Technology Roadmap

Delivering Sustainable Bioenergy

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Foreword

Bioenergy is the main source of renewable energy today, contributing to energy used in power generation, heat for industry and buildings, and for transport. Despite recent high profile increases in wind and solar electricity, bioenergy provides five times their contribution to global final energy consumption, when traditional use of biomass is excluded. IEA modelling also indicates that modern bioenergy is an essential component of the future low carbon global energy system if global climate change commitments are to be met. This is especially the case since bioenergy can play an important role in helping to decarbonise sectors for which other options are scarce, such as in aviation, shipping or long haul road transport.

However, the current rate of bioenergy deployment is well below the levels required within IEA long term climate models. Acceleration is urgently needed to ramp up the contribution of bioenergy across all sectors notably in the transport sector where consumption is required to triple by 2030.

Moreover, bioenergy is a complex subject with many potential feedstocks, conversion processes and energy applications. It interacts strongly with the agriculture, forestry and waste management sectors, and its prospects are linked to the growth of a broader bioeconomy. Bioenergy can also sometimes be a controversial topic, and there is an increasing understanding that bioenergy can only expand if supplied and used in a sustainable manner.

This Roadmap re-examines the role of bioenergy in light of changes to the energy landscape over the past five years as well as recent experience in bioenergy policy, market development and regulation. It identifies the principal opportunities and the technical, policy and financial barriers to deployment, and it suggests a range of solutions to overcome them, outlining those which are available now and in the longer term. Many of these opportunities are highly suitable for emerging and developing economies experiencing rapid energy demand growth.

This publication is part of the new cycle of IEA Technology Roadmaps, a series that looks at the long term vision for clean energy technologies and offers guidance on the near-term priorities and key steps to accelerating technology development and deployment.

This Roadmap has been developed in in close co operation with the IEA Technology Collaboration Programme on Bioenergy and has benefited from extensive consultation with a wide range of international organisations and other stakeholders. We hope that this roadmap will play a valuable role by emphasising the potential for sustainable bioenergy and identifying the key opportunities and actions needed to fulfil its potential, as part of an enhanced international effort to provide new impetus to this important sector.

Fatih Birol
Executive Director
International Energy Agency

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For more information on this document, please contact the Renewable Energy Division, IEA at bioenergyroadmap@iea.org.

Key findings and recommendations

Achieving a low-carbon future will be challenging and will require a comprehensive portfolio of technologies and policy measures. Modern bioenergy plays an essential role in the International Energy Agency (IEA) 2°C Scenario (2DS),[1] providing nearly 17% of final energy demand in 2060 compared to 4.5% in 2015. Bioenergy provides almost 20% of the cumulative carbon savings to 2060. It would be difficult to replace this important contribution. To play this important role, bioenergy must be produced and used in a sustainable way – significantly reducing greenhouse gas (GHG) emissions compared to fossil fuels and helping to achieve sustainable development goals.

Bioenergy is particularly important in sectors for which other decarbonisation options are not available. For example, in the transport sector bioenergy complements improved efficiency and electrification, and is particularly important in aviation and shipping. Its contribution to the sector grows ten-fold between 2015 and 2060. The use of bioenergy coupled with carbon capture and storage becomes particularly important in scenarios aiming to go beyond the 2°C level, such as the more ambitious IEA Beyond 2DS (B2DS) low-carbon scenario.

Current rates of bioenergy deployment in the transport, electricity and heat sectors are well below those needed to follow the 2DS trajectory. In addition, current deployment is concentrated geographically. For example, 90% of transport biofuel use happens in Brazil, the European Union (EU), the Peoples Republic of China, and the United States (US). Achieving the levels associated with the 2DS will require bioenergy to be used much more widely.

The growth of bioenergy will need to rely on a mix of technologies. A number of mature technologies can be used to produce heat, electricity and transport fuels. These options can provide immediate benefits in the form of green-house gas (GHG) savings, energy security and diversity, as well as complementary socio-economic benefits. Mature technologies include the production and use of biomethane from waste and residues, production of heat for district heating networks, the efficient use of agricultural residues for electricity generation and a number of options for producing transport fuels.

To accelerate the uptake of these options, appropriate policies, market design and regulatory frameworks will need to be put in place in more countries and regions. These can level the playing field for bioenergy by removing measures which favour fossil fuels, recognise the GHG and other benefits from bioenergy projects, and remove unnecessary regulatory barriers. Frameworks can also provide a low-risk investment climate, ensuring market access and predictable revenue streams that can facilitate lower-cost finance. Technical and institutional capacity-building support will be essential in emerging and developing economies so that such enabling legislation and regulation can be put in place to stimulate the deployment of these solutions.

Meeting the long-term potential of bioenergy will also depend on a number of novel technologies which are not yet fully mature and commercialised. One priority is the development and commercialisation of the range of technologies that can provide appropriate transport fuels while at the same time providing significant GHG savings. Recent progress has been promising in demonstrating the necessary technologies (such as biomass gasification, pyrolysis and the production of ethanol from cellulosic feedstocks), but much remains to be done.

Development and commercialisation of these technologies will require specific policies to support their development and deployment. These include obligations for deployment of sustainable novel fuels, appropriate and dedicated financial mechanisms, and instruments to facilitate technological development and subsequent market deployment, such as loan guarantees. Enhanced support for research, development and demonstration (RD&D) aimed at expanding technology options and reducing costs will also be important.

Enabling bioenergy to play a key role in decarbonisation of the energy system will require a fivefold increase in the supply of biomass feedstock for modern bioenergy uses compared to today. This is challenging but within the range of global estimates of long term potential. Wastes and residues can provide around two-thirds of this requirement,

1. The IEA 2DS, linked to the *Energy Technology Perspectives 2017* publication, lays out an energy system pathway and a CO_2 emissions trajectory consistent with at least a 50% chance of limiting the average global temperature increase to 2°C by 2100.

but supply will also be needed from other sources. Materials from forestry operations can make a contribution when produced and used as part of a sustainable forestry strategy, taking economic, social and environmental aspects, including impacts on carbon stocks, fully into account. Many options are also available for producing such materials from agriculture, while avoiding significant land-use change emissions and threats to food security. These include use of land that is currently underproductive, intensification of production and improved productivity, and crop rotation and intercropping systems, which can provide bioenergy feedstock along with food and other products.

To support this expansion, internationally recognised sustainability governance measures will be essential to prevent unacceptable environmental, social and economic affects. Certification of biomass fuel supply chains can play an important role in this, especially for internationally traded biofuels, along with best practice applied at a local level. Sustainability governance also needs to incentivise sustainable supply and promote innovation. Such a system needs to:

- Be based on the actual GHG performance of specific routes from feedstock to energy, rather than a classification based on feedstocks or technologies.
- Signal the need for continuous improvement (for example, by gradually reducing GHG emission thresholds).
- Build on wider efforts to manage sustainability of the whole bioeconomy, including food and forestry chains.
- Recognise regional and sectoral differences relating to the supply opportunities, risks and the quality of governance.
- Be increasingly based on real-life data and experience, with feedback into best practice and regulation.

To mobilise the necessary investment, especially in emerging and developing economies, a coordinated international effort will be needed to develop the institutional capacity and the stakeholder skills needed to put the required regulatory and market frameworks in place and to facilitate deployment. This will require the more active engagement of development agencies and international funding organisations such as development banks. Investment in bioenergy needs to rise from current levels of around USD 25 billion per year to USD 60 billion per year by 2030, and to around USD 200 billion per year between 2050 and 2060.

1. Introduction

This document provides an update of the two IEA Technology Roadmaps relating to bioenergy. In 2011 a roadmap on *Biofuels for Transport* was produced, followed in 2012 by a separate roadmap on *Bioenergy for Heat and Power* (IEA, 2011; IEA, 2012). These roadmaps have played an important role in informing stakeholder discussions on the future of bioenergy.

Since then, the context influencing bioenergy has altered considerably. Key changes include:

- A growing urgency of the need to tackle climate change through dramatic reductions in GHG emissions, and the landmark 2015 Paris Climate Change Agreement, which includes more ambitious temperature targets than previously agreed under the United Nations Framework Convention on Climate Change (UNFCCC).
- Increasing competition from fossil fuels at prices lower than anticipated when the last *Bioenergy Roadmaps* were published.
- Strong deployment and cost reductions for other sources of renewable electricity (notably wind and solar photovoltaic [PV]).
- Good progress in development and deployment of some complementary technologies (e.g. electric vehicles).
- A growing appreciation of bioenergy's role in the broader bioeconomy. This includes the prospects for the production of a wider range of biomass-based products and chemicals in addition to the traditional production of food and wood-based products, such as those for construction and paper and pulp.
- Increased scrutiny of the level and timing of carbon savings and sustainability issues relating to bioenergy, including direct and indirect land use change and potential competition with food production.
- Significant progress in developing, demonstrating and commercialising new bioenergy technologies, but at rates much slower than originally foreseen.
- A slowdown in the rate of deployment of transport biofuels, and slower-than-expected growth in bioenergy for heat and electricity generation.

It is therefore timely to review the vision for the future of bioenergy as part of a new cycle of IEA Roadmaps (Box 1), so as to update the role of bioenergy in low-carbon energy futures and to identify the key opportunities and the obstacles that need to be resolved. This roadmap therefore looks at the prospects and challenges for bioenergy within the context of the updated IEA *Energy Technology Perspectives* (*ETP*) Scenarios published in June 2017 (IEA, 2017a).

The IEA intends to track progress in bioenergy using the milestones and other metrics developed in the roadmap via the IEA *Tracking Clean Energy Progress* analysis (IEA, 2017b). It is also intended that the roadmap should provide a strategic basis on which the IEA Bioenergy Technology Collaboration Programme (TCP) can develop its priorities and workplans for the coming years, while other international and national efforts on bioenergy take account of its findings and recommendations.

This IEA Technology Roadmap complements the analysis of current market trends and the forecast of likely market developments for bioenergy in the transport, electricity and heating sectors over the next five years that are contained in the annual IEA *Renewables Market Report* publications (IEA, 2016a; IEA, 2017c). It also builds on the *How2Guide for Bioenergy*, a joint IEA and Food and Agriculture Organization (FAO) publication, released in early 2017, which provides guidance on the preparation of national and regional bioenergy roadmaps (IEA and FAO, 2017). It has been prepared in close collaboration with the IEA Bioenergy TCP.

Box 1: IEA Technology Roadmaps

The aim of a Technology Roadmap is to accelerate the deployment of a specific technology or group of technologies. A roadmap is a strategy or a plan describing the steps to be taken in order to achieve stated and agreed goals on a defined schedule. It defines the technical, policy, legal, financial, market and organisational barriers that lie before these goals, and the range of known solutions to overcome them. Roadmaps can be developed for varying levels of deployment, including global, national and regional, and can be sector- or technology-specific.

The process by which a roadmap is created, implemented, monitored and updated as necessary is referred to as road-mapping. The way this process is organised is crucial to the effectiveness of the final roadmap document itself. An effective road-mapping process maximises participants' engagement in creating the plan, thereby building consensus, increasing the likelihood that those involved will implement the roadmap priorities and seeking early solutions to anticipate potential barriers. Ideally, a roadmap is a dynamic document, incorporating metrics to facilitate monitoring of progress towards its stated goals, with the flexibility to be updated as the market, technology and policy context evolve.

Between 2010 and 2016, a first cycle of 32 IEA Technology Roadmaps were produced covering 21 different technology areas. A new cycle of roadmaps was endorsed at the G7 Energy Ministerial Meeting in May 2016 (Kitakyushu). These roadmaps aim to:

- Set out a long-term vision to 2060 and emphasise actions required in the near term.
- Analyse regional differences and identify key partners for implementation.
- Use the IEA *ETP* 2°C Scenario (2DS) as the basis for the vision, but also consider what extra measures would be needed to meet more ambitious deployment and climate goals, such as the *ETP* Beyond 2°C Scenario (B2DS).
- Highlight appropriate metrics that can be used to track progress via the IEA *Tracking Clean Energy Progress* analysis. (IEA, 2017b).

The new cycle of IEA Technology Roadmaps benefits of close cooperation with the relevant IEA TCPs, and with other international organisations and initiatives including those organised under the Mission Innovation umbrella. It is intended that these roadmaps should be taken up as the strategic documents underpinning these activities.

About bioenergy

What is bioenergy?

Burning harvested organic matter – biomass – provided most of mankind's energy needs for millennia.[2] Using such fuels remains the primary energy source for many people in developing and emerging economies, but such "traditional use" of biomass is often unsustainable, with inefficient combustion leading to harmful emissions with serious health implications.

Modern technologies can convert this organic matter to solid, liquid and gaseous forms that can more efficiently provide for energy needs and replace fossil fuels. A wide range of biomass feedstocks can be used as sources of bioenergy. These include: wet organic wastes, such as sewage sludge, animal wastes and organic liquid effluents, and the organic fraction of municipal solid waste (MSW); residues and co-products from agro-industries and the timber industry; crops grown for energy, including food crops such as corn, wheat, sugar and vegetable oils produced from palm, rapeseed and other raw materials; and non-food crops such as perennial lignocellulosic plants (e.g. grasses such as miscanthus and trees such as short-rotation willow and eucalyptus) and oil-bearing plants (such as jatropha and camelina).

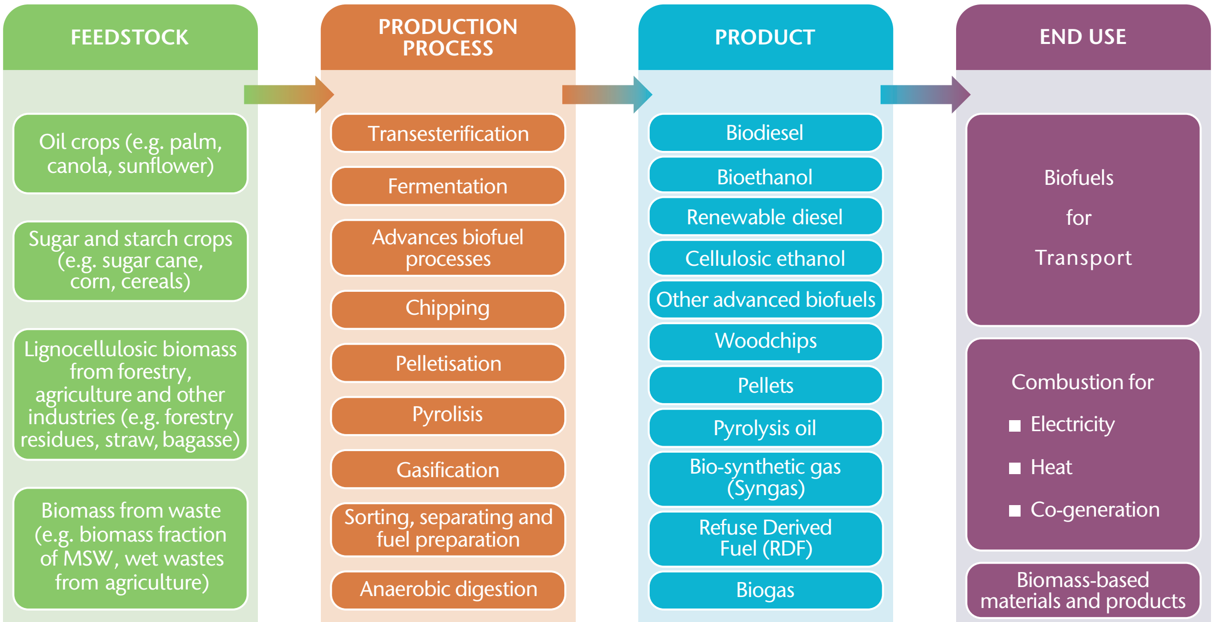
Many processes are available to turn these feedstocks into a product that can be used for electricity, heat or transport. Figure 1 illustrates a number of the main pathways available for

2. A glossary is provided which provides definitions and an overview of the terminology used in this roadmap.

these applications (IEA and FAO, 2017). The most common pathways to date have been: the production of heat and power from wood, agricultural residues and the biogenic fraction of wastes; maize and sugarcane to ethanol; and rapeseed, soybean and oil crops to biodiesel.

Each of these bioenergy pathways consists of several steps, which include biomass production, collection or harvesting, processing to improve the physical characteristics of the fuel, pre-treatment to alter chemical properties, and finally conversion of the biomass to useful energy. The number of these steps may differ depending on the type, location and source of biomass, and the technology used to provide the relevant final energy use.

Figure 1: Potential bioenergy pathways: From biomass to final energy use



Source: IEA and FAO, 2017, *How2Guide for Bioenergy*, www.iea.org/publications/freepublications/publication/How2GuideforBioenergyRoadmapDevelopmentandImplementation.pdf.

Bioenergy and sustainable development

The contribution of bioenergy to the achievement of low-carbon scenarios such as the IEA 2DS must be based on pathways which unequivocally provide significant reductions in life-cycle GHG emissions compared to the use of fossil fuels. This roadmap concentrates on identifying opportunities to produce and use bioenergy sustainably, that is, in ways that avoid negative impacts on the environment, foster both food and energy security, and contribute to sustainable development goals for agriculture, rural development and climate.

Like other renewable energy technologies, bioenergy can provide a number of environmental and social benefits. It can:

- Reduce GHG emissions (especially in sectors such as long-haul transport where other opportunities are limited).
- Improve energy security by enhancing diversity of energy supply and reducing exposure to fluctuating global energy markets and import dependency.
- Provide economic opportunities, including jobs and income for rural economies.
- Complement efforts to improve waste management and air and water quality.
- Contribute to the improvement of modern energy access for heating, cooking and electricity for the 2.7 billion people who lack it.

- Support investments in rural infrastructure and development that are essential for improving food security.
- Provide additional market incentives and opportunities for afforestation and reclamation of degraded lands.

Bioenergy interacts extensively with the agricultural, forestry and waste management sectors. The related environmental, economic, and social implications associated with the production and use of bioenergy have many implications that reach beyond the energy sector. These create both benefits and potential risks for the environmental, social and economic pillars of sustainability.

These benefits and potential risks relate particularly to the United Nations Sustainable Development Goals (SDGs). An ongoing analysis being conducted as part of the Global Bioenergy Partnership (GBEP) activities notes that while biomass, bioenergy and biofuels are not explicitly mentioned in the SDGs, bioenergy has the potential to contribute to or have positive impacts on nearly all the SDGs (Fritsche U. et al., 2017a).

The SDGs can drive the expanded use of bioenergy as part of a growing bioeconomy, while also providing safeguards against unsustainable bioenergy practices. This goes beyond SDG 7, which is primarily concerned with energy. For example, bioenergy can contribute to combatting climate change (SDG 13). SDG 3 (Health) can be a driver for avoiding the health implications of air pollution due to inefficient traditional use of biomass, while encouraging the efficient use of biomass to replace polluting fossil fuels.

Bioenergy in the bioeconomy

Far more than any other type of renewable energy, bioenergy is strongly related to the whole system of land use and agricultural and forestry production that make up the global bioeconomy. The "traditional bioeconomy" has largely been concerned with the production of food, feed for animals, forest products including construction materials and paper and pulp, and textiles, while also providing a substantial contribution to local energy needs through the provision of firewood.

There is now greater recognition of the potential for an expanded bioeconomy with the capacity to reduce dependence on fossil fuels and many other finite resources. There is increased emphasis on recycling bio-based materials (within a "circular economy") and the development of a wider range of high added-value products based on sustainably produced biomass feedstocks. These products include speciality chemicals based on cellulose or lignin, building materials, wood-based textiles and many others – as well as modern and efficient production of energy.

New and existing products of the bioeconomy can provide energy and carbon savings compared to fossil-intensive products. For example, using wood as a construction material reduces the need for steel and concrete in buildings as well as sequestering carbon for an extended period. While estimates of the actual energy and carbon benefits vary widely depending on assumptions about lifetimes and eventual disposal methods, these uses are generally considered to be highly carbon efficient as they replace materials that are produced by carbon-intensive processes (Oliver et al., 2014; Kuittinen et al., 2013).

In theory, the growth of the bioeconomy could lead to increased competition between the use of biomass resource for food and feed, materials, chemicals, and energy. In practice, such competition is limited because the value of bioenergy products is much lower than those used for food, chemicals or materials. However if policies and regulations introduced to stimulate a rapid phasing out of fossil resources cause unacceptable socioeconomic impacts, additional policy measures might be needed (for example to ensure that carbon pricing applies to all affected sectors). In most cases the use of a fraction of the biomass feedstock for energy complements the use for other products. Bioenergy can improve the economics and carbon benefits of these primary bioproducts, helping to maintain existing industries and strengthening the overall economic case for new projects, as economies of scale help to bring down costs of new technologies. Examples include the use of sawmill residues and co-products as fuel for heating or electricity generation, digestion of waste waters and organic effluents in agro-industrial processes, and integrated production of chemical products and bioenergy in biorefineries. Conversely, subsidies for energy production alone, without recognising the carbon and other benefits that can be associated with the production of biomaterials, could produce market distortions and in some cases lead to increased GHG emissions.

Roadmap structure

The roadmap is organised in eight further chapters as follows:

- Section 2 – Bioenergy: recent progress and developments – provides a snapshot of the current status of bioenergy markets globally and of global trends.
- Section 3 – The vision – outlines the role bioenergy plays in the IEA low-carbon 2DS and B2DS.
- Section 4 – Bioenergy technology – looks at the current status of bioenergy technologies, highlights a number of bioenergy options which could be deployed immediately, and identifies the technologies needed to deliver the 2DS vision and the RD&D priorities associated with them.
- Section 5 – Supplying sustainable bioenergy – looks at the conditions that feedstocks need to meet to be considered sustainable, and at the likely availability of the feedstocks needed to fulfil the roadmap requirements. It also considers aspects of the governance system that will be needed to facilitate deployment while ensuring sustainability, and addresses some of the challenges of scaling up feedstock supply to the levels needed.
- Section 6 – Policy and finance issues – highlights the importance of a supportive enabling policy and regulatory framework, and looks at some of the issues that will be needed to ensure that financing is available.
- Section 7 – Bioenergy deployment – looks at the deployment milestones that would be consistent with the 2DS pathway.
- Section 8 – International collaboration – looks at current initiatives aimed at promoting sustainable bioenergy deployment and the scope for enhancement.
- Section 9 – Conclusions – summarises the main findings and conclusions of the roadmap.

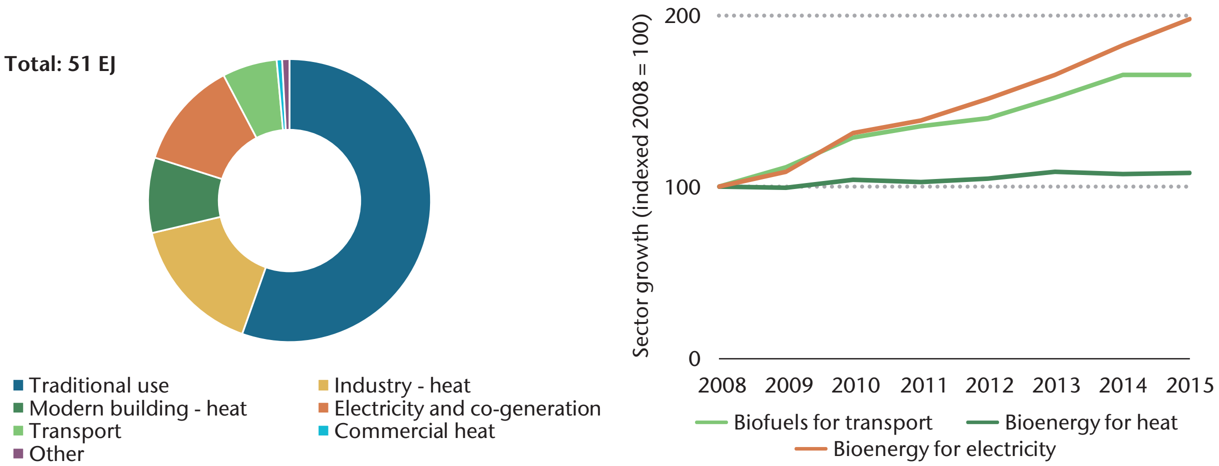
These main sections are complemented by three annexes: Annex 1 highlights certain aspects of the IEA ETP model that underpin the roadmap; Annex 2 provides more detail on the status of the main bioenergy technologies; and Annex 3 gives more detail of the examples of technologies that could be readily deployed in the short term and which are highlighted in Section 4. These are available separately online at: http://www.iea.org/publications/freepublications/publication/technology-roadmap-on-bioenergy.html

2. Bioenergy: Recent progress and developments

To provide an understanding of the current market landscape for bioenergy, an overview of market developments across the heat, electricity and transport sectors over the 2010-16 period is provided. This highlights key market trends since the production of the previous IEA technology roadmaps on bioenergy, and puts the longer-term scenarios in this roadmap into context.

Biomass and waste are already a significant global energy source, accounting for over 70% of all renewable energy production, and making a contribution to final energy consumption in 2015 that was roughly equivalent to that of coal. The largest end use of biomass and waste remains the traditional use of biomass, which is generally considered an unsustainable application of these resources. The focus of this publication is modern bioenergy solutions; the term bioenergy is generally used to refer to these and exclude the traditional use of biomass. Modern bioenergy consumption is largest in the heat sector, although bioenergy for electricity and transport biofuels is growing faster, mainly due to higher levels of policy support (Figure 2).

Figure 2: Consumption of biomass and waste resources by end use in 2015 (left) and modern bioenergy growth by sector, 2008-15 (right)



Notes: EJ = exajoule.

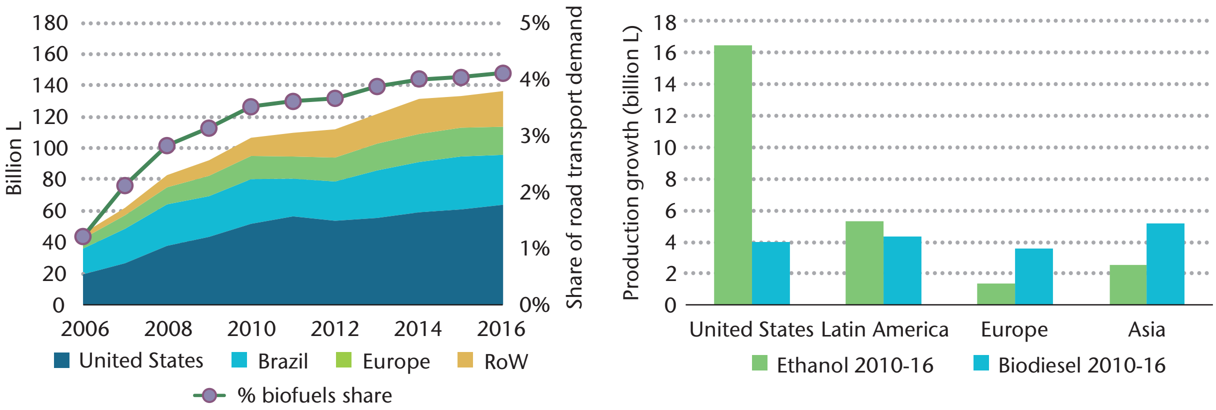
Sources: IEA (2017d), *World Energy Statistics and Balances 2017*, www.iea.org/statistics/; IEA (2017c), *Market Report Series: Renewables 2017*; IEA (2017e), *World Energy Outlook 2017*.

Transport biofuel markets

Global production of conventional biofuels reached 136.5 billion litres (L) (79 million tonnes of oil equivalent [Mtoe]) in 2016, accounting for around 4% by energy of world road transport fuel. Double-digit global output growth pre-2010 has slowed due to economic and structural challenges, as well as policy uncertainty in key markets. As a result, production increased at a slower average annual growth rate of 4% over 2010-16. The current market context indicates that global growth in conventional biofuels output is to slow further still over the next five years.

Transport biofuels play an important role in a limited number of markets. In 2016, just six countries had fuel ethanol production levels over 1 billion L, in a global market dominated by the United States and Brazil, who jointly represented around 85% of 101 billion L of global production (Figure 3). Biodiesel production is more evenly distributed, with ten markets having production levels over 1 billion L, contributing to a total of just under 36 billion L of global production. Looking ahead, crude oil-importing Asian countries, driven by security of supply considerations, are poised to make a key contribution to conventional biofuels market growth.

Figure 3: Global biofuels production and share of world road transport fuel demand, 2006-16 (left), and ethanol and biodiesel production growth for key regions, 2010-16 (right)



Notes: Share of world road transport fuel demand calculated based on energy adjusted data; biodiesel production numbers include hydrotreated vegetable oil (HVO) production.

Source: IEA (2017c), *Market Report Series: Renewables 2017.*

Globally, the majority of biofuel production is policy driven, principally through mandates stipulating blending at low levels.[3] However, there are signs of more widespread application of technology-neutral frameworks that stipulate defined reductions in the life-cycle carbon intensity of transport fuels, for example as established in California and Germany, with such an approach also under development in Canada. In addition, fiscal incentives play an important role in increasing biofuels' competitiveness at the pump, and therefore consumption.

Mandates have proved to be effective in shielding biofuels from low oil prices. However, lower petroleum product prices cause market-specific challenges, such as a more difficult investment climate and limited opportunities for discretionary blending above mandated volumes. In the European Union, 92% (by energy) of biofuels used in 2015 were compliant with mandatory sustainability criteria, and these accounted for the vast majority of transport sector renewable energy consumption (European Commission, 2017a). Nevertheless, ensuring sustainability remains a crucial consideration, particularly in growing markets where governance frameworks are yet to be established.

3. Low-level ethanol and biodiesel blends can be readily used within existing internal combustion engines. However, the utilisation of higher blend shares requires a transition in vehicle fleets towards suitably adapted vehicles.

