – such as application of nutrients, herbicides, pesticides and water – could significantly increase yields. Adoption of best practices is required, however, to ensure that the use of fertiliser and irrigation does not lead to undesired negative impacts such as eutrophication or depletion of water reserves.

Biofuel feedstocks have also proven their ability to restore degraded or contaminated soils. Perennial crops are particularly suited to reducing erosion and land degradation, and can increase soil fertility and soil carbon stocks. The cultivation of perennial feedstocks could therefore help in maintaining the quality of agricultural land and so benefit the whole agricultural sector. The identification of degraded land suitable for biofuel feedstock is not straightforward, however, and will require careful verification on the ground of the land's biodiversity value and its function for rural livelihoods.

In addition to these options, expansion of dedicated energy crops on arable and pasture land will be needed in the long term to meet the growing biofuel demand in this roadmap. This expansion should follow the latest biomass potential analyses, and needs to comply with sustainability certification schemes.

Cultivation concepts 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). At the same time, IFES provide several benefits to farmers such as access to energy, diversification of income streams and economic and efficient utilisation of residues.

26 Agro-ecological zoning has been developed by the FAO in collaboration with the International Institute for Applied System Analysis (IIASA) and enables rational land-use planning on the basis of an inventory of land resources and evaluation of biophysical limitations and potentials, www.iiasa.ac.at/Research/LUC/GAEZ/index.htm?sb

Improving GHG performance

The overall GHG balance of biofuels can be optimised by choice of feedstock and cultivation technique, by maximising the conversion efficiency, or by improving energy efficiency of the plant. In detail, the life-cycle GHG balance can be improved by using waste and residue feedstocks, maximising land-use efficiency by increasing yields and productivities, and using perennial energy crops that require less fertiliser and can improve soil carbon sequestration. Other measures that need to be pursued are minimising process-based emissions through energy efficiency measures and use of renewable energy, and through cascade utilisation of biomass (*i.e.* linking industrial and subsequent uses of biomass for energy), for instance within a biorefinery. Some of these measures will also lead to cost reductions and should thus be pursued vigorously.

Support policies based on life-cycle GHG reductions are best suited to promote the most efficient biofuel technologies. However, this requires a solid scientific basis on which life-cycle emissions can be evaluated. As discussed earlier, there is no standardised methodology yet for assessing the GHG emissions of biofuels. More work is needed, especially to develop a methodology for assessing and evaluating emissions caused by indirect land-use change.

In order to reduce and eventually avoid land use changes caused by biofuel production, further improvement of modeling is required to provide solid and realistic data on LUC and ILUC induced by biofuel production. Such a scientific basis is needed to adopt sound biofuel policies and introduce measures to reduce land-use change risks. However, even with current uncertainties on the impact of LUC and ILUC, policy action can be taken by incentivising biofuel production from residues and wastes, use of high productive feedstocks, use of co-products, and introducing sustainable land-use management.

Enhancing biomass and fuel trade

Dismantling trade barriers is a key task to support the development of international trade between biomass-rich regions and biofuel production/consumption centres. Tariffs need to be reduced and eventually abolished. Technical standards for biomass, biofuels and intermediate products (*e.g.* pyrolysis oil) need to be aligned internationally. International trade agreements can stimulate production of biofuels for export, especially in developing countries. Sustainability certification for biofuels is needed, but must be aligned so that it does not act as a trade barrier, in particular for developing countries.

Policy framework: roadmap actions and milestones

This roadmap recommends the following actions:	*Dates*
Create a stable, long-term policy framework for biofuels, to increase investor confidence and allow for the expansion of biofuel production.	2010-30
Provide sufficient support (*e.g.* through grants and loan guarantees) that addresses the high investment risks related to commercial-scale advanced biofuel plants.	2010-20
Reduce fossil fuel subsidies and introduce CO_2 emission pricing schemes.	2010-30
Introduce mandatory sustainability requirements based on internationally aligned certification schemes.	2010-20
Link financial support schemes to the sustainable performance of biofuels.	2010-30
Adjust economic incentives over time, as biofuels move towards competitiveness with fossil counterparts.	long-term

Overcoming economic barriers

The economics of conversion processes need to be further improved for biofuels to be competitive with fossil fuels without subsidies in the longer term (given sound policy framework conditions, including CO_2 emission pricing).

