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Bioenergy review

Committee on Climate Change
December 2011

Preface

The Committee on Climate Change (the Committee) is an independent statutory body which was established under the Climate Change Act (2008) to advise UK and Devolved Administration governments on setting and meeting carbon budgets, and preparing for climate change.

Setting carbon budgets

In December 2008 we published our first report, *'Building a low-carbon economy – the UK's contribution to tackling climate change'*, containing our advice on the level of the first three carbon budgets and the 2050 target; this advice was accepted by the Government and legislated by Parliament. In December 2010, we set out our advice on the fourth carbon budget, covering the period 2023-27, as required under Section 4 of the Climate Change Act; the fourth carbon budget was legislated in June 2011 at the level that we recommended.

Progress meeting carbon budgets

The Climate Change Act requires that we report annually to Parliament on progress meeting carbon budgets; we have published three progress reports in October 2009, June 2010 and June 2011.

Advice requested by Government

We provide ad hoc advice in response to requests by the Government and the Devolved Administrations. Under a process set out in the Climate Change Act, we have advised on reducing UK aviation emissions, Scottish emissions reduction targets, UK support for low-carbon technology innovation, design of the Carbon Reduction Commitment and renewable energy ambition. In September 2010 and July 2011, we published advice on adaptation, assessing how well prepared the UK is to deal with the impacts of climate change.

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Foreword

This report sets out our assessment of the role for bioenergy in meeting carbon budgets. A crucial issue is the extent to which bioenergy is sustainable. To assess this, we need to account for emissions on a complete lifecycle basis, and to understand whether increasing levels of bioenergy penetration are compatible with providing food for a growing and increasingly wealthy global population, and with wider environmental and social objectives.

In the report we consider these various aspects of sustainability, and develop scenarios for sustainable supply of bioenergy out to 2050. We conclude that there is likely to be some but limited supply of sustainable bioenergy, that this is needed to meet carbon budgets, and that levels of bioenergy penetration required may require trade-offs with other objectives. We then make recommendations on the regulatory framework to ensure sustainability, focusing on European approaches to biofuels and UK approaches to biomass over the next decade.

We also present analysis of where scarce bioenergy might best be used across sectors. This suggests a particularly important role for carbon sequestration, either through the use of wood in construction or the use of carbon capture and storage (CCS) with bioenergy. CCS should therefore be demonstrated as a matter of urgency, not just because of its benefits when used with fossil fuels, but because negative emissions from using it with bioenergy will reduce costs and risks of meeting carbon budgets. Additionally, the scope for greater use of wood in construction should be explored by the Government.

This report will be an input into our advice on the inclusion of international aviation and shipping emissions in carbon budgets (e.g. since the inclusion of these emissions would have implications for the required emissions reductions in other sectors of the economy). We will publish this advice in spring 2012, with a Government decision on inclusion required before the end of 2012 under the Climate Change Act.

On behalf of the Committee, I would like to thank the team who prepared the report for their great efforts, particularly as this follows a busy 12 months in which we have produced reports on the fourth carbon budget, renewable energy, progress meeting carbon budgets, and shipping emissions.

Adair Turner

Lord Adair Turner

Chair

Acknowledgements

The Committee would like to thank:

The core team that prepared the analysis for the report. This was led by Ute Collier and David Kennedy and included: Alice Barrs, Russell Bishop, Adrian Gault, Jonathan Haynes, David Joffe, Alex Kazaglis, Anna Leatherdale, Eric Ling, Nina Meddings, Stephen Smith, Kavita Srinivasan, Indra Thillainathan, and Katherine White.

Other members of the secretariat who contributed to the report: Neil Golborne, Swati Khare-Zodgekar, Eleanor Pierce, Meera Sarda, Mike Thompson, Emily Towers and Jo Wilson.

A number of individuals who provided significant support: Rob Arnold, Dr. Ausilio Bauen, Tim Beringer, Melanie Coath, Matt Georges, Jackie Honey, Pat Howes, Michael Humphries, Annabel Kelly, Akira Kirton, Ewa Kmietowicz, Ben Marriott, Stella Matakidou, Robert Matthews, László Máthé, Cameron Maxwell, Dr. James Morison, Dr. Nigel Mortimer, Dr. Richard J. Murphy, Prof. Martin Parry, Alexis Raichoudhury, Caroline Season, Dr. Raphael Slade, Prof. Gail Taylor, John Tebbit, Dr. Patricia Thornley, Ian Tubby, Prof. Detlef van Vuuren, Graham Wynne, Dr. Jeremy Woods and Mark Workman.

Professor Pete Smith, Aberdeen University, for his expert advice on the review.

The following organisations who have hosted visits for the CCC Bioenergy team: Drax Power, Renewable Energy Growers Ltd and Miscanthus Growers Ltd, PwC More London office, Rothamsted Research, RWE npower at Tilbury and Uptown Oil.

A number of organisations for their support, including: Association of Electricity Producers, BIOENERGY 2020+, Construction Products Association, Defra, DECC, DfT, E4tech, Forestry Commission, IEA Bioenergy, NFU, Northern Ireland Executive, Scottish Government and Welsh Government.

A wide range of stakeholders who sent us evidence, attended our stakeholder meetings, or met with us bilaterally.

The Committee

Lord Adair Turner, Chair

Lord Turner of Ecchinswell is the Chair of the Committee on Climate Change and Chair of the Financial Services Authority. He has previously been Chair at the Low Pay Commission, Chair at the Pension Commission, and Director-general of the Confederation of British Industry (CBI).

David Kennedy, Chief Executive

David Kennedy is the Chief Executive of the Committee on Climate Change. Previously he worked on energy strategy and investment at the World Bank, and the design of infrastructure investment projects at the European Bank for Reconstruction and Development. He has a PhD in economics from the London School of Economics.

Professor Samuel Fankhauser

Professor Samuel Fankhauser is acting Co-Director of the Grantham Research Institute on Climate Change at the London School of Economics and a Director at Vivid Economics. He is a former Deputy Chief Economist of the European Bank for Reconstruction and Development.

Sir Brian Hoskins

Professor Sir Brian Hoskins, CBE, FRS is the Director of the Grantham Institute for Climate Change at Imperial College and Professor of Meteorology at the University of Reading. He is a Royal Society Research Professor and is also a member of the National Science Academies of the USA and China.

Professor Julia King

Professor Julia King CBE FREng is Vice-Chancellor of Aston University. She led the 'King Review' for HM Treasury in 2007/8 on decarbonising road transport. She was formerly Director of Advanced Engineering for the Rolls-Royce industrial businesses. Julia is one of the UK's Business Ambassadors, supporting UK companies and inward investment in low-carbon technologies.

Lord John Krebs

Professor Lord Krebs Kt FRS, is currently Principal of Jesus College Oxford. Previously, he held posts at the University of British Columbia, the University of Wales, and Oxford, where he was lecturer in Zoology, 1976-88, and Royal Society Research Professor, 1988-2005. From 1994-1999, he was Chief Executive of the Natural Environment Research Council and, from 2000-2005, Chairman of the Food Standards Agency. He is a member of the U.S. National Academy of Sciences. He is chairman of the House of Lords Science & Technology Select Committee.

Lord Robert May

Professor Lord May of Oxford, OM AC FRS holds a Professorship jointly at Oxford University and Imperial College. He is a Fellow of Merton College, Oxford. He was until recently President of The Royal Society, and before that Chief Scientific Adviser to the UK Government and Head of its Office of Science & Technology.

Professor Jim Skea

Professor Jim Skea is Research Director at UK Energy Research Centre (UKERC) having previously been Director of the Policy Studies Institute (PSI). He led the launch of the Low Carbon Vehicle Partnership and was Director of the Economic and Social Research Council's Global Environmental Change Programme.

Executive summary

Bioenergy refers to solid, liquid or gas fuels made from biomass feedstocks which may or may not have undergone some form of conversion process.

The role of bioenergy in climate change mitigation is controversial. Specifically, there are questions over the extent to which bioenergy use results in emissions reductions when lifecycle impacts are accounted for, and tensions between the use of bioenergy and sustainability objectives (e.g. relating to the use of land for growing food, protecting biodiversity and water resources).

This review provides an assessment of the potential roles for bioenergy given lifecycle emissions and other sustainability concerns, and also considers alternative uses for bioenergy feedstocks (e.g. use of wood in construction).

In it, we set out three blocks of analysis:

- We consider lifecycle emissions, and the extent to which bioenergy can be regarded as low-carbon when these are accounted for.
- We develop scenarios for long-term supply of sustainable bioenergy, reflecting concerns about food production, biodiversity, water stress and social issues.
- We assess the most appropriate uses of sustainable bioenergy, and draw out implications for near-term low-carbon strategy.