The IEA defines advanced biofuels as sustainable fuels produced from non-food crop feedstocks, which are capable of delivering significant life-cycle GHG emissions savings compared with fossil fuel alternatives, and which do not directly compete with food and feed crops for agricultural land or cause adverse sustainability impacts. Currently, novel advanced biofuel production is at a low level and, even considering anticipated growth over the next five years, output is only expected to increase to around 1-2% of total biofuel production (1.5 to 3 billion L). The most evident progress is being made in the production of cellulosic ethanol, with a number of commercial-scale plants constructed and working to scale up production. However, further development is required to reduce investment and production costs.

Several aviation biofuel production processes are already certified to industry standards, and with a growing number of commercial flights and fuel off-take agreements, biofuels are poised to play a central role in the aviation industry's long-term decarbonisation plans. However, regional supply chain development and actions to reduce cost premiums over conventional jet fuels are needed. Biofuel consumption remains limited in the marine transport sector due to high cost premiums over bunker fuel and the need to build supply chains. The lack of a supportive regulatory environment for biofuels is a barrier to their adoption in both aviation and marine transport.

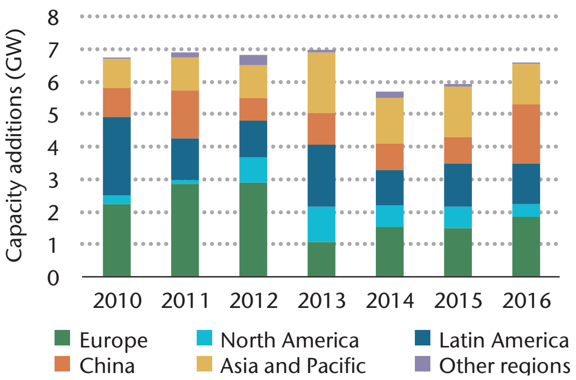
Bioenergy electricity markets

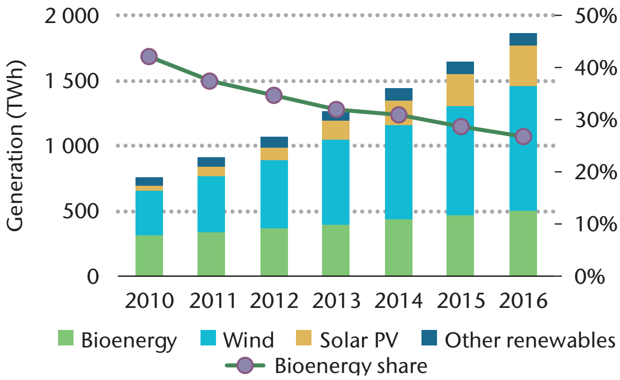
Bioenergy electricity generation is based on a variety of biomass and waste fuels in solid, liquid and gaseous forms, with consumption commonly determined by available national resources. For example, in China bioenergy capacity principally uses energy from waste (EfW) and agricultural residue (straw) fuels, while in the United States and Nordic countries forestry residues are more prominent. In most markets, solid biomass and wastes are the main contributors, accounting for over 70% of bioenergy electricity capacity in member countries of the Organisation for Economic Cooperation and Development (OECD) on average in 2015.

Bioenergy supplied around 500 terawatt hours (TWh) of electricity in 2016, accounting for 2% of global electricity production. In the same year cumulative bioenergy electricity capacity reached 110 gigawatts (GW), increasing at an annual average growth rate of 6.5% since 2010. Over 2010-16 annual capacity additions were steady in the range of 5-7 GW (Figure 4). Looking ahead, Asia is expected to replace Europe as the largest market for bioenergy electricity deployment due to a combination of increasing energy demand, low-cost biomass waste and residue resources, and long-term targets in emerging economies such as China, India and Thailand.

However, bioenergy only plays a prominent role in the electricity generation portfolios of a limited number of countries. In 2016, 90% of all capacity was located in just 26 countries. Current market trends indicate that bioenergy capacity is growing in these existing markets but not expanding strongly into a wider array of countries, in many cases despite biomass resource availability. Establishing the use of biomass and waste fuels in new markets will be essential to meeting the needs of the IEA's long-term climate scenarios.

Figure 4: Annual bioelectricity capacity additions by country and region (left) and global electricity generation from non-hydro renewables (right), both 2010-16





Source: IEA (2017c), *Market Report Series: Renewables 2017.*

Globally, bioenergy accounted for only 4% of renewable power capacity additions in 2016. A constraining factor to accelerated deployment in the electricity sector is anticipated to be its relatively high electricity generation costs and limited scope for lowering these from mature technologies. Cost competition from onshore wind and solar PV technologies has strengthened considerably since 2010, driven by reductions in investment and operating costs and an expansion into new markets with excellent resources.

However, a range of bioenergy technologies and fuels can still deliver cost-competitive electricity generation in diverse markets.

Despite a lower share of capacity additions compared to variable renewable energy (VRE) technologies, bioenergy remains an important contributor to renewable electricity generation, contributing 8% of total global renewable electricity generation (including hydro) in 2016. This is because bioenergy plants generally have higher capacity factors than VRE technologies.

Within OECD countries, the average bioenergy capacity factor in 2015 was 50%,[4] compared with 13% for solar PV and 26% for onshore wind.

Higher generation costs compared to VRE technologies need to be balanced against the dispatchable nature of some bioenergy electricity technologies and the potential for wider benefits associated with rural development, enhanced waste management and job creation across the fuel supply chain. However, these benefits only help to stimulate bioenergy electricity deployment when monetised, for example through the receipt of gate fees[5] for waste or where markets for flexible generation and electricity system services exist. Most bioenergy electricity deployment is driven by policy support mechanisms, and a shift to directing policy support for renewable electricity towards competitive, cost-driven auctions is evident in many markets. Where auctions are used, how their design accounts for the flexible generation potential and the wider benefits provided by bioenergy will be crucial in shaping deployment opportunities.

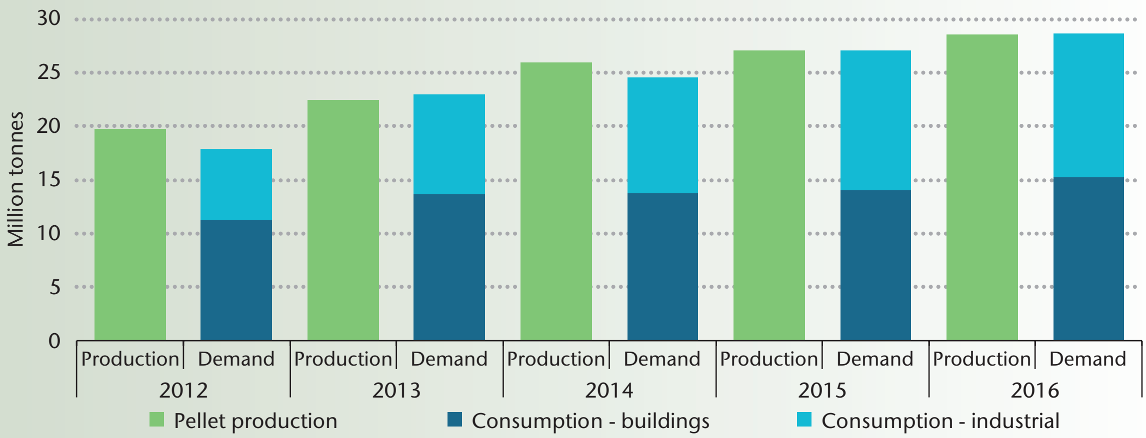
4. The ratio of electricity generation over an extended period (e.g. a year) compared to maximum theoretical generation possible given the rated capacity of the technology.

5. A gate fee (or tipping fee) is the charge levied upon a given quantity of waste received at a waste processing facility.

Box 2: Global wood pellet market developments

Global wood pellet consumption for both industrial and heating purposes increased by 60% during 2010-16. Wood pellet production in 2016 reached 28.5 million tonnes (Figure 5), with the United States, the European Union and Canada key producers. In Canada, high levels of third-party certification are particularly evident. The principal markets for industrial and heating wood pellets are found in the European Union, supplemented by industrial pellet demand in Japan and Korea and heating demand in North America. Industrial wood pellet demand is still dominated by a relatively small number of large-capacity consumers, e.g. coal power stations converted to biomass, and therefore can undergo notable demand changes as a result of technical, economic or policy factors. Conversely, fuel consumption in heating markets is influenced by weather conditions and biomass fuel costs relative to competing heating fuels and technologies.

Figure 5: Global wood pellet production and consumption by end use, 2012-16



Note: Industrial pellet consumption refers to demand from power generation and co-generation plants.

Sources: Analysis from Hawkins Wright Ltd., using FAO data, sourced via personal communication May 2017.

Box 2: Global wood pellet market developments (continued)

The relatively high energy density of wood pellets allows for their long-distance shipment, especially as marine freight.* In 2015 over half of global wood pellet production was traded internationally. As a result, wood pellets are used in countries without sufficient national forestry resources to meet domestic demand, as shown by consumption of imported industrial pellets in Denmark, Japan, Korea and the United Kingdom.

When the production of biomass fuels occurs far from the point of use, certification schemes that track the origins of the fuel and supply chain can give confidence to end users regarding the sustainability and suitability of fuels. Therefore, market access for suppliers is maximised by obtaining third-party certification from bodies such as the Forest Stewardship Council, Sustainable Forestry Initiative (both forestry), Sustainable Biomass Programme (fuel sustainability) and ENplus (fuel quality). There is room to increase supply liquidity by the adoption of common certification criteria as well as standardisation of quality requirements and trade terms. Potential also exists for more widespread application of wood pellet futures contracts and trading platforms to improve price transparency in wood pellet markets.

* Marine freight has the lowest GHG emissions of all transport modes e.g. significantly lower than road freight and diesel rail transport.

The traditional use of biomass

The "traditional use of biomass" primarily refers to the inefficient use of local solid biomass resources by low-income households who do not have access to modern cooking and heating fuels or technologies. Such consumption principally occurs in emerging economies and developing economies.[6] Biomass resources commonly used in a traditional manner to provide energy for cooking, hot water and residential heating (in colder climates) include wood, animal dung and agricultural wastes and residues.

These resources are used in open fires or basic stoves at very low efficiency e.g. 5-15%, consequently leading to high particulate matter (PM) emissions and other air pollutants. Combined with poor ventilation, such pollutants result in household indoor air pollution, which is responsible for a range of severe health conditions and a leading cause of premature deaths. Around 2.8 million premature deaths per year are caused by indoor air pollution, primarily due to the traditional use of biomass for cooking (IEA, 2017e). Social impacts also arise since the labour-intensive collection of biomass, often undertaken by women and children, consequentially limits available time for other activities and education. Demand for local biomass resources can also exceed sustainable supply and therefore result in environmental impacts, while associated black carbon and methane emissions are potent climate change pollutants (WHO, 2016).

It is difficult to quantify the traditional use of biomass precisely given the unregulated nature of its use and a lack of detailed and coordinated efforts necessary to more accurately gauge consumption levels. However, current estimates indicate that over 2.5 billion people still rely on the traditional use of biomass as their principal source of energy (IEA, 2017e), equating to 28 EJ of solid biomass resource and around 7% of global final energy demand.

In order to promote more sustainable use of solid biomass resources and reduce the associated health and social impacts from their traditional use, activities have been coordinated under the UN Sustainable Energy for All (SEforALL) initiative to ensure universal access to clean energy by 2030. The transition away from traditional use of solid biomass to more modern and efficient heating and cooking solutions can be achieved through fossil fuels, such as liquefied petroleum gas (LPG), as well as renewable energy solutions. More advanced biomass stoves (e.g. microgasifiers) and biogas systems are available to offer improved efficiency and lower pollutant emissions, reducing health impacts and biomass resource demand.

6. It should be noted that biomass can also be used at low efficiency, e.g. combustion of split logs in fireplaces, in developed countries.

Reducing the traditional use of biomass remains a significant challenge, particularly considering the increasing population trends in many countries, e.g. sub-Saharan Africa and developing Asia, where such practices are prevalent. Without a transition to a more sustainable and efficient use of biomass resources, consequential environmental, ecosystem and social impacts will be accentuated. As such, further international efforts to promote the uptake of modern heating and cooking solutions, which include but are not limited to bioenergy options, are imperative.

Modern bioenergy heat markets

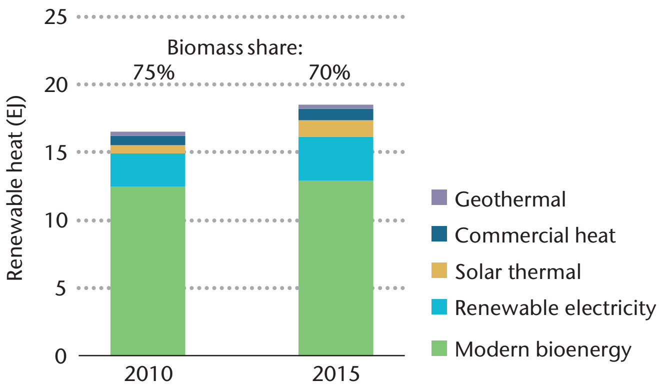
The largest application of modern bioenergy[7] is for the provision of heat. This equated to 12.9 EJ and accounted for 70%[8] of all renewable energy use for heat in 2015 (Figure 3). The provision of heat for industrial processes was the largest end user (63%), followed by buildings (34%) and agriculture (3%). However, growth has been slow: between 2010 and 2015 consumption of bioenergy in the heating sector increased at an annual average growth rate of around 1%.

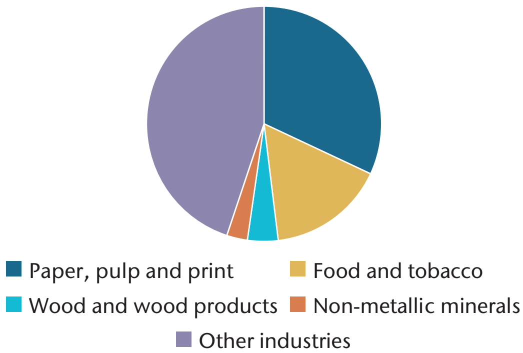
Biomass and waste fuels are well-placed to meet the temperature, pressure and quantity of heat and steam required by many industrial processes. Bioenergy deployment is highest within industries that produce biomass wastes and residues as part of their operations, such as the pulp, paper and print industry (Figure 6). Consumption is less evident in other industries, e.g. iron and steel, where biomass wastes and residues are not produced and fuel supply chains need to be mobilised; notably, however, the cement industry often uses wastes as a supplementary fuel.

7. Modern bioenergy excludes the traditional use of biomass. The analysis of bioenergy for heat markets covers the period 2010-15 due to data availability.

8. Percentage excludes biomass's contribution to renewable commercial heat (95% of supply in 2015) and the traditional use of biomass.

Figure 6: Renewable energy consumption for heat 2010 and 2015 (left) and bioenergy use within industrial final energy consumption in 2015 (right)





Sources: IEA (2017d), *World Energy Statistics and Balances 2017*, www.iea.org/statistics/; IEA (2017e), *World Energy Outlook 2017*.

Modern biomass boilers and stoves offer ease of use comparable to fossil fuel heating, as well as high efficiency and low air quality impacts where emissions control equipment is fitted. Combustion in well-designed plants is highly efficient, and, in larger-scale plants, emissions can be carefully controlled to meet stringent air quality standards. At a smaller scale, meeting these standards is also possible but it is relatively more expensive; and, ensuring low particulate emissions requires high specifications for boilers and stoves as well as for the fuels that are used.

Biomass fuel costs also demonstrate a higher degree of stability compared to fossil heating fuels. However, biomass boilers generally have higher investment costs than natural gas and oil heating systems. Consequently, low and stable biomass fuel costs relative to these fuels are essential to ensure uptake, which is typically strongest in areas without a connection to the natural gas network. Within the buildings sector, biomass heating also faces non-economic barriers that can constrain deployment. These include customer inertia, building suitability and a limited workforce to undertake design, installation and operation and maintenance (O&M) in some markets.

The most well-developed modern bioenergy heating markets are found in the European Union due to member state renewable energy targets for 2020 under the Renewable Energy Directive (RED), which have resulted in the introduction of policy support measures such as investment grants, soft loans and tax incentives. Biomass heating is a core contributor in those EU member states that have already met their 2020 targets. However, at present there is little policy support for bioenergy heat technologies elsewhere, especially in emerging economies and developing countries.

District heating networks and co-generation are proven facilitators for the consumption of biomass and waste for heating. Deployment in Nordic and Baltic countries has been driven by a combination of the need to reduce fossil fuel import dependence, excellent forestry resources and existing district heating networks suitable for conversion from using fossil fuels to biomass. In Nordic countries fossil fuel and carbon taxation is also a key growth factor.

Conclusions on current bioenergy markets

Bioenergy is by far the largest renewable contributor to the transport and heating sectors, and also provides an important share of renewable electricity generation. However, market growth across all three sectors since 2010, and the latest IEA five-year market forecasts, indicate that deployment is expected to be well below that required under the long-term 2DS by 2025, as signalled by the IEA *ETP Tracking Clean Energy Progress* analysis (IEA, 2017b).

Across heat, electricity and transport, the combination of increasing energy demand, security of supply considerations and resource availability means that Asia is increasingly expected to play a leading role in bioenergy deployment in the coming years. However, despite this and ongoing growth in other existing markets, bioenergy is not aggressively expanding into new countries or market sectors (e.g. new industry sectors, aviation), despite ample resources in many cases.

In cases where bioenergy is cost-effective, accelerated deployment can still be constrained by a lack of policy and regulatory frameworks that provide the long-term certainty needed to deliver project investment. In some cases, even when these frameworks are in place, policy uncertainty has nonetheless hampered investment. In addition, the challenge of mobilising fuel supply chains from dispersed biomass resources also constrains uptake in certain markets.

Market prospects for bioenergy are influenced by developments in alternative fuels and technologies, for example, VRE electricity generation, light passenger electric vehicles and heat pumps. Cost and performance improvements among these, as well as current low fossil fuel prices, create greater competition for the use of bioenergy. This is accentuated where technology-neutral support measures are employed (e.g. renewable electricity auctions and carbon intensity reduction-based transport policies). Such frameworks provide a driver to focus deployment on the lowest-cost bioenergy solutions and also emphasise the need to ensure that the wider environmental, economic and social benefits of bioenergy deployment are considered in policy development and, where possible, are monetised.

3. The vision

IEA scenarios

The vision for this roadmap is based on the modelling carried out for the IEA *ETP* publication, 2017 (IEA, 2017b). This presented three scenarios with different energy technology and policy pathways for a low-carbon energy system in the period to 2060. In short these are:

- The Reference Technology Scenario (RTS), which provides a baseline scenario that takes into account existing and planned energy and climate-related commitments by countries, including nationally determined contributions (NDCs) pledged under the 21st session of the Conference of the Parties (COP21) global climate agreement.
- The 2°C Scenario (2DS), which is consistent with a 50% chance of limiting future global average temperature increases to 2°C by 2100 and represents an inherently challenging and ambitious transformation of the energy sector.
- The Beyond 2°C Scenario (B2DS), which explores the feasibility of accelerating clean energy technology deployment in pursuit of more ambitious climate goals. The B2DS has the potential to approach carbon neutrality by 2060 and limit temperature increases to 1.75°C by 2100.

Further details of the scenarios are provided in Annex 1.

In each scenario, a full portfolio of technologies is deployed in order to reduce energy-related emissions. The 2DS demands major improvements in energy efficiency across all sectors, the widespread deployment of renewable energy technologies, especially in the electricity sector, fuel switching and the deployment of carbon capture and storage (CCS).

In the B2DS, these trends are extended further as GHG reduction becomes a higher priority, with a stronger role for CCS, including an important contribution from bioenergy with CCS (BECCS), in order to deliver the additional emission savings required. It is recognised that achieving a scenario such as the B2DS would present exceptional technical and political challenges.

This roadmap focuses on the measures necessary to deliver the bioenergy required in the 2DS, but also highlights a number of further steps necessary to move along the more ambitious decarbonisation pathway under the B2DS.

Role of bioenergy in the 2DS

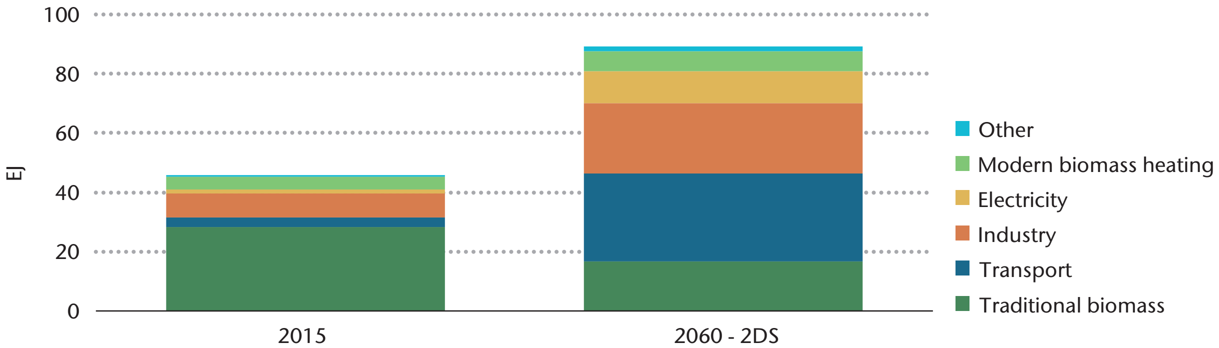
Overall contribution to energy supply and emission savings

The role of bioenergy grows significantly in the 2DS and is concentrated where it can help decarbonise sectors for which other options are scarce, or where it can play complementary roles to other technologies (Figure 7). Given potential constraints on the supply of sustainable biomass feedstocks, primary bioenergy supply is restricted to below 150 EJ.

Under the 2DS, modern bioenergy:

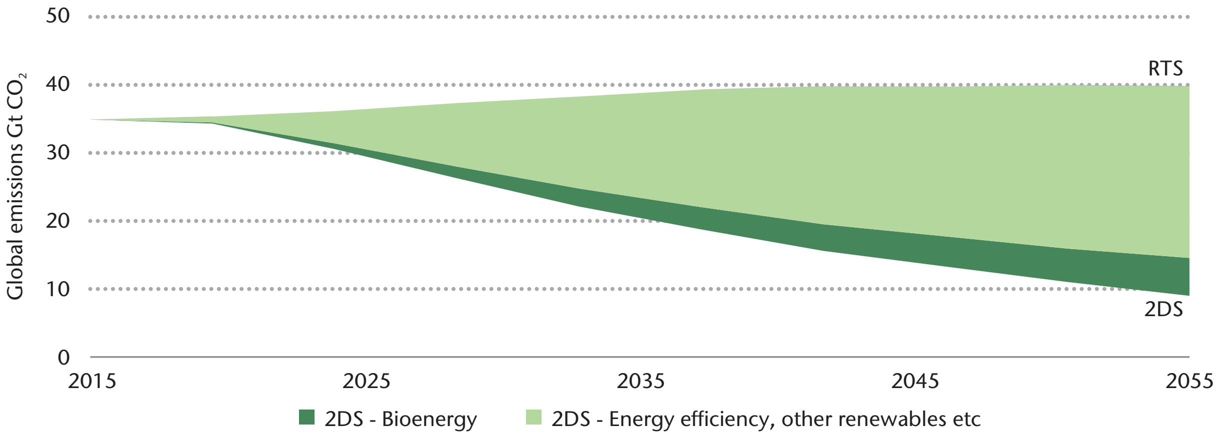
- Provides nearly 17% of final energy demand in 2060, compared with 4.5% in 2015.
- Grows most in the transport sector (where its contribution to final energy demand increases ten-fold from 2015 levels by 2060).
- Increases significantly in electricity generation and in industry.

Figure 7: Contribution of bioenergy to final energy demand in 2015 and in the 2DS, 2060



Bioenergy plays an important role in delivering the emission reductions needed between the RTS and the 2DS. It provides some 18% of the total annual savings in 2060 (5.7 gigatonnes of carbon dioxide [$GtCO_2$] out of 31 $GtCO_2$), and is responsible for some 17% of the cumulative reduction in emissions to 2060 (128 $GtCO_2$ out of the total of 763 $GtCO_2$) (Figure 8). It is therefore an essential part of the portfolio of technologies needed to make these reductions.

Figure 8: Contribution of bioenergy to emissions reductions in 2DS



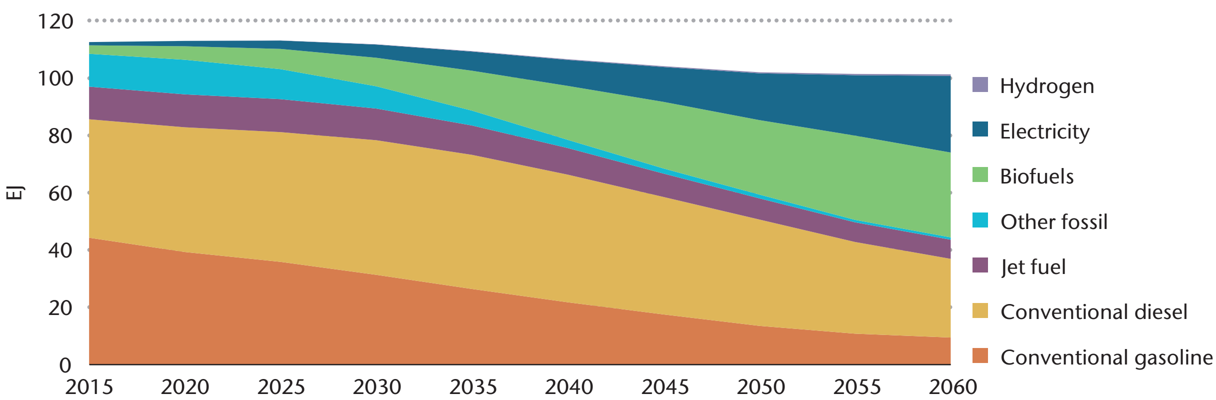
Bioenergy for transport

In the 2DS, final energy demand for transport is lower than under the RTS due to efficiency improvements and other measures, such as changes in transport modes and reductions in the need for travel (Figure 9). In addition:

- Fossil fuel consumption (gasoline, diesel and jet fuels) is sharply reduced.
- There is a major expansion in the role of bioenergy in the sector, reaching nearly 30 EJ in 2060 (nearly 10 times 2016 levels), and providing 29% of total transport final energy demand.
- Electricity use in transport also grows sharply to nearly 27 EJ (26% of total transport final energy demand) in 2060.[9]

9. Bioenergy will also make a contribution to electricity consumption in transport, as 7% of electricity generation in 2060 will come from biomass and waste fuels.

Figure 9: Transport final energy demand in the 2DS



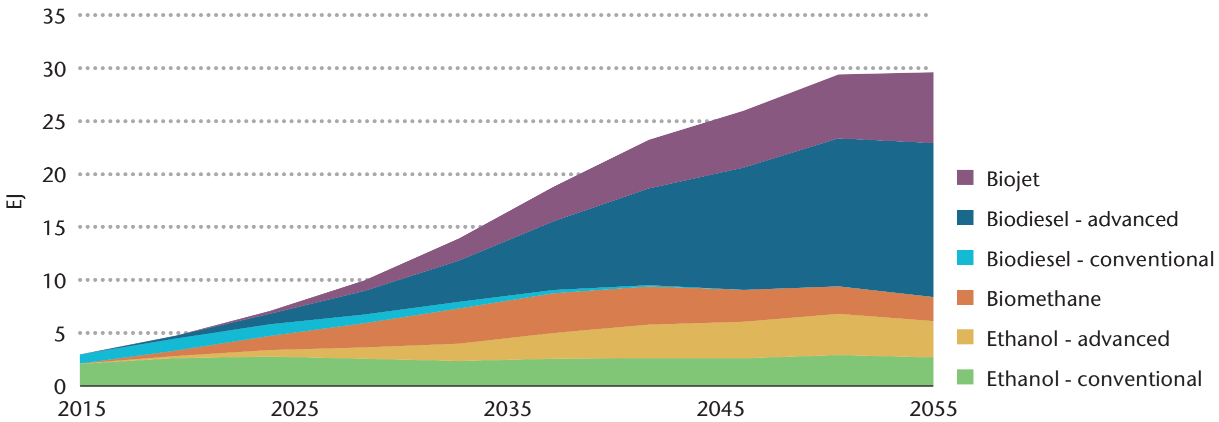
Biofuels play a key role in the decarbonisation of long-haul transport modes, complementing measures aimed at constraining the sector's energy needs and the enhanced role of electrification and other measures in urban and other shorter-haul transport applications. Biofuels provide some 40% of air transport fuel in 2060, and 30% of bunker fuel for shipping.

Meeting these levels of biofuel production and use will require a considerable acceleration in deployment compared with today's levels of growth.

The pattern of biofuel production also changes markedly to meet these specific end uses (Figure 10), with growth concentrated on biofuels that have better overall GHG performance, and which have properties suitable for use in sectors where demand for liquid fuels will be concentrated. These include advanced ethanol, jet fuel (biojet) and advanced biodiesel. Conventional biofuels such as bioethanol or fatty acid methyl ester (FAME) biodiesel are likely to be unsuitable for some of these applications (such as aviation and shipping). Only those biofuels with very low associated life-cycle emissions will be compatible with the low-carbon scenarios. Biofuels suitable for the diesel pool include those produced from biomass-to-liquid (BtL) processes as well as HVO from waste and residue feedstocks.

Conventional fuel ethanol production will have a continuing role where production costs are low and where the strongest GHG reductions can be provided, which is likely to favour sugar cane feedstock. The role of biomethane is likely to expand, especially in applications such as captive fleets and heavy freight trucks, where fossil compressed natural gas (CNG) and liquefied natural gas (LNG) vehicles are available. But conventional oil-crop based biodiesel is phased out in favour of fuels which offer stronger GHG emissions reduction.