As a first step, fossil fuel subsidies, which are still applied in many countries (IEA, 2010f), should be phased out. Introducing a CO_2 price through a global carbon market will be an important element in fostering the deployment of biofuels and other low-carbon technologies in the longer term and would help considerably to improve their competitiveness.

Conventional biofuels today are not generally competitive with fossil fuels at market prices,[27] although competitiveness varies depending on feedstock costs and oil price. Some biofuels already perform well in economic terms, particularly sugarcane ethanol and some other low-cost conventional biofuels. The support requirements for conventional biofuels differ from those of advanced biofuels, which are in an earlier stage of technology development and still subject to comparably high production costs. To stimulate the large investments required for commercial-scale production units, specific support measures are needed that sufficiently address the financial risks associated with scaling up innovative processes and the insecurity of product markets for advanced biofuels.

27 In some cases this can be due to fossil fuel subsidies.

Given the numerous new conversion routes that are emerging, along with biorefinery concepts, a portfolio approach is needed to stimulate promising technology routes and to demonstrate their capability of producing sustainable biofuels.

Both the United States, through the Department of Energy's Biomass Program, and the European Union, through its Seventh Framework Program, and the European Industrial Bioenergy Initiative, provide financial support to advanced biofuel production plants. The grants and loan guarantees reduce investment risks and have led to a considerable number of pilot and demonstration plants operating or currently being constructed. However, few commercial-scale advanced biofuel projects have been announced and none are operating yet. More government support - delivered through public-private partnerships - is needed to bring these technologies to full-scale operation.

Creating incentives for biofuel deployment

It is critical that all policy measures provide a stable, long-term framework that creates investor confidence and drives the expansion of biofuel production and use. Blending mandates or targets that have been adopted in 50 countries (Table 1), are a suitable measure to drive biofuel use and production. They need to be sufficiently ambitious to drive biofuel deployment, without inducing undesired competition with food and fibre production. However, mandates alone are not enough to promote the deployment of those technologies that perform best in terms of land use, energy efficiency, GHG reductions, and social and economic impacts. This is particularly true for advanced biofuels, which are currently disadvantaged by higher production costs.

The US is the only country with a specific quota for cellulosic biofuels today. The EU Renewable Energy Directive promotes lignocellulosic biofuels, as well as biofuels from algae, wastes and residues, by counting their contribution twice towards the 2020 target. However, neither support measure addresses sufficiently the higher production costs of advanced biofuels compared with conventional biofuels and fossil fuels.

To drive development of biofuels that provide considerable emission savings and at the same time are socially and environmentally acceptable, support measures need to be based on the sustainable performance of biofuels. Minimum GHG savings for biofuels as mandated in the US RFS II and the EU RED are an important step to ensure that biofuel use contributes to emissions reduction targets. Another approach is to directly link financial support to life-cycle CO_2-emission reductions (calculated with a standard LCA methodology agreed on internationally) to support those biofuels that perform best in terms of CO_2 savings. In both cases, advanced biofuels could profit as they promise particularly high GHG savings. However, well-performing conventional biofuels would be supported equally, meaning the cost disadvantage that advanced biofuels face in the short term would not be fully addressed.

Neither specific advanced biofuel quota, nor performance based support measures on their own seem to be effective to address the higher production costs of advanced biofuels in the short term. Specific transitional measures may thus be needed to support the introduction of the new technologies.

Financial incentives, for instance a tax incentive or perhaps analogous to feed-in tariffs for electricity, could be coupled to the use of co-products such as waste heat to promote efficient use of by-products (*e.g.* a mechanism similar to the co-generation bonus for biogas electricity in Germany). Rewarding best practices in the cultivation of feedstocks can also help to promote the use of sustainable biofuels.

Sustainability certification will also be needed, as mentioned earlier. In the EU, for instance, biofuels will need to be certified to count towards the 2020 mandate. Each Member State needs to adopt a certification system, but there is no EU-wide alignment. Harmonisation of certification systems internationally is important, to avoid the creation of uncertainty for both producers and consumers, and to prevent the creation of trade barriers. Certification can then become a driver for biofuels as it allows for producer to access to wider markets.

Import and export tariffs are used to protect the biofuel sector in certain countries and regions. These measures are not, however, increasing the general competitiveness of biofuels. Rather, they act as trade barriers and should be reduced to pave the way towards enhanced international biofuel and biomass trade that will be needed to meet the targets in this roadmap.