Our analysis takes into account two types of uncertainty:

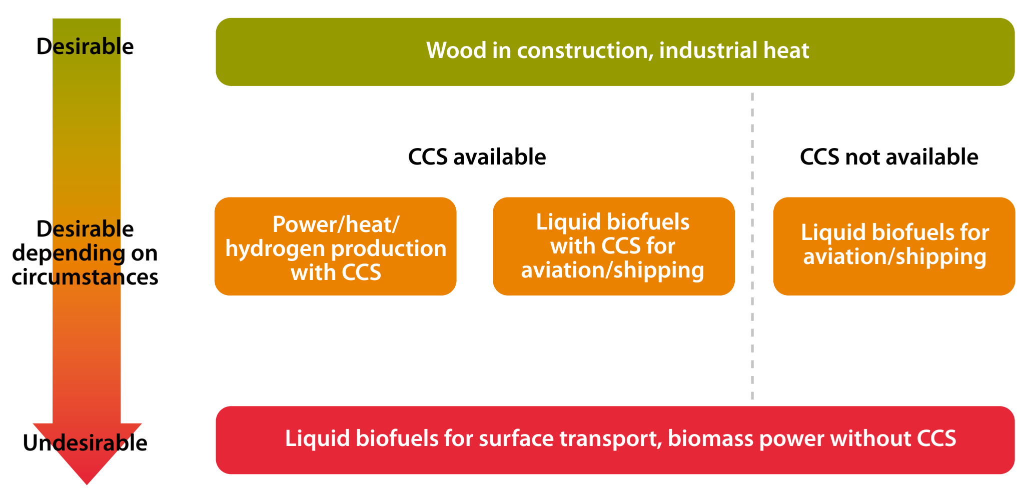
- Those where further development of the evidence base is desirable and feasible given additional detailed research. These relate to: (i) full lifecycle emissions associated with energy crops, forest biomass and agricultural residues (ii) the current use and characteristics of land potentially available for growing energy crops, including social (e.g. displacement of people) and environmental (e.g. soil carbon release, biodiversity loss) impacts that might follow from bioenergy production.
- Uncertainties which are more inherent and will only be resolved over time and in the light of technology demonstration. These relate to: (i) the development of new bioenergy technologies (ii) the development of carbon capture and storage (CCS) (iii) improvements in agricultural productivity (iv) trends in fossil fuel prices (v) population growth and diet.

We develop a range of scenarios which reflect these uncertainties, and identify technology options which if developed would enable us, in some combination, to meet carbon budgets and the 2050 target.

Our analysis leads us to reach four key conclusions:

- **The need for bioenergy versus its sustainable supply:**
  - It will be difficult to meet the overall 2050 emissions target unless bioenergy can account for around 10% of total UK primary energy (compared to the current 2%) and CCS is a feasible technology. This reflects the fact that there are a small number of economic activities where alternatives to hydrocarbons may either not be feasible (e.g. in aviation) or have not yet been identified (e.g. in iron and steel).
  - Scenarios for global land use which take account of required food production suggest that a reasonable UK share of potential sustainable bioenergy supply could extend to around 10% (200 TWh) of primary energy demand in 2050. However, it would be unsafe at present to assume any higher levels of bioenergy supply, and even the 10% level might require some trade-offs versus other desirable environmental and social objectives (e.g. through energy crops production encroaching on land of high biodiversity value).
  - If CCS is not available at the scale envisaged, the amount of bioenergy required to meet the 2050 target would have to be significantly higher than 10% of primary energy demand, and would imply land use change exceeding currently estimated sustainability limits.
  - Therefore if CCS does not prove a viable technology, or if subsequent developments in food or energy crop productivity suggest that the land use to achieve 10% bioenergy penetration is unsustainable, achieving the 2050 target will then require bioenergy technology breakthroughs (e.g. algae), breakthroughs in other areas (e.g. for production of iron and steel without hydrocarbons or product substitution), further reductions in non-CO_2 emissions, or changes in consumer behaviour (e.g. in relation to diet or travel).
- **Lifecycle emissions.** It is important that the role of bioenergy in low-carbon strategy reflects realistic estimates of total lifecycle emissions for different types of feedstock, including both direct and indirect land use change impacts. EU and UK regulatory approaches do not fully mitigate the risks of emissions from indirect land use change, and should therefore be strengthened. Specifically, both frameworks should reflect indirect land use change emissions, and the emissions saving relative to fossil fuels required for use of biomass in UK power and heat generation should be increased. If more robust regulations limit the supply of bioenergy which can meet defined sustainability criteria, the current 2020 targets for biofuels and biomass penetration should be adjusted down.

Figure ES.1: Hierarchy of appropriate use of bioenergy in 2050



Source: CCC.

- **Appropriate use of limited sustainable bioenergy supply in the long term.** Given limits to the global supply of sustainable bioenergy, it is important that this is used in an optimal fashion. In general, this implies use in applications where there are currently no feasible low-carbon alternatives to hydrocarbon input. However, our analysis has illustrated that the appropriate use depends crucially on whether or not CCS is an available technology (Figure ES.1).
  - If CCS is available, it is appropriate to use bioenergy in applications with CCS, making it possible to achieve negative emissions. These applications could include power and/or heat generation, the production of hydrogen, and the production of biofuels for use in aviation and shipping.
  - If CCS is not available, bioenergy use should be skewed towards heat generation in energy-intensive industry, and to biofuels in aviation and shipping, with no appropriate role in power generation or surface transport.
  - In either case, the use of woody biomass in construction (rather than as an energy source) should be a high priority, given that this generates negative emissions through a very efficient form of carbon capture.
- **Implications of bioenergy availability for overall low-carbon strategy.** Our analysis has revealed that supplies of sustainable bioenergy may only just be sufficient to make meeting the 2050 target achievable, and only then if CCS is available. Policy should therefore place a high priority on:
  - Developing and demonstrating CCS technology.

  - Ensuring that sectors which do not need to rely on bioenergy achieve decarbonisation via other means (e.g. through investment in a range of low-carbon power technologies, energy efficiency and electric heat deployment in buildings, and the development of electric vehicles (battery or hydrogen)).
  - Supporting research in areas where it is possible that there could be breakthroughs which will lessen sustainability constraints (e.g. new bioenergy technologies and technologies for improving agricultural productivity), or provide alternatives to the use of hydrocarbons.

We also make a number of recommendations following from these conclusions, and from our analysis of specific sectors (Box ES.1):

- **Power generation.** There should be limited if any support for new large-scale dedicated biomass generation.
  - Any longer-term role for new dedicated biomass power plants without CCS should be very limited given its relatively high cost compared to other options for power sector decarbonisation.
  - Detailed analysis of the power sector suggests this result also holds for the near term, and that any near-term investment should be limited to biomass co-firing and the conversion of existing coal-fired power plants.
  - Therefore while the Government's current focus on co-firing and conversion is appropriate, safeguards should be introduced to ensure that proposed support for new dedicated biomass under the Renewables Obligation (RO) does not result in unnecessary cost escalation or increased emissions. For new dedicated biomass power plants, support should be limited to small-scale plants and combined heat and power (CHP) plants or, at a minimum, support for large-scale new dedicated biomass should be limited to a very small number of projects.
- **Industry.** Continued support for the use of biomass in industry is appropriate. In addition, industry CCS should be developed and the scope for using wood in construction explored further.
  - There is a clear role for the long-term use of biomass in energy-intensive industry, whether or not CCS is viable. Therefore support for this should be continued under the Renewable Heat Incentive (RHI).
  - Given the importance of CCS in industry, which in conjunction with biomass would become a negative emissions option, the Government should develop a plan for demonstration and/or deployment of this technology.
  - There may be scope for significant emission reductions through the use of woody biomass in construction. This opportunity and supporting policies should be considered further by the Government.

- **Aviation.** Meeting aviation emissions targets is likely to require a combination of biofuels, efficiency improvements and constrained demand growth.
  - In a world without CCS, our analysis suggests an important role for aviation biofuels from the 2020s.
  - Where CCS is viable, continued use of biofuels in aviation would require application of CCS to biofuels plants. Recognising this possibility, any investment in aviation biofuels plants over the next decade with a payback period more than twenty years should be planned on the basis that CCS may have to be retrofitted.
  - In either case, meeting the target to reduce aviation emissions in 2050 back to 2005 levels is likely to require a combination of biofuels, technology and operational efficiency improvement, as well as constrained demand growth.
- **Surface transport.** Battery and hydrogen electric vehicles are the most promising options for decarbonising surface transport and should therefore be supported.
  - In the longer term, there is likely to be only niche use of liquid biofuels in surface transport. This reflects opportunities for cost-effective decarbonisation of cars, vans and heavy goods vehicles (HGVs) through electric (battery and hydrogen) technologies.
  - Therefore support for electric vehicle development is appropriate now in order to prepare for this future.
  - The declining role for biofuels in surface transport should be factored into investment decisions about biofuels plants (e.g. these should pay back by the early 2030s, or should be based on advanced conversion processes and around this time switch to other markets such as shipping or surface transport in other countries).

In addition to large-scale bioenergy applications that deliver large emission savings, we recognise that there is a range of sensible smaller-scale applications using local resources (e.g. buses running on used cooking oil, anaerobic digestion plants using food or farm waste, or biomass boilers using woodchip from tree surgery waste).