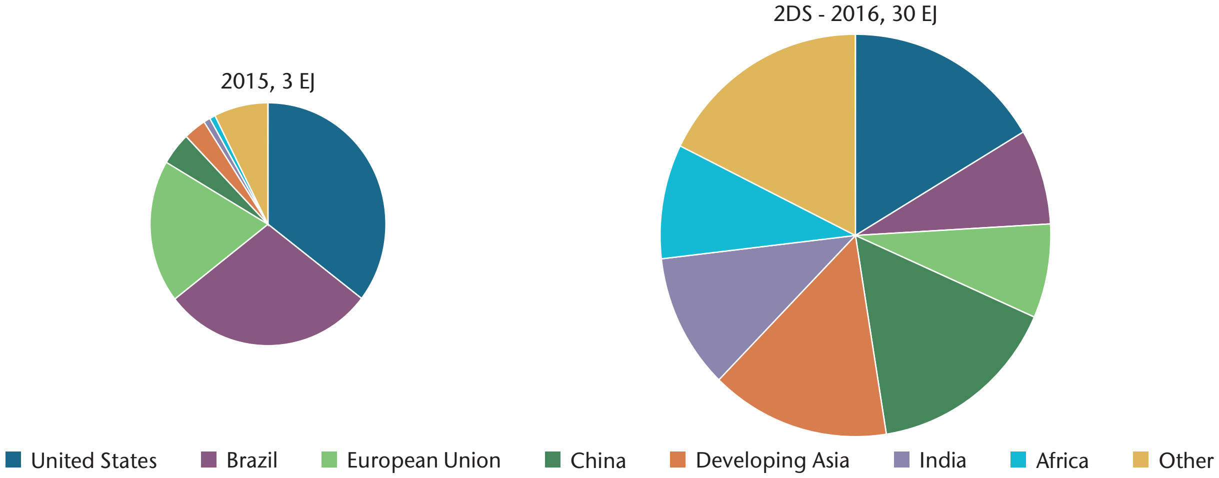
Figure 10: Biofuels final transport energy demand by fuel type in the 2DS, 2060



Notes: Conventional biodiesel refers to crop-based FAME biodiesel; advanced biodiesel refers to a range of advanced biofuels suitable for use in the diesel pool.

A further significant change will be the need for a much more diverse use of biofuels for transport geographically. Currently some 90% of biofuels are used in the United States, Brazil, the European Union and China, whereas in the 2DS use will be much more balanced between the regions (Figure 11).

Figure 11: Comparison of regional distribution of biofuels final energy demand in 2015 and 2060 in the 2DS



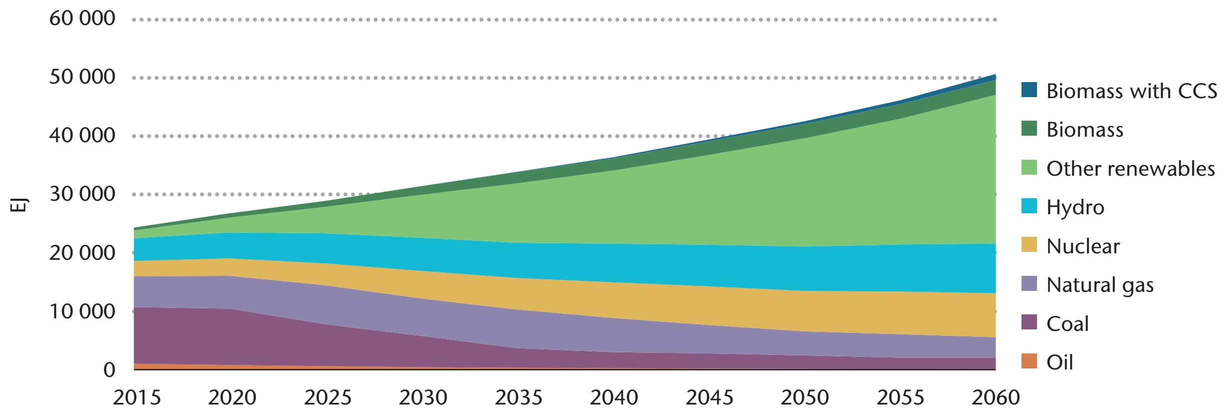
Electricity

In the 2DS, total electricity generation doubles between 2015 and 2060. The generation mix changes dramatically. Generation from oil and coal, and in later years from natural gas, are reduced. The proportion of generation from fossil fuels falls from 65% to under 11% by 2060 (Figure 12). There is strong growth of low-carbon electricity sources, with renewables increasing their share from 23% to 75%. Wind and solar PV grow fastest, to 37% of total generation.

In this dramatically changed context, bioenergy-based electricity can play an enhanced role in circumstances where:

- Its generation costs are low compared with other sources (for example, where biomass feedstock costs are low or where the heat can be efficiently used in co-generation systems).
- There are strong complementary drivers for bioenergy, such as can be the case for EfW facilities or co-generation plants integrated with industrial facilities.
- It can complement high levels of VRE generation from wind and solar by providing flexible renewable electricity generation.
- It can be linked to carbon capture and storage (BECCS) or use (bioenergy with carbon capture and utilisation [BECCU]).

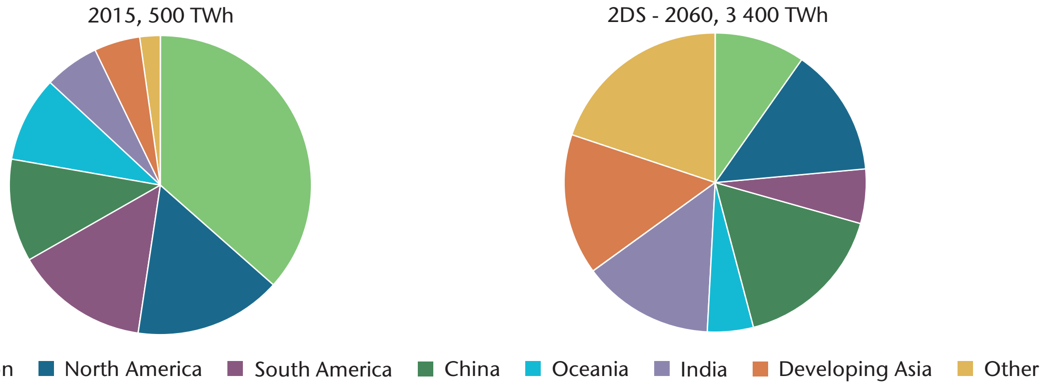
Figure 12: Electricity generation in the 2DS



In the 2DS, the contribution of bioelectricity generation increases seven-fold between 2015 and 2060, to 3 400 TWh, with its contribution increasing from 2% of total generation in 2015 to over 7% by 2060. This implies a significantly higher growth rate than currently being achieved is sustained through until 2060. Towards the end of the modelled period, BECCS begins to play an important role.

Figure 13 shows the regional development of bioelectricity generation in the 2DS. China becomes the largest generator, with the rest of Asia, North America and Europe outside the European Union also growing strongly. EU generation grows only slowly.

Figure 13: Regional distribution of bioenergy-based electricity generation in 2015 and 2060 in the 2DS



Biomass for heat provision in industry

The industrial sector is the greatest user of bioenergy after the transport sector in the 2DS. Bioenergy can help reduce emissions in the industrial sector by replacing fossil sources in both low- and medium-temperature applications (e.g. for hot water production or for drying), as well as for higher-temperature applications, such as high-temperature steam supply and for direct use in kilns and furnaces.

In the 2DS, growth in industrial energy demand is reduced by improved energy efficiency, implementation of best available technologies, switching to less energy-intensive secondary production routes and the deployment of innovative process technologies. Demand only rises by 14% to 175 EJ by 2060, despite a considerable increase in industrial activity. By 2060, the use of bioenergy rises by a factor of nearly three, to 24 EJ, providing nearly 14% of industrial energy needs. Particularly strong growth is seen in the use of commercially traded heat, which rises by a factor of eight by 2060.

Growth is concentrated in the provision of process heat and steam in non-energy-intensive industries, including food and beverage (accounting for almost 80% of total industrial bioenergy use in 2060 in the 2DS). Bioenergy also makes a growing contribution to energy demand in the pulp and paper sector.

For high-temperature applications, growth is concentrated in the cement industry where some 10% of energy comes from biomass sources (plus a further 15% from other fossil-based waste materials). Achieving these higher levels of biomass utilisation in the cement industry will necessitate the mobilisation of fuel supply chains. Biomass-based routes for the production of chemicals, such as bioethanol dehydration to produce ethylene, account for 3% of total energy use in the sector by 2060. This represents ten-fold growth of bioenergy use in absolute terms compared with current levels.

Biomass heat for buildings

In the 2DS, traditional use of biomass declines by around 40% between 2015 and 2060, largely due to urbanisation, rising incomes and improving access to commercial fuels. However, it remains a significant component of the global energy picture, reflecting the difficulties of transitioning to modern energy sources. Traditional use of biomass is expected to become even more concentrated in sub-Saharan Africa and Asia in the period to 2060.

In the short term, many significant opportunities are available to use biomass as a fuel for heating and potentially cooling buildings, notably to replace fossil fuels in district heating systems. However, in the medium to longer term the potential for increased use of bioenergy in the buildings heating sector within the 2DS is constrained for many reasons, including: heat demands that are reduced through the use of higher levels of energy efficiency within buildings; the use of other low-carbon technologies (such as solar thermal technologies, direct electric heating and use of heat pumps powered by low-carbon electricity); limited applications in many emerging markets (due to far smaller demand for heat in hot climates); and the extended use of other sources of low-carbon heat (such as heat from industrial processes or from heat recovery systems).

The use of modern biomass heating grows from 4.4 EJ in 2015 to reach some 6.8 EJ in the 2DS by 2060. This growth is driven by shifts to sophisticated biomass equipment in colder climates (typically as a substitute for or supplement to traditional boilers) and notably the increased use of bioenergy in commercial (district) heat production, where the share of bioenergy rises from 7% to around 50% by 2060.

Bioenergy in the B2DS

In the B2DS, the pattern of growth for bioenergy is similar to that in the 2DS, with bioenergy providing nearly 20% of final energy demand in 2060. However, some change of emphasis is seen in response to other changes in energy use and the fuel mix, brought about by higher levels of energy efficiency and the greater contribution of other technologies in certain sectors. Bioenergy plays a stronger role in industry and electricity generation. One key change is the greater extent to which bioenergy production is coupled with BECCS, so providing a source of "negative emissions".

In terms of CO_2 reduction, bioenergy provides some 20% of the additional annual savings needed in the B2DS in 2060 compared to the 2DS (1.7 $GtCO_2$ out of 9.0 $GtCO_2$), and is responsible for some 22% of the additional cumulative reduction in emissions to 2060 (60 $GtCO_2$ out of the total of 259 $GtCO_2$).

In the B2DS, overall transport energy demand is reduced by a further 20% compared with the 2DS, and fossil gasoline and diesel use drop more sharply than in 2DS. Electricity use grows more strongly, to 38 EJ, 46% of total transport energy use, so overtaking biofuels. Biofuels still expand dramatically in B2DS, and their share of total transport final energy demand is the same as in the 2DS (29%). However, their absolute contribution in 2060 is lower in the B2DS (24 EJ compared with 30 EJ), due to the lower overall transport energy demand and the stronger role for electricity in the sector, aided by significant decarbonisation of electricity generation in the B2DS.

Industrial energy demand is further constrained to around 165 EJ, due to a greater deployment of energy efficiency strategies previously outlined driven by a considerably tighter carbon budget. Bioenergy makes a 17% higher contribution to the final energy demand of the industrial sector than under the 2DS, with strong growth in non-energy-intensive sectors and the cement industry. This scenario also sees greater growth in the use of biomass as chemical feedstock.

Total electricity generation increases more strongly than in the 2DS, and the trend to reduce fossil power generation, including from natural gas, and to increase renewables is even stronger. Bioelectricity generation increases more than in the 2DS, to nearly 5 000 TWh, accounting for 10% of total electricity generation in 2060. This scenario foresees a strong shift to increased use of electricity generation coupled with BECCS, which accounts for nearly half of bioelectricity generation by 2060.

In the B2DS, the contribution of bioenergy to buildings energy needs grows more strongly, reaching 8.2 EJ by 2060, with even stronger growth of bioenergy in commercial heat, where it provides 60% of the total supply.

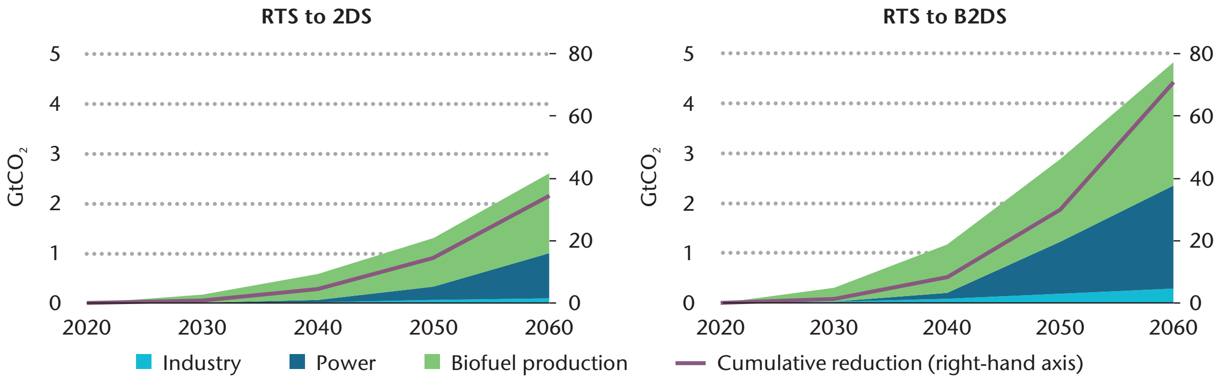
Role of BECCS

BECCS can be employed in association with transport biofuel production (where a concentrated CO_2 stream is often produced, so reducing costs), power generation, or industrial processes based on bioenergy.

In the scenarios, BECCS plays an important role in reducing future emissions. In the 2DS, annual CO_2 capture rates from BECCS build up to over 2.7 $GtCO_2$ by 2060 (Figure 14). Over 60% is associated with transport biofuel production, with electricity generation and industrial BECCS playing less significant roles. By 2060 cumulative emission reductions from BECCS reach over 34 $GtCO_2$, 5% of the total reductions between the RTS and 2DS.

BECCS is an indispensable component of the further CO_2 emission reductions needed in the B2DS, providing annual emissions reductions that increase to 4.9 $GtCO_2$ by 2060. BECCS associated with power generation plays a more important role than in the 2DS, equalling that in transport biofuels production. Cumulative emission reductions rise to almost 72 $GtCO_2$, and so provide 14% of the total emissions reduction between the 2DS and B2DS.

Figure 14: Role of BECCS in the 2DS and B2DS



4. Bioenergy technology

Many bioenergy technologies are mature and already widely deployed, while others, which can play an important role in providing an enhanced contribution from sustainable bioenergy, are not yet fully developed or commercialised. The range of bioenergy technologies and their status, in respect of their maturity and readiness for deployment, are also discussed in some detail in Annex 2.[10] This section summarises the current technology status, provides examples of opportunities to accelerate deployment in the short term, and then highlights the technologies that will be needed in the 2DS and the consequent priorities for RD&D.

Current technology status

The physical and chemical characteristics of the wide range of biomass feedstocks differ markedly from those of fossil fuels and also depend on the various collection and harvesting methods used. Systems for using biomass have to be specifically designed to match these feedstock properties. Processing of biomass before conversion to energy is often necessary to optimise the efficiency and economics of the bioenergy pathway. When considering the pathways, three stages need to be taken into account:

- Fuel preparation: used to change the physical nature of the feedstocks to make the fuels more homogeneous and easier to handle and transport, and to improve their energy density.
- Pretreatment: used to change the chemical nature of the feedstocks and to produce intermediate products that are more amenable to conversion to usable end products.
- Conversion: to produce heat, electricity (or both via co-generation) and transport fuels, along with other useful products.

Many bioenergy technology options are mature and already widely deployed commercially. Others, including several that can play important roles in the 2DS, are still not fully developed and commercialised. The technology options are briefly described in Annex 2 and their readiness for deployment is summarised in Table 1.

There is continuing scope for performance improvement and for cost reduction, even for the most mature technologies. However, as discussed later in this section, these can provide the basis for a substantial expansion of sustainable bioenergy in the short term.

10. The bioenergy technologies and RD&D priorities are also discussed in some detail in the bioenergy chapter (Chapter 7) in the IEA *ETP 2017* publication (IEA, 2017a).

Table 1: Bioenergy technologies: Technology readiness status

Technology	Lab and prototype	Demonstration	Early market development	Widely deployed
FUEL PREPARATION				
Drying				
Size reduction				
Pelletisation				
Torrefaction				
PRETREATMENT				
Anaerobic digestion				
Biogas upgrading				

Notes: BIGCC= biomass integrated gasification and combined cycle; ORC= organic Rankine cycle.

Table 1: Bioenergy technologies: Technology readiness status (continued)

Technology	Lab and prototype	Demonstration	Early market development	Widely deployed
Pyrolysis			■	
Gasification			■	
Small scale			■	
Large scale		■	■	
CONVERSION				
Heat				■
Electricity				
Large-scale generation/co-generation				■
Co-firing				■
BIGCC		■		
ORC			■	
Gasification/engines			■	
Bio fuel cells	■			
Transport biofuels				
Ethanol from sugar and starch crops				■
Biodiesel from oil crops				■
Biomethane for transport			■	
Cellulosic ethanol			■	
Other biological routes	■			
HVO				■
Upgraded pyrolysis oil – stand-alone plant		■		
Upgraded pyrolysis oil – co-processing with crude oil			■	
Upgraded synthesis gas		■		
Hydrothermal liquefaction	■			
Non-biomass low-carbon fuels		■		
BECCS and BECCU	■			
BECCS		■		
BECCU	■			

Notes: BIGCC= biomass integrated gasification and combined cycle; ORC= organic Rankine cycle.

Short-term deployment opportunities

Current rates of bioenergy deployment across the heat, electricity and transport sectors are currently falling short of those required by the 2DS in 2025 (IEA, 2017b). Scaling up bioenergy deployment in the period to 2025 will largely depend on greater utilisation of technically mature solutions that hold potential for accelerated roll-out should conducive policies and market conditions be established. Many of these opportunities rely on the enhanced use of wastes and residues as feedstocks, and so provide immediate benefits with respect to waste management or resource efficiency and limited land use change considerations. There are many such solutions currently available that have been successfully utilised in certain countries, delivering GHG emission savings compared to fossil fuels and helping to fulfil wider social, environmental and economic policy objectives (e.g. rural development, security of supply and waste management).

A scale-up in the uptake of the best-performing bioenergy solutions would help to close the gap between current bioenergy deployment trends and the levels of market penetration required to meet the 2DS. In addition, widespread adoption of many of these bioenergy solutions would provide an enabling environment for the delivery of bioenergy technologies currently at a lower technology readiness level that will be essential to keep pace with the 2DS.

Scale-up solutions

Eight bioenergy technology solutions have been identified that broadly satisfy the majority of the following selection criteria:

- technically mature and already demonstrated at commercial scale
- benefit from economic drivers to support competitiveness versus alternatives
- facilitate the delivery of wider non-energy-related policy objectives
- deliver demonstrable GHG savings versus fossil fuels
- able to avoid sustainability and food-versus-fuel impacts[11]
- utilise biomass and waste resources of which consumption can be sustainably scaled up
- applicable globally, particularly within countries with increasing energy demand
- provide an enabling environment for other bioenergy or renewable technologies.

An overview of the eight solutions outlined is provided in Table 2. Further details regarding deployment examples, benefits offered, as well as the policies and enabling factors needed for increased uptake of each of these is provided in Annex 3. The eight solutions highlighted should be viewed as a non-exhaustive set of examples, since a wider array of mature bioenergy technologies is available and will also be required to keep pace with 2DS deployment needs.

11. The solutions highlighted either have an inherently low risk of impact in these areas, e.g. they are based on wastes and residues, or it is considered that potential risks can be avoided by the application of effective sustainability governance, e.g. regulation or certification scheme.

Table 2: Bioenergy solutions suitable for immediate scale up which meet the defined selection criteria

Solution description	*Current deployment*	*Benefits*	*Enabling environment*
1. Biomethane from waste and residue feedstocks for use as a transport fuel. The most mature means of biomethane production is via anaerobic digestion. Feedstocks include organic wastes e.g. manure, agricultural residues and wastewater effluent.	Europe and the United States. Biomethane is used in Sweden within municipal bus fleets. Consumption is scaling up in the United States due to the federal RFS and California's LCFS.	Significantly reduced GHG emissions compared with fossil transport fuels, e.g. >80% GHG emissions reduction. Avoids direct methane emissions to the atmosphere, which have a far higher global warming potential than CO_2. Air quality benefits (e.g. reduced CO, NO_x and PM) compared with diesel, as well as lower engine noise. Can help to facilitate improved waste management practices.	Use of existing natural gas grids for biomethane transport, with registries to track injection and consumption. Biomethane use in captive fleets, e.g. city buses. Roll-out of fuelling infrastructure along key transport corridors. Technical specifications which cover biomethane for use as a transport fuel. Greater vehicle availability.

Notes: CO = carbon monoxide; ESCO = energy service company; EU FQD = EU Fuel Quality Directive; HEFA = hydrotreated esters and fatty acids; LCFS = low-carbon fuel standard; MWh = megawatt hour; NOx = oxides of nitrogen; OEM = original equipment manufacturer; RFS = renewable fuel standard; SRF = solid recovered fuel; commercial heating pellet consumption refers to the volume used in dedicated heat boilers with a capacity greater than 50 kilowatts (kW).

Table 2: Bioenergy solutions suitable for immediate scale up which meet the defined selection criteria (continued)

Solution description	***Current deployment***	***Benefits***	***Enabling environment***
2. HVO and HEFA biofuels from waste and residue feedstocks for use in heavy-duty road freight and aviation transport. Examples of suitable feedstocks include food processing fats and oils, technical corn oil and tall oil.	Global HVO production has reached around 5 billion L. Consumption in road freight is commonly in 30-50% blends. HEFA blended with fossil kerosene used in regular flights by some US and European airlines.	When waste and residue feedstocks are used, HVO and HEFA can deliver low life-cycle GHG emissions compared with petroleum products, as well as good operational properties in cold climates. HVO is technically a "drop-in" fuel with the potential for use unblended without fuelling infrastructure and vehicle modifications where OEM approvals are provided. Limited other low-carbon alternatives to biofuels for aviation.	Waste and residue feedstock supply chain development. Development of pretreatment processes to expand suitable feedstock resources. Fuelling infrastructure roll-out on key transport corridors and at airports. Engine OEM approvals and fuel quality standards. Measures to reduce cost premiums over fossil fuels. Aviation biofuel supply chain development.
3. Higher ethanol blends and unblended ethanol in road transport. These comprise mid (E20-E40) and high (E85) ethanol blends, hydrous ethanol (E100) and ED95 for heavy-duty vehicles.	Brazil has a mandated blend level of 27% and extensive use of unblended hydrous ethanol in flex-fuel vehicles. Growing markets for E85 in Thailand and the United States. ED95 bus fleets in Sweden.	Higher blends maximise GHG emissions reduction from biofuels compared with fossil fuels. Typical GHG emissions within the EU FQD indicate 32-71% reductions on fossil gasoline. Ethanol acts as a fuel octane enhancer. Domestically produced fuel ethanol supports energy security, the co-production of high-protein animal feed products and agricultural employment.	Higher crop yields and lower carbon process fuels to reduce fuel carbon intensity. Expansion of suitable vehicle fleets, e.g. flex-fuel vehicles. Strategic roll-out of fuelling infrastructure. National targets for emissions reductions, renewable energy consumption or fossil fuel phase-out in transport. OEM approvals for use of high-level ethanol blends and ED95.
4. Bioenergy-based district heating networks in urban areas, serving heat demand in buildings and industry. Typical fuels used include forestry residue wood chips and pellets; however, agricultural residues and MSW can also be utilised.	Nordic and Baltic countries, e.g. in Sweden and Lithuania, over 60% of district heat is from biomass. In Nordic countries co-generation has been the principal technology used.	Lower CO_2 emissions from heat supplied where fossil fuels are directly replaced. Diversification of fuel supply and lower reliance on imported fossil heating fuels. Where coal-fired systems are replaced, reduced SO_2 and NO_x emissions. District heating also negates some barriers associated with individual building systems, e.g. relating to accessing economies of scale in capital and fuel costs and building suitability.	Municipal and local government support. Urban heat planning and mapping exercises. Existing district heating network infrastructure for conversion from fossil to biomass fuels. Non-domestic customers e.g. industrial facilities, to ensure year-round heat demand. Financial de-risking measures, to facilitate private sector investment in district heating.

Notes: CO = carbon monoxide; ESCO = energy service company; EU FQD = EU Fuel Quality Directive; HEFA = hydrotreated esters and fatty acids; LCFS = low-carbon fuel standard; MWh = megawatt hour; NOx = oxides of nitrogen; OEM = original equipment manufacturer; RFS = renewable fuel standard; SRF = solid recovered fuel; commercial heating pellet consumption refers to the volume used in dedicated heat boilers with a capacity greater than 50 kilowatts (kW).

Table 2: Bioenergy solutions suitable for immediate scale up which meet the defined selection criteria (continued)

Solution description	*Current deployment*	*Benefits*	*Enabling environment*
5. Medium-scale biomass wood chip and pellet heating systems in public and commercial buildings. To minimise PM emissions the use of modern emissions-control equipment is advocated.	Most widespread in Europe, particularly Germany and Sweden. Commercial building heat demand accounted for over 20% of EU wood pellet consumption in 2015.	Medium-scale biomass systems facilitate lower investment costs through economies of scale. Fuel costs reduced through higher quantity purchases. Wood pellets offer more stable fuel costs compared to heating oil. Domestic market barriers, such as building suitability and O&M needs, are mitigated at larger scale. Competitiveness is most evident in areas off the natural gas grid.	Renovation programmes that include the upgrade of outdated heating plant Planning rules and buildings codes which stipulate renewable heating for new buildings. Skilled workforce to undertake system design, specification, installation and O&M. ESCO business models.
6. Maximising the efficiency of bagasse and other sugar cane residue co-generation in the sugar and ethanol industry. Comprising the transition to modern co-generation technologies with higher efficiency and reliability.	Brazil, India, Pakistan and Thailand have programmes to facilitate higher efficiency bagasse co-generation; but potential is unexploited in many sugar cane cultivating countries.	Competitive electricity generation, e.g. <USD 60/MWh, achievable in Brazil. Lower sugar and ethanol production costs from higher energy self-sufficiency. Increased revenue generation from surplus electricity export as well as enhanced potential for heat sales. These can diversify mill revenue streams. Greater financial incentive for more efficient sugar cane straw collection, and air quality benefits where straw burning in the field is avoided.	Affordable finance to invest in modernised bagasse co-generation systems. Steps to remove physical and administrative grid access barriers Energy cane, which creates more bagasse residues with comparable sugar content. International co-operation to facilitate knowledge transfer and best practice between sugar-producing countries.
7. Energy recovery from municipal waste solutions. Thermal EfW and landfill gas utilised in the context of the waste management hierarchy. This solution requires best available pollution control technologies and emissions monitoring to be used.	China (5 GW capacity), Japan (2 GW) and the United Kingdom (1 GW), lead EfW deployment in the electricity sector. Landfill gas capture and utilisation is prominent in the United States and United Kingdom.	Compared to landfill disposal, EfW facilities deliver significant waste volume reduction and require a smaller land area. Polluting emissions to land, groundwater and odour are also reduced. Diversification of energy supply is achieved by using indigenous fuel resources. Electricity and heat is generated close to urban centres. Direct methane emissions to the atmosphere are avoided by both EfW and landfill gas utilisation.	Gate fees to lower EfW generation costs. Landfill taxation and in certain cases landfill bans. Extensive public consultation for EfW plants. Integrated waste management planning. Improved collection and source separation to improve the quality of waste fuels. Fuel quality standards for waste fuels, e.g. SRF in Europe.

Notes: CO = carbon monoxide; ESCO = energy service company; EU FQD = EU Fuel Quality Directive; HEFA = hydrotreated esters and fatty acids; LCFS = low-carbon fuel standard; MWh = megawatt hour; NOx = oxides of nitrogen; OEM = original equipment manufacturer; RFS = renewable fuel standard; SRF = solid recovered fuel; commercial heating pellet consumption refers to the volume used in dedicated heat boilers with a capacity greater than 50 kilowatts (kW).

Table 2: Bioenergy solutions suitable for immediate scale up which meet the defined selection criteria (continued)

Solution description	Current deployment	Benefits	Enabling environment
8. The conversion of existing fossil fuel infrastructure for bioenergy use. Opportunities include district heating networks, power generation assets, the addition of biomass powder burners to fossil fuel boilers and the conversion of fossil refineries to HVO/ HEFA fuel production.	Refer to solution 4 for district heating. Coal-to-biomass power station conversions in Canada, Denmark and the United Kingdom. Numerous wood burners in use worldwide. Fossil to HVO refinery conversion projects underway in France and Italy; and delivered in the USA for HEFA.	Significantly reduced investment costs through the use of existing fossil fuel infrastructure. GHG reductions associated with the direct substitution of fossil fuels. Coal power stations converted to biomass can offer renewable system flexibility (e.g. back-up and balancing). Wood fuel burners provide similar load response to gas and oil burners. Faster delivery of capacity compared to deployment via smaller-scale new-build projects. Conservation of jobs within stranded assets that may otherwise have been lost.	The application of carbon pricing mechanisms. Policies which provide long-term demand visibility. The mobilisation of biomass fuel and feedstock supply chains at scale. Higher wood pellet production and logistics infrastructure. Appropriate sustainability governance is especially important given high biomass consumption volumes. For HVO enabling factors refer to solution 2, and district heating solution 4.

Notes: CO = carbon monoxide; ESCO = energy service company; EU FQD = EU Fuel Quality Directive; HEFA = hydrotreated esters and fatty acids; LCFS = low-carbon fuel standard; MWh = megawatt hour; NOx = oxides of nitrogen; OEM = original equipment manufacturer; RFS = renewable fuel standard; SRF = solid recovered fuel; commercial heating pellet consumption refers to the volume used in dedicated heat boilers with a capacity greater than 50 kilowatts (kW).