Addressing non-economic barriers

A key non-economic barrier to development of biofuels is uncertainty regarding their sustainability. The sometimes controversial public debate on competition with food production and the potential destruction of valuable ecosystems has put biofuels in the centre of a sustainability discussion that concerns all forms of bioenergy and which (in parts) is relevant to the entire agricultural and forestry sector.

To avoid creating market uncertainty, and potentially preventing required investments into sustainable biofuel production and use, public discussion on biofuels needs to be driven by objective information on the benefits and drawbacks of biofuel production and use, based on state-of-the-art research results. Integrating sound sustainability schemes into biofuel support policies, and acknowledging clearly which fuels meet the requirements, is essential in order to provide market stability and improve consumer acceptance, which will attract investors for sustainable biofuel projects.

Insufficient development of biofuel infrastructure – including feedstock supply, conversion and end-use related infrastructure, can form a non-economic barrier to the growing biofuel production envisioned in this roadmap. In developing countries, in particular, poor rural infrastructure may form a barrier to feedstock supply and fuel transport. Infrastructure should best be developed as part of an overall land use and rural development strategy that helps to attract urgently needed investments in agricultural infrastructure and promote overall rural development.

In addition, sound feedstock supply systems - based on specific regional conditions need to be developed - given the large biomass demand (up to 600 000 dry tons/year) of advanced biofuel plants. This may require pre-conditioning of biomass through pelletisation, pyrolysis or torrefaction, and may also involve long-distance shipping of the intermediates.

End-use infrastructure requirements need to be adressed to avoid bottlenecks caused by incompatibility with deployed biofuels. The ethanol "blending wall" – the limiting of ethanol in gasoline to 10% to 15% because of vehicle compatibility constraints – is one example of potential infrastructure bottlenecks that need to be addressed. Introduction of flex-fuel vehicles (FFV) and high-level ethanol blends is a suitable measure to avoid infrastructure incompatibility issues for ethanol, as has been successfully demonstrated in Brazil and Sweden. Policy measures maybe required, such as obligations for retailers to provide high-level biofuel blends (*e.g.* E85) or tax incentives for FFVs.

Fully fungible biofuels (*e.g.* BtL-diesel) can be distributed through existing infrastructure and used in unmodified engines. The reduced investment needs in new infrastructure could thus partially off-set cost disadvantages caused by higher production prices.

A key requirement for all biofuels to get access to the market will be compliance with international fuel quality standards. This will ensure vehicle and infrastructure compatibility among different regions and promote consumer acceptance for new fuels.

Research, development and demonstration support

Over recent decades, substantial RD&D in biofuels has been undertaken in OECD countries as well as in developing countries. Several conventional biofuels have reached commercial production and further technology improvements have been made. Several significant improvements have also been made to advanced biofuel conversion routes, such as more efficient enzymes. Global expenditure on biofuel R&D has increased significantly, to USD 800 million in 2009 (up 57% from 2008), with much of this directed towards the development of advanced biofuels (UNEP and BNEF, 2010). This is a considerable amount, but given the large number of emerging biofuel technologies and the additional R&D needs listed above (Table 4), significantly more investment in R&D and demonstration is needed, especially during the next 20 years, to ensure that advanced biofuels reach full technology maturity.

Policies that support RD&D should focus on the whole biofuel production chain. As mentioned earlier, RD&D on new crop varieties and improvement of existing crops suitable for biofuel production, is needed. Large field trials in different parts of the world are essential in order to develop well-adapted, high-yielding biofuel feedstocks that are ready for market deployment once advanced biofuels have been commercialised. Further RD&D should focus on biomass handling and transport, biofuel conversion (see Table 4) and end-use, to avoid bottlenecks in one part of the chain that would slow down the technology development as a whole. In order to reduce total expenditure on RD&D, international collaboration should be promoted to the greatest extent possible and results from publicly funded RD&D projects should be accessible to the public. This will be particularly helpful for less-developed countries seeking to build capacity and adopt conversion technologies that reach commercial scale.

Synergies between RD&D investments in biofuels and in other sectors – such as agriculture, forestry and the chemical industry – need to be maximised. For instance, the development of biomass gasification technology is also of interest to the chemical industry; RD&D on improving feedstock supply systems can benefit agricultural production in general; better land-use data will aid sustainable land-use management of the whole agricultural and forestry sector, considerably benefitting rural communities.