Box ES.1: Key recommendations

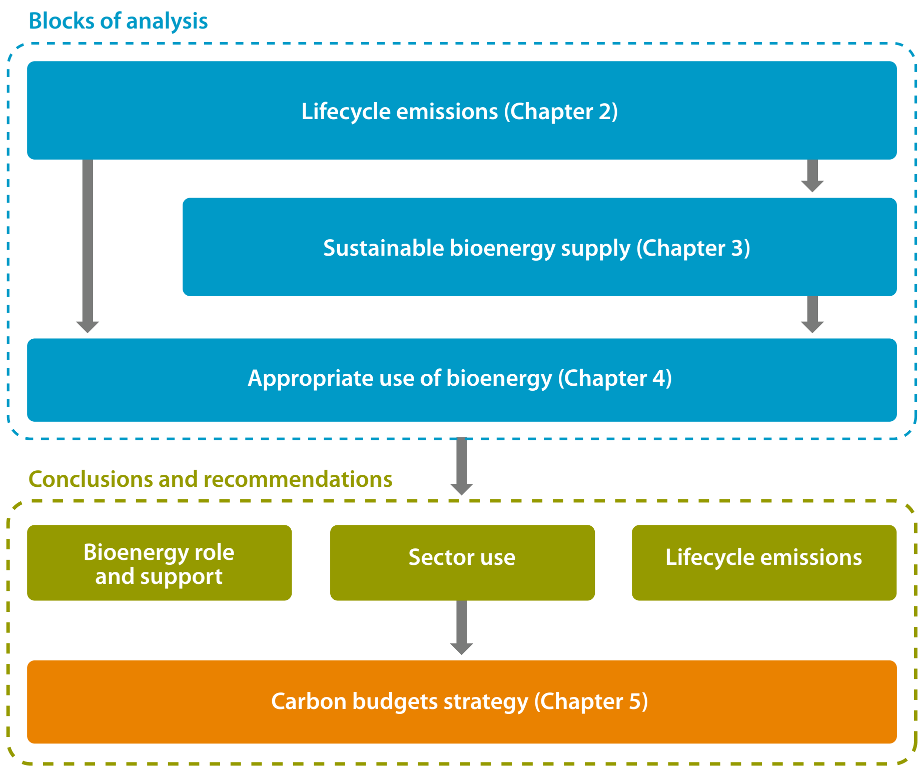
- **Bioenergy penetration.** The Government should plan for levels of bioenergy penetration of around 10% of primary energy but no higher to meet the 2050 target.
- **Liquid biofuels sustainability.** The Government should argue strongly for extending the European sustainability framework under the Renewable Energy Directive to cover indirect land use change (ILUC) emissions. This should either be through the use of ILUC factors or by capping the use of feedstocks with associated risks of ILUC at sustainable levels.
- **Forest biomass sustainability.** The minimum emissions threshold under the sustainability framework for the Renewables Obligation (RO) should be tightened from the current level of 285 gCO_2/kWh to 200 gCO_2/kWh. Serious consideration should also be given to introducing a sustainability standard for all wood used in the UK (e.g. pulp and paper, construction) which would provide more confidence that RO support for biomass in power does not result in indirect deforestation.
- **Flexibility of targets.** Liquid biofuels targets under the Renewable Transport Fuel Obligation and biomass targets in the Renewable Energy Strategy should be regarded as flexible, and adjusted in the event that there is insufficient supply of sustainable bioenergy.
- **New targets.** No new targets for longer-term bioenergy penetration should be set until new regulatory arrangements are introduced to ensure achievement of sustainability objectives.
- **Accounting.** Any new global agreement limiting emissions should fully account for agriculture, forestry and land use change emissions, including those related to the use of bioenergy.
- **Carbon capture and storage (CCS) demonstration.** CCS should be demonstrated as a matter of urgency, particularly because the negative emissions ensuing when this is used with biomass may be required to meet long-term emissions targets.
- **Biomass power generation.** Support for biomass power generation under the RO should be focused on co-firing and conversion of existing coal power plants. Any support for new dedicated biomass generation should be limited to small-scale only or, at a minimum, any support for new large-scale dedicated biomass should be limited to a very small number of projects.
- **Biomass heat generation and biogas production.** There should be continued support for the use of biomass in heat generation and production of biogas from waste under the Renewable Heat Incentive.
- **Support for non-bioenergy technologies.** Going beyond bioenergy, our analysis confirms the need to continue incentivising energy efficiency improvement, decarbonisation of the power sector, use of heat pumps in buildings, and electric vehicles, all of which appear to be least-regrets options for the longer-term decarbonisation path for the economy.

The main considerations in reaching these conclusions are (Figure ES.2):

- **Lifecycle emissions.** We set out estimates of lifecycle emissions for different types of land and feedstocks. These include emissions from cultivation, production and transportation of feedstocks, together with emissions from direct and indirect land use impacts, both as regards crops and biomass from forests. We identify crops and land types to minimise lifecycle emissions, and consider regulatory approaches to ensure this. This assessment is reflected in our estimates of the sustainable bioenergy resource and our analysis of appropriate use, which accounts for lifecycle emissions.

- **Bioenergy resource estimates.** We set out four scenarios which represent possible bioenergy supply (dedicated energy crops, forestry and agricultural residues, and waste resources) under plausible assumptions on population growth, diet change, agricultural productivity, sustainability constraints (e.g. relating to biodiversity and water stress) and implied land available for growth of energy crops. These illustrate a range of possible futures that allow planning for different bioenergy contributions to meeting UK carbon budgets. We use these scenarios as inputs to our modelling of appropriate bioenergy use across sectors.
- **Analysis of appropriate uses of bioenergy.** We use a model to identify where scarce supplies of sustainable bioenergy might best be used across sectors (minimising costs and maximising abatement), given other low-carbon technologies available. Within this, we consider the use of biomass as a substitute for carbon-intense products in construction or industry. From our assessment of appropriate use in the longer term, we draw out implications for near-term strategy, relating to the development of bioenergy and other low-carbon options.

Figure ES.2: Analytical approach in the Bioenergy Review



Source: CCC.

Our analysis covers both global and UK levels, with a focus on UK insights and implications that are also relevant more generally:

- The lifecycle emissions analysis takes an international perspective, considering emissions for a range of crops grown globally. The recommendations that follow from this analysis relate to EU and UK bioenergy sustainability frameworks.
- The starting point of the analysis of future bioenergy supply is global, reflecting the fact that a lot of bioenergy feedstocks are likely to be traded globally.
- Given our global analysis, and a range of estimates of UK-produced feedstocks, we develop scenarios for UK bioenergy supply, which we use as inputs to our detailed analysis and modelling of the UK energy system. These scenarios assume a UK share of total global bioenergy in line with the UK's share in total global energy (i.e. not a disproportionately high level of UK bioenergy consumption relative to the global total).
- The analysis of appropriate use of scarce bioenergy is at the UK level, with the aim to draw out implications for UK low-carbon strategy. These implications are also relevant more generally, considering that all countries subject to a tight carbon constraint are likely to follow broadly similar decarbonisation paths, although at different paces and with a different mix of abatement options.

We set out our analysis in five chapters, starting with an introduction, then setting out the three blocks of analysis described above, and finishing with a conclusion:

1. What is bioenergy?
2. Is bioenergy low-carbon?
3. Sustainable bioenergy supply
4. Appropriate use of scarce bioenergy
5. Summary of conclusions and recommendations for low-carbon strategy

More detailed analysis is set out in full in four technical papers available on our website (http://www.theccc.org.uk/reports/bioenergy-review).

1. Is bioenergy low-carbon?
2. Global and UK bioenergy supply scenarios
3. Appropriate use of scarce bioenergy
4. Biomass in power generation

This review is an input to our advice on the inclusion of aviation and shipping emissions in carbon budgets which we will publish in spring 2012. It will inform our assessment of how carbon budgets and targets might be achieved when aviation and shipping emissions are included. Following our advice, the Government will make a decision on inclusion and – depending on the decision – propose a statutory instrument to Parliament before the end of the year. The review also provides recommendations to Government to feed into its new bioenergy strategy to be published in early 2012 and its current review of banding within the Renewable Obligation Certificate regime from 2013 onwards.

Chapter 1

What is bioenergy?

Bioenergy feedstocks and technologies

The key bioenergy feedstocks are food and fodder crops, dedicated energy crops, forestry, waste and agricultural residues (Box 1.1). Currently the vast majority of modern bioenergy (excluding traditional biomass, i.e. small-scale uses for heating, lighting and cooking) comes from food and fodder crops. These are used to produce conventional liquid biofuels through a range of established conversion processes.

Box 1.1: Bioenergy key terms and definitions

Bioenergy is created by combusting solid, liquid or gas fuels made from **biomass** feedstocks which may or may not have undergone some form of **conversion process**.

Biomass:

Various different types of biomass can be used as a feedstock for bioenergy:

- **Food (and fodder) crops** are the edible parts of sugar, starch and oil plants traditionally developed and grown to produce food for humans and animals. Food crops being used for fuel include wheat, maize, soya, palm oil and sugar cane.
- **Agricultural residues** are the by-products from crops, such as wheat straw and seed husks, as well as other agricultural by-products including slurry and manure.
- **Forestry & forest residues** denote woody material from existing forests (which may or may not be managed) plus residues from sawmills, forest floors and tree pruning.
- **Waste** denotes food waste, sewage and other biological waste from homes or industry, which otherwise tend to be discarded.
- **'Dedicated' energy crops** are not grown for food but are being targeted for energy use. Examples include fast-growing trees and grasses with a high lignin content such as miscanthus and willow, and oil crops such as jatropha.

Conversion processes:

While biomass can be combusted directly for heat and power, chemical processes are often used to convert a feedstock into a viable fuel. For the purposes of this report we identify two general types:

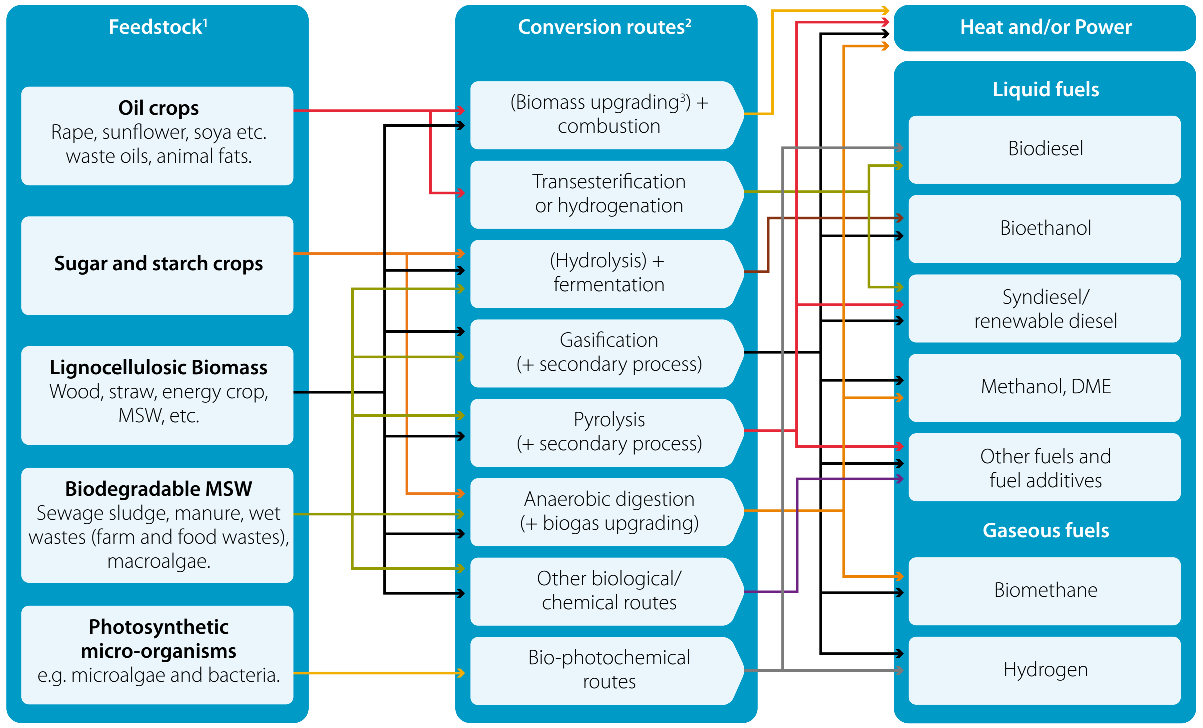
- **Current** conversion processes are mature technologies which are already being widely used to produce biofuels on industrial scales, including fermentation and anaerobic digestion.
- **Advanced** conversion processes are the subject of current research, with some demonstration plants in operation, however they are not yet widely deployed. Examples include cellulosic ethanol production, Fischer-Tropsch synthesis, and pyrolysis.

Research and development is under way to create new and improved fuels from biomass. Much of this is devoted to methods for creating liquid fuels from alternative feedstocks. We therefore refer to two types of liquid biofuel signifying their stages of development:

- **Conventional biofuels** are derived from crops and waste using current conversion processes. Examples include bio-ethanol from sugar cane and biodiesel from cooking oil.
- **Advanced biofuels** incorporate a range of less developed methods. Many of these apply advanced conversion processes to the dedicated energy crops and the lignocellulosic parts of residues. Others use novel feedstocks such as algae and bacteria.

In future, there may also be scope to use new dedicated energy crops which are not yet widely cultivated (e.g. perennial grassy or woody crops such as miscanthus and short rotation coppice, and oily crops such as jatropha and camelina), as well as a greater use of waste and residues as feedstocks. Through various technologies and conversion chains, it will be possible to use the full range of feedstocks either as solid, liquid or gaseous fuels in a range of applications (power, heat, surface transport, aviation and shipping) (Figure 1.1).

Figure 1.1: Feedstock conversion chains



Source: Bauen et al. (2009), Bioenergy – A reliable and sustainable energy source: A review of status and prospects, IEA Bioenergy, International Energy Agency, Paris, 2009.
Notes: 1 Parts of each feedstock, e.g. crop residues, could also be used in other routes. 2 Each route also gives co-products. 3 Biomass upgrading includes any one of the densification processes (pelletisation, pyrolysis, torrefaction, etc.).

There is also the possibility that novel processes and technologies currently at the pilot stage will be developed. This includes the cultivation of microalgae, which may provide potential to reduce emissions where CCS proves not to be viable (Box 1.2). Breakthroughs in these currently unproven technologies could significantly increase the supply of sustainable bioenergy, with implications for decarbonisation strategies.

Box 1.2: Microalgae

Microalgae include a wide variety of photosynthetic micro-organisms capable of fixing CO2 to produce biomass more efficiently and rapidly than terrestrial plants. Furthermore, many algal strains have high oil content. Due to these characteristics, microalgae have very high potential energy yields relative to other feedstocks, consume little water, and can be cultivated on non-arable land or in brackish, saline, or waste water. Production of liquid biofuels from microalgae is therefore considered to be attractive because they can be cultivated without causing indirect land use change (ILUC).

Production of biofuels from microalgal oil, using similar processes to production from vegetable oils, is well understood, with the major challenges relating to cultivation and harvesting of microalgae and extraction of the algal oil at sufficiently low cost. The innovations necessary to reduce costs require significant research and development and are only expected over the longer term.

Even with the necessary cost reductions, it is not clear that microalgal biofuels will deliver significant greenhouse gas savings. A number of studies estimate lifecycle emissions of microalgae cultivation to be high, mainly due to energy inputs and high mineral fertilizer use, though these issues could potentially be addressed.

More significantly, it is likely that much of the carbon content of algal biofuels will not be atmospheric CO2. This is because atmospheric CO2 cannot diffuse into intensive microalgae mass cultures at a sufficient rate to enable high growth. This means that to enable sufficient yields, the majority of the CO2 required by the algae must be supplied from non-atmospheric sources. This CO2 would therefore be produced during the combustion of fossil fuels or biomass during power generation or industrial processes and captured for transfer to the algae cultivation process.

There is limited scope for continued burning of fossil fuels in an increasingly carbon-constrained world. Although there is scope for continued burning of biomass, this will be limited by sustainable biomass supply, and very limited in a world where CCS can be applied to processes where biomass is burned.

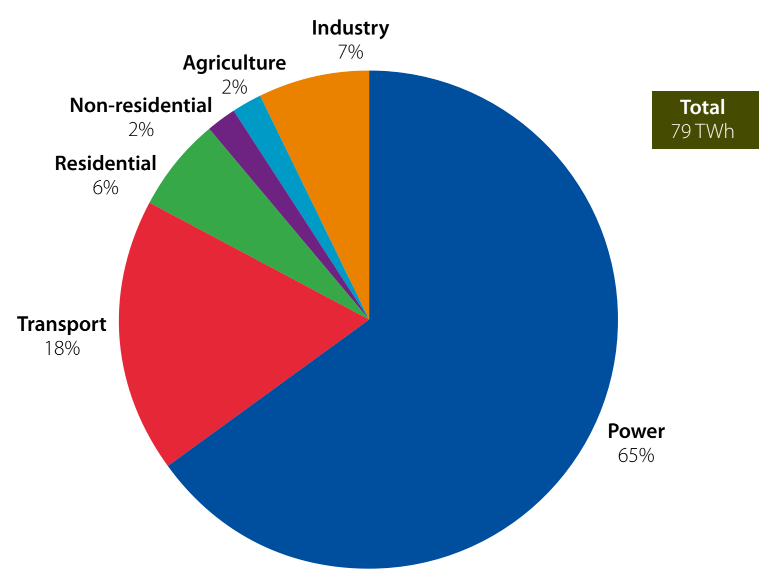
Therefore it is possible that microalgal biofuels will be used in sectors such as aviation, where low-carbon alternatives are limited. However, widespread use across the transport sector is unlikely given constraints on the availability of non-atmospheric CO2 in a carbon-constrained world.

Current and projected bioenergy use in the UK and globally

Currently bioenergy accounts for around 2% of total primary energy in the UK. Most bioenergy (65%) is used in the form of solid (forest) biomass and biogas (from landfill) in power generation, followed by biofuels in surface transport (18%). The remainder is used in buildings, industry and agriculture (Figure 1.2):

- **Liquid biofuels.** The use of liquid biofuels in transport has increased in recent years under the UK's Renewable Transport Fuel Obligation (RTFO). This requires that biofuels penetration reaches 5% by volume (4% by energy) in 2013/14. The proportion of biofuels in the UK transport fuel mix was 3.3% by volume in 2009/10, which is in line with the RTFO requirements.
- **Solid biomass.** Solid biomass is currently primarily used in power generation for co-firing with coal and accounts for around 3% of total generation. There is also limited use in biomass boilers, which currently delivers around 1% of total heat generation.
- **Biogas.** Waste gas from landfill currently contributes around 3% of total power generation, with a small amount of additional generation from sewage sludge digestion.

Figure 1.2: UK bioenergy use (2010)



Source: DECC DUKES (2011).

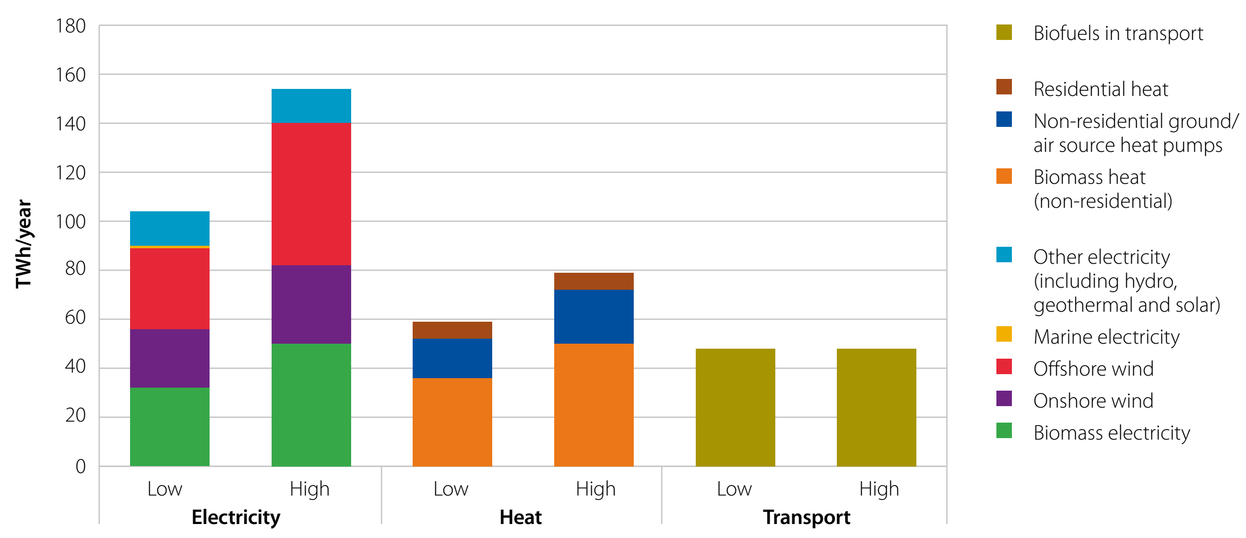
Over the next decade, the Government's Renewable Energy Roadmap envisages that bioenergy penetration will rise significantly, with increased use in surface transport, power generation and heat generation (Figure 1.3).