In addition to the enabling factors outlined in Table 2, a variety of policies have played a key role in facilitating deployment of these eight bioenergy solutions. Delivering accelerated deployment in line with 2DS needs, using these and other bioenergy technologies, will depend on the establishment of supportive policy and market frameworks in order that investment for project development can be secured.

Examples of supportive policy and market frameworks related to the solutions outlined above include:

- For solutions 1-3, life-cycle fuel carbon intensity policies, e.g. low-carbon fuel standards, applied on a technology-neutral basis create demand for transport fuels that offer the most significant levels of decarbonisation over fossil fuels relative to cost. Where these policies are applied, biofuel producers have responded by reducing fuel life-cycle GHG emissions.
- Where high levels of initial investment are required, e.g. for solutions 2, 4, 6 and 8, financial de-risking measures such as loan guarantees or policies which provide guaranteed long-term demand (e.g. advanced biofuel quotas, mandated connections to district heating networks, power purchase agreements) can be applied to mobilise private-sector investment.
- Solutions 4, 5 and 7 would all benefit from active municipal government support, e.g. relating to planning requirements, waste management strategies, public procurement.
- Bioenergy market expansion should be undertaken in accordance with robust sustainability governance frameworks which include the benchmarking of performance against recognised environmental, social and economic indicators. These should also include life-cycle assessment of GHG emissions, including land use change, to allow comparison of bioenergy with other policy options. Adequate governance is essential to provide confidence to policy makers currently cautious regarding the application of policy support for forestry residue and crop feedstock bioenergy on sustainability grounds. This is relevant to solutions 3, 4, 5 and 8 in particular.

General policy principles needed to sustain bioenergy deployment are discussed in section 6.

Apart from the eight solutions outlined, other bioenergy technologies can deliver GHG emission reduction and socio-economic benefits. Table 3 provides an overview of a range of wider bioenergy solutions based on mature technologies, and a further set of technologies currently at a lower technology readiness level for which deployment could be subsequently enabled.

Table 3: Wider bioenergy solutions at different levels of technical maturity

Bioenergy solution	***Wider solutions using mature technologies***	***Wider solutions at a lower technology readiness level***
1. Biomethane from waste and residue feedstocks for use as a transport fuel.	Heat, electricity and co-generation from biogas produced via anaerobic digestion. Biogas for cooking and heating to provide energy access in developing countries and emerging economies.	The uptake of biomethane in transport based on anaerobic digestion can facilitate consumption of SNG from the gasification of lignocellulosic and MSW feedstocks if production scales up in the future. Biogas as a feedstock for chemical production.
2. HVO and HEFA biofuels from waste and residue feedstocks for use in heavy-duty road freight and aviation transport.	HVO use in light-duty vehicles. The likelihood of OEM approvals for unblended HVO in these vehicles is supported by the European standard for paraffinic diesel (EN 15940). FAME biodiesel from waste and residue feedstocks used in blends e.g. up to B20 in heavy-duty transport.	HEFA use in aviation helps establish aviation biofuel supply chains and markets, paving the way for other aviation biofuels produced via Fischer-Tropsch, alcohol-to-jet and direct sugars-to-hydrocarbons processes, which are all certified to industry standards. Co-processing of pyrolysis oil and SNG intermediates in refineries. Lipids from algae are a potential future source of feedstock.
3. Higher ethanol blends and unblended ethanol in road transport.	FAME biodiesel or HVO produced from technical corn oil (a non-edible co-product of fuel ethanol production from corn). Bagasse co-generation. Anaerobic digestion of vinasse.	Cellulosic ethanol production, either from bolt-on technologies e.g. using corn kernel fibres, or co-located facilities. Ethanol consumption at high levels is a key enabler for cellulosic ethanol market access by facilitating suitable vehicle fleets and fuel distribution infrastructure.
4. Bioenergy-based district heating networks in urban areas.	District energy networks providing heating and cooling from a portfolio of renewable technologies, e.g. biomass, heat pumps and solar thermal as well as waste industrial heat.	Biomass district heating networks supplemented by heat pumps using excess VRE generation, and accumulators to store thermal energy during periods of low electricity generation. Biomass-fuelled district cooling networks, e.g. absorption cooling.
5. Medium-scale biomass wood chip and pellet heating systems in commercial and public buildings.	Domestic biomass boilers and stoves, particularly in rural areas without access to the natural gas network. Biomass co-generation systems for commercial and public buildings.	Grid-connected or decentralised gasification systems offer scope for smaller-capacity (100-500 kW scale) co-generation.

Notes: C&I = commercial and industrial; SNG = synthetic natural gas; given that solution 8 in Table 2 is applicable across heat, electricity and transport sectors, numerous wider solutions could be stated – some of these are outlined for solutions 2 and 4 above.

Table 3: Wider bioenergy solutions at different levels of technical maturity (continued)

Bioenergy solution	***Wider solutions using mature technologies***	***Wider solutions at a lower technology readiness level***
6. Maximising the efficiency of bagasse and other sugar cane residue co-generation in the sugar and ethanol industry.	Anaerobic digestion of vinasse. Bagasse gasification technologies. The efficient use of secondary residues from other industries, e.g. coconut shell and husks, palm fatty acid distillate and rice straw.	Cellulosic ethanol from bagasse and other agricultural residues, e.g. corn stover. The use of energy cane varieties which creates more bagasse residues for comparable sugar content to standard cane varieties.
7. Energy recovery from municipal waste solutions.	Energy facilities using C&I wastes, anaerobic digestion of food wastes, sewage gas from wastewater treatment facilities, industrial-scale biogas systems, e.g. using palm oil mill effluent and ethanol plant vinasse.	EfW combustion and the development of homogeneous waste fuel supply can act as a precursor to advanced thermochemical (e.g. gasification and pyrolysis) routes for waste treatment to produce fuels or feedstocks for the chemicals industry.

Notes: C&I = commercial and industrial; SNG = synthetic natural gas; given that solution 8 in Table 2 is applicable across heat, electricity and transport sectors, numerous wider solutions could be stated – some of these are outlined for solutions 2 and 4 above.

Technology implications of moving to the 2DS

The changing context associated with a move to the 2DS will affect the role that bioenergy can usefully play as one component of an integrated low-carbon system. In the electricity sector, for example, bioenergy will need to find roles that complement much higher levels of generation from variable sources of electricity such as wind and solar. While these new roles may not need radically new technologies, they will require some adaptation and demonstration of new flexible operating practices, such as the ability to ramp generation up or down with a short response time.

In other cases, new technologies will be required to improve the prospects for sustainable bioenergy deployment, both in the short term, and in paving the way for the extended role for bioenergy in the 2DS and B2DS.

The following sections discuss the evolving role of bioenergy in each of the main sectors and the appropriate RD&D needs.

Biofuels for transport

The technologies for producing ethanol from sugar and starch-based feedstocks, and FAME[12] biodiesel from vegetable oils and other lipid feedstocks (including wastes and by-products) are well-established, and provide most of today's transport biofuels. Biogas production by anaerobic digestion, with subsequent gas upgrading to biomethane, is also a mature technology. The short-term deployment of sustainable transport fuels could be boosted by RD&D that lead to improvements in conversion rates, costs and life-cycle GHG emission savings, improve the production of co-products such as animal feed, and broaden the range of feedstocks used, to include those with limited land-use implications. Scope also exists for increasing the deployment of bioethanol at higher blend levels with gasoline or unblended to maximise GHG emission reduction.

In recent years, technology to produce HVO, also known as renewable diesel, has been successfully commercialised. HVO has advantageous fuel characteristics compared to FAME, such as the potential for use as a drop-in fuel and good suitability for cold climates.[13] HVO production can be controlled to produce a range of fuels, including

12. FAME – fatty acid methyl ester, made by processing the oils or fats with methanol, and producing glycerol as a by-product.

13. Drop-in fuels can be used unblended without modifications to engines, maintenance regimes or fuel supply infrastructure.

advanced biodiesel, naphtha and aviation fuels. It is now increasingly produced from waste and residue oil and animal fat feedstocks rather than oil crops.

The very significant longer-term growth of biofuels in the transport sector in the 2DS relies on the widespread supply of novel advanced biofuels produced by processes that are generally not yet mature. (See Box 3). The need is for biofuels with very good life-cycle carbon performance that are also capable of being used in long-haul transport applications as drop-in fuels.

Box 3: What's in a name? Classification of biofuels

A range of terminology is used to distinguish between different forms of biofuels. The way biofuels are classified is important to ensure regulations and policies are developed that can distinguish between biofuels sourced from different raw materials and produced by processes at different technical and commercial stages of development.

Labelling biofuels is challenging as several dimensions have to be taken into account. These include the status of the technology's development, the source of the raw material, the level of carbon emissions (either taking into account indirect land use issues or not), and the technical properties of the end product (whether, for example, it is a drop-in fuel or used blended).

The terms first, second and third generation have been used to distinguish between established and commercialised production routes and successive generations of new technologies, but there is no consistent approach to the way these terms are used, which can lead to confusion.

Another way of classifying is to distinguish between conventional biofuels – principally ethanol and biodiesel, produced from sugar, corn and cereals and oil-based crops, and processed by using fully commercial technologies – and advanced biofuels. However, there are several different definitions of advanced biofuels. These are used for the purposes of specifying which fuels are eligible under specific biofuel support programmes, for example under the US RFS, and within the provisions of the EU RED, but differ significantly in what is included and this can lead to confusion. It is also important that the classifications do not discriminate unnecessarily against certain technologies. For example, the overall GHG performance of some "conventional biofuels" can, under certain circumstances, be at least as good as that of some "advanced biofuels".

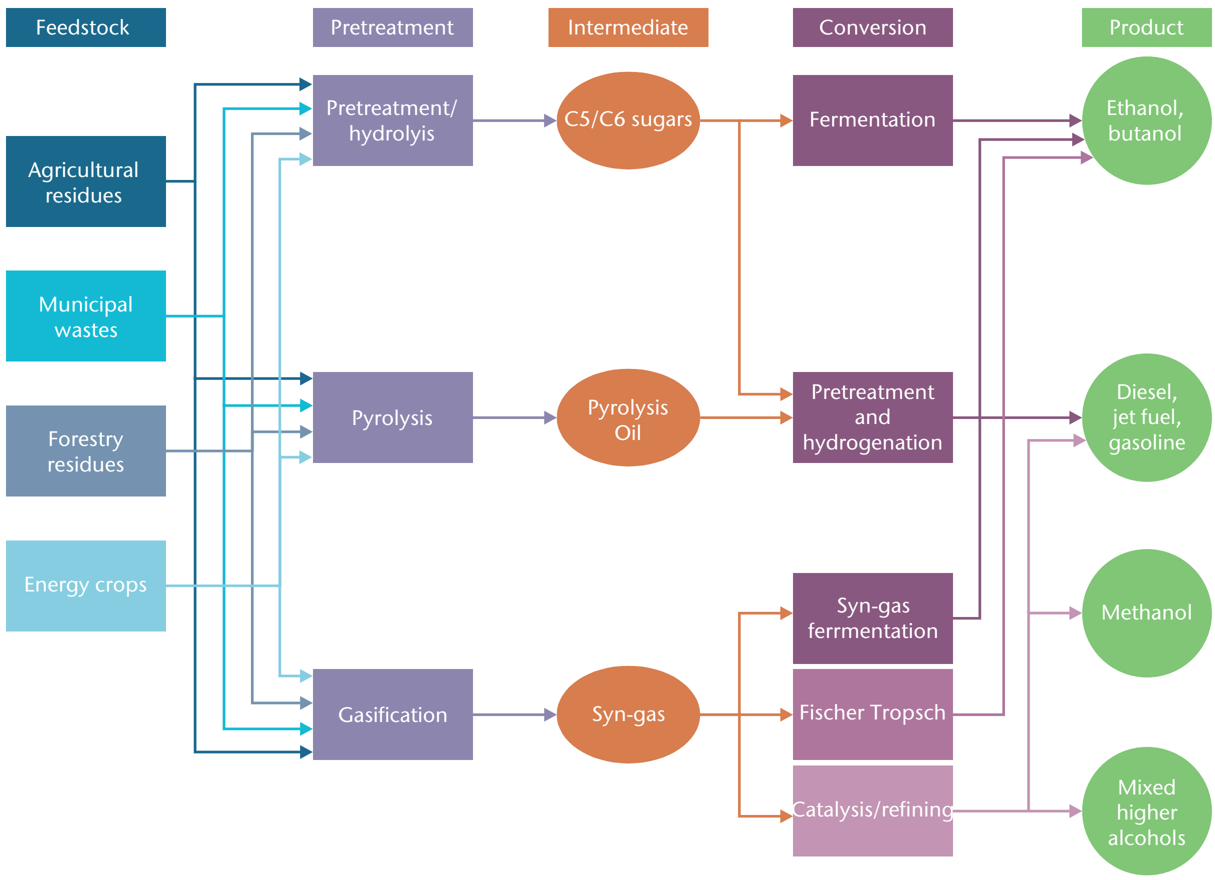
The definition used by the IEA for advanced biofuels is:

"Advanced biofuels are sustainable fuels produced from non-food crop feedstocks, which are capable of delivering significant life-cycle GHG emissions savings compared with fossil fuel alternatives, and which do not directly compete with food and feed crops for agricultural land or cause adverse sustainability impacts."

Within the range of advanced biofuels, a distinction needs to made based on the technical and commercial maturity of the technology used to produce the fuels, so as to distinguish between fuels based on established technologies and those which are not yet fully commercialised. This roadmap terms the second category "novel advanced biofuels". This distinction is important to assist the introduction of innovative technologies that offer the promise of low-carbon performance and other benefits, but which still require support to offset financial, technical and market barriers.

A range of approaches have been actively under development using either biological or thermochemical routes. While advances in the development and commercialisation of some these technologies have been slower than expected, promising signs of increasing maturity have emerged in the last five years (IRENA, 2016a). Several technologies have now moved beyond pilot-scale operations to early deployment (IEA 2017c). These are discussed further in Annexe 2 and summarised in Figure 15.

Figure 15: Some innovative biofuels routes



Biochemical processes concentrate on the conversion of lignocellulosic materials to sugars. These can then be turned into alcohols, e.g. ethanol, or directly or indirectly into other hydrocarbon fuels. Cellulosic ethanol production is the best-developed of the various novel biological routes to biofuels, with more than 5 commercial-scale facilities having been constructed and commissioned, with a similar number of demonstration plants and over 40 pilot-scale plants.

Pyrolysis oils (produced by heating the raw material in the absence of air) can be upgraded by breaking down the larger molecules and then reduction at high temperatures with a catalyst. This can either be done by feeding them as a small percentage of feedstock into the fluid catalytic cracking unit of a petroleum refinery, or in stand-alone hydrotreating plant. Recent years have seen increasing success in demonstrating these technologies, (for example in the EMPYRO project in the Netherlands and ENSYN in the United States and Canada). Renewed interest has been stimulated by the prospect of converting the pyrolysis oil intermediates into biojet fuels, with two such plants in development in the United States.

Synthesis gas (a mixture of CO, hydrogen, CO_2, methane and water) is produced by biomass gasification. This can be transformed into fuel and chemical products, including biomethane, methanol and di-methyl ether, or can be processed to co-produce gasoline, diesel and aviation fuels by, for example, the Fischer-Tropsch process, or by using microbial processes to directly produce ethanol, higher alcohols or hydrocarbons. While the potential of biomass gasification has long been appreciated, it is only in recent years that large-scale operation to produce synthesis gas of sufficient quality to enable downstream processing has been successfully demonstrated (for example in the GoBiGas project in Sweden, and the Enerkem Alberta Biofuels plant in Canada) (Alamia et al., 2017).

The challenge of producing fuels from biomass with the same chemical composition and properties as fossil fuels should not be underestimated.

In particular, biomass materials (and fuels such as ethanol and biodiesel) contain significant proportions of oxygen, which are preferably removed to make drop-in fuels (IEA Bioenergy, 2014).

The costs of the resulting biofuels are currently well above those of fossil fuels and of more conventional biofuels. Recent studies indicate that current production costs range from USD 19 per gigajoule (GJ) to over USD 60/GJ, compared with a cost of equivalent fossil fuels of some USD 13/GJ at crude oil prices of around USD 50/bbl (European Commission, 2017b; IRENA, 2016a). This is unsurprising given the early stage of development of the biomass-based processes, and considering the cost of biomass feedstocks. There is confidence in industry that, with more widespread deployment, significant conversion cost reductions can be achieved with additional research and development (R&D) and experience of operating larger-scale plants that should allow for lower-cost follow-on projects. However, at present the costs of production are a major barrier to widespread deployment, and significant policy support will be required to enable these technologies to develop and be commercialised at scale (see Section 6, Policy and Finance).

In addition to biofuels based on these processes and a broad range of biomass feedstocks, progress is being made in producing low-carbon fuels from other carbon sources, such as waste gases. These offer similar carbon benefits to biofuels and face similar barriers to introduction, but may have fewer land use and agricultural implications (see Box 4). Conversely, the costs and potential for replication are less well understood. This is a topic which the IEA plans to review more closely in the future.

Box 4: Other low-carbon fuels

A range of other fuels with low life-cycle carbon content are under development. For example, hydrocarbons and alcohols can be made from industrial waste gases. In addition, the potential availability of lower-cost, low-carbon electricity has stimulated interest in "power-to-gas" and "power-to-liquid" technologies, in which hydrogen is produced by electrolysis and then combined with CO_2 catalytically to form methane or methanol. The CO_2 can either be from a fossil or a biological source – for example from the gas produced in fermentation in a biofuels production plant. These technologies are currently reaching demonstration scale. (European Commission, 2017b). For example:

- A consortium including Lanza Tech and ArcelorMittal Primetals Technologies are building a demonstration facility at a steel plant in Ghent, Belgium, which will make ethanol from CO-rich waste gases produced during the steel-making process, using a gas fermentation process.
- Eon's power-to-gas pilot plant in Germany uses renewably sourced electricity to produce hydrogen, which is then injected into the natural gas grid.
- SolarFuel GmbH, working with Audi, has developed a power-to-gas demonstration facility with a 6.3 megawatt electrical capacity in Germany, which produces methane using CO_2 from a nearby waste treatment biogas facility.
- In Iceland, the largest power-to-methanol plant has been in operation for five years. This plant uses CO_2 captured from a geothermal power plant and hydrogen produced through electrolysis using electricity produced from hydro and geothermal sources.

Such processes can produce a range of fuels with similar carbon advantages to biofuels, depending on the source of the hydrogen. Their use in conjunction with gases produced during bioenergy production can also "gear-up" the useful energy produced for each unit of bioenergy produced. Other options would use no-carbon hydrogen-rich chemicals, such as ammonia, directly as a fuel or as an energy carrier.

These technologies share many of the same barriers to commercialisation with bioenergy, and their commercialisation will require a similar policy and regulatory framework. If this is put in place, there are good prospects for rapid scale-up once successfully demonstrated and if costs can be reduced. It is, for example, considered possible that between 1.2% and 1.7% of EU transport fuels could come from such sources by 2030 (European Commission, 2017b).

Electricity

The 2DS sees a large-scale shift to decarbonise the electricity sector, particularly through the widespread deployment of low-cost VRE sources along with other renewable generation technologies. In many cases, bioelectricity will face increasing competition from these, but it can still have an important role to play, in particular in the situations where its costs are competitive, when co-generation is employed and the heat produced is efficiently used, or where it can complement variable sources of renewable electricity.

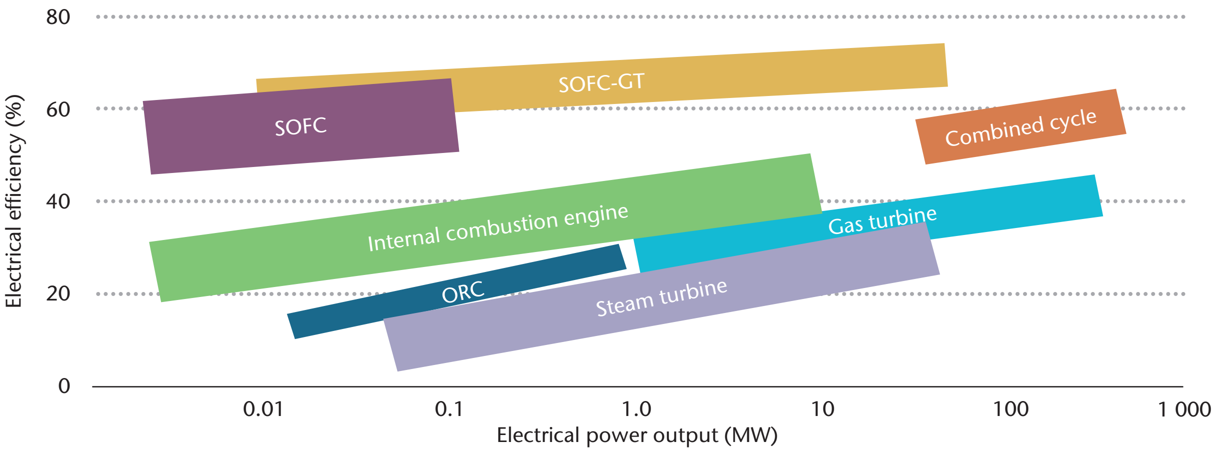
Electricity production from biomass uses well-developed, fully commercial technologies, based on direct combustion of solid fuels or the use of gases from anaerobic digestion or thermal gasification of wastes and residues, in engines or turbines, often with co-generation of heat. Since these technologies are mature, the scope for reducing costs or improving performance is limited.

Cost competition will favour the generation of electricity from low-cost fuel supplies (such as processing residues) or where other benefits are available (such as waste management). In addition, where requirements are in place that stipulate that biomass resources be used as efficiently as possible, co-generation will be favoured as long as the heat produced can also be effectively used.

Given more intensive efforts to reduce heat needs through improved energy efficiency measures and to recycle waste heat from a number of sources, in the 2DS the opportunities for using heat from bioenergy co-generation systems may in the longer term be more constrained. This suggests that priority needs to be given to the development and demonstration of smaller-scale generation systems with higher electrical generating efficiency, rather than concentrating on overall system efficiency including heat recovery.

The proportion of energy that is turned into electricity in systems based on steam turbines is limited, especially at smaller scales of operation where the additional costs of improved efficiency outweigh the benefits (see Figure 16). Systems based on gasification and organic Rankine cycles are currently being commercialised for small-scale applications, but significant efforts are still needed to improve system performance and to bring down costs. The development of biomass-fuelled solid oxide fuel cells (SOFCs) offers the promise of much higher electricity generation efficiencies (Bio-Hypp, 2017). These systems are so far much less well developed, and merit further investment in RD&D.

Figure 16: Thermal efficiency of selected technologies for generating electricity from bioenergy



Notes: MW = megawatt ; SOFC-GT = solid oxide fuel cell-gas turbine.

The huge expansion in electricity generated by VRE sources will create a greater demand for flexible bioenergy plants that are able to generate during periods of low VRE generation to supply system loads, as well as reduce generation when VRE generation is high. This will change the role that bioenergy can play in the electricity system and the value of the electricity it produces. This is now receiving increased attention and is already happening in certain European markets, such as Germany (IEA, 2016a).

Bioenergy technologies are inherently dispatchable. However, the technical ability of different technologies to operate flexibly in line with the needs of a VRE-intensive power system varies. Examples of technical flexibility include using the turndown ratio of boilers to modulate generation, the use of liquid biofuel generators to serve peak loads, and the thermal storage of biomass co-generation plants to operate flexibly where there is a heat and power demand mismatch. Biogas and biomethane systems can increase flexibility by increasing the volume of gas storage and generator capacity, adapting feeding regimes to control gas production. Virtual power plant concepts can be used to control a larger number of systems in unison (IEA Bioenergy, 2017a).

Fuel costs are a key consideration that will influence the willingness of bio-generators to provide such services. For example, EfW plants that receive a gate fee for each tonne of waste used have a strong incentive to continue to generate so as to maintain continuity of waste disposal, even when power prices and ancillary service income are low, while systems using fuels that are higher cost (for example pelletised wood fuels) will be more willing to respond to market signals.

Flexible operation also generally means that annual output, and so income, is reduced as generation is constrained or curtailed when VRE generation is high, and this means that the effective cost of generation increases.

The investment required to allow flexible generation, or the reduced income due to lower annual output, will need to be offset by increased revenue from flexible generation – for example, by accessing additional revenue streams for balancing power and ancillary services, and by benefiting from peak power prices. Bioelectricity plants, along with other potential providers of flexibility, will therefore need to be able to participate in these markets if their flexibility capabilities are to be monetised.

The value of such flexibility services will be highly system dependent, given that it will depend on the development of demand-side response and storage technologies, and so it is difficult to generalise what level of additional revenue might be available. Further system studies and practical demonstrations of bioenergy systems playing such a facilitating role are needed to establish best practice. These will need to be complemented by market rules that properly value such flexible generation.

Finally, the need will also grow for systems capable of large-scale efficient generation that is compatible with CCS. Options here include the development of biomass-fired integrated gasification and combined-cycle systems, and fuel-cell-based systems. Currently this is not a highly active area of research, and further work to identify and demonstrate affordable systems at scales compatible with biomass supply is needed.

Heat

High-temperature industrial applications

The 2DS sees an increased use of bioenergy in high-temperature industrial applications, such as the use of biogenic waste fuels in the cement industry, and the replacement of high-/medium-temperature fossil-based chemicals processes with bio-based routes (e.g. bioethanol to ethylene, biomass gasification to ammonia/methanol). To date, applications in other high-temperature sectors, such as the iron and steel sector, have been very limited, although there have been a number of such plants in Brazil (Nogueira et al., n.d.)

A priority topic for RD&D is the identification and subsequent development and demonstration of the efficient use of bioenergy as part of low-carbon manufacturing in these sectors – for example the use of biomass-based fuels in the iron and steel sector. A biomass-based route to produce steel has already been commercialised using charcoal blast furnaces. This is deployed in Brazil. Wider commercial deployment of bioenergy is more limited due to a lack of regional biomass resources in some cases limiting fuel supply, and the capacity limitations of such furnaces due to the lower mechanical resistance of charcoal compared with that of coke.

Research is also under way to identify and develop "indirect" ways of using biomass for such processes – such as via gasification routes that are used to produce bio-based hydrogen. The critical issues and R&D needs relate not to the processing and combustion technologies themselves, but rather to process integration that preserves process efficiency and product quality.

There is also a need to identify and develop opportunities for BECCS associated with large-scale industrial applications.

Low- and medium-temperature applications

Industry

In the industrial sector, the 2DS provides an expanded role for bioenergy in providing energy for relatively low-temperature applications within the existing end-use sectors – paper and pulp, and the food and drink sector, and more widely in non-energy-intensive industrial sectors. Existing experience of bioenergy to supply heat (by direct combustion or co-generation) to bio-based industries, using process residues and liquid effluents, can be significantly expanded, and provides one of many opportunities for early and rapid deployment, as highlighted in Annex 3.

Bioenergy could also play a role in delivering energy to a broader range of sectors with significant low-temperature energy needs outside the bio-industrial sectors. This can be most cost-effectively delivered when the energy is provided in an integrated way to different users via heating networks linked to biomass co-generation systems, making use of synergies between industries and other users that are located within a particular zone. In cases where biomass secondary residues are not produced on site, increased use of biomass fuels would require a supply chain which can provide fuel at a suitable cost and which offers the long-term security of supply needed to justify the investment in the boiler plant.

Buildings

Within the 2DS, traditional use of biomass is significantly reduced. This includes an extensive roll-out of more sustainable cooking and heating solutions in developing and emerging economies, including more efficient fossil fuel solutions (e.g. LPG and electric cookstoves), other renewable solutions, and more sustainable ways of using biomass (linked to sustainable supply of fuelwood from managed wood fuel plantations and the use of community scale biodigesters).

In the 2DS, the need for heating in residential and commercial buildings is constrained through the use of energy efficiency measures (e.g. building energy codes for new construction complemented by a wider deployment of energy retrofits across existing stock) and other low-carbon solutions (such as heat pumps). In the medium term, there will be a continuing role for smaller-scale biomass heating devices for residential and especially institutional and commercial buildings (See Annex 3). To help grow these opportunities, continuing work is needed to reduce system costs and improve efficiency and emission performance, which can be a problem particularly in small-scale appliances. While most modern designs can meet very high emissions standards, including for PM emissions, such abatement systems add to the costs significantly at small scale.

In the longer term, the expansion of biomass as a provider of heating for individual buildings is likely to be constrained, except for buildings in remote or isolated situations. Bioenergy can play an important role in providing energy in highly integrated systems for urban heating and cooling through district heating and cooling networks. These networks bring together sources such as heat from waste management operations and water treatment, bioenergy from heat and co-generation operations. They can be used together with solar or geothermal energy, and waste heat recovered from cooling systems and industrial processes, using heat pumps as appropriate, to link building and industrial users. Bioenergy fuels are sometimes used to help meet peak demand, with other low-cost sources used for base load (IEA, 2014). Such systems can also play a role in balancing and facilitating electricity generation from systems with high levels of VRE generation by acting as a heat source and sink, as well as by modulating electricity output. Operation in such a manner may utilise thermal storage, e.g. accumulator tanks.

This evolution will not require specific new bioenergy technologies. The key RD&D challenge is to increase experience of the design and operation of such integrated systems in areas with different seasonal energy demand profiles and potential energy supplies, building on examples such as that of Helsinki and other cities in the Nordic region (Box 5). The availability of existing district heating infrastructure utilising fossil fuels represents a key opportunity for substitution with biomass at lower investment cost. Where this is not the case, municipal governments will play a key role in developing new district heating networks (see Annex 3).

Box 5: Helsinki: Integrated low-carbon district heating and cooling

In Helsinki, 9% of heat needs are met by district heating provided through a network owned and operated by Helen Ltd, a company owned by the city of Helsinki. Much of the heat comes from fossil sources, albeit from highly efficient gas and coal co-generation systems. There is also a growing cooling demand (in well-insulated buildings) with over 300 buildings connected to a district cooling system. Of the energy used for cooling, 80% is heat that would otherwise be wasted.