International collaboration

This roadmap recommends the following actions:	*Dates*
Expand international RD&D collaboration, making best use of national competencies.	2010-50
Enhance exchange of technology and deployment, including best practices for sustainable biofuel production.	2010-30
Enhance efforts to align certification schemes based on commonly agreed sustainability indicators.	2010-20
Increase efforts to align technical standards for biofuels and vehicles to reduce trade barriers and infrastructure compatibility problems.	2010-20

International collaboration will be required in many fields to create a sustainable global biofuel sector. Joint international efforts in field mapping will result in better land-use data and will help to improve the analysis of global biomass potentials. 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.

Joint RD&D efforts to develop biofuel 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 for the successful large-scale deployment of biofuels, especially advanced biofuels. 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 or access to technologies and know-how for sustainable biofuel production.

International collaboration to develop sound sustainability criteria and align certification schemes for biofuels and other biomass products should be enhanced. This is critical to ensure not only the sustainable production of biofuels but also the marketability of biofuels with different certification schemes in different markets, thereby enhancing international biofuel trade. Global alignment of technical standards – including fuel and vehicle standards – will improve biofuel and feedstock tradeability and help to overcome non-economic barriers related to infrastructure compatibility and consumer acceptance. Exchange of experiences between emerging markets and large biofuel-producing countries and regions (such as Brazil, the United States and the European Union) will help to avoid infrastructure barriers, and allow for smooth introduction of biofuels in new markets.

Many international organisations and initiatives are working on development of sustainable bioenergy and biofuels. The IEA Bioenergy Implementing Agreement,[28] for instance, is working on RD&D and is also emphasising large-scale global deployment of bioenergy. The IEA Bioenergy Implementing Agreement consists of 12 tasks that focus on different technologies and aspects of bioenergy development along the whole supply chain. Task 39[29] provides a good platform for greater collaboration among OECD and non-OECD countries focusing on the commercialisation of biofuels.

Biofuel deployment in developing countries

To reach the biofuel deployment envisioned in this roadmap, it will be crucial to consider the specific policy framework and particular needs of

28 www.ieabioenergy.com

29 www.task39.org

developing countries. Several countries outside the OECD are already producing biofuels commercially, with Brazil, Argentina, China and Thailand being the most active (IEA, 2010b). Other developing countries have started biofuel production only recently and in most African countries there is currently no large-scale commercial biofuel production. Given these countries' limited financial resources and lack of access to primary energy needs (such as lighting and cooking), the suitability of different types of biofuel has to be evaluated against other renewable energy options that might be of higher priority in the short term.

Growing biofuel production and the increasing number of countries adopting biofuel support policies show that many developing countries are realising the potential economic and social benefits of producing and using biofuels. Creating new sources of income for rural communities is a key driver in many regions, along with the potential to cut expenditures for importing petroleum products. In addition, potential exists to export biofuels to regions with strong demand, like the United States and the European Union, which would help to increase foreign currency reserves (IEA, 2010b).

Many developing countries, however, face barriers towards the development of a viable, sustainable biofuel industry. Poor infrastructure, lack of skilled labour, lack of formal land ownership structures and limited financial resources are among the most significant barriers. In order to make investments in sustainable biofuel production worthwhile, synergies between biofuel and crop/timber production should be created to the greatest extent possible. The benefits of infrastructure investments (*e.g.* road/rail infrastructure, electricity access) can be maximised when undertaken as part of an overall rural development strategy that promotes rural development with positive impacts on overall productivity.

Capacity building will be crucial, in the field of feedstock cultivation, supply and handling as well as in the area of technical expertise. Building capacity for feedstock cultivation needs to involve best agricultural practices, which will benefit farmers and can increase productivity and sustainability of the whole agricultural sector. It will be particularly important to ensure that biofuel producers comply with sustainability requirements to enable access to international markets. International collaboration and investments through public-private partnerships are needed to couple business models with comprehensive agricultural education and training concepts for farmers. Supporting smallholder participation in biofuel value chains will be vital to avoid displacement of local populations and maximise benefits for rural development.