At the global level, bioenergy accounts for 10% of total primary energy use and around 50% of all renewable energy. The majority of this (around two-thirds of total bioenergy) is accounted for by traditional biomass. The largest users of bioenergy are Brazil, China, India, and the United States, which together account for around 40% of all bioenergy used across the world, with another 30% used across Africa.

Between 1990 and 2009, a 36% increase in the use of bioenergy globally has been due mainly to increased bioenergy demand from the EU, Africa, Brazil and India. Between 2009 and 2020, the IEA[1] projects a further increase in bioenergy use of up to 26%, driven by policy initiatives across the world to stimulate the uptake of bioenergy as an alternative to fossil fuels. In the EU, many member states are planning for a major expansion of bioenergy, which is expected to account for two-thirds of the 20% renewables target under the EU Renewable Energy Directive (RED, Figure 1.4).

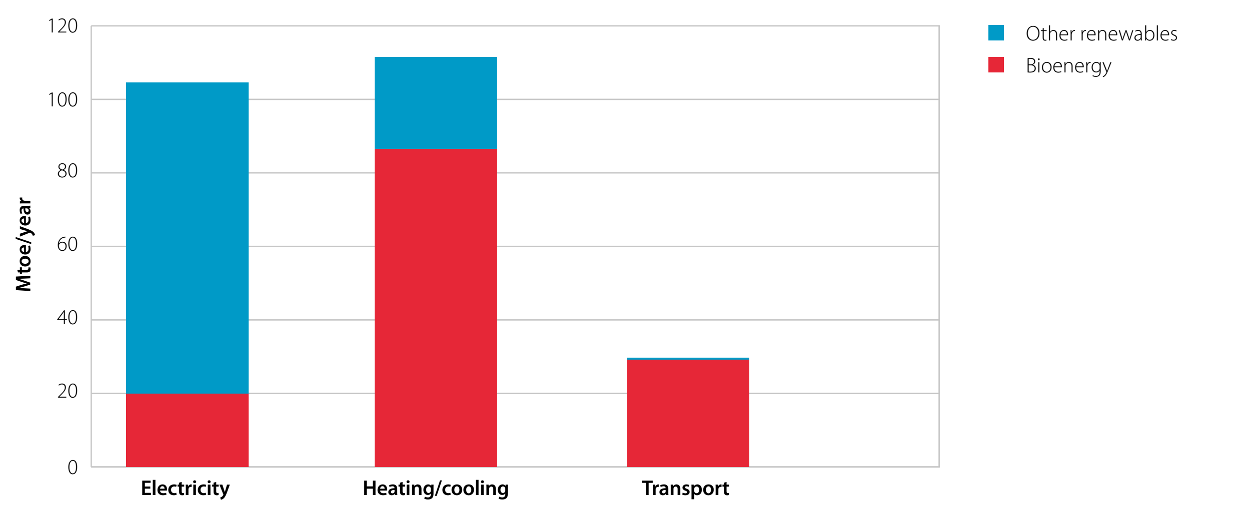
1 World Energy Outlook 2012, 450ppm Scenario.

Figure 1.3: UK Renewables Roadmap ambition in 2020



Source: DECC (2011).
Note: The category "residential heat" includes some biomass heating.

Figure 1.4: EU Renewable Energy Directive expected contribution from bioenergy in 2020



Source: EU National Renewable Energy Action Plans – published by the European Environment Agency (2011).
Note: Data can be accessed from: http://www.ecn.nl/docs/library/report/2010/e10069.pdf. 1 Mtoe = 0.086 TWh.

Chapter 2

Is bioenergy low-carbon?

Bioenergy could in principle be zero carbon, as carbon is absorbed in the growth phase of feedstocks and released when these are combusted (i.e. bioenergy effectively acts as a carrier of solar energy).

In practice this is not the case, given 'lifecycle emissions' from cultivation, processing and transportation of biomass feedstocks and products, and possible direct and indirect changes in land use emissions.

The current accounting framework in the UK reflects these lifecycle emissions only for domestically-produced bioenergy feedstocks. Imported bioenergy, which accounts for the majority of total UK bioenergy consumption, is regarded as zero carbon in the national inventory, and hence in carbon budgets.

In the international context, some of the emissions related to the growth or harvesting of biomass feedstocks are recorded under the Kyoto Protocol of the United Nations Framework Convention on Climate Change, for example as emissions from agriculture or land use change.

However, current coverage is incomplete, given that land use change emissions are not fully accounted for even in some Annex 1 countries to the Kyoto Protocol (e.g. forest and crop management emissions), and that non-Annex 1 countries (e.g. the majority of developing countries) together with the United States (which did not ratify the Protocol) do not report emissions and removals under the Protocol, and are major feedstock suppliers.

It is important to consider these emissions in the near term, where there is the possibility that ambitious bioenergy targets may have limited benefits or negative greenhouse gas emissions impacts. In the longer term, lifecycle emissions are key to assessing the contribution bioenergy can make to meeting emissions targets, both in the UK and internationally.

Our aim in what follows is to assess the implications of lifecycle emissions for near-term bioenergy ambition, and to understand the extent to which these may persist in the longer term, as an input to our assessment of appropriate bioenergy use. We do this in six sections:

(i) Emissions from cultivation, processing and transportation of bioenergy crops

(ii) Land use change emissions from bioenergy crops

(iii) Limiting lifecycle emissions from bioenergy crops

(iv) Limiting emissions from forest biomass

(v) Conclusions – is bioenergy low-carbon?

(vi) Approaches to lifecycle emissions in assessing appropriate bioenergy use

We do not cover lifecycle emissions related to wastes and agricultural residues, as in most cases these are significantly lower than for other feedstocks, especially where there are avoided methane emissions. This has been recognised under the Renewables Obligation (RO) sustainability criteria which have an exemption for various waste feedstocks (e.g. sewage gas, municipal solid waste and food waste).

We do not consider the design of a future global agreement to reduce emissions as this should relate to emissions associated with bioenergy. However, given gaps in the current approach, any agreement should fully record all lifecycle emissions associated with bioenergy including those from agriculture and land use impacts. Failure to fully account for bioenergy emissions would result in a level of total emissions incompatible with limits required to achieve climate objectives.

(i) Emissions from cultivation, processing and transportation of bioenergy crops

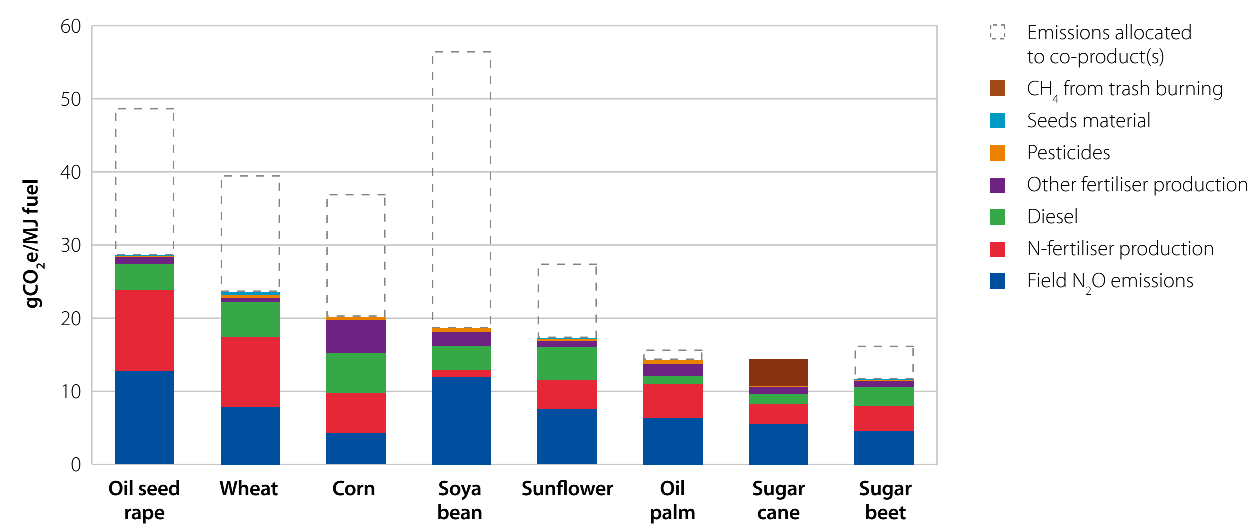
Emissions from cultivation

Emissions related to the cultivation of bioenergy crops (food and fodder crops and dedicated energy crops) occur because of energy-related emissions from the manufacture of fertiliser and other agrochemicals, nitrous oxide emissions from the application of fertiliser to soil, and the use of fossil fuel-powered farm machinery.