Helsinki has a vision to become carbon neutral by 2050. The contribution from renewable heat, mostly through co-firing of biomass pellets, has been growing with a target of 20% renewables in heating by 2020. A new biomass boiler will begin operation in 2018, and the Hanasaari coal plant will be replaced by renewable sources by the end of 2024.

One innovative element is the Katri Vala integrated heating and cooling plant. This operates the world's largest heat pump system based on heat from purified sewage and sea water. The system also includes underground thermal storage. Further options under consideration include biomass co-generation systems and the use of waste heat from sources such as data centres.

Integrated uses

Biorefining is the processing of biomass into a range of bio-based products, including bioenergy and transport biofuels. This has similarities with the approach of the petrochemical industry, which makes higher added-value products at relatively low volume and lower-value fuels at high volume (de Jong and Jungmeier, 2015).

Biorefineries are common in the food, feed and dairy, and pulp and paper sectors. Bioenergy supply is an increasingly important feature of such plants, with energy providing an important supplementary source of income and enabling the biomass feedstocks to be more highly valorised. An increasing number of plants are producing a wide variety of bio-derived chemicals, including some with a very high value but small markets, as well as biopolymers and many other chemicals which can substitute for those derived from fossil fuels, along with an energy fraction. The 2DS sees some expansion in the role of bio-feedstocks in supplying chemicals.

There is a strong synergy between the production of many bio-based products and bioenergy. Producing higher net added-value products improves the economics of the production of the bioenergy, while income from energy production provides productive uses for low-grade materials, and so helps the economy of the biorefinery. A recent study by VTT (VTT, 2017) illustrates this synergy. It considers two scenarios, one in which biomass is used primarily for energy production and another where a biorefinery approach is emphasised. The two scenarios provide similar carbon benefits, but the biorefinery approach yields significantly higher economic benefits.

Integrated approaches to bioenergy generation need to be developed and demonstrated given the need to optimise the use of biomass feedstocks – both to improve the overall economics and to maximise the efficiency of use from a resource and land use perspective. This implies not only further development of the biorefinery concept, but also a wider integration of bioenergy into the whole bioeconomy.

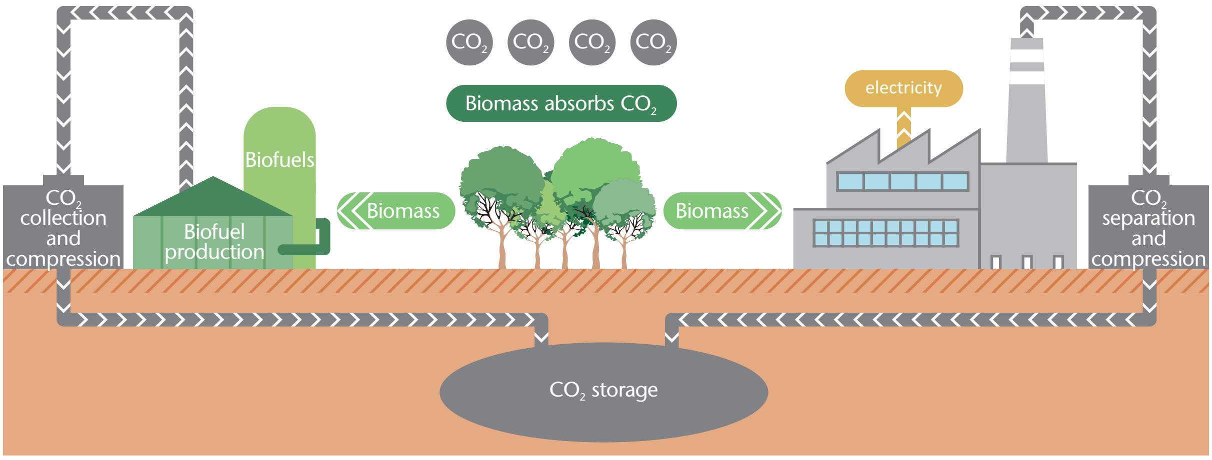
BECCS

CCS is mainly discussed in the context of avoiding CO_2 emissions from the combustion of fossil fuels, but the technology can also be deployed in bioenergy conversion plants as BECCS. In such a system, the CO_2 emitted during bioenergy combustion or in the manufacture of biofuels is injected into permanent geological storage. This provides the possibility to remove CO_2 from the atmosphere, thus providing "negative emissions" (Figure 17). This is one of very few demonstrated energy technologies able to deliver negative emissions – and the most mature.

Potential applications of BECCS include:

- Biofuel production facilities, including ethanol distilleries and gasification plants.
- Dedicated or co-firing of biomass in power, co-generation or heating plants.
- Pulp and paper mills.
- Lime and cement kilns using biomass or waste fuels.

Figure 17: Schematic view of BECCS



Five BECCS projects using ethanol plants as the source of CO_2 are under way, including a large-scale project in Illinois (see Box 6).

While the technologies needed for BECCS are available, it should be noted that there are significant efficiency or cost penalties associated with the technology. Work remains to be done to identify the optimum combinations of bioenergy technologies and CCS. A further important issue concerns the scale of bioenergy operations – often much smaller than fossil fuel equivalents – which may encourage the development of alternatives to large-scale geological storage, for example by making carbon biomass char. Further techno-economic studies of such systems are needed.

Box 6: Bioenergy combined with CCS: A first large-scale project in Illinois, United States

The Illinois Industrial CCS Project, owned and operated by Archer Daniels Midland company in Decatur, Illinois, is the first large-scale project that combines CO_2 capture and storage with a bioenergy feedstock. Operation started during the first half of 2017 (US DoE 2017) and the project will capture 1 $MtCO_2$/year from the distillation of corn into bioethanol. The CO_2 is then compressed and dehydrated, after which it is injected, on site, for permanent storage in the Mount Simon sandstone formation at approximately 2.1 kilometre (km) depth.

The project has received USD 140 million in capital support from the US Department of Energy and will also be able to claim tax credits to the value of USD 20 per tonne of CO_2 stored. The relatively modest level of

Box 6: Bioenergy combined with CCS: A first large-scale project in Illinois, United States (continued)

support (compared, for example, to power generation applications of CCS) highlights that, in the right circumstances, ethanol production with CCS can be a relatively low-cost CCS application. The favourable economics of the project are in part due to the earlier investment in geological storage characterisation, which was undertaken as part of a pilot project, as well as the fact that no CO_2 transport is required. Aspects of this project have the potential to be replicated in other areas of the United States, with the bioethanol mandate currently supporting production of 50 billion litres of ethanol each year.

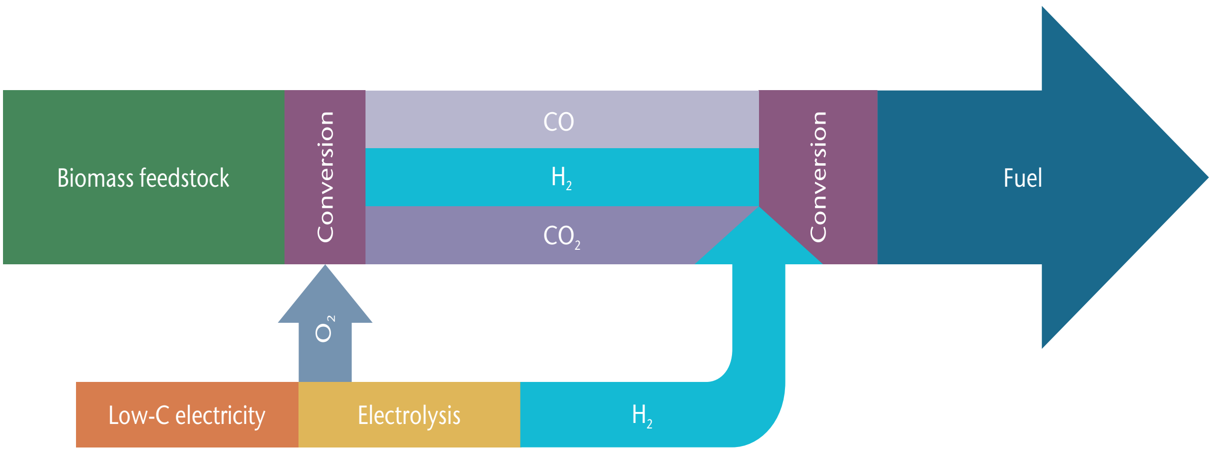
BECCU

A further interesting possibility is to recycle the captured carbon via chemical or biological processes to form fuels or chemicals, using hydrogen. Such CO_2 usage options would not in themselves lead to permanent storage of the CO_2, and therefore would not generate "negative emissions", but could deliver other important benefits, including more efficient use of the bio-based carbon.

As well as providing a potential revenue stream for the captured carbon, such processes could also reduce land use requirements for energy production through reuse of the carbon components. Fuel manufacture would require provision of low-carbon sources of hydrogen, which could come from electrolysis powered by increasingly low-cost renewable electricity in regions with good solar and wind resources (Philibert, 2017).

An alternative is to inject such renewable hydrogen into the synthesis gas stream produced by biomass gasification. This means that a higher proportion of the carbon contained in the biomass can be converted to fuels, rather than to CO_2. This has the potential to increase the yield of biogenic carbon in the biofuels and so increase the output of biofuels and the efficiency with which the biomass can be used, so contributing to reduce the biomass feedstock needed to supply the end uses (Figure 18) (Hannula, 2016; IEA Bioenergy, 2017b).

Figure 18: Using low-carbon hydrogen to increase biofuel production



Notes: CO = carbon monoxide, CO_2 = carbon dioxide, H_2 = hydrogen, O_2 = oxygen.

Source: Hannula (2016), Hydrogen enhancement potential of synthetic biofuels manufacture in the European context: A techno-economic assessment.

Further life-cycle analysis and techno-economic appraisal of such systems and research on process optimisation is required, and will need to take account of issues such as the siting of plants to make the best use both of biomass resources and of opportunities to produce low-carbon hydrogen.

RD&D priorities: Summary

Table 4 highlights the main RD&D challenges that will need to be tackled in order to deliver the expanded production and use of bioenergy identified above, covering each end use.

While many of these challenges are currently being tackled in international, national and industrial research programmes, current efforts in several areas are likely to be insufficient to enable progress to be made towards commercialisation and deployment. Government and international initiatives should consider refocusing efforts to ensure that these topics are properly addressed in future RD&D initiatives.

Table 4: Bioenergy: Technology RD&D priorities

Sector/application	***R&D requirements***	***Demonstration requirements***
TRANSPORT FUELS		
Conventional biofuels	Continuing RD&D to improve conversion efficiencies, reduce costs and improve GHG benefits. Improvements in efficiency of biofuel use in engines and other conversion devices.	
Advanced biofuels	Development at laboratory and pilot scale of efficient biofuel technologies based on thermal routes such as pyrolysis and gasification and of "hybrid" thermal and biochemical processes. Development and demonstration of routes to diesel and biojet with improved costs, better C efficiency and GHG performance including integration of bioenergy with renewables-based hydrogen. Identification of potential and development paths for cost reduction.	Demonstration of reliable performance of existing advanced biofuels projects. Demonstration and wider deployment of novel advanced biofuels solutions and cellulosic ethanol plants. Demonstration of new pretreatment solutions to widen the array of waste and residue feedstocks suitable for HVO production. Co-processing of feedstocks such as pyrolysis oils with crude oil in oil refineries.
Non-bio-based low-carbon fuels	Development of processes for low-carbon fuels from waste gases and other sources.	Demonstration of production of low-carbon fuels.
ELECTRICITY		
Biomass co-generation linked to urban energy systems	Low-cost, high-efficiency, smaller-scale generation systems such as those based on ORC and fuel cells. Improvements in part-load efficiency and capability.	Demonstration of role of bioenergy co-generation within systems with high shares of VRE. Demonstration of flexible bioelectricity generation systems.

Table 4: Bioenergy: Technology RD&D priorities (continued)

Sector/application	*R&D requirements*	*Demonstration requirements*
Large-scale efficient generation appropriate for BECCS	Feasibility studies on optimal generation configurations and development of BIGCC systems.	
INDUSTRY		
Low-temperature applications		Demonstration of bioenergy use outside bio-based industry sectors.
High-temperature applications	Identification and development of bio-based systems for high-temperature sectors including iron and steel.	Demonstration of bio-based chemicals and co-processing of bio and fossil feedstocks.
BUILDINGS		
Sustainable cooking and heating solutions		Wider roll-out of sustainable biomass, electric and fossil-based systems.
Bioenergy in integrated heating and cooling systems	Advanced heat storage systems.	Demonstration of optimised integrated heating and cooling systems using bioenergy.
INTEGRATED APPROACHES		
Biorefineries	Identification of range of efficient integrated biorefinery approaches.	Demonstration of biorefinery and other systems co-producing different elements.
Integration of bioenergy into bioeconomy	Further studies of the role of bioenergy within integrated bioeconomy.	
BECCS AND BECCU		
BECCS	System studies and techno-economic appraisals of optimum BECCS configurations for electricity and industrial applications, including siting studies.	
BECCU	System and techno-economic studies of options for combining bioenergy production with CCU.	

Technology: Key actions and milestones

The following key actions and milestones would be consistent with the deployment pathway associated with the 2DS.

Table 5: Technology: Key actions and milestones

Action	Milestone	Timing
Demonstrate successful production from cellulosic ethanol plants and scale up production.	Reach high utilisation rates in first generation cellulosic ethanol plants and develop 25 additional plants.	2025
Commercial-scale demonstration of pyrolysis-based drop-in biofuels:		
in co-processing applications.	2 commercial operations in production.	2020
In stand-alone applications.	2 commercial operations in production.	2025
Commercial-scale demonstration of drop-in biofuels based on gasification processes.	2 commercial operations in production.	2020
Further development and demonstration of novel advanced biofuels, with improved efficiency of conversion and lower costs.	Novel advanced biofuel production reaches 1.9 EJ and costs reduce by 50% reaching USD 15/ GJ by 2025.	2017-30
Continuing research and demonstration of production of non-biomass-based low-carbon fuels	Five large-scale demonstration plants operational.	2025
Development of high-efficiency (>50%) smaller-scale electricity generation systems, such as those based on fuel cells.	Technology demonstrated.	2030
Development and demonstration of higher-efficiency (>40%) large-scale bioelectricity generation.	Technology demonstrated.	2025
Pilot-scale demonstration of use of biomass in iron and steel industry.	3 pilot-scale plants in operation.	2020
System studies and techno-economic appraisals of optimum BECCS configurations for biofuel production, electricity and industry applications, including siting studies.	Pilot-plant operation of 5 novel concepts.	2035
System and techno-economic studies of options for combining bioenergy production with CCU.	Pilot-plant operation of optimised systems.	2025
Integrate biofuel production in innovative biorefinery concepts.	Demonstration of 100 large-scale replicable biorefinery applications.	2017-25

5. Delivering sustainable bioenergy

Bioenergy will only play an important role in low-carbon futures such as the 2DS and B2DS if its use reduces GHG emissions, avoids other unacceptable social, environmental or economic impacts, and plays a positive role in efforts to achieve sustainable development goals. Unless it can meet these criteria, it will be impossible to gain and maintain political support for the policy measures needed to promote bioenergy growth at sufficient scale. It is vital to understand and manage the impacts of bioenergy to ensure this confidence. Bioenergy is not unique in this regard; sustainability challenges associated with extensive deployment must be also be understood and managed for other low-carbon energy options, including hydropower, solar PV and wind.

In the 2DS and B2DS, the total primary energy supply from biomass in 2060 has been capped at a level of around 145 EJ, in view of potential constraints on supply. This includes a continuing requirement of around 17 EJ for traditional use of biomass. Current total primary energy supply from biomass is some 53 EJ, or around 25 EJ if traditional use of biomass is excluded. It is uncertain how much of the supply of feedstock for traditonal use of biomass is produced in a sustainable fashion. An expansion in sustainable biomass supply of at least five times (i.e. from 25 EJ to 128 EJ) will therefore be needed for the scenarios discussed above.

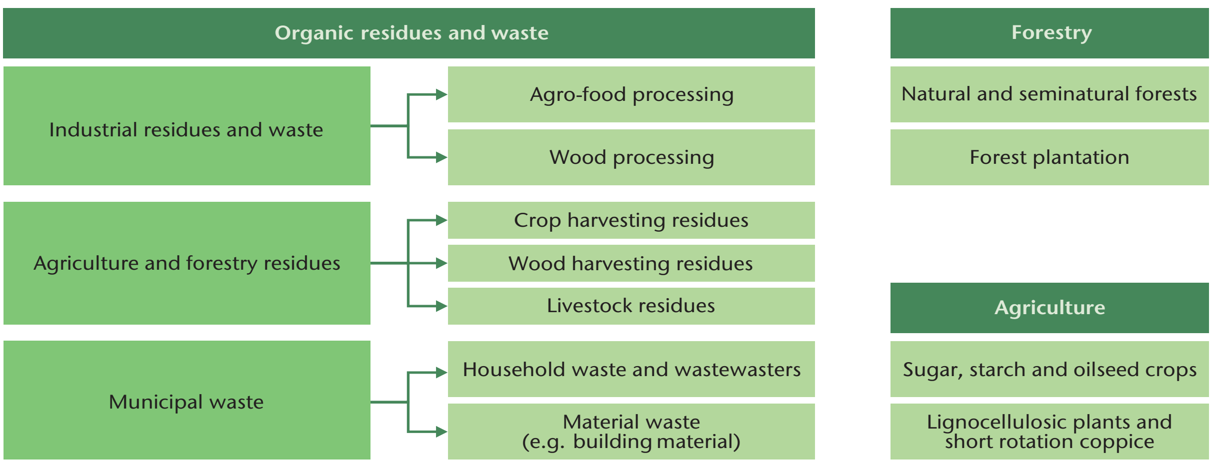
This section considers what sorts of biomass might be available and under what conditions they would be likely to meet sustainability requirements. It then considers the extent to which each source might contribute to the 145 EJ, the risks to its delivery and what measures could make it more attainable. The need for internationally recognised sustainability governance frameworks is emphasised, and the necessary features are highlighted. Finally, the issues relating to mobilising such an increase in bioenergy feedstock are discussed.

What sources of biomass are there?

Biomass resources can be classified into three classes of feedstock, determined by their origin (Figure 19): residues and wastes; forestry (including biomass streams generated in forest management); and agriculture, including crops and lignocellulosic plants such as fast-growing grasses and trees. Detailed guidance on assessing sustainable biomass resources are provided in the *How2Guide for Bioenergy* (IEA and FAO, 2017).

In addition, a number of potential new sources are being explored, for example algae and other aquatic biomass, which could provide sources of raw material for a number of higher-added-value applications including food, with a potential contribution to energy supply. To date, potential estimates of practical contributions from these sources to energy supply are speculative (IEA Bioenergy, 2016a).

Figure 19: Biomass sources by origin



Source: IEA and FAO, (2017), *How2Guide for Bioenergy.*

When is biomass "sustainable"?

A detailed consideration of the main sustainability issues associated with bioenergy has been carried out by the GBEP, an intergovernmental initiative that brings together 50 national governments and 26 international organisations. To facilitate the assessment and monitoring of bioenergy sustainability at a national level, GBEP produced a set of 24 indicators and related assessment methodologies under the three "pillars of sustainability", which gained consensus amongst its partners and stakeholders as representing the major issues that need to be managed (Table 6) (FAO, 2011).

Table 6: GBEP Sustainability Indicators

Environmental	***Social***	***Economic***
1. Life-cycle GHG emissions	9. Allocation and tenure of land for new bioenergy production	17. Productivity
2. Soil quality	10. Price and supply of a national food basket	18. Net energy balance
3. Harvest levels of wood resources	11. Change in income	19. Gross value added
4. Emissions of non-GHG air pollutants, including air toxics	12. Jobs in the bioenergy sector	20. Change in consumption of fossil fuels and traditional use of biomass
5. Water use and efficiency	13. Change in unpaid time spent by women and children collecting biomass	21. Training and re-qualification of the workforce
6. Water quality	14. Bioenergy used to expand access to modern energy services	22. Energy diversity
7. Biological diversity in the landscape	15. Change in mortality and burden of disease attributable to indoor smoke	23. Infrastructure and logistics for distribution of bioenergy
8. Land use and land use change related to bioenergy feedstock production	16. Incidence of occupational injury, illness and fatalities	24. Capacity and flexibility of use of bioenergy

The GBEP indicators, aimed principally at governments as an aid to bioenergy strategy development, are complemented by the standard ISO 13065: 2015 *Sustainability criteria for bioenergy*. This gives a practical framework for considering environmental, social and economic aspects to facilitate the evaluation and comparability of bioenergy production and products, supply chains and applications and is more directed at market actors (ISO, 2015).

Consideration of these indicators can highlight potential negative impacts from bioenergy, but can also highlight potential positive environmental, social and economic outcomes associated with bioenergy use when undertaken according to best practice. Bioenergy can be an integral part of waste management practice, and can also offer considerable opportunities for the agricultural and forestry sectors, by providing new markets for products and making economic use of biomass previously considered waste. There are also many opportunities to develop synergies between different land uses, including biomass production systems, so as to mitigate impacts on land, water and biodiversity (Fritsche U. et al., 2017b; GBEP-IEA Bioenergy, 2016).

While all these issues merit analysis in sustainability assessment, two key factors are addressed here because they have been a source of most uncertainty and debate around the availability of sustainable bioenergy:

- What types of bioenergy lead to significant GHG emission savings, and under what conditions?
- Can sufficient bioenergy be produced under economically viable conditions without causing unacceptable environmental impacts and/or compromising current and future food supplies or prices?

Bioenergy and GHG emission savings

Bioenergy systems form part of a natural cycle of growth and decomposition, operating within the fast domain of the carbon cycle (the atmosphere, ocean, vegetation and soil), whereas fossil fuel use transfers carbon from geological reservoirs into the atmosphere (IPPC, 2014).

Plants absorb CO_2 from the atmosphere as they grow. This is then reduced in photosynthesis to form cellulose, sugars and other biochemicals. At some point the plant dies and then most of the carbon in the plant material is turned back into CO_2 and returned to the atmosphere through natural physical and biological oxidation (for example through decay or by fire), so completing the cycle. The system is of course more complex, with some of the carbon-containing material being retained in the soil, some consumed by animals (including humans), or used, for example as construction materials, which may delay the point at which the carbon is returned to the atmosphere, sometimes by decades.

In using biomass as an energy source, the carbon cycle is being intercepted and the stored energy released during oxidation is used productively, rather than just being released into nature. This means that use of bioenergy to replace fossil fuels can reduce net carbon emissions even when the biomass is not grown specifically for energy purposes.

If fossil fuels are used in the processes to produce, convert, transport and use bioenergy, or other GHGs are produced, together known as “supply chain emissions”, these reduce the emission savings generated. These emissions can be quantified with some certainty. Bioenergy production can also induce emissions if its production and use lead to changes in carbon stocks in soils or vegetation or to the ways in which the carbon cycle operates. These are classed as “biogenic emissions”. It is more difficult to understand and quantify these emissions and there is less agreement about their consequences.

Supply chain emissions

GHG emissions are associated with the use of fossil fuels to produce, convert, transport and use bioenergy. In addition, there may be emissions of other GHGs, such as nitrous oxide (N_2O) from land use and fertiliser production and application, and methane (CH_4) from land use biomass storage and biogas processing. Some bioenergy systems help avoid GHG emissions, the notable example being anaerobic digestion of organic waste to produce biogas, which can lead to avoided methane emissions.

If the energy economy is progressively decarbonised by following a low-carbon pathway, such as the IEA 2DS, the GHG implications of energy use in the supply chain will be reduced (since electricity and transport fuels, for example, will be less carbon intensive) and so supply chain emissions will decrease.

Life-cycle assessment (LCA) is one commonly used approach to evaluate and compare supply chain emissions from bioenergy and other energy systems. The methodologies used in LCA have evolved considerably over the last ten years. Current methods can yield consistent results when differences in assumptions are accounted for (Chum et al., 2017; Pereira et al., 2017). There is a continuing need for data sets that provide regionally specific data for use in LCAs, and which properly represent new processes as they are developed.

LCA shows that many bioenergy pathways can have much lower supply chain emissions than fossil fuels, in the best cases over 90% lower than those emitted by the fossil fuel equivalent. The result depends on the detailed design of the supply chains and conversion processes and also on the fossil fuel that is being replaced.

For example, the European Commission lists default values for carbon savings for nearly 250 specific bioenergy options, which are summarised in Table 7 (European Commission, 2016a).

Table 7: Summary of default values for GHG reductions in EU RED

Bioenergy option	No. of routes	Max. saving %	Min. saving %
Conventional biofuels	35	98	24
Advanced biofuels	14	89	78
Biomethane for transport	12	179*	17
Electricity – agricultural residues	15	90	33
Electricity – wood chips	21	90	35
Electricity - wood pellets	57	93	-2
Electricity - biogas	18	219*	14
Heat – agricultural residues	15	93	11
Heat – wood chips	21	93	57
Heat – wood pellets	57	94	32

* In cases where direct methane emissions to the atmosphere are reduced, emission savings can exceed 100% of those associated with fossil fuel use alone, as methane is a significantly more potent GHG than CO_2.

Note: These savings do not take account of emissions due to land use change.

Source: European Commission (2016a), Proposal for Directive on Renewable Energy, 2016, Annexe 5.

LCA allows analysis of many of the issues that are responsible for residual supply chain emissions from bioenergy consumption, and aids the identification of measures that can improve performance. These can include improvements in the efficiency with which bioenergy is produced or used, replacement of fossil fuels used in the process with low-carbon fuels (for example, biomass residues or other renewable sources), improved transport logistics, or the optimisation of the production of co-products.

Land use change and GHG emissions

Removing natural vegetation and soils to support human activities, or "land use change", can be associated with urban development, food production, bioenergy plantations or other uses such as hydropower projects, or the extraction of fossil fuels, metals, and other resources. Concern about the negative effects of such land use change are understandable given the well-documented impacts of forest conversion and of cropland expansion into uncultivated areas, mostly so far driven by food and fibre demand. These include reductions to the carbon stock, habitat loss, and degradation of soils and water bodies. Such changes can give rise to significant changes to carbon stocks both above and below ground, and also affect the rates of carbon sequestration. Examples include the burning of forest, or when soils containing high levels of carbon, such as peat, are exposed and the carbon oxidises to CO_2.

When land is converted for bioenergy feedstock production, in the worst cases the annual emission savings obtained from displacing fossil fuels with the bioenergy may correspond to just a fraction of the carbon emissions caused by the initial land use change. There is agreement that clearing such high-carbon stock lands for bioenergy is counterproductive and does not support sustainable development goals. For example, the EU RED excludes support for biofuels (including imports) made from raw materials obtained from converted high-carbon stock land or land with high biodiversity value, such as wetlands, primary forests and highly biodiverse grasslands.

While land use change is often associated with deforestation and negative impacts on carbon stocks, it can also result in positive impacts. For example, if land is reforested, or degraded soils are managed and planted with suitable crops to restore productivity, or fires are controlled and reduced in extent or intensity, or perennial crops are planted on land previously used for annual crops, then net carbon increases can occur over time. Afforestation of degraded or abandoned land can provide substantial carbon benefits while also providing significant resources for sustainable local food and energy use.

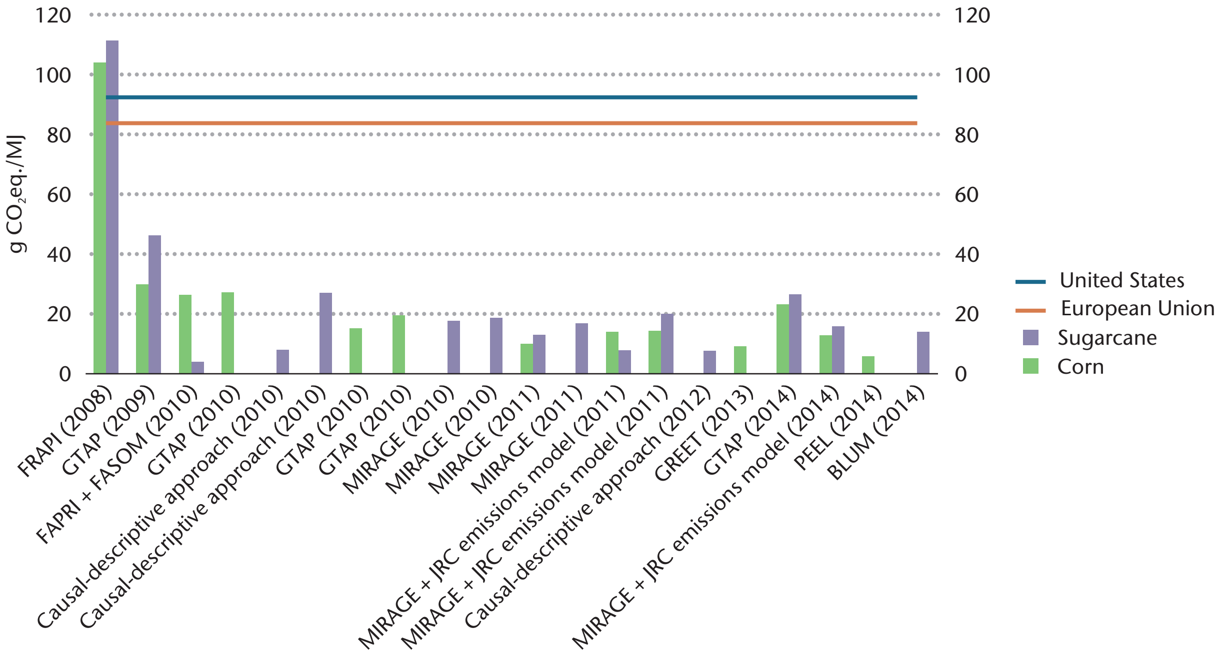
The potential also exists for the production of bioenergy to lead to land use change if it causes a shortfall in the production of agricultural commodities, such as food or feed. This may mean that that the remaining agriculture land is used more intensively, or that more land is converted to agriculture to make up for the lost food or material production capacity, so potentially leading to deforestation with consequent loss of carbon stocks. This is referred to as indirect land use change (ILUC).