To ensure technology access and transfer, co-operation on RD&D should be enhanced among industrialised and developing countries, as well as among developing countries. Technologies and biofuel supply concepts suitable to a country's specific needs should be developed with regard to experiences in other countries. In the short term, feedstock trade might be an option for countries that do not have any biofuel production infrastructure or that produce surplus feedstock. For biofuel production, focus should be on biofuel concepts that are technically less complex and do not require large investments. In the longer term, developing countries can profit from experiences with sustainable conventional biofuel production and adopt advanced biofuel technologies once they are commercially proven.

To develop a viable biofuel sector, developing countries may need foreign investment in addition to domestic funding. Administrative and governance problems may severely affect large-scale foreign investment in developing countries in general. But even if these issues are less severe, foreign investment in biofuel projects might be constrained by the limited size of domestic markets. Ensuring access to international markets for biofuel exports is likely to increase investor confidence, but this will require complying with sustainability standards in the importing countries. A key challenge at the moment is the broad number of sustainability schemes in key consuming countries. Internationally agreed sustainability criteria and certification schemes for biofuel production are thus needed and developing countries should get actively involved in their development. A challenge for developing countries is that costs of certification are typically higher than in industrialised countries and can reach up to 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 biofuel production.

Conclusion: 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 biofuels, a key carbon mitigation technology. The biofuel roadmap is intended to be 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 biofuel development efforts are on track to achieve reductions in GHG emissions that are required by 2050 in a sustainable manner. The IEA, together with government, industry and NGO stakeholders, will report regularly on the progress achieved toward this roadmap's vision. For more information about the biofuel roadmap actions and implementation, visit www.iea.org/roadmaps.

Stakeholder	Action items
National governments	• Provide long-term targets and support policies that stimulate investments in sustainable biofuel production and ensure that advanced biofuels reach commercial production. • Ensure increased and sustained RD&D funding to promote cost and efficiency gains for conventional and advanced biofuels. • Implement sound sustainability criteria for biofuels, based on internationally agreed indicators. • Promote good practices in biofuel production, particularly in feedstock production. • Set minimum GHG reduction targets and integrate the environmental and social performance of biofuels in national support schemes. • Work towards the development of an international market for biofuels by seeking commoditisation of biofuels and elimination of trade barriers. • Progressively eliminate subsidies to fossil fuels, and establish a price for CO_2 emissions. • Consumer countries should offer technical and financial support to producer countries for land-use planning and mapping. • Ensure that biofuel policies are aligned with policies in related sectors, such as agriculture, rural development and energy. • Extend sustainability criteria for biofuels to all biomass products (including food and fibre) to ensure sustainable land use.
Industry	• Establish commercial-scale cellulosic-ethanol, BtL and bio-SG plants by 2015. • Develop and implement credible, independent sustainability certification schemes. • Develop concepts for efficient process integration within a biorefinery approach. • Improve feedstock flexibility of processes to allow a broader range of feedstocks and reduce feedstock competition. • Engage in public-private partnerships to support smallholder qualification and participation in biofuel value chains. • Establish large-scale field trials and vigorously pursue the development of new, more sustainable feedstocks. • Share demonstration project data more widely to improve public acceptance.

Stakeholder	Action items
Universities and other research institutions	• Further improve life-cycle assessment methodology for biofuels, and refine methodology to account for indirect land-use change. • Collaborate with industry on large-scale energy crop field trials. • Improve economic models based on detailed cost-curves for feedstock supply in different regions to improve analysis of bioenergy potentials. • Develop national biofuel RD&D roadmaps to identify critical technology breakthroughs needed for sustainable biofuel production. • Develop systems to monitor and avoid (indirect) land-use change.
Non-governmental organisations	• Monitor progress toward biofuel development and policy milestones and publish results regularly to keep governments and industry on track. • Provide objective information on the potential of sustainable biofuels to mitigate climate change, increase energy security, and provide economic benefits to rural communities.
Intergovernmental organisations and multilateral development agencies	• Work on standardisation of fuel and feedstock quality to enhance trade between countries. • Provide capacity building/training for regulatory frameworks and business models to help developing countries implement sustainable cultivation techniques, feedstock supply and biofuel conversion. • Promote and facilitate a structured dialogue between policy makers and the roundtables that are developing standards for the certification of biofuels or biofuel feedstocks, in order to ensure coherence between regulatory frameworks and standards. • Serve as platforms for research and exchange between different sectors – including government, research institutions and the private sector. • Provide technical support to help developing countries devise and implement certification schemes and biofuel support policies.