Although these emissions could erode up to around 35% of the potential savings from using biofuels instead of fossil fuels for transport use on a lifecycle basis, there are crops with lower associated emissions (Figure 2.1) and increased availability expected in the future:

- **Oil seed rape and wheat.** Temperate annual crops, such as oil seed rape and wheat have cultivation emissions of the order 23-28 gCO_2e/MJ of biofuel, equivalent to between 28-34% of lifecycle emissions from conventional fuels. This reflects:
  - The fertiliser intensity of the annual crops, with high emissions associated with both the production (CO_2) and application (N_2O) of nitrogen fertiliser. Combined, these emissions account for around 80% of the total cultivation emissions of these crops.
  - The need to re-establish the plant each year has implications for emissions arising from site preparation and planting (e.g. tractor diesel emits CO_2).
  - For these crops in particular, there is scope to reduce emissions through efficient fertiliser use, both as regards quantity and timing of application and crop development and breeding.
  - Wheat, maize and oil seed rape can also produce useful co-products such as dried distillers grain with solubles (DDGS) and rape meal for use as animal feed.

Figure 2.1: Cultivation emissions of food and fodder crops



Source: Biograce.
Note: Biograce is an EU funded project which aims to harmonise calculations of GHG emissions that are performed in the EU under legislation implementing the Renewable Energy Directive and the Fuel Quality Directive. The EU-RED method for allocating emissions to co-products is based on energy content; soya meal is the main product and soya biofuel is the co-product, so in this exhibit the emissions in the lower section of the soya bar corresponds to the biofuel (the co-product) and emissions in the upper section to the soya meal.

- **Oil palm and sugar cane.** These perennial crops require relatively less fertiliser than annual crops, reflected in associated cultivation emissions of around 14 gCO_2e/MJ of fuel for both crops (n.b. land use change emissions from oil palm can be very high, see Section (ii) below).
- **Sugar beet.** Despite being a temperate annual crop, cultivation emissions are low (around 12 gCO_2e/MJ of fuel), reflecting relatively lower nitrogen fertiliser requirement. This is due in part to soil incorporation of the sugar beet tops, which is a nitrogen rich residue.
- **Oil crops.** New types of oil crops such as camelina and jatropha are at an early stage of development as biofuels but evidence suggests that they could have relatively low cultivation emissions due to low fertiliser requirements.
- **Dedicated energy crops.** Dedicated energy crops such as miscanthus and short rotation coppice (SRC) have very low fertiliser requirements. They are already used in biomass combustion for power and heat but as advanced conversion technologies become commercially available, they are likely to compete with food and fodder crops as a liquid biofuel feedstock.

Emissions from production and transportation

Emissions arising from the production and transportation of conventional biofuels produced from food and fodder crops (i.e. excluding cultivation emissions) further erode the emissions savings of biofuels over the use of fossil fuels on a lifecycle basis:

- Emissions from producing biofuels can exceed 30 gCO_2e/MJ of fuel, eroding over 36% of emissions savings. However, emissions can be significantly lowered by altering the fuel used to power the processing of the feedstock. For example, while processing wheat into ethanol fuelled by lignite can generate emissions of around 32 gCO_2e/MJ, using natural gas will lower processing emissions by around 10 gCO_2e/MJ.
- Emissions from transporting biofuels are of a similar order to those for transporting conventional fuels.

In future, emissions from the use of dedicated energy crops with new technologies (e.g. biofuel derived from ligno-cellulosic conversion) are expected to be significantly lower. We reflect emissions associated with different feedstocks and technologies in our modelling of appropriate use of bioenergy in Chapter 4.

Summary on emissions from cultivation, production and transportation of bioenergy crops

Taking the combined emissions from cultivation, production and transportation, these could significantly erode emissions savings, depending on crop type, production process and transport distance (Figure 2.2). They are therefore material, and should be accounted for when considering the emissions impacts of bioenergy. The aim should be to minimise these emissions, through crop choice, farming practices, and production processes.

(ii) Land use change emissions from bioenergy crops

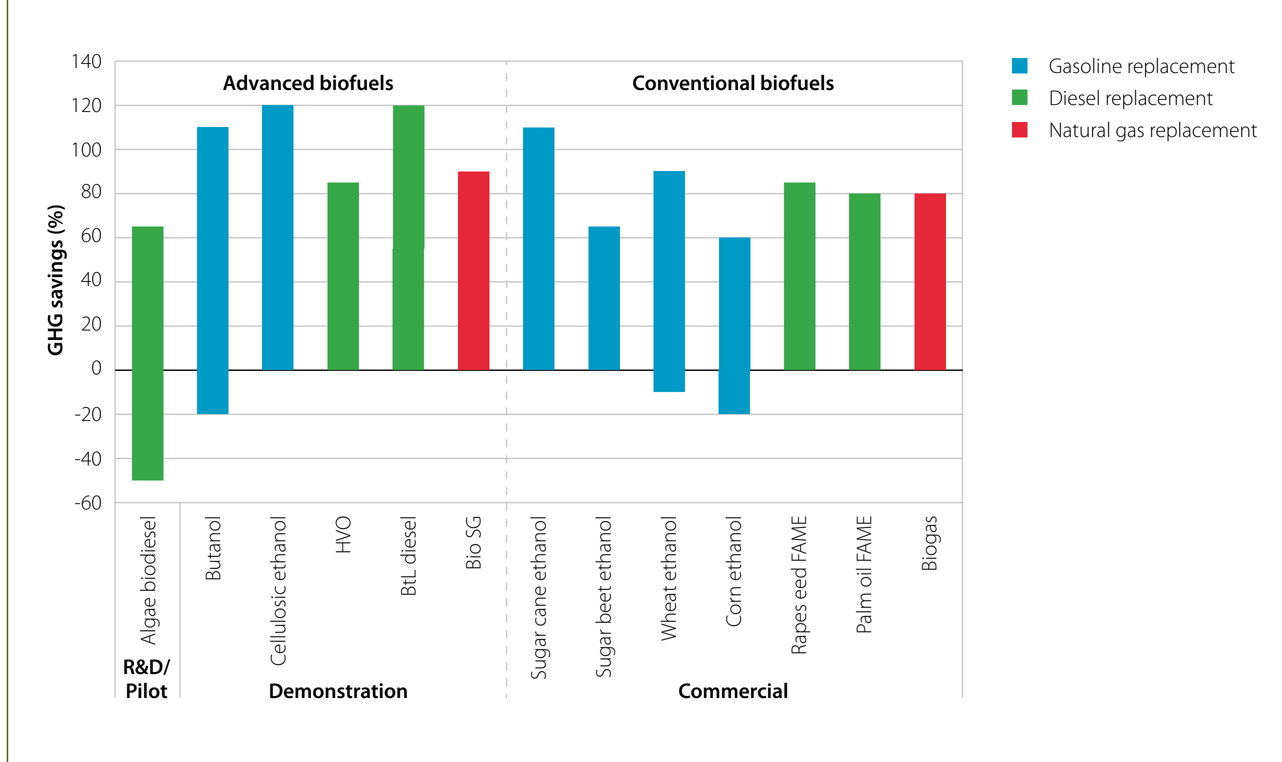
Why land use change results in emissions

There are many drivers of land use change, which include amongst other factors, bioenergy, agriculture, and urbanisation. Land use change can result in a change in the level of sequestered carbon in two main carbon pools:

– **Soil organic carbon.** Carbon is captured from decomposing organic matter such as leaves and root tissues and accumulation can take from decades to centuries.

– **Living and dead vegetation (biomass).** This is found below (e.g. roots) and above ground (e.g. leaves and branches).

Figure 2.2: Range of GHG savings of different biofuel chains compared to fossil fuel



Source: OECD/IEA (2011).
Note: Exhibit based on 60 "well-to-wheel" lifecycle emissions studies and shows a large range for each biofuel. Excludes land use change emissions.

Direct versus indirect land use emissions

There are two types of land use changes associated with growing bioenergy crops (food and fodder and dedicated energy crops):

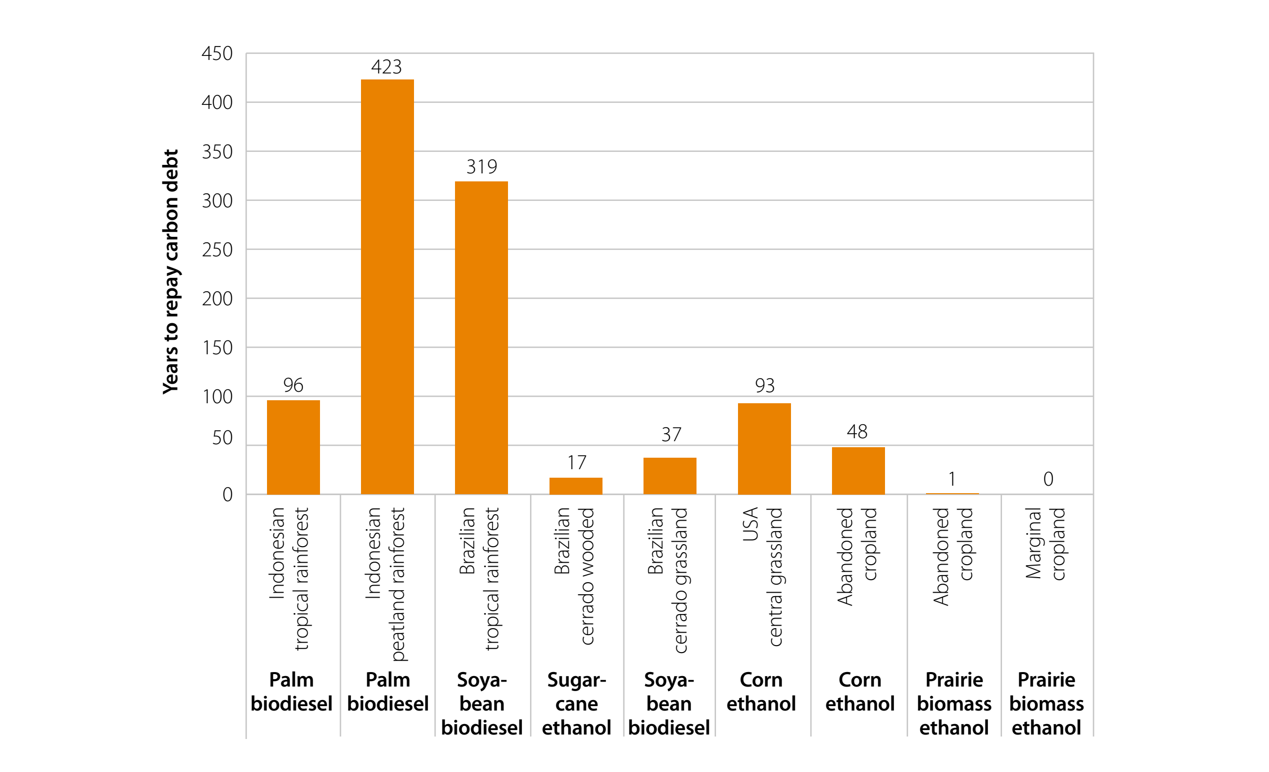
- **Direct land use change emissions** occur when converting land to grow crops, resulting in a release of carbon stored in the soil and existing vegetation.
- **Indirect land use change (ILUC) emissions** result when growth of bioenergy crops displaces an existing economic activity (e.g. agricultural and timber production) to new land which on conversion releases emissions.