Estimating the impact of these indirect changes is a challenge given the complex interactions within the global agricultural and land use system. Initial work suggested that this effect might be very significant and offset to a large extent the carbon benefits of crop-based biofuels (Searchinger et al, 2008). However, subsequent analysis has progressively reduced the range of likely impacts (Brown, 2014).

Recent studies confirm the potential importance of ILUC when crops may provoke an expansion of agriculture into primary forest areas and the exposure of high carbon-containing peat soils. They also point to much lower ILUC-related emission levels for other crops, such as cereals (European Commission, 2012; European Commission, 2015a; Langeveld et al., 2013). Figure 20 shows one analysis whch indicates that ILUC could reduce the GHG savings from using sugar- and cereal-based biofuels in place of fossil fuels by some 10-20%. Once these and the supply chain emissions are taken into account, the GHG benefits of using such fuels at the scales analysed are still significant.

In order not to constrain the use of biofuels unnecessarily, regulation of biofuels should be based on a quantitative assessment of the GHG benefits compared to fossil fuel use when possible, rather than regulating on the basis of feedstock types or processes. This should be coupled with an objective to progressively lower the associated GHG emissions.

Figure 20: Modelled ILUC emissions for ethanol feedstocks, corn and sugarcane



Notes: Figure shows the method/model used and publication year. When a study reports a range for ILUC emissions, two bars are shown in the figure. Reference emissions for petroleum fuels in the European Union and United States are included in the diagram. gCO_2eq/MJ = grams of carbon dioxide equivalent per megajoule.

Source: Macedo et al (2014), "Greenhouse gas emissions from bioenergy".

Significant potential also exists to produce biomass for energy without causing land use change (IEA Bioenergy, 2015). The use of post-consumer organic residues and by-products from the agricultural and forest industries does not cause any land use change if these biomass sources are wastes, i.e. not used for other purposes. Residues that are generated in agriculture and forest operations can also be used to the extent that these can be extracted without impacting on soil fertility or biodiversity. Biomass residues that are burned, such as agricultural residues on fields or natural vegetation during forest clearing, are obvious examples.

In addition, there is considerable scope to make use of land which is appropriate for agricultural use but where production is low, or of agricultural crops which are not needed for food and feed use. For example:

- Europe has increasing areas of agricultural land that are unused or underused for agriculture. Some 14 million hectares of utilised agricultural area has come out of production in just four countries (Italy, Spain, Germany and France) since the 1970s – including nearly 20% of Italy's productive arable land. This is due to conversion to other uses, a lack of attractive revenue streams for farmers, and degradation due to climate change and drought that make it increasingly difficult to produce food crops economically (European Commission, 2017b).

- In India, it is estimated that there are some 100 million hectares that are not productively used, and 150 million hectares where there is potential for increasing production by growing additional crops in additional annual rotations, so improving rural incomes (Ramakrishna, 2017).

- In the United States, over 1 billion tonnes of dry biomass could be produced annually from existing agricultural and pasture landscapes through investments to improve management on a relatively small share of pasture, and by making use of a proportion of the cropland that is otherwise being lost each year to other uses (US DoE, 2016).

- China has recently changed its policies on biofuel production. Improvements in agricultural production have led to high levels of corn stocks that are at risk of spoiling, and which are being converted to ethanol for fuel use.

In addition, many countries also have large areas of degraded or marginal land which is unfit for food or feed production, but which may be suitable for bioenergy feedstock cultivation (Fritsche et al., 2017). Producing bioenergy feedstock along with other products on lands that have been abandoned or degraded could provide an economic driver for land improvement as well as satisfying local energy needs.

Several other ways are available in which bioenergy can be produced from crops while minimising or avoiding competition with agricultural production and the need to extend agricultural land areas. These include the following:

- Intensification of production. For example, in Brazil increasing the number of cattle per hectare has made land available for additional sugar cane production (Berndes et al., 2016a).

- Improved productivity by increasing crop yields through breeding and improved cultivation practice. This reduces the land needed to supply food needs, releasing production for energy use.

- Altered crop rotations and intercropping systems, including different types of agro-forestry systems which can provide bioenergy feedstock along with food (EMBRAPA, 2017). For example, the oil-yielding brassica carinata can be cultivated as a winter crop, complementing conventional food crops which are grown earlier in the year (UPM, 2017.)

Taken together, these opportunities demonstrate the presence of significant potential for producing bioenergy feedstocks while avoiding negative land use change impacts and also limiting impacts on food production and availability.

Forestry, bioenergy and carbon

Forests cover about 4 billion hectares, corresponding to some 31% of the world's land area. They are a major store of carbon and currently function as a net carbon sink on the global level (Ciais et al., 2013). Forests provide many different economic, environmental and social benefits above and beyond their function of sequestering and storing carbon. Forests are an important resource for people and the global economy, contributing USD 600 billion annually to gross domestic product and providing employment to over 50 million people (FAO, 2015a and 2015b).

There are widely differing views amongst different interest groups, such as environmental non-governmental organisations (NGOs) and industry stakeholders, and amongst academics, on whether and how forests should be managed and used. These stem from different perspectives on the relative importance of the economic value of forests and of biodiversity, amenity value and other ecosystem services provided by forests (including wood production), and their role as a carbon reservoir.

The balance between these various interest groups and points of view needs to be considered within a comprehensive local or national sustainable forestry strategy. This should be developed with stakeholder agreement at a national and forest level, and take into account the full variety of issues, including the carbon perspective, in deciding how the forest should be used and for what products. Such a strategy should take into account the potential use of some forest products for bioenergy.

From an economic perspective, it is unlikely that whole mature trees can be used entirely for energy purposes since their value is much higher in other uses (such as construction materials). However, it may be economic to use a range of residues and by-products from forestry operations for energy purposes. So doing can lead to significant carbon benefits, but careful assessment of the amount and timing of these benefits is needed, as discussed below.

Impact of forest management

When unmanaged, some forest landscapes can provide significant carbon sequestration thanks to strong forest growth, at least for some decades However, unharvested forests have declining mitigation value over time, because the carbon sequestration rate diminishes as forests approach maturity. The sequestered carbon is also vulnerable to being released through fires, storms, droughts and insect attack, which are likely to become more common due to climate change impacts. In California, for example, drought and insect attack are reported to have killed more than 102 million trees over an area of over 3 million hectares. The plan to reduce fire risk associated with these trees includes using material for energy production (Biomass Magazine, 2017).

In the absence of strong preventive legislation or a high price on biogenic carbon emissions, landowners may make management decisions that can cause losses in stored carbon. For example, high food or fibre prices may make it attractive to convert the land to productive uses. Strong preventive legislation or a high price on biogenic carbon emissions can prevent or discourage such conversion, but land use change in response to the food and fibre demand may then cause carbon losses elsewhere

In contrast to the option where forests are left unharvested, sustainable forest management to produce wood for bioenergy and other products can lead to climate benefits over multiple cycles of forest harvest and regrowth, by displacing products that are associated with fossil carbon emissions. Wood demand can encourage owners to preserve and extend their forest areas by providing an income stream and opportunities for employment.

Timing of emission savings

The GHG balances for forestry systems vary because conditions differ around the world. The assessment is also affected by methodological decisions and assumptions – notably on timescale, the area involved, and on likely counterfactuals – which have a strong influence on the assessed climate effects of forest bioenergy. One important complicating factor is that the biogenic carbon cycle for some forests and forestry materials can be long, since forest rotations are lengthy and biomass decay can be a relatively slow process. This differs from many other potential bioenergy sources with a short carbon life cycle, such as annual crops and their residues. This introduces a time element into the considerations about carbon benefits or dis-benefits from using forestry products.

Research to reduce scientific uncertainty over the timing of carbon savings is continuing and scientific understanding of the issues has improved in recent years. However, an ongoing vigorous debate continues about how to interpret the science in respect of recommendations and conclusions as to which forestry products should be used for bioenergy (Berndes et al., 2016b; Brack, 2017; European Commission, 2015b; EASAC, 2017; IEA Bioenergy, 2017c; WWF, 2017).

The time at which forest products used for energy lead to carbon savings depends on which fractions are being considered. It also depends on the local context, since the real baseline or counterfactual depends on the specific forestry management strategy. For example, if forestry residues are burned as part of forestry practice, to minimise the risk of uncontrolled wild fires, then using the residues as fuel leads to immediate carbon savings, while other practices mean the savings may be delayed.

It is therefore not possible to make generalised statements about which forest products lead to immediate carbon savings, and which only provide such savings later. Instead the use of particular forestry products and the timescale at which any climate benefits might be achieved need to be considered in a transparent way and in the light of the real "counterfactual". This is one of the issues that should be considered within the local sustainable forest management strategy or plan.

There are also contrasting views on priorities. Should short-term GHG savings be prioritised in order to reach political GHG targets or to reduce the risk of reaching potential "tipping points" that might lead suddenly to catastrophic climate change? Or should there be a focus on longer-term temperature targets and the transition away from a fossil-based economy to one based on more sustainable energy sources? This is a matter of judgement, which can be allowed for in a national emissions strategy and trajectory (for example, by bringing forward some fossil fuel reductions so as to create emissions "head space").

The use of forestry materials for energy and bioproducts should therefore be part of a clear overall national emissions management strategy, which includes energy, forestry and land use issues and which is consistent with national and international climate change commitments, taking into account the timing of savings.

Accounting for forestry energy

The accounting system for the full carbon cycle associated with forestry is complicated and can give rise to misunderstandings (although the accounting system used changes nothing in the physics and chemistry of the carbon flows that occur). Under the most commonly used accounting frameworks (Intergovernmental Panel on Climate Change [IPCC] and European Union, for example), process-related emissions are included in national energy-related carbon accounts. Carbon emissions and withdrawls associated with land use changes are included in the land use, land use change and forestry (LULUCF) accounting system, but not included in the process-related emissions, to avoid double counting. When biomass for bioenergy is traded internationally, a gap in the accounting can occur if the country where the forest biomass originates does not adequately take account of LULUCF emissions. This gap can be avoided by the use of sustainability criteria for biomass based on comprehensive carbon LCA, supplemented to some extent by constraining the use of forest biomass imported from countries who do not properly account for such emissions in their national inventories.

A crucial issue relating to the accounting issue is the need to decide what baseline should be chosen as the basis for setting LULUCF ambitions – a baseline which looks at the absolute level of carbon stocks in the forest, or a baseline which takes into account some anticipated changes in this level (based on past or projected changes in forest stock or economic uses of the forest, given certain national policy priorities such as the desire to increase forest harvesting for bioenergy purposes). This is a matter of debate, and should be clearly established as part of a country's NDC under the COP21 global climate agreement.

Bioenergy and food supply

In principle, the use of land to produce energy could result in impacts on food availability and price. However, the issue of adequate food availability now and into the future is a complex one. In 2008 and 2009, concerns were raised when a period of strong increases in global biofuel production coincided with increasing food prices. However, subsequent analysis showed that many factors (including high energy prices and market speculation) contributed to these increases, with bioenergy being only one factor in a complicated picture (World Bank, 2010).

There is an increasing understanding that bioenergy is not in itself either good or bad for food security, but that there can be important synergies. This is recognised by the Committee on World Food Security and the FAO (FAO, 2013).

For the longer term, inevitable concerns are apparent about the availability of sufficient land to provide enough food to feed the growing global population and also to contribute to energy production, given the many factors and the long timescales involved. The land available for energy production will be influenced by a number of factors, which are difficult to forecast or influence, including:

- The balance between increases in agricultural yields, production efficiency (especially the reduction of waste and losses in the food chain) and food needs, which are in turn dictated by population growth rates and dietary habits.

- Availability and cost of organic and mineral fertilisers to support high productivity and yields without land degradation.
- Impacts of climate change on water availability and food productivity.
- Other pressures on land use, such as land degradation due to poor conservation and urbanisation.

The land requirements for food production will be affected by the efficiency with which food produced is used. Over 30% of current food production is wasted either during the production and distribution cycle (for example, because of a lack of a "cold chain" which permits food delivery in good condition), or by users. Land requirements will also be affected by dietary choices, with a diet high in meat (especially beef and lamb) and dairy requiring significantly more land than one based more on vegetables, or on chicken or pork consumption (the same area can produce 250 kilograms [kg] of beef, 1 000 kg of chicken or pork, or 15 000 kg of vegetables) (Global Calculator, 2013).

However, it is clear that a number of actions related to improved land and resource management and efficiency would make the required supply easier to achieve, and therefore potentially release land for bioenergy production (IRENA, 2016b). These measures form a set of "no regret" options, as summarised in Box 7.

Box 7: No regret options to improve land and resource management

A number of sensible land management steps should be promoted even without a need to improve the prospects for bioenergy or biomaterial production. They include measures to increase the potential for food production and to ensure that resources are used as efficiently as possible:

- Improving food crop yields through improved crop varieties and management practices, but especially by narrowing the "yield gap" between best practice and achieved food production, thus enabling more to be produced on less land.
- Improvements in the land efficiency of animal husbandry, which could make more efficient use of the land used to raise animals for meat and dairy products (nearly half of all high-quality "good" and "prime" agricultural land) by increasing intensity.
- Improving the efficiency of food production, notably by reducing food waste and losses. In developing and emerging economies, most food is lost during production and distribution (for example, because of problems bringing food to market in good condition and the lack of cold chains to preserve the quality of the products). In more developed economies a larger share of food is wasted by consumers after it is purchased.
- Improving the efficiency with which biomass is used for energy (notably in traditional uses of bioenergy).
- Afforestation of derelict and abandoned land, which could provide significant resources for local food and energy use. The Bonn Challenge and New York Declaration on Forests seek pledges from countries to restore 350 million hectares of degraded land to productive use. The African Forest Landscape Restoration initiative, launched at COP21 in Paris, aims to restore 100 million hectares, and this initiative has already been joined by 21 African nations.

It is important that the potential impact of biofuel production on food security in a particular country be closely examined before major biofuel production policies and initiatives are undertaken, in particular where these relate to changes in land use and impacts on staple crops. Tools are now available to evaluate the interactions between food and fuel at a country level, such as the FAO Sustainable Bioenergy Support Package. This includes the Bioenergy and Food Security Rapid

Appraisal, which consists of a set of easily applicable methodologies and user-friendly tools that allow countries to generate an initial indication of their sustainable bioenergy potential and the associated opportunities, risks and tradeoffs (FAO, 2014).

The FAO, the International Renewable Energy Agency (IRENA) and IEA Bioenergy TCP have recently published a memorandum summarising good practice in these areas (IEA Bioenergy, 2017d). More generally, bioenergy production should follow the Principles for Responsible Investment in Agriculture and Food Systems that were approved by the Committee on World Food Security in 2014, and which focus on production that ensures food security while protecting the rights of individuals, including land tenure (IEA Bioenergy, 2017d).

Other issues

While much of the debate about bioenergy principally focuses on the carbon issues and on the potential impacts of bioenergy on food supply, a range of other issues relating to the environmental, social and economic pillars of sustainability also need to be carefully considered. These issues do not generally question the overall merits, or otherwise, of producing and using bioenergy, but lead rather to guidelines relating to good practice that should be observed. They often relate to issues which are much broader than those strictly related to bioenergy, but may be significant for issues such as the regrowth rate of forests or crops or the GHG impacts of fertiliser use, and hence the climate impacts of bioenergy choices.

Particular issues which need to be carefully considered include the following:

- impact on soil quality
- need for and availability of fertiliser
- emissions to air and water (including adequate measures to minimise emissions from biomass combustion when used at a small scale, through tight controls on equipment design and on the fuels used)
- water use, efficiency and quality
- biodiversity
- land tenure
- labour rights.

An overall sustainability assessment should be carried out before a country embarks on large-scale bioenergy production or introduces policies that incentivise this. The production and use of bioenergy should also be subject to sustainability certification that assures that best practice, including as regards carbon savings, is applied.

How much sustainable bioenergy supply might there be by 2060?

Availability of bioenergy feedstocks

A wide range of estimates of the availability of biomass for energy purposes is apparent in the literature, ranging from levels close to zero to well in excess of today's total energy use (1 500 EJ). Resource estimates depend on what is included in the estimates (wastes, agricultural and forestry residues, other forestry materials, energy crops, algae, etc.) and on the constraints to biomass supply that are applied.

Despite the continuing or increasing need for a better appreciation of how much bioenergy might be available in the medium to long term, most papers making detailed global bioenergy resource assessments predate 2011 and were written before there was such a focus on the concerns over the impacts of direct and indirect land use change and the "food versus fuel" debate. However, more recent papers have tried to understand the reasons for the widely differing estimates and to reduce the range by harmonising and updating the underlying assumptions.[14] In 2016, IRENA and IEA convened a workshop to review recent estimates of global bioenergy potential so as to seek consensus over the numbers (IRENA, 2016c).

These global studies are complemented by detailed regional and national studies, including an update of the US "billion tonne study" (US DOE, 2016) and of the potential in Europe through the S2Biom Futures project (S2Biom, 2016).

Recent assessments indicate that at least 100 EJ could be available in 2050 or 2060, and that potentials within the 100-300 EJ range may still

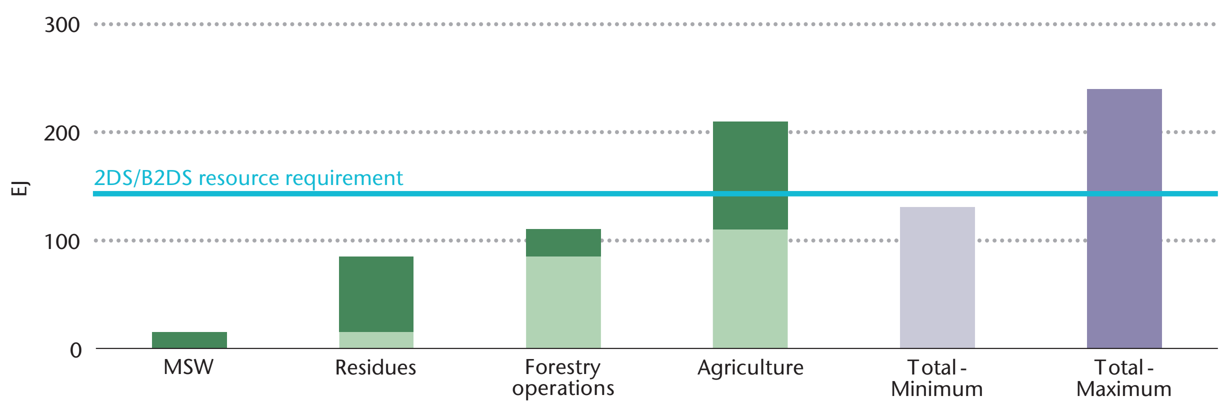
14. See, for example, Creutzig et al. (2014); Daioglou (2016); IRENA (2014) and (2016b); Searle and Malins (2014); Slade et al. (2011); Slade, Bauen and Gross (2014).

be considered reasonable, although the risks of delivery of sustainable feedstock increase as the estimate rises. The principal sources, the conditions under which they could be made available, and ranges of the potential by 2060 are outlined in Table 8 and summarised in Figure 21.

Table 8: Summary of sustainable biomass resources

Bioenergy resource	Conditions for sustainability	Potential in 2060 (EJ)
Municipal wastes	Taking account of the waste management hierarchy, which favours waste prevention and minimisation and recycling, and evolution of waste management systems in economies as they develop.	10-15
Agricultural wastes, residues and processing residues from wood and agro-industry	Respecting the need to reserve some of the available resource for animal feed and to leave sufficient residues in the field for soil protection, and consistent with other uses.	46-95
Wood harvesting residues co-products	Used within the context of a sustainable forestry plan, which takes carbon aspects fully into account, along with measures to maintain other forest characteristics including biodiversity.	15-30
Agriculture	Produced on land in ways which do not threaten food availability and whose use leads to low land use change emissions, and subject to a positive assessment on other sustainability indicators such as biodiversity and water availability and quality. Crop or forestry production on degraded and derelict land linked to attempts to afforest, reforest or otherwise improve the quality of these areas.	60- 100

Figure 21: Potential sustainable biomass resources



Based on these estimates and given the uncertainties and issues around deploying the resource, a level of primary biomass supply of around 145 EJ, as required by the 2DS and B2DS, is challenging but achievable. Many low-carbon scenarios have similar contributions from bioenergy. In its *Special Report on Renewable Energy and Climate Mitigation*, the IPCC examined a range of scenarios and found that bioenergy contributed between 120 EJ and 180 EJ to such scenarios by 2050 (IPCC, 2011). A more recent paper based on the Global Carbon Calculator Model finds a global sustainable potential for 2050 of around 180 EJ (Strapasson et al., 2017).

A number of studies have narrowed the range of estimates of global sustainable bioenergy potential. These are complemented by detailed regional and national studies, including an update of the US "billion tonne study" (USDOE, 2016) and of the potential in Europe through the S2Biom Futures project (S2Biom, 2016). Further work to establish the likely resource level, taking specific regional sustainability issues into account is needed. Establishing a generally recognised methodology for such would be a useful step in ensuring that such assessments are comparable.

Each of the resources has significant uncertainty associated with it and it is not prudent at this stage to propose a "recipe" for the mix of supply that is likely to be deployed in 2060, since this will only become clear in time.

However, it is clear that the 145 EJ level is unlikely to be achieved just through the use of municipal wastes and agricultural and forestry processing residues (which can provide a level around the 90 EJ that is needed in the RTS), but will require further supply from forestry or from energy crops.

The most likely outcome is a mix of the different biomass resources, recognising that the opportunities for each differ regionally. For example, Scandinavia, Canada and the northern forestry regions offer greater opportunities for use of forest industry residues. At this stage, there should be continuing efforts to build up supply from all the categories that deliver genuine GHG benefits over fossil fuels.

Outside the general measures to improve resource and land efficiency discussed above, specific measures associated with bioenergy production can be taken. In particular, once a decision has been taken to use land to produce energy, its productivity should then be optimised by using crops that are best adapted to the land and climate so as to maximise energy yield, taking both production efficiency and energy conversion processes into account. In some cases, this may involve crops that in other circumstances can be used as food crops. For example, in some climates crops such as palm and sugar cane can be the most productive crops if land can be made available without the serious direct or indirect land use change emissions which occur when high-carbon forest land is converted to biofuel production.

Producing "dual purpose" crops that can be used for food or feed or for energy production has a number of advantages, including the ability to switch between markets in cases of surpluses or shortages, diversifying income streams, the production of co-products (such as animal feed from corn ethanol production) and the reduced need to commit land to energy crops for long periods. Farmers are also more experienced in producing conventional crops to serve a mix of energy and other markets.

Scope also exists to further enhance the yields of such crops. For example, trials of "energy cane" – a variety of sugar cane designed to maximise overall biomass yield without compromising sugar content – suggest that very high overall yields (as much as 200 dry tonnes/hectare) can be obtained. This represents up to three times that of more conventional cane varieties, opening the way to the production of energy on much smaller land areas than with other crops (CGEE, 2016; CTB, 2017; Junqueira et al., 2017) (see Figure 22).

Figure 22: Trials with energy cane in Brazil

Notes: Trial plot of energy cane growing in Brazil. The cane that is third from the left is the highest-yielding variety of "normal" sugar cane.

Source: CTBE (2017), Personal Communication.

Other measures that can enhance the potential for energy feedstocks while minimising other impacts include:

- Co-producing food and energy by using food crop residues for energy purposes and planting nitrogen-fixing wood crops together with food crops to boost their yields (agroforestry), or planting food and fuel crops in alternation (intercropping or crop rotation).
- Using degraded or abandoned lands to grow a mix of food and energy crops.
- Reducing waste and losses in the food chain to reduce land needed for food production.
- Improving waste management practices and developing waste-to-energy systems.
- Making more efficient use of bioenergy resources to produce a mix of electricity, heat, liquid biofuels, high-value chemicals and materials.

In addition, measures aimed at "recycling" the CO_2 from biomass-based energy production to produce fuels or other products with CCU, or introducing low-carbon hydrogen during gasification, can maximise the efficiency of biomass carbon use and reduce feedstock requirements.

Managing sustainability: Regulation and certification

Understanding the issues associated with bioenergy is an important but not sufficient step in ensuring that it produces significant carbon savings and avoids other serious sustainability concerns. The understanding needs to be embodied in policies, regulations and certification systems that define good practice, and that are complemented by an adequate enforcement system which ensures best practice is delivered in reality.

A number of comprehensive regulatory packages have been put in place that take into account issues relating to direct and indirect land use change and a broad range of other sustainability concerns, usually linked to policies that mandate or financially incentivise bioenergy use and set sustainability conditions that must be met for particular materials and uses to qualify.

Industry-led certification schemes aim to assure sustainable supply and use at a project level, to demonstrate compliance with sustainability best practice and with the appropriate legislation. Examples include the Sustainable Biomass Programme and the Roundtable on Sustainable Biomaterials. These industry-led approaches are further encouraged by customers and investors who increasingly insist on measures to reduce regulatory and reputation risks. Use of formal certification schemes is likely to be important for large-scale projects, especially where bioenergy feedstocks or products are traded internationally. They can be complemented by locally based systems reliant on best practice, especially for smaller-scale projects where the costs of detailed certification can be prohibitive.

However, these schemes need to be reinforced by provisions at a national and regional level, which can set overall sustainability criteria and standards and ensure that project- and product-level schemes meet minimum standards. One such example are the provisions under the EU RED and the Commission proposals for the revised directive that will apply from 2020 to 2030 (European Commission, 2016), and the national legislation and regulations that give practical effect to these overarching principles in the EU member states.

As part of the work to develop this roadmap, a workshop was organised to consider the extent to which these current sustainability management schemes provide adequate measures to ensure the sustainable production and use of bioenergy (IEA, 2017f). The conclusions are summarised in Box 8.

Discussions indicated that the current sustainability management regimes form a basis on which the necessary internationally recognised sustainability regime could be built, and it was agreed that for many sorts of biomass feedstocks considered, and subject to certain conditions and safeguards, such as those developed by FAO, that bioenergy could be produced and used sustainably (FAO, 2012). A good level of agreement was evident on areas requiring further work to identify what constitutes best practice, and some areas where there are practical difficulties in monitoring performance. However, as stated above, the same level of consensus was not evident around the use of forestry-based materials, notably the timing of carbon savings and the specific regulatory frameworks needed.

The development of biomass sustainability governance frameworks needs to consider not just sustainability issues, notably the GHG impacts of different bioenergy sources, but also the cost of compliance with these to fuel suppliers.

Box 8: Conclusions of workshop on sustainability governance

To what extent have current sustainability initiatives covered the principal issues relating to sustainability in the specific sector?

- The current initiatives are comprehensive, but some areas are difficult to manage given practical difficulties (e.g. food security, soil carbon retention, secure land tenure) or continuing lack of consensus (e.g. use of some forestry products).
- Balancing a comprehensive approach with operability is a challenge.

Are there issues that are not sufficiently controlled within current sustainability frameworks?

- Fully include carbon aspects within whole supply chains associated with forest management systems.
- Improve LULUCF accounting based on transparent assumptions.
- Consider risk-based approaches for food security and secure land tenure.

Do current measures provide sufficient stimulus to promote the good practice and the innovation needed to deliver large-scale sustainable supply?

- Sustainability certification schemes often promote best practice, but approaches differ among countries.
- Current systems focus on prevention and do not generally incentivise innovation.

How can the key actors collaborate in the development and implementation of the framework?

- A continuing dialogue backed up by efforts to reduce areas of uncertainty.
- Joint learning on (global) supply-chain sustainability approaches, including those outside the bioenergy sector.
- Further consideration of risk-based approaches for key commodities (e.g. forest products), and sustainability aspects (e.g. food security, land tenure).
- Supported by regulation based on observed data of impacts of large-scale implementation.

The need to certify to multiple schemes with different requirements in order to gain market access carries a cost and administrative burden for biomass fuel suppliers. This could constrain biomass trade and undermine the increased consumption of bioenergy required by the 2DS. Therefore, certification schemes with a wide geographical scope or aligned principles for national sustainability legislation represent best practice.

Much of the understanding of sustainability impacts is so far based on modelling and theoretical considerations, and with limited solid evidence on the real impact of large-scale bioenergy deployment, although some such studies are now under way. Further research to identify and quantify the impacts of practical large-scale deployment will be important to corroborate the results of more theoretical studies, for example by using satellite-based technologies to study land use changes and the impact on carbon stocks.

New roles for sustainability governance regimes

Well-designed sustainability policy and regulation, backed up by appropriate sustainability assurance schemes, are an essential requirement for ensuring the global supply of sustainable bioenergy, as discussed above. To facilitate the sustainable biomass requirements associated with the 2DS and B2DS, the sustainability regime must effectively prevent bad practice. But it must go further. Adopting a too-strict interpretation of the “precautionary principle”, could close off some sustainable options and so undermine the contribution of bioenergy to a low-carbon future. With the improved understanding of the issues that constitute sustainable production and use, and the potential for more specific measurement of real effects, a more nuanced approach to sustainability management is possible and necessary. Appropriate sustainability governance frameworks must play two additional roles.

First, they must provide a clear and long-term set of rules for market players. Policy uncertainties, including those around sustainability regulation, create an unstable investment climate that inhibits investment both in deployment and in new technology development and commercialisation. There is experience of such instability – for example in Europe where concerns about sustainability have led to three major revisions to the policy framework supporting biofuels for transport. This has led to unused production assets and made the investment climate difficult for more advanced technologies (European Commission, 2017b).

Secondly, the regime needs to encourage and incentivise good practice and innovation in sustainable biomass supply, given the need for a significant expansion if the 2DS is to be achieved, and not to unnecessarily close off options which could, when carefully managed, provide significant sources of sustainable bioenergy. Such a system would need to acknowledge that sustainability impacts of particular bioenergy chains are context-specific and complex, and that through R&D and experience it is possible to significantly improve the performance of individual chains, given appropriate regulatory signals or incentives.