Appendix I: additional biofuel technologies and blending characteristics

Hydrothermal processing. Biomass can be processed in a liquid media (typically water) under pressure and at temperatures between 300-400°C. The reaction yields oils and residual solids that have a low water content, and a lower oxygen content than oils from fast pyrolysis (NABC, 2010). Upgrading of the so-called "bio-crude" is similar to that of pyrolysis oil (see below).

Pyrolysis oil can be produced by fast pyrolysis, a process involving rapidly heating the biomass to temperatures between 400-600°C, followed by rapid cooling. Through this process, thermally unstable biomass compounds are converted to a liquid product. The obtained pyrolysis-oil is more suitable for long-distance transport than for for instance straw or wood-chips. As a by-product, bio-char is produced that can be used as solid fuel, or applied on land as a measure of carbon sequestration and soil fertilisation. The oil can be processed in ways similar to crude oil, and several research efforts are currently undertaken to upgrade pyrolysis oil to advanced biofuels (EBTP, 2010).

Dimethylether (DME) can be produced from methanol through the process of catalytic dehydration or it can be produced from syngas through gasifying lignocellulosic and other biomass feedstocks. Production of DME from gasification of biomass is in the demonstration stage, and the first plant started production in September 2010 in Sweden (Chemrec, 2010). DME is the simplest ether and can substitut for propane in liquefied petroleum gas (LPG) used as fuel, and it is a promising fuel in diesel engines, due to its high cetane number (55) (IEA, 2008).

Biobutanol can be used as a fuel in an internal combustion engine. It has a greater energy density (29.2 MJ/l) and is more similar to gasoline than ethanol, and could thus be distributed through existing gasoline infrastructure (USDOE, 2009). Biobutanol can be produced by fermentation of sugar via the acetone-butanol-ethanol (ABE) process using bacteria such as *Clastridium acetobutylicum*. Demonstration plants are operating in Germany and the US and others are currently under construction. Biobutanol can be produced from the same starch and sugar feedstocks that are used for conventional ethanol. In addition sugars can also be derived from lignocellulosic biomass, using the same biochemical conversion steps required for advanced ethanol production. This underlines the need for enhanced RD&D on the biochemical conversion of biomass to sugars.

Solarfuels. Biomass can be gasified to syngas using heat generated by a concentrating solar plant, thus potentially improving the conversion efficiency and providing higher GHG emission savings. More demonstration plants and further research is needed to make the process more efficient and allow for commercial-scale operation. Another technology that could evolve as a process to produce liquid transport fuels is the splitting of water or CO_2 to hydrogen or carbon monoxide which can then be turned to liquid fuels via a catalytic progress. This process is currently in the laboratory stage and considerable R&D efforts on a larger-scale are needed to support further development of solarfuels as part of the transport fuel mix in the longer term.

Table 5: Overview on different biofuels' blending characteristics

Biofuel	*Blending characteristics*
Sugar-based ethanol	E10-E15 (E25 in Brazil) in conventional gasoline vehicles; E85-E100 in FFV or ethanol vehicles
Starch-based ethanol	same as above
Cellulosic-ethanol	same as above
Conventional biodiesel (FAME)	up to B20 in conventional diesel engines
Hydrotreated vegetable oil (HVO)	fully compatible with existing vehicle and distribution infrastructure
BtL-diesel	same as above
Algae oil based biodiesel/ bio-jet fuel	after hydrotreating: fully compatible with existing vehicle and distribution infrastructure
Biogas	after upgrading: Fully compatible with natural gas vehicles and fuelling infrastructure
Bio-SG	same as above
Bio-butanol	use in gasoline vehicles in blends up to 85%
Dimethylether	compatible with LPG infrastructure
Methanol	10%-20% blends in gasoline; blend up to 85% in FFVs
Sugar-based diesel/jet-fuel	fully compatible with existing vehicle and distribution infrastructure

Source: IEA analysis, based on IEA, 2008; IEA, 2009; EBTP, 2010.