Bioenergy impacts by land and crop type

The extent of carbon release depends upon the type of land and crop grown:

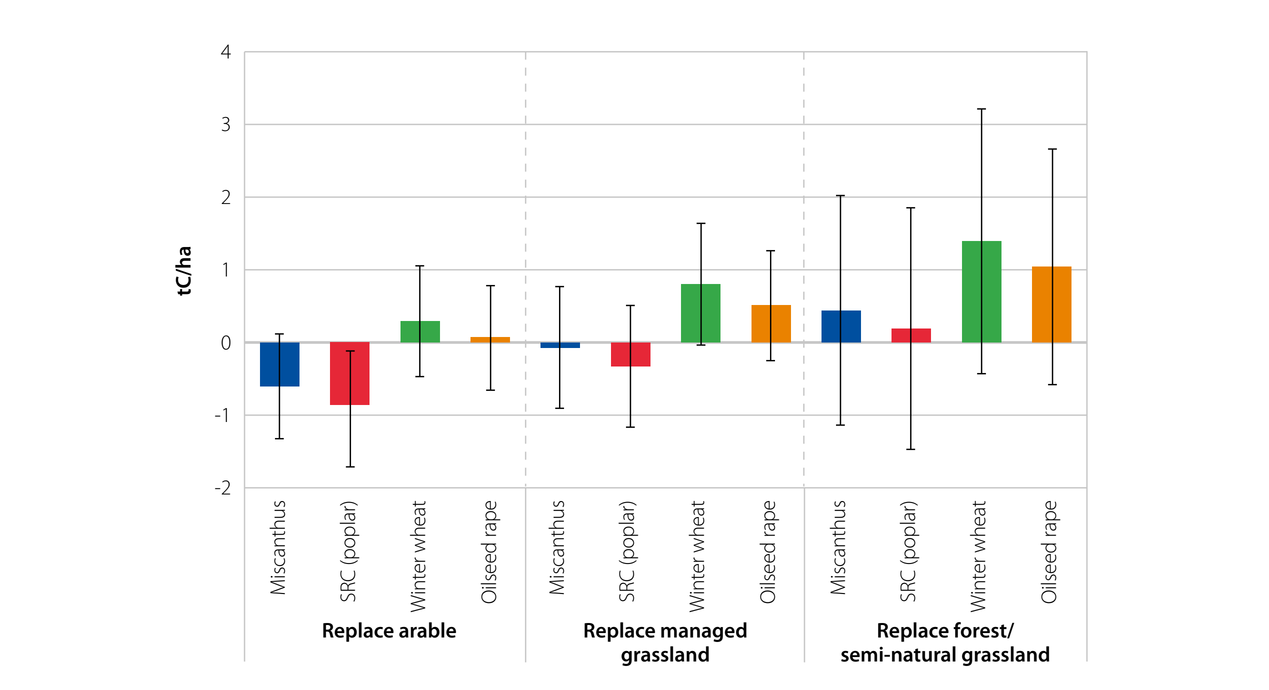
- Where land used for crop growth was formerly carbon-rich (e.g. tropical rainforest or grassland), resulting emissions could be hundreds of times the annual emissions saving from the use of bioenergy rather than fossil fuels. This can result in a 'carbon debt' which takes decades if not centuries to repay (Figure 2.3).
- More generally, dedicated energy crops have lower direct land use change emissions than arable food crops, and may actually result in negative emissions (i.e. additional storing of carbon in soil) when planted on arable and degraded land (Figure 2.4).

Figure 2.3: Carbon debt incurred from land conversion to grow food and fodder crops



Source: J. Fargione et al (2008).

Figure 2.4: Annual soil carbon changes of arable crops and dedicated energy crops



Source: Hillier, Smith et al (2009).
Note: Mean soil emissions and error bars for the soil emissions represent 2 x standard deviation. It can be interpreted that 95% of the data points lie between the two extremes.

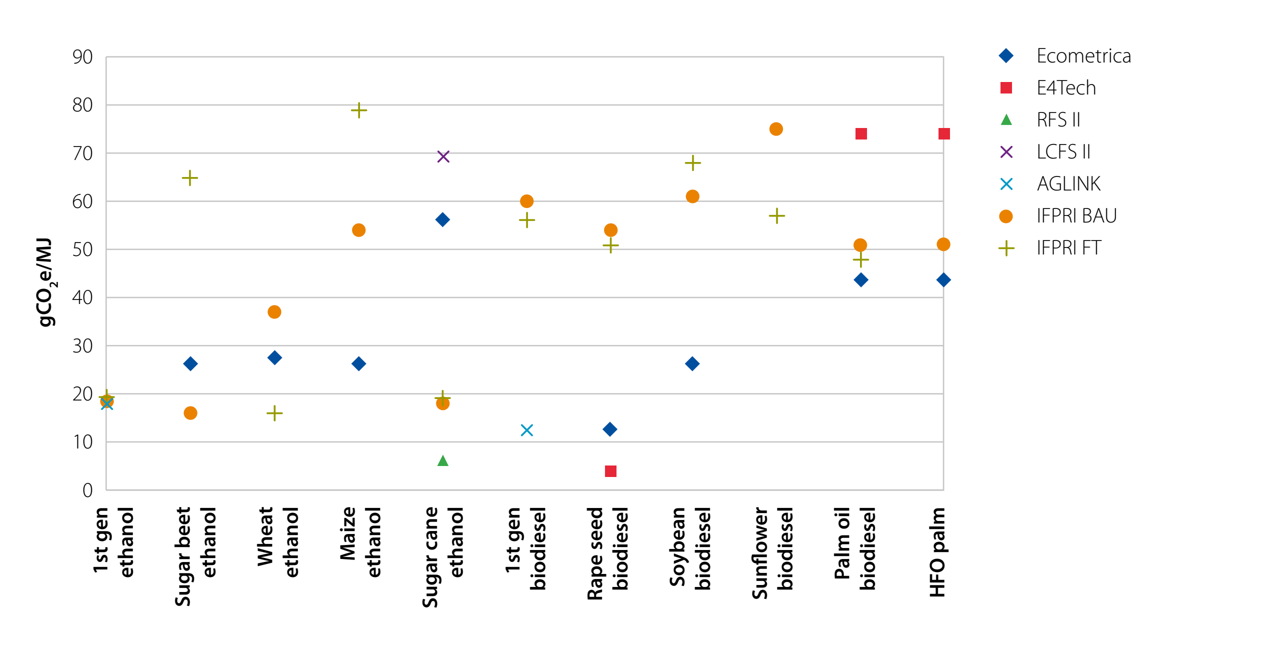
It is therefore important to ensure that crops are not grown on carbon rich land, but on land which would result in minimal (or a positive) change in the carbon balance.

Measuring land use change impacts

Direct land use impacts can be measured and regulated against (e.g. by limiting the use of crops from land with high stocks of carbon). Indirect land use change emissions, on the other hand, are more uncertain and harder to regulate, particularly in the absence of a global agreement to reduce emissions covering all countries.

This is reflected in the large range for estimated indirect land use change emissions (Figure 2.5) and the focus of current policy on limiting direct rather than indirect land use change emissions. Given that ILUC emissions are potentially very large and are currently unaccounted for, reducing uncertainties and developing robust frameworks to account for ILUC should be a priority.

Figure 2.5: Range of estimates for ILUC emissions



Source: CE Delft (2010).

(iii) Limiting lifecycle emissions from bioenergy crops

Short-term measures to limit lifecycle emissions

The EU's sustainability framework

The sum total of cultivation, production and transportation emissions and land use change impacts means that overall emissions savings from bioenergy crops (food and fodder and dedicated energy crops) to meet near-term targets for liquid biofuels are highly uncertain and could be very low or even negative.

Rather than invalidating the targets, this suggests the need to ensure that bioenergy does actually result in emissions savings when lifecycle impacts are fully accounted for. This in turn requires a regulatory approach for the types of crops and land that are allowed to count towards targets. Recognising this, the EU is attempting to limit lifecycle emissions through employing sustainability criteria under the Renewable Energy Directive (RED):

- The criteria require that biofuels and bioliquids should deliver emissions savings of at least 35% on a lifecycle basis relative to use of transport fossil fuels, rising to 50% in 2017 and to 60% in 2018 for new installations.
- It effectively rules out the conversion of certain land types with high carbon stocks (e.g. peatland, wetlands, and rainforest).