Such a system needs to have the following features:

- Be based on the GHG performance related to the use of specific feedstocks and processes, rather than being based on lists of feedstocks and or processes.
- Signal the need for continuous improvement (for example, by gradually improving GHG emission performance).
- Build on and integrate with wider efforts to manage sustainability of the bioeconomy and the sustainability measures being taken across broader sectors, such as waste management, forestry, and sustainable agriculture and land management.
- Recognise regional and sectoral differences relating to the supply opportunities, risks and the quality of governance. For example, land ownership can vary significantly by region and country.
- Be increasingly based on real-life data and experience, with feedback into best practice and regulation.
- Be sufficiently simple and entailing low costs in order not to penalise genuinely low-carbon biomass relative to fossil fuels, or disadvantage numerous smaller production units relative to larger-scale producers.

It should also be recognised that sustainability governance will learn and adapt with experience and once large-scale deployment occurs. Only then can the real risks and uncertainties be appreciated. Real-world experience will influence regulation and allow informed decisions about what may be possible in the future, based on real evidence on impacts and on behaviour of key players. Good practice in this area is demonstrated by California's LCFS, which has applied ILUC emissions factors to fuels while also encouraging ongoing reassessment of these alongside key stakeholders and according to new scientific findings. For example, initial ILUC values in the LCFS for crop-based biofuels have in some cases been revised in the light of new evidence.

Longer-term deployment: Mobilising supply

Longer-term deployment will depend heavily on the successful development and commercialisation of the technologies discussed in Table 1, and fostered by a supportive policy and regulatory enabling environment. It will also require the commercialisation and large-scale deployment of the less mature technologies discussed in Section 3.

To complement this technology deployment, it will be necessary to mobilise the supply chains needed to deliver some 145 EJ of sustainable bioenergy supply needed for the 2DS and B2DS. This will be extremely challenging and raises important questions about how this supply can best be mobilised and which needs to come first – a stable demand or a stable supply.

Evidence from recent experience shows that once strong demand is established, a supply chain can be put in place to supply it. For example, the supply chain for corn residues, such as corn stover, established to support large-scale use in the production of cellulosic ethanol at the DuPont plant in Iowa uses 375 000 tonnes of corn stover supplied by 500 farmers within a 50 kilometre radius of the plant (DuPont, 2016).

Developing these supply chains has not been easy, and the end users have had to make enormous efforts to establish them and to invest in the systems needed to transport and process the fuels. Once a more diversified user base has been established, it is possible that the challenge of supply will be taken up more strongly by players in the traditional bio-industries (the agricultural and forestry industries, for example) and a more liquid supply chain infrastructure will develop.

However, for these markets for sustainable bioenergy feedstocks to grow, a clear market framework, combined with effective sustainability criteria, is needed to give confidence that a sufficiently sized and stable market will endure so as to justify the investment in supply chain development.

International trade

There are advantages to be gained in using locally sourced sustainable bioenergy – with reduced transport and logistical costs and associated emissions, and with the economic benefits associated with production kept close to the point of use. However, the large-scale deployment that would be required to support the level of bioenergy ambition in the 2DS would require an increasing international trade in biomass products.

In 2016, 16.5 million tonnes of wood pellets (around 0.3 EJ) were traded internationally. Key wood pellet production countries include the United States (mainly in the south east), Canada and Europe. Europe is the principal demand centre, along with growing consumption in Japan and Korea (IEA, 2017c). This international trade is likely to continue to grow (IEA Bioenergy, 2017e).

International trade will need to play a key role if the levels of deployment envisaged within the 2DS are to be achieved. An analysis of potential future trade patterns broadly consistent with the 2DS indicates that by 2030, Western Europe, India, China and Japan become major importers of bioenergy, while Canada, South America, Central Africa and the Russian Federation could become major exporters.

Developing the infrastructure for such levels of trade will be challenging and unlikely to happen unless there is strong confidence that the policy frameworks in importing countries will lead to long-term stable markets. Further analysis of regional production and use patterns and of likely barriers to trade will be important to facilitate such market developments. It will also be important to align technical standards for biomass intermediates so as to facilitate trade and avoid infrastructure compatibility problems. Other trade barriers (such as import tariffs) will need to be removed if in place, and the need for such international trade also has implications for the sustainability governance regimes discussed above, which will have to be internationally recognised.

Sustainable feedstock supply: Key actions

This roadmap recommends the following key actions.

Table 9: Sustainable feedstock: Key actions and milestones

Action	Timing
Continue efforts to understand the role of forests as a carbon sink and interactions with sustainable forestry management and bioenergy.	2017-25
Continue efforts to understand interactions between bioenergy and land use, including work to establish real impacts of large-scale bioenergy deployment.	2017-25
Improve ongoing biomass potential analysis with particular emphasis on detailed regional and national studies, including the potential associated with low productivity agricultural land.	2017-22
Promote efforts to improve overall agricultural yields and production efficiency, especially in developing economies, through dissemination of best practice via international development initiatives.	Ongoing
Develop and demonstrate at scale co-production of energy alongside food and other agricultural products via agro-forestry and intercropping.	2017-30
Continue research on likely impacts of climate change on food production and availability of biomass for energy purposes.	
Develop, trial and produce energy crops with higher yields, such as "energy cane".	2017-25
Continue work to evaluate the potential of novel energy feedstocks such as algae and aquatic biomass.	2017-40
Develop and implement internationally recognised sustainability governance systems that cover all bioproducts, and which support sustainability best practice and stimulate innovation.	2017-25

6. Policy and finance issues

Policy requirements for increased bioenergy deployment

An appropriate policy and regulatory environment is needed to support the expansion of bioenergy, even for technologies which are mature. The features that are desirable to provide a supportive enabling framework for low-carbon technologies in general, and which can promote deployment at low cost, have been identified and apply equally to the range of bioenergy options (Barnsley et al., 2015).

These include measures which "level the playing field" as far as bioenergy or other renewable and low-carbon technologies are concerned. Measures which help with this include:

- Reduction or abolition of subsidies for the production and use of fossil fuels.
- Wider introduction and improvement of ways of pricing-in the environmental externalities caused by fossil fuel use, through a carbon pricing regime. To be effective this needs to cover all energy sectors and scales of operation and reflect the real societal cost of carbon emissions.
- Systematic removal of barriers to low-carbon energy production in the taxation and wider regulatory system, which OECD studies have shown to be major barriers slowing down low-carbon technology deployment (OECD, 2015). These include unnecessarily strict state aid regulations, which can unnecessarily prevent measures aimed at favouring low-carbon technologies, but which have no impact on international competitiveness.

While these measures are necessary to enable low-carbon technologies, including bioenergy, to prosper, they are not sufficient on their own. This is because bioenergy systems are generally more capital intensive than fossil fuel systems. The costs of energy delivered are not subject to global fossil fuel price fluctuations, but they are very sensitive to the cost of capital. This in turn is highly influenced by the extent to which investors have confidence that a stable income can be expected, and this depends strongly on perceived policy and regulatory risk. A favourable enabling policy environment for bioenergy, as for other renewable technologies, needs to have the following features:

- A long-term stable policy and regulatory framework that provides certainty about the market for an extended period (10 to 15 years), sufficient to justify investment in a series of production plants. For example, ambitious national transport sector ambitions or targets for emissions reduction, shares of renewable energy or, as in Sweden, phasing out fossil fuels provide a favourable investment climate. These frameworks can include subtargets for the road freight, marine and aviation sectors, which are more difficult to decarbonise.
- Clear and specific targets for the use of sustainable bioenergy as part of a national strategy, plan or roadmap and which cover transport fuels, heat and electricity generation.
- Ensuring that bioenergy producers have access to the relevant markets (e.g. to be able to legally produce and sell bioelectricity and to access the grid under reasonable conditions, or to access the transport fuel market).
- Appropriate and sufficiently compensating mechanisms to reward low-carbon energy production, and which provide sufficient revenue visibility to attract finance at competitive terms that will be available (such as long-term PPAs for power generation or other long-term off-take agreements).
- Measures to avoid non-financial barriers to deployment, such as appropriate and clear regulations relating to planning, environmental permitting and energy market access.

For bioenergy technologies, particular issues include the need:

- To have stringent but stable sustainability governance regimes, which insist on proven and globally accepted good bioenergy practices and policy instruments to promote them, as discussed in Section 5.
- To put in place transparent and appropriate environmental safeguards (such as emissions standards).
- To monetise the enhanced flexibility that certain bioelectricity options offer to facilitate the market penetration of variable wind and solar technologies as part of the development of a flexible electricity infrastructure.

- To recognise the social benefits of bioenergy, such as rural employment and income, and the contribution that bioenergy can make to energy security and diversity.
- For appropriate regulations relating to the integration of bioenergy (for example, the regulations and standards that apply to biofuel/gasoline or diesel blends).

National bioenergy strategies and roadmaps

One key element in such a framework is the establishment of a national or regional bioenergy strategy or roadmap that identifies key bioenergy development opportunities and the steps needed to bring these to fruition. Such a bioenergy strategy can mobilise the necessary stakeholders to identify specific opportunities based on available resources and sustainability and strategic energy needs. However, its preparation is a complex undertaking. It requires close coordination between a number of different government and regulatory bodies, and engagement of a wide range of stakeholders. The IEA and the FAO have recently published the *How2Guide for Bioenergy*, which provides a framework to help with the planning and implementation of such a national strategy or roadmap (IEA and FAO, 2017).

Supportive policies

A number of different policy and regulatory measures can be applied to mitigate the financial and economic barriers to bioenergy development, reflecting considerable experience of these measures in different national situations (IEA and FAO, 2017). These can be considered under two main headings: measures to mandate an increasing share of bioenergy in specific sectors; and financial support measures to provide adequate financial returns to investors while promoting low-cost energy production. In addition governments can play an important role in providing clear information about the rationale behind their bioenergy policies so as to explain the benefits and improve public perception of bioenergy.

The following paragraphs provide a summary and examples of the main measures used in the transport, electricity and heat sectors.[15]

Transport

Biofuel mandates are the most-used means of introducing biofuels in the transport sector. Many countries have introduced such mandates, often with separate mandates for bioethanol blends into gasoline and for biodiesel into the diesel pool, and such mandates are being expanded and increased. Malaysia and Indonesia increased their biodiesel blending requirements, and India set goals for bioethanol and biodiesel (IEA, 2017c).

To ensure compliance with the blending mandate, it is necessary to establish a compliance regime. Where the transport fuel market is not based on a monopoly or state supply, the mandates are placed on fuel suppliers and often linked to a tradeable certificate scheme. The different suppliers must gain or buy sufficient certificates to demonstrate their compliance or face financial penalties.

Policies aimed at introducing biofuels should be part of an integrated approach to reducing emissions from the transport sector, which also transitions to electrification and other complementary low-carbon measures. In more advanced markets, systems such as low-carbon fuel standards are being increasingly used, allowing a technology-neutral approach to decarbonisation, including biofuels, and favouring those that offer the deepest decarbonisation for the least cost (see Box 9).

15. Further details of the policies used in different countries and their relative merits can be found in IEA and FAO (2017).

Box 9: Low-carbon fuel standards

Policy frameworks that stipulate defined reductions in the average life-cycle carbon intensity of transport fuels over a given timescale have been introduced in a number of countries and regions (Table 10).* These technology-neutral approaches offer a level playing field by stimulating demand for transport fuels that can offer the highest levels of GHG emissions reduction relative to their cost. A variety of fuels capable of delivering emissions reduction relative to fossil gasoline and diesel are utilised in such frameworks, including biofuel (e.g. ethanol, biodiesel, HVO, biomethane) and non-biofuel options (e.g. natural gas and electricity).

Table 10: Carbon intensity-based policy frameworks

Policy name	Country or region	Baseline year	Target
Low Carbon Fuel Standard	State of California, the United States	2010	A 10% reduction in the carbon intensity of the transport fuel pool by 2020.
Low Carbon Fuel Standard	State of Oregon, the United States	2015	Reduce the average transport fuel carbon intensity by 10% by 2025.
Low Carbon Fuel Standard	Province of British Columbia, Canada	2010	Progressively decrease the average carbon intensity of transport fuels supplied to achieve a 10% reduction in 2020.
Federal Clean Fuel Standard**	Canada	2005	Overall target 30 Mt of annual GHG emissions reduction by 2030.
Climate Protection Quota	Germany	2010	A 6% reduction in GHG emissions from mineral oil industry products.
Fuel Quality Directive	European Union	2010	A reduction in the average GHG intensity of vehicle fuels of 6% by 2020.

Notes: Mt = million tonnes; ** Canada's Federal Clean Fuel Standard is currently in development; only final year targets are shown, although many of these frameworks also include intermediate targets to progressively reduce GHG emissions over time.

These policy frameworks can drive innovation to reduce emissions from biofuels production. For example, the introduction of the Climate Protection Quota (CPQ) in Germany has resulted in greater emissions reduction from the biofuels used for compliance. This is also highlighted within California's LCFS, where despite a relatively steady volume of ethanol used for compliance since 2011, the number of emissions reduction credits issued for the fuel has more than tripled (CARB, 2017) (Figure 23).***

As GHG emission reductions required by these policies tighten over time, market prospects should improve for those fuels that can offer the deepest decarbonisation. This was demonstrated in California's LCFS, where the tightening of the standard in 2016 to require a 2% reduction in carbon intensity resulted in increased biomethane, waste and residue HVO and electricity being used for compliance. Increased demand for biofuels able to offer very high levels of GHG emissions reduction favours the use of waste and residue feedstocks. In 2016, almost all emissions reduction credits for biodiesel and HVO in California's LCFS were produced from waste and residue feedstocks, such as tallow, fish oil and used cooking oil (CARB, 2017).

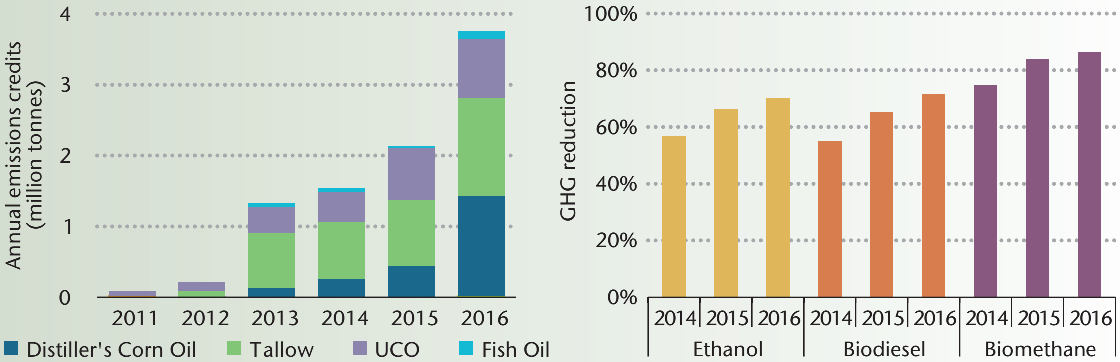
* The average life-cycle carbon intensity the GHG emissions produced from a fuel on a life-cycle basis. For example, complete fuel production pathway encompasses GHG emissions from raw material extraction or recovery, feedstock cultivation, fuel production, transport, processing and consumption.

*** One credit is awarded per tonne of emissions avoided, measured in CO_2-equivalent.

Box 9: Low-carbon fuel standards (continued)

Where decarbonisation over a short- to medium-term timescale is the principal policy objective, carbon intensity-based policy frameworks are an effective solution, since the fuels used for compliance are determined by the ratio of costs to emissions reduction offered relative to other means of decarbonisation. However, for novel advanced biofuels that possess significant longer-term decarbonisation potential, but are currently less technically mature and therefore entail high investment and production costs, a dedicated quota to provide guaranteed demand volumes may still be necessary to secure industry investment and support the initial market growth required to deliver longer-term potential.

Figure 23: Annual emission credits for waste and residue biodiesel and HVO production in California LCFS, 2011-16 (left), and GHG emissions reduction from selected biofuels under Germany's CPQ, 201516



Note: UCO = used cooking oil.

Sources: CARB (2017), Data Dashboard; F.O. Lichts (2017), "*Germany – GHG savings of biofuels continue to rise.*"

Such mandates are also increasingly linked to sustainability governance programmes that aim to ensure that only biofuels which meet strict sustainability standards can qualify under the obligations (see Section 5). Policies to expand flexible-fuel heavy-duty vehicle fleets and biofuel distribution infrastructure also support market growth.

Electricity

In the electricity sector, supportive policies can include mandatory targets for electricity generated from bioenergy (usually as part of a wider effort to promote renewable energy) and quotas or obligations on industry to provide a share of electricity form bioenergy. In the United States this has often taken the form of a renewable portfolio standard, while in other countries an obligation has been imposed on the utilities (e.g. the Renewables Obligation in the United Kingdom).

These measures are often complemented by measures that provide financial support to generators, such as long-term PPAs (often awarded through competition), feed-in tariffs (FITs) and the use of tradeable green certificates. The optimum measures depend on many factors, which include the scale of the technologies likely to be deployed and the maturity of the market in a given country (IEA, 2015). For large-scale projects, providing long-term PPAs through a competitive process is increasingly seen as the most effective way to promote low-cost deployment, while for smaller projects providing standard PPAs in the form of FITs may be the most effective route. Given higher generation costs than VRE technologies in many cases, the design of auctions that takes account of bioenergy's dispatchability and ability to offer flexible generation and wider socio-econmic benefits, is likely to be key to deployment prospects where such mechanisms are used to award support for renewable electricity. These can be backed up by measures which reduce capital costs (such as capital grants and subsidies), reduce financing costs (soft loans), and provide tax relief.

Heat

To date, far fewer countries have introduced policy measures designed to promote deployment of renewable heat technologies in general, and of bioenergy for heating in particular, than have supported bioelectricity or biofuels. By the end of 2016 it was estimated that 29 countries had supportive heat policy measures in place (REN21, 2017). These include mandates insisting that a certain proportion of heat comes from renewable sources.

Measures also include financial incentives, such as:

- Carbon taxes. Sweden has seen the widespread adoption of biomass fuels in district heating systems, replacing coal and driven principally by a carbon tax.
- Capital grants, widely used to encourage uptake of biomass systems in Europe (e.g. in Austria, Finland and Germany), in some US states and in provinces in Canada.
- Heat FITs (e.g. in the United Kingdom, where the Renewable Heat Incentive programme includes support for biomass boilers and biomethane injected into the gas grid).

The production of heat alongside electricity is often encouraged within schemes designed to promote biomass power generation, by providing additional incentives or by excluding heat-only projects. Such mandates are sometimes complemented by schemes that encourage best practice in installation by insisting that the heating systems and the installers meet quality standards via a certification scheme. There are also requirements that the fuels meet sustainability standards.

The need for capacity building

As discussed earlier, widespread deployment of bioenergy technologies is currently concentrated in relatively few countries and regions, with potential for deployment in many more regions. This more diverse deployment will only happen when the necessary legal and regulatory framework has been put in place in more countries and is backed up by institutions that can carry out the regulatory functions efficiently – for example, to organise the necessary contract frameworks such as fair and transparent auctions for electricity capacity, to manage environmental permitting and to ensure sustainability governance. Without such policy and regulatory environments, it is unlikely that the financing necessary for deployment will be available and the risk arises that projects which do not meet best practice in sustainability terms could be promoted.

Given the complex nature of some of the issues, it is unlikely that countries, especially those developing their economies, will be able to put such frameworks in place without capacity-building assistance. International organisations have an important role, especially the international development agencies, development banks and scientific bodies, to assist in such capacity-building exercises. However, at present bioenergy is not given much priority in development aid programmes. If genuinely sustainable bioenergy is to develop more rapidly, then international agencies will need to give higher priority to these topics.

One good example of is the role of GBEP, who are working with the Economic Community of West African States (ECOWAS) countries to develop the capacity necessary to be able to apply the GBEP Sustainability Indicators in the region (ECREE, 2017).

Policy support for new technologies

The general policy principles discussed above apply to both established and newly commercialising technologies that will be needed to deliver the 2DS vision for bioenergy. But this scenario depends heavily on the new technologies, and appropriate policy and regulatory measures will be needed to help them to mature and avoid the "valley of death" between prototype or pilot plant operation and full commercial deployment.

Significant barriers stand in the way of the investment needed to demonstrate the necessary new technologies at scale and to bring costs down. These include the technical risks associated with scaling up to full-size commercial plants (for example, large-scale cellulosic biomass-to-ethanol plants that have initially encountered problems scaling up). In addition, commercial and financial barriers result from early plants not having benefited from technology learning, causing their outputs to be more expensive than both their fossil fuel and other renewable energy competitors, and other more established bioenergy technologies.

This means that technology-neutral measures (such as an increased price for carbon emissions), while useful by discriminating against fossil options, are unlikely to promote the commercialisation of the technologies needed to meet longer-term needs, and on their own may lock in less desirable technology choices (e.g. established rather than novel advanced biofuels).

Bioenergy has specific characteristics that make a number of these barriers more significant than for other new sustainable energy technologies. For example, most bioenergy technologies are not modular (as they are for solar PV or wind), and so a relatively larger investment is needed to demonstrate commercial-scale bioenergy and biofuel plants. The sums involved are beyond the balance sheet capabilities of many energy companies and also beyond the budget of many national RD&D programmes.

Deploying novel advanced biofuels is one of the most significant challenges for bioenergy in the 2DS. Additional measures are needed to promote the development of these fuels and processes, since these will not initially be able to compete in a "technology-neutral" policy environment. These can include:

- Mandatory obligations for deployment of sustainable novel fuels and for specific subcategories that are at different stages of technical and market maturity.
- Appropriate and dedicated financial mechanisms and instruments to facilitate technological development and subsequent market deployment. These can include loan guarantees, and ways of bridging the initial cost differences between the novel energy sources and more established ones (fossil or other bioenergy).
- Support for RD&D focused on priorities identified in previous sections.

The mandatory obligations need to be accompanied by financial measures that provide investors in early-stage plants confidence that they can secure a stable and sufficient income stream to run the plants and recover their investments. The output from the plants will initially be more expensive than both fossil-based energy and that from existing bioenergy production. As deployment proceeds, then the cost gap can be reduced through a number of factors: technical improvements brought about by R&D, operational learning, scale-up effects and through greater investor confidence, which reduces the financing costs. The cost differential will have to be met either by consumers or public sources, until the point where costs converge (see Box 11). When in place, carbon pricing initiatives also help close the cost differential. Without adequate financial support, it is unlikely that the necessary new technologies will be deployed.

Box 10: How much will commercialising novel advanced biofuels cost?

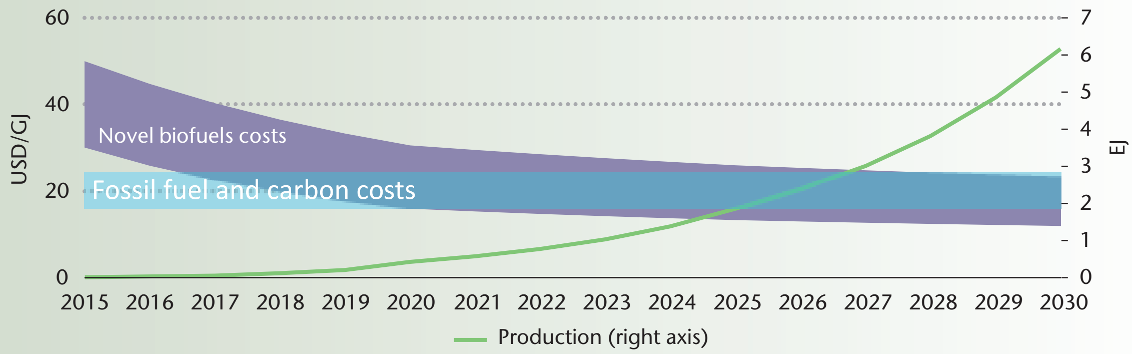
The current costs of novel transport biofuels exceed those of fossil fuels and of those of conventional biofuels by a significant margin, as shown in Section 4, with different new fuels having different price points depending on their maturity, feedstocks and the products that they provide.

In order to provide a ball-park estimate of the overall costs of commercialising these technologies, a range of costs of USD 30-50/GJ has been taken as a representative range of current costs. This compares to a price for fossil-based diesel, gasoline and jet kerosene of USD 11-12/GJ at an oil price of USD 50/barrel. If it is assumed that deployment of novel advanced biofuels accelerates rapidly so as to be in line with the 2DS trajectory, then by 2030 these fuels would provide around 4% of

Box 10: How much will commercialising novel advanced biofuels cost? (continued)

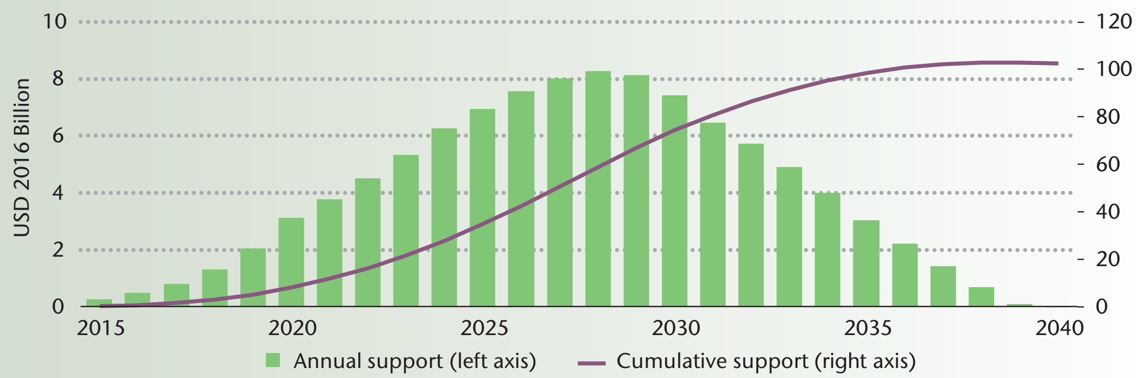
global transport fuel use (6 EJ). If learning rates of between 15% and 20% are applied to the capital and operating cost elements (taking a cautionary view that there is no reduction in the cost of the feedstock), then by 2030 the costs would have reduced significantly, as shown in Figure 24. This also shows fossil fuel equivalent costs based on a range of fossil fuel costs (USD 50-60/barrel) and CO_2 costs (USD 0-100/tonne CO_2). By 2030, biofuel costs approach those of their fossil fuel equivalents.

Figure 24: Cost reduction trajectory for novel advanced biofuels



If, in order to facilitate the deployment of the capacity necessary to "buy down" the costs in this way, developers were offered fuel purchase offtake agreements at the cost prevailing in the year of construction of the plants, in a central case support costs would build up annually, reaching USD 8.3 billion/year in 2029, and then declining until 2040. The total support cost would be some USD 100 billion. (Figure 25). This sum, while substantial, represents a very small fraction of the total fossil fuel costs from here to 2040, which would total some USD 30 trillion. The support costs for advanced biofuels under these assumptions would amount to less than 0.5% of fossil fuel costs over this period.

Figure 25: Evolution of support costs for novel advanced biofuels



Policy implications for going beyond the 2DS

More ambitious deployment policies associated with the B2DS goals mean first of all that the measures associated with the 2DS must be accelerated. This implies a very high level of ambition and financial commitments from governments and industry, since that the policy initiatives required above must be introduced earlier and more widely to achieve faster progress in both existing and new technology deployment.

Strong policy measures will also be needed to drive the other significant difference between the 2DS and the B2DS – the earlier and much more extensive uptake of BECCS. One element of this could be a carbon price, which can provide an incentive for deployment and counter the higher capital and operating costs of BECCS plants. Carbon pricing mechanisms will need to reward the "double carbon benefits" of BECCS, taking account of both the low-carbon production of energy and the additional carbon saved through CCS.

In addition, technology-specific measures will be needed in order to promote specifically BECCS and BECCU technologies. Apart from measures to support studies of optimised systems and early examples of the technologies in practice, longer-term measures could include limits on emissions from biomass power plants and other similar sources of CO_2 emissions from bioenergy. There will also need to be an early start to CCS infrastructure planning, including transport and storage, and this will need to specifically take into account the potential for BECCS.

Early action to stimulate the uptake of BECCS will be essential to stimulate the interest and investment necessary to demonstrate and deploy the technologies. This will require enormous ambition and commitment from governments all around the world. Without such commitment and ambition, the prospects for delivering a very low-carbon scenario such as B2DS will be slim.

Finance

How much finance will be needed?

Making the transition to a low-carbon energy system will require massive investment. In *ETP 2017*, the total investment needed between now and 2060 to deliver the 2DS (including investments in technology and infrastructure) amounts to around USD 900 trillion; reaching the B2DS would require over USD 950 trillion.

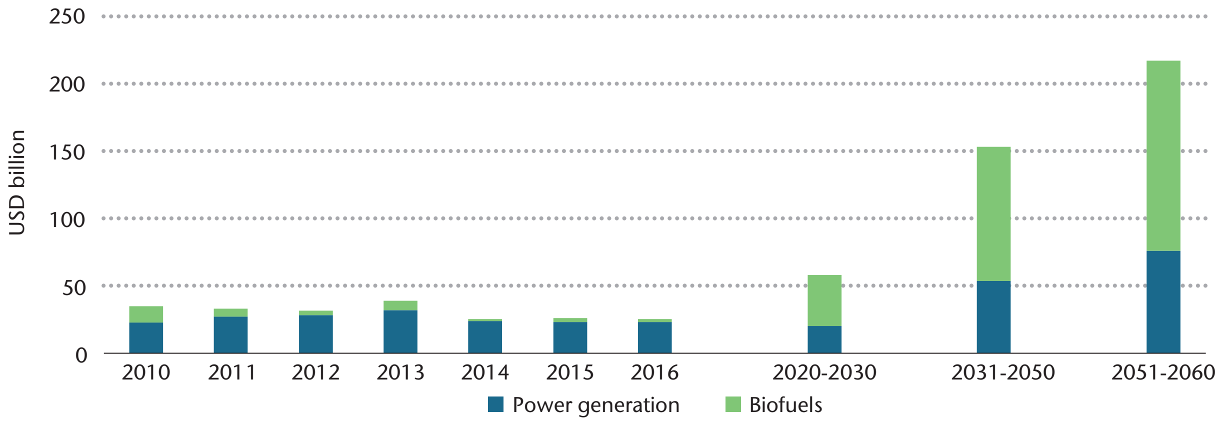
The total investment in bioenergy needed to deliver the 2DS is estimated at USD 6.1 trillion, with some USD 1.6 trillion in bioelectricity systems and USD 4.5 trillion in transport biofuels production. A breakdown of investment by period is shown in Table 11. In the B2DS the figure rises to USD 7.8 trillion (USD 3.2 trillion and USD 4.6 trillion for electricity and biofuels respectively).