Appendix II: acronyms and abbreviations, relevant websites and literature, workshop participants and reviewers

Acronyms and abbreviations

ABE	acetone-butanol-ethanol (process used in the production of butanol)
AD	anaerobic digestion
AEZ	agro-ecological zoning
Bio-SG	bio synthetic gas (also referred to as bio synthetic natural gas)
BTL	biomass-to-liquids
CCS	carbon capture and storage
CNG	compressed natural gas
CO_2	carbon dioxide
DDGS	dried distiller's grains with solubles
DME	dimethylether
ETP	Energy Technology Perspectives
EPA	Environmental Protection Agency
EU	European Union
FAME	fatty acid methyl ester
FAO	Food and Agriculture Organisation of the United Nations
FFV	Flex-fuel vehicle
FT	Fischer-Tropsch
GBEP	Global Bioenergy Partnership
GHG	greenhouse gas
H_2S	hydrogen sulfide
HVO	hydrotreated vegetable oil
IFES	Integrated Food and Energy Systems
IGO	international government organisations
IIASA	International Institute for Applied Systems Analysis
ILUC	indirect land-use change
ISCC	International Sustainability and Carbon Certification System
LCA	life-cycle assessment
LDE	litre of diesel equivalent (energy content 36.1 MJ/litre)
LGE	litre gasoline equivalent (energy content 33.5 MJ/litre)
LPG	liquefied petroleum gas
LUC	land-use change
NA	not applicable
NGO	non-governmental organisation
NGV	natural gas vehicle
R&D	research and development
RD&D	research, development and demonstration
RDD&D	research, development, demonstration and deployment
RED	Renewable Energy Directive
RSB	Roundtable for Sustainable Biofuel
USD	US dollar

Units of measure

EJ	exajoule
GT	gigatonne
MHA	million hectares
MJ	megajoule
MTOE	million tons of oil equivalent
PPM	parts per million

List of relevant websites and selected literature for further reading

Websites	
International Energy Agency	www.iea.org
IEA Technology Roadmaps	www.iea.org/roadmaps
IEA Policies and Measures Database	renewables.iea.org
IEA Energy Training and Capacity-Building	www.iea.org/training
IEA Bioenergy Implementing Agreement	www.ieabioenergy.com
Task 34: Pyrolysis of Biomass	www.pyne.co.uk
Task 37: Energy from Biogas	www.iea-biogas.net
Task 38: Greenhouse Gas Balances of Biomass and Bioenergy Systems	www.ieabioenergy-task38.org

Websites	
Task 39: Commercialising Liquid Biofuels from Biomass	www.task39.org
Task 40: Sustainable International Bioenergy Trade	www.bioenergytrade.org
Task 42: Biorefineries	www.biorefinery.nl
IEA Implementing Agreement on Advanced Motorfuels	www.iea-amf.vtt.fi
European Biofuels Technology Platform	www.biofuelstp.eu
Global Bioenergy Partnership	www.globalbioenergy.org
Global Environmental Fund	www.thegef.org
International Sustainability and Carbon Certification System	www.iscc-system.org
National Advanced Biofuel Consortia	www.nabcprojects.org
Roundtable on Sustainable Biofuels	rsb.epfl.ch

Literature for further reading	
IEA (2008), *From 1st- to 2nd-Generation Biofuel Technologies*	www.iea.org
IEA (2009), *Transport, Energy and* CO_2	www.iea.org
IEA (2010), *Sustainable Production of Second-Generation Biofuels*	www.iea.org
IEA (2011, forthcoming), *Analysis of Alternative Transport Fuel Costs Under Different Oil Price Assumptions in the Near and Longer Term*	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
Bogdanski *et al.* (2010), *Making Integrated Food-Energy Systems Work for People and Climate. An Overview*	www.fao.org
Bradley *et al.* (2009), *World Biofuel Maritime Shipping Study*	www.bioenergytrade.org
Darzins *et al.* (2010), *Current Status and Potential for Algal Biofuels Production*	www.task39.org
FAO (2009), *Algae-based biofuels: A Review of Challenges and Opportunities for Developing Countries*	www.fao.org
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UNEP (2011, forthcoming), *Zooming in the Bioenergy and Water Nexus*	www.unep.org
UNEP (2009), *Towards Sustainable Production and Use of Resources: Assessing Biofuels*	www.unep.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 biofuel production.

Workshop participants and reviewers

Participants of the Project Workshops (15-16 April 2010/ 15-16 September, 2010)

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