Table 11: Cumulative bioenergy investments, 2017-60 (trillion USD, 2015)

Scenario	*2017-30*	*2031-50*	*2051-60*
2DS	0.8	3.1	2.2
B2DS	1.1	4.2	2.5

Assessments of recent levels of annual investment in bioelectricity and biofuels are between USD 25 billion and USD 38 billion per year (Figure 26) (IEA, 2017g). This compares to the total annual investment in renewable electricity technologies of USD 297 billion, and total energy sector investment of USD 1.7 trillion. In the 2DS, annual levels of investment in bioenergy would need to almost double to around USD 60 billion/year in coming years, and further increase to reach around USD 200 billion/year towards the end of the scenario periods.

Figure 26: Annual bioenergy investments, 2010-16 and investment needed in the 2DS



Barriers to finance

The principal barriers to investment in bioenergy technologies relate to the risks as perceived by potential developers and, in particular, by other investors. Higher levels of risk can prevent access to finance or make raise the cost of capital, with different classes of investors having different appetites for risk or reward.

Financing for clean energy projects is a competitive environment. It is therefore important to consider what risks investors perceive and how these differ for bioenergy projects as opposed to other renewable technologies. It is also fundamental to consider how any additional risks can be mitigated or managed. Governments can influence this risk perception and take measures to facilitate finance and to offset particular risks related to bioenergy projects. Risks can be categorised as those related to the national situation (for example, country and currency risks), which apply to all investments, and those more specifically for bioenergy projects (e.g. technical, contractual and policy-related risks).

Technology risks for bioenergy projects can primarily be reduced by demonstration plants and validation programmes, and can later increasingly be mitigated by using tried and tested technologies, supplied by experienced contractors. Nonetheless, even for projects involving proven technologies, there are still risks during the early stages of projects. The feedstock associated with any particular project can vary and so the interaction between the feedstock and equipment systems can be difficult. This may necessitate time for fine-tuning before operation can reach target utilisation and performance levels. Time and finance need to be set aside to cope with such problems if and when they arise.

Contractual risks include those associated with the sale of the products – electricity, heat and transport fuels, and also unlike other renewable technologies, the supply of feedstocks and fuels. Offtake risk can be reduced through long-term purchase agreements for the product – for example, through power purchase and biofuel offtake agreements – so long as the countersigning party is credit worthy. Where there are multiple products (electricity, heat, fuels, other bioproducts etc.), then several such supply contracts may need to be put in place. In some cases, for example where the counterparty is a specially established arms-length body responsible for contracting for PPAs, it is necessary for its credit worthiness to be assured, for example via a government guarantee, before the risk is judged acceptable by investors.

The additional risks associated with the need to provide for the long-term supply of fuels or feedstock at an affordable cost and which meet appropriate sustainability criteria, are a significant complicating factor for financing bioenergy projects. This is especially because, at present, the markets for sustainable biomass feedstocks have limited liquidity. The risks can be mitigated where there is a dedicated supply and where the project developers either invest in the upstream supply, or where fuel providers are involved in the project as investors. However, this increases the complexity and cost of project preparation and development. Other means to increase market liquidity include common fuel quality standards, trading platforms to allow hedging future price risk, and fuel exchanges to increase price transparency. However, the extra complexities associated with securing stable feedstock supply often lead to difficulties in financing projects, or to risk premiums. For example, fuel price escalation which occurred after the construction of biomass electricity plants in countries such as India and China has reduced confidence in further market development.

Because of the perceived higher technical, policy and contractual risks, the very low financing rates secured for certain other renewable technologies such as wind or solar PV (where the technology, policy and contractual risks are judged to be low when long-term offtake agreements are available) may never be achieved for biomass projects.

Policy risk in particular is an important consideration. The policy environment can play a vital part in either creating or undermining investor confidence. A stable and supportive policy and regulatory framework, as discussed above, is essential. Creating this enabling framework is complex and time consuming and so requires significant legislative and regulatory capability in government bodies and regulators. If bioenergy deployment is to succeed in more countries (including many emerging and developing economies with significant opportunity to produce and use sustainable bioenergy and great need for clean energy sources), then significant international effort will be needed to help develop the necessary capacity, based on best practice achieved elsewhere. The role of development banks and aid agencies will therefore be crucial.

Development banks can play a critical role in facilitating finance for bioenergy projects, particularly in new markets such as in emerging and developing economies, which will be important if the technologies are to be more widely deployed. Alongside development agencies, they can help build the institutional capacity necessary to create a context in which projects become bankable, and by providing finance for early projects can catalyse investment from local and international banks. However, bioenergy projects currently play only a minor role in the investment portfolio of development banks and in the programmes of aid agencies. Further work to understand how sustainable bioenergy projects can be given more prominence in such programmes is necessary to encourage their more active participation.

Policy and finance: Key actions

This roadmap recommends the following key actions.

Table 12: Policy and finance: Key actions and milestones

Action	Timing
Phase out inefficient fossil fuel subsidies and introduce CO_2 emission pricing schemes.	2017-25
Create a stable, long-term policy framework for bioenergy, to increase investor confidence and allow for sustainable bioenergy production.	2017-22
Implement sustainability governance frameworks based on GHG performance.	2022
Identify and remove unnecessary administrative barriers to bioenergy deployment, consistent with sustainability objectives.	2017-22
Establish LCFS approaches, providing technology-neutral support but ensuring significant benefits over fossil fuels and favouring those which offer the deepest decarbonisation for the least cost.	2017-25
Establish appropriate and dedicated financial mechanisms and instruments for advanced low-carbon bioenergy systems that facilitate technological development and market deployment.	2017-22
Provide sufficient support (e.g. through grants and loan guarantees) that addresses the high investment risks related to commercial-scale advanced, low-carbon biofuel plants.	2017-30
Analyse and introduce appropriate accounting in CO_2 pricing schemes for negative emissions related to CCS on biomass-based installations.	2025-40

Table 12: Policy and finance: Key actions and milestones (continued)

Action	Timing
Increase the number of national and regional roadmaps, strategies and sustainability regimes for bioenergy, especially in countries with significant resource where these are not in place.	2017-30
Enhance sustainable bioenergy capacity building activities within portfolios of international aid and development bank activities.	2017-25
Increase share of development bank finance directed to advanced, low-carbon bioenergy projects.	2017-25
Increase total finance for advanced, low-carbon bioenergy projects so as to reach USD 50 billion/year by 2030.	2017-30

7. Bioenergy: Deployment

The key indicators for monitoring bioenergy deployment progress are shown in Table 13. These should include the overall contribution of bioenergy to final energy consumption, along with the particular contributions of bioenergy feedstocks in the various subsectors. An indicator that checks whether geographic diversity in deployment is occurring is also included, given its importance.

Table 13: Deployment: Key indicators

Indicator	*Unit*
Modern bioenergy in final energy consumption	EJ and % of TFEC
Number of countries with >5% modern, sustainable bioenergy in their final energy consumption	
Gross electricity generation from sustainable biomass	TWh
Modern bioenergy for buildings heating and cooling	EJ
Bioenergy used in industry	EJ
Total biofuels used as transport fuels	EJ
Advanced biofuels used in transport	EJ

Note: TFEC = total final energy consumption.

Figure 27: 2DS deployment trajectories: Modern bioenergy in final energy consumption (left); gross bioelectricity generation (right)

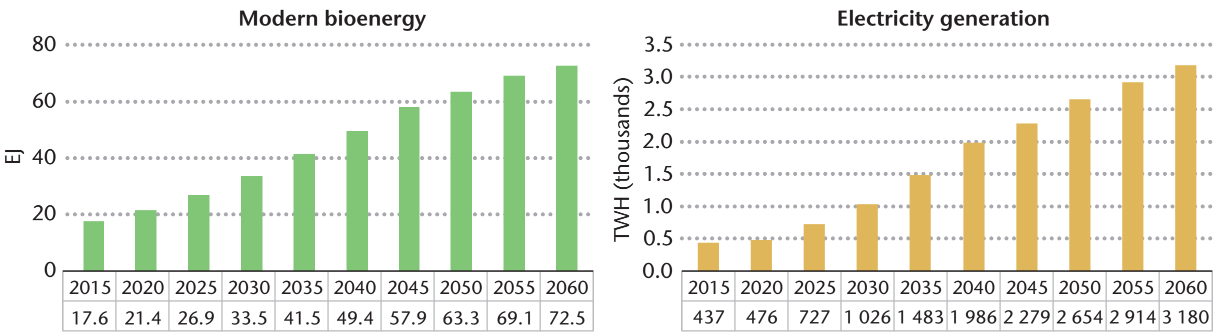
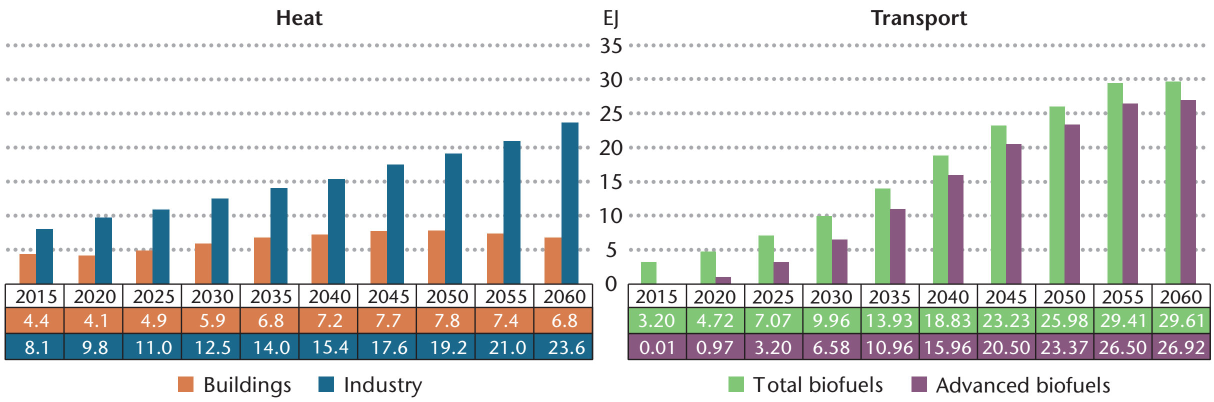


Figure 28: 2DS deployment trajectories: Modern bioenergy in final energy demand in buildings (left); Bioenergy in Transport (right)



The deployment trajectories that would be consistent with the 2DS are shown in Figures 27 and 28. These reflect the ambitious deployment objectives associated with the 2DS. The scenario shows that a substantial acceleration in deployment is needed immediately. If take-off is slower, this implies even faster deployment later on, which would be challenging. Early action is therefore important.

8. International collaboration

To accelerate the development and deployment of innovative energy technologies, stakeholders from both the public and private sector can benefit from sharing knowledge, working collaboratively and, where appropriate, pooling resources to deliver integrated, cost-effective solutions to common challenges.

The IEA works closely with the principal existing international collaborations and initiatives which are working to improve the understanding of the many issues involved in bioenergy and promoting the sustainable expansion of the sector. These are summarised below.

IEA Bioenergy TCP

The IEA Bioenergy TCP is one of the best-established of the 38 IEA TCPs, having been initiated in 1978. It has 23 Contracting Parties, including many IEA member countries plus the European Commission, Brazil, Croatia and South Africa. Its work focuses on the main RD&D challenges associated with bioenergy and is organised under ten active "tasks". In addition, a number of projects are organised to deal with cross-cutting issues or to respond to particular issues of interest to participant members. For example, a project is currently ongoing in relation to bioenergy sustainability, and special projects have been established to improve understanding of future market change-driven deployment of BECCS and BECCU technologies. The TCP produces a significant number of authoritative publications each year, as well as organising workshops and conferences.[16] The IEA Bioenergy TCP has been a cooperating partner in the production of this Technology Roadmap, and intends to adopt its conclusions and priorities for RD&D in its strategy.

Further scope exists to enhance the leading role of the IEA Bioenergy TCP by expanding its membership and its work programme, and serving as the nucleus around which other international efforts should develop, building on its strengths and avoiding duplication.

16. See www.ieabioenergy.com/.

Biofuture Platform

The Biofuture Platform is a government-led, multi-stakeholder initiative designed to promote international coordination on advanced low-carbon fuels and bioeconomy development.[17] Government members include Argentina, Brazil, Canada, China, Denmark, Egypt, Finland, France, India, Indonesia, Italy, Morocco, Mozambique, the Netherlands, Paraguay, the Philippines, Sweden, the United Kingdom and the United States. It is designed to complement the work of existing international institutions and initiatives (including the Clean Energy Ministerial, GBEP, IEA Bioenergy TCP, IRENA, Mission Innovation and SE4ALL), and to formulate ways to best address existing gaps.

Food and Agriculture Organization

The FAO focuses its bioenergy efforts on making bioenergy development sustainable by seeking to capture its potential benefits to rural development, climate and energy security. It promotes an integrated approach to address these links and both "food and fuel". This approach requires:

- An in-depth understanding of the situation and the related opportunities, risks, synergies and trade-offs.
- An enabling policy and institutional environment, with sound and flexible policies and effective means to implement them.
- Implementation of good practices by investors and producers in order to reduce risks and increase opportunitie, with appropriate policy instruments to promote these good practices.
- Proper impact monitoring, evaluation and response.

To promote this sound and integrated approach, FAO, in collaboration with partners, has developed the FAO Support Package to Decision-Making for Sustainable Bioenergy. This includes different elements that can be used independently or together at different stages within the decision-making and monitoring processes of bioenergy development.

17. See http://biofutureplatform.org/.

Global Bioenergy Partnership

The GBEP is an intergovernmental initiative that brings together 50 national governments and 26 international organisations.[18] It was established to implement the commitments taken by the Group of Eight major world economies (G8) in the 2005 Gleneagles Plan of Action to support "biomass and biofuels deployment, particularly in developing countries where biomass use is prevalent".

One important GBEP activity has been the development of a set of 24 indicators and related methodologies in order to facilitate the assessment and monitoring of bioenergy sustainability at a national level (FAO, 2011). These indicators, which are based on a series of relevant themes under the three pillars of sustainable development, address the production and use of liquid, solid and gaseous biofuels for heat and power and for transport. They are intended to inform policy makers about the environmental, social and economic sustainability aspects of the bioenergy sector in their country and guide them towards policies that foster sustainable development.

International Renewable Energy Agency

IRENA was founded in 2011, and is approaching universality with 151 member countries as of mid-2017.[19] IRENA is a hub for information on renewable energy of all kinds – wind, solar, hydro, geothermal, ocean and biomass energy. Its extensive bioenergy activities include estimation of sustainable biomass potential, bioenergy resource mapping, bioenergy statistics, and economic assessment of the costs of biofuel conversion technologies. It is working with partners to assess practical strategies for bioenergy scale-up.

Mission Innovation

The 23 governments that have joined Mission Innovation have each pledged to seek a doubling of their governmental and/or state-directed investment in clean energy R&D over five years and identified seven Innovation Challenges (ICs) – thematic areas for enhanced individual and collaborative innovation efforts.[20] The IC on Sustainable Biofuels aims to accelerate biofuels RD&D in order to achieve performance breakthroughs and cost reductions with the potential to substantially reduce GHG emissions. The objective is to develop ways to produce, at scale, widely affordable advanced biofuels for transport and industrial applications.

Sustainable Energy for All – Sustainable Bioenergy Accelerator and below50

Sustainable Energy for All (SE4All) is a multi-stakeholder partnership between governments, the private sector and civil society that was launched by the UN Secretary-General in 2011.[21] SE4ALL has three interlinked objectives to be achieved by 2030:

- Ensure universal access to modern energy services.
- Double the global rate of improvement in energy efficiency.
- Double the share of renewable energy in the global energy mix.

SE4ALL leverages the global leadership and convening power of the United Nations and the World Bank to assemble a network of leaders from all sectors of society into a partnership that can transform the world's energy sector and achieve Sustainable Development Goal 7.

In response to the UN Secretary-General's call for the private sector to partner with SE4ALL, the Sustainable Bioenergy Accelerator (SBA) was launched in May 2015, catalysed by Novozymes and with strong industry participation. Several types of bioenergy projects are being promoted, including: on-farm bioenergy production to boost agricultural yield and reduce post-harvest losses; distributed electricity production using sustainable biomass from forestry and agriculture co-products; electricity and fuels from MSW; ethanol for clean cooking and transport; and sustainable aviation biofuels.

18. See www.globalbioenergy.org/.

19. See www.irena.org.

20. See http://mission-innovation.net/our-work/innovation-challenges/sustainable-biofuels-challenge/.

21. See www.se4all.org.

The SE4ALL SBA, in partnership with World Business Council for Sustainable Development (WBCSD), have also created below50, a public-private partnership which is promoting the use of transport fuels that have less than 50% of the life-cycle GHG emissions of those of fossil fuels, and is successfully encouraging corporate commitment to the purchase of such fuels.

Future priorities

There is good co-operation amongst the main international organisations with an interest in bioenergy, and they have all contributed to the development of this roadmap. The IEA Bioenergy TCP is aiming to adopt this roadmap as the strategic document which underpins its workplan for the coming years. The roadmap is also being taken into account in the development of the mission statement being considered for adoption by the Biofuture Platform, and in developing the workplan for the Mission Innovation Bioenergy Challenge.

Further initiatives aiming to expand international collaboration on R&D should build on existing successful networks to avoid duplication and redundancy. Such efforts should extend to include a systematic development of best practices and technology, and policy case studies which can be widely promoted to encourage replication in more countries.

Current co-operation also needs to be extended to engage more strongly with the international development and financing organisations, to identify regional and local deployment opportunities that assist in the achievement of a number of Sustainable Development Goals, and to build the necessary technical and regulatory capacity so as to enable increased levels of investment.

Table 14: International co-operation: Key actions

Action	*Timing*
Expand international RD&D collaboration, making best use of national competencies and avoiding overlap within international co-operation initiatives.	2017-30
Enhance exchange of technology and deployment, including best practices for sustainable bioenergy production.	2017-30
Increase efforts aimed at institutional capacity building, especially related to sustainability governance systems.	2017-20
Build enhanced links with development agencies and international financial institutions to increase emphasis on bioenergy sustainability in their activities.	2017-25

9. Conclusions

Bioenergy is an important component of the comprehensive portfolio of measures and technologies required in the 2DS, providing 17% of the cumulative emission savings to 2060. It plays a particularly important role in sectors for which limited low-carbon alternatives exist or where it can complement other low-carbon options. These include long-haul transport (such as aviation, international shipping and heavy freight transport), in industry, and to provide low-carbon flexible generation in the power sector, complementing variable sources of renewables. In the B2DS, the role of BECCS becomes critical with a change in deployment patterns to maximise carbon benefits.

Although a range of technologies is commercially available, the current rate of deployment of bioenergy within electricity, heat and transport is well below that required under the 2DS, and four key action areas are identified to accelerate the deployment of sustainable bioenergy.

- **Accelerate deployment of proven bioenergy solutions:** Many deployment opportunities based on commercial technologies could be widely deployed in the short term, with immediate benefits in the form of CO_2 savings, energy security and complementary benefits, given appropriate policy and regulatory frameworks, as discussed in Section 7 and Annex 3. To accelerate this short-term deployment, an appropriate policy and regulatory environment (discussed in Section 6) is a prerequisite to enabling projects to be developed and financed. Putting such enabling environments in place, especially in emerging and developing economies, requires considerable institutional capacity; providing help in building this will be the key to short-term growth in a broader range of countries.

- **Enable the development of new bioenergy technologies:** Delivering the longer-term bioenergy deployment levels required by the 2DS will require a mix of mature bioenergy technologies and new technologies that are suited to the context and market roles that bioenergy will need to fulfil, especially sustainable and low-carbon biofuels for transport. Good progress has been made recently in developing and demonstrating some of these (e.g. waste and residue HVO, cellulosic ethanol, gasification and syngas conversion, and pyrolysis).

  However, supporting these technologies through the commercialisation stage will require specific policies to support their development and deployment including, for example, quotas for advanced bioenergy systems (RFS2, proposed changes to the RED post-2020 (RED2)), financial de-risking measures, continued support for RD&D and enhanced international cooperation in innovation.

- **Mobilise sustainable biomass feedstock supply:** Delivering the vision will require a fivefold increase in the supply of bioenergy feedstock (from around 23 EJ now to around 128 EJ by 2060). This will be challenging and will require the mobilisation of a range of biomass and waste resources. It is unlikely that wastes and residues alone can provide sufficient raw material, so other sources, such as from forestry management operations and agriculture, will be required.

  The likelihood of achieving this supply in a sustainable manner can be enhanced in three ways:

  - Through "no regrets measures" that can help optimise land and resource use (Section 5).
  - Through innovation to optimise the life-cycle carbon benefits from bioenergy and, for example, stimulate the production of energy crops with minimum pressure on land use (higher yields, co-production of food, biomaterials and energy, use of poor quality land, etc.).
  - Boosting the efficiency with which the carbon in bioresources is used. This involves the efficient use of biomass in integrated systems, where possible through the co-production of materials, fuels, electricity and heat in biorefineries. The bio-based carbon can also be efficiently used when linked to hydrogen produced from renewable sources, either during fuel production (e.g. during gasification) or in reusing biomass-based carbon emissions through BECCU.

  These measures will need to be accompanied by internationally recognised sustainability governance systems which ensure that bad practice is eliminated while at the same time providing a stable regulatory framework and incentivising continuous improvement in GHG performance.

- **Enhance international co-operation on bioenergy:** There is good co-operation amongst the main international organisations with an interest in bioenergy. Further international initiatives should build on existing networks, where successful, to avoid duplication and redundancy.

Current co-operation needs to be extended to engage international development, environmental and financing organisations so as to: identify regional and local deployment opportunities that assist in the achievement of a number of Sustainable Development Goals; and build the necessary technical and regulatory capacity to enable increased levels of investment in genuinely sustainable bioenergy, which needs to double to reach USD 60 billion per year in coming years and ultimately to some USD 200 billion per year towards the end of the scenario periods.

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Glossary

The terminology in this publication seeks to be consistent with the recent How2Guide for Bioenergy (IEA and FAO, 2017) and definitions might partly differ from those contained in other IEA publications. The FAO Unified Bioenergy Terminology provides an alternative, comprehensive repository of definitions for biomass-related terms used in FAO and other databases (FAO, 2004).

Advanced biofuels: sustainable fuels produced from non-food crop feedstocks, which are capable of delivering significant life-cycle GHG emissions savings compared with fossil fuel alternatives, and which do not directly compete with food and feed crops for agricultural land or cause adverse sustainability impacts.

Bioenergy: energy generated from the conversion of solid, liquid and gaseous products derived from biomass.

Bioeconomy: a set of economic activities related to the invention, development, production and use of biological products and/or processes in the conversion of biomass into renewable energy, materials and chemicals.

Biofuels: liquid fuels derived from biomass. They include ethanol, a liquid produced from fermenting any biomass type high in carbohydrates, and biodiesel, a diesel-equivalent processed fuel made from both vegetable oil and animal fats.

Biogas: a mixture of methane (CH_4) and carbon dioxide (CO_2) used as fuel and produced by bacterial degradation of organic matter or through gasification of biomass. Anaerobic digestion is the biological degradation of biomass in oxygenfree conditions to produce biogas, that is, a methanerich gas. Anaerobic digestion is particularly suited to wet feedstocks such as animal manure, sewage sludge from wastewater treatment plants and wet agricultural residues, and the organic fraction of MSW, including that in landfill sites. Gasification occurs when biomass is transformed through a thermochemical process into fuel gas. It is a highly versatile process because virtually any dry biomass feedstock can be efficiently converted to fuel gas. The output of this process is referred to as biosynthetic gas (syngas).

Biomass: any organic matter, i.e. biological material, available on a renewable basis. Includes feedstock derived from animals or plants, such as wood and agricultural crops, and organic waste from municipal and industrial sources.

Biomethane: methane from biological sources, produced by upgrading raw biogas and removing any CO_2 present.

Biorefining: the sustainable processing of biomass into a spectrum of marketable bio-based products and bioenergy.

Conventional biofuels: also referred to as firstgeneration (1G) biofuels, these are obtained through wellestablished processes and include sugar- and starch-based ethanol, oil-crop-based biodiesel and straight vegetable oil. Common feedstocks used in these processes include sugar cane and sugar beet, starch-bearing grains such as corn and wheat, oil crops such as oil palm, soya, rape, sunflower and canola.

Modern bioenergy: bioenergy excluding the traditional use of bioenergy and other low-efficiency or unsustainable practices.

Traditional use of biomass: the use of solid biomass such as wood, charcoal, agricultural residues and animal dung converted with basic techniques, such as a threestone fire, for heating and cooking in the residential sector. It tends to have very low conversion efficiency (10% to 20%) and often relies upon an unsustainable biomass supply.

Novel advanced biofuels: fuels which meet the advanced biofuels definition, but which are produced by processes that are not yet fully developed or commercialised and so may merit specific support to assist their development and deployment.

Abbreviations and acronyms

AFID	Alternative Fuels Infrastructure Directive
BECCS	bioenergy with carbon capture and storage
BECCU	bioenergy with carbon capture and utilisation
BIGCC	biomass integrated gasification and combined cycle
BtL	biomass to liquid
B2DS	Beyond 2DS
C	carbon
CCS	carbon capture and storage
CCU	carbon capture and utilisation
CERT	Committee on Energy Research and Technology
CNG	compressed natural gas
CO	carbon monoxide
COP21	21st session of the Conference of the Parties
CO_2	carbon dioxide
CPQ	Climate Protection Quota (Germany)
CTBE	Brazilian Bioethanol Science and Technology Laboratory
ECOWAS	Economic Community of West African States
EfW	energy from waste
EIO	Economics and Investment Office (IEA)
ESCO	energy service company
ETP	Energy Technology Perspectives
EU	European Union
FAME	fatty acid methyl ester
FAO	Food and Agriculture Organization
FIT	feed-in tariff
FQD	Fuel Quality Directive
GBEP	Global Bioenergy Partnership
GHG	greenhouse gas
G8	Group of Eight
HEFA	hydrotreated esters and fatty acids
HVO	hydrotreated vegetable oil, also known as renewable diesel
H_2	hydrogen
IC	innovation challenge
IEA	International Energy Agency
IGCC	integrated gasification and combined cycle
ILUC	indirect land use change
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency

ISO	International Organization for Standardization
LCA	life-cycle assessment
LCFS	low-carbon fuel standard
LCOE	levelised cost of energy
LNG	liquefied natural gas
LPG	liquefied petroleum gas
LUC	land use change
LULUCF	land use, land use change and forestry
MSW	municipal solid waste
NDC	nationally determined contribution
NGO	non-governmental organisation
NO_x	oxides of nitrogen
OECD	Organisation for Economic Cooperation and Development
OEM	original equipment manufacturer
ORC	organic Rankine cycle
O&M	operation and maintenance
O_2	oxygen
PM	particulate matter
PPA	power purchase agreement
PV	photovoltaic
R&D	research and development
RD&D	research, development and demonstration
RDF	refuse-derived fuel
RED	Renewable Energy Division (IEA)
REWP	Renewable Energy Working Party (IEA)
RFS	renewable fuel standard
RHI	Renewable Heat Incentive
RTS	Reference Technology Scenario
SBA	Sustainable Bioenergy Accelerator
SDG	Sustainable Development Goal
SE4All	Sustainable Energy for All
SLT	Standing Group on Long Term Cooperation
SNG	synthetic natural gas
SOFC	solid oxide fuel cell
SOFC-GT	solid oxide fuel cell-gas turbine
SO_2	sulphur dioxide
SRF	solid recovered fuel
STO	Sustainability Technology and Outlook Division (IEA)

TCP	Technology Collaboration Programme (IEA)
TFEC	total final energy consumption
UCO	used cooking oil
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
VRE	variable renewable energy
WBCSD	World Business Council for Sustainable Development
WEO	*World Energy Outlook*
2DS	2°C Scenario

Units of measure

bbl	barrel (of oil)
gCO_2eq/MJ	grams of carbon dioxide equivalent per megajoule
gCO_2/km	grams of carbon dioxide per kilometre
GJ	gigajoule
GJ/m^3	gigajoules per cubic metre
Gt	gigatonne
$GtCO_2$	gigatonnes of carbon dioxide
GW	gigawatt
GWh	gigawatt hour
EJ	exajoule
kg	kilogram
km	kilometre
kW	kilowatt
kW_e	kilowatt electrical
L	litre
mbbl	million barrels (of oil)
Mt	million tonnes
Mtoe	million tonnes of oil equivalent
MW	megawatt
MW_e	megawatt electric
MWh	megawatt hour
MW_{th}	megawatt thermal
TWh	terawatt hour

Conversion factors

1EJ=277.8 TWh = 23.9 Mtoe

1 billion litres = 264 million US Gallons =
220 million Imperial Gallons

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International Energy Agency – IEA
31-35 rue de la Fédération, 75015 Paris, France
Tel: +33 (0)1 40 57 65 00/01, Fax: +33 (0)1 40 57 65 59
Email: info@iea.org, Web: www.iea.org