Questions have been raised whether this approach fully accounts for direct land use change (e.g. it has been suggested that the current approach does not fully reflect forgone sequestration on land that is converted for growth of bioenergy crops); and about the extent to which these emissions are accurately recorded under the RED framework.

More fundamentally, the EU approach only includes direct land use impacts, and as a consequence it leaves open the possibility that biofuels which have resulted in indirect land use emissions will be used to meet RED targets.

Extending the framework to cover indirect land use change impacts

The EU is currently considering whether and ways in which to reflect ILUC emissions within the RED sustainability criteria.

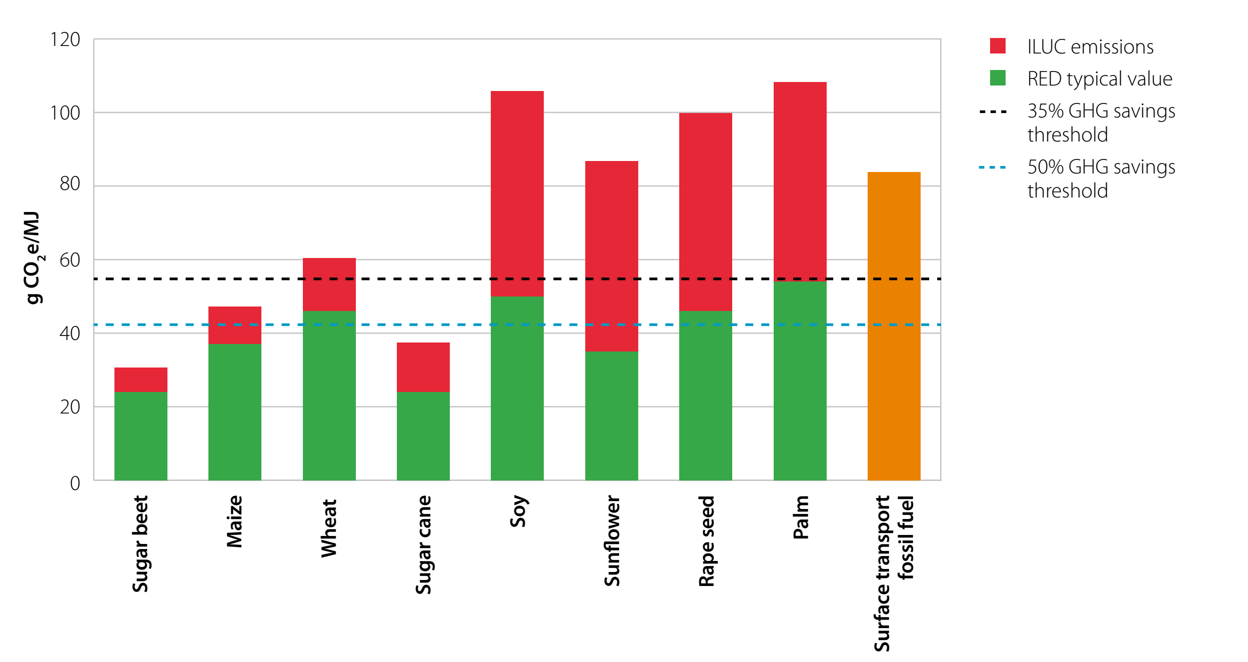
Given the importance of ensuring emissions reductions from biofuels produced from food and fodder crops, it is imperative that lifecycle emissions are fully accounted for, and that the EU introduces ILUC emissions to its framework in the near term, in order to avoid damaging ILUC that might occur under the current framework.

Of the various options under consideration, we recommend that the UK Government should strongly support either the use of crop-specific ILUC factors (i.e. adding estimates of ILUC emissions by crop, Figure 2.6), or the setting of caps on the use of feedstocks with associated risks of ILUC at levels consistent with sustainable supply.

In support of these approaches, positive incentives could be included for growth of feedstocks with low ILUC risk. For example, in a framework with ILUC factors, these factors could be reduced if it can be demonstrated that crops are grown on degraded land with low ILUC risk.

In view of uncertainties over ILUC emissions, the introduction of ILUC factors or capping the use of feedstocks with ILUC risks would necessarily be imperfect. However, both would be preferable to simply increasing the emissions savings thresholds (which could restrict potentially sustainable supply) or ignoring ILUC emissions altogether (which could allow unsustainable supply).

Figure 2.6: Addition of crop specific ILUC factors to EU-RED typical emission values



Source: IFPRI (2011), EU-RED.
Note: ILUC is central scenario based on biofuel target use by 2020 under the NREAPs.

Implications for biofuels targets and carbon budgets

Reflecting ILUC impacts could significantly reduce the supply of sustainable bioenergy relative to what is available under the current sustainability criteria, with implications for the 2020 liquid biofuels target. For example, the 2008 Gallagher Review on the indirect effects of biofuels production suggested that a lower level of ambition may be appropriate, without ruling out that current targets could be achieved sustainably.

If it were to become clear that current targets cannot be achieved when indirect emissions are accounted, then these should be adjusted. The imperative should be to deliver sustainable bioenergy, rather than to deliver current targets which may go beyond sustainability limits.

We note that the first four legislated carbon budgets build in lower transport biofuels penetration than assumed by the Government (i.e. 8% in 2020 rather than the Government's 10%). A reduction in biofuels ambition of this order of magnitude or slightly higher would therefore not jeopardise meeting carbon budgets, assuming full delivery on other measures to reduce emissions across the economy.

Longer-term measures to limit lifecycle emissions

In the longer term, there is scope for limiting lifecycle emissions through growing dedicated energy crops which do not require prime agricultural land, require limited use of fertiliser and can result in increased soil carbon sequestration when grown on certain land types. Other options include more integrated production systems for food and fuel, e.g. through agro-forestry or the greater use of co-products.

The aim should be for a comprehensive international agreement to reduce global emissions, covering all countries and fully accounting for all land use change emissions. This would reduce risks of lifecycle emissions from bioenergy crops. Provided such an agreement can be effectively monitored and enforced, the need for complementary arrangements to limit lifecycle emissions may no longer be required. They should therefore be kept under review.

(iv) Limiting emissions from forest biomass

Lifecycle emissions from forest biomass

While the discussion above has focused on lifecycle emissions associated with bioenergy crops, there are also important issues relating to emissions from forest biomass (e.g. wood chips or wood pellets) used in the power and heat sectors. Forests are important carbon reservoirs and intensified harvesting (e.g. going beyond thinning forest stands to practising stump removal) or deforestation could result in a very significant loss of forest carbon stocks and increased emissions relative to burning fossil fuels. There is a need to ensure sustainable forestry management practices if emission reductions from the use of forest biomass are to ensue.

High ambition and risk of unsustainable forest biomass

Near-term measures to ensure forest biomass results in emissions reductions are particularly important given targets for renewable energy penetration over the next decade, to which forest biomass used in power and heat generation is likely to contribute.

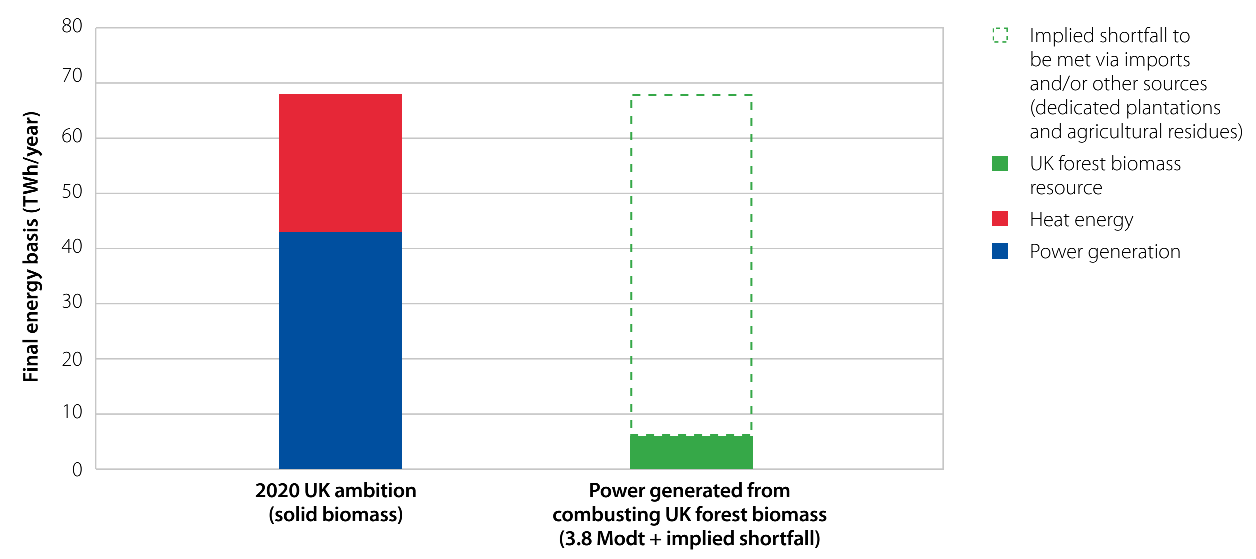
For UK forest biomass, we can be reasonably confident that this is from sustainable sources, given arrangements in place to prevent deforestation, strategies to encourage sustainable forest management, and scope for increased growth of short rotation forestry for use in biomass power and heat generation.

However, given limits on domestic supply much of the forest biomass for power and heat used in the UK will have to be imported (Figure 2.7). In addition, ambitious EU targets are at the limits of potential global supply of sustainable biomass over the next decade, as estimated by the Forestry Commission (Figure 2.8). The risk, therefore, is that biomass is imported from countries where frameworks to ensure sustainable forest management are less robust, in which case emissions benefits would be eroded (Figure 2.9).

Ensuring low-carbon forest biomass: current framework under the Renewables Obligation (RO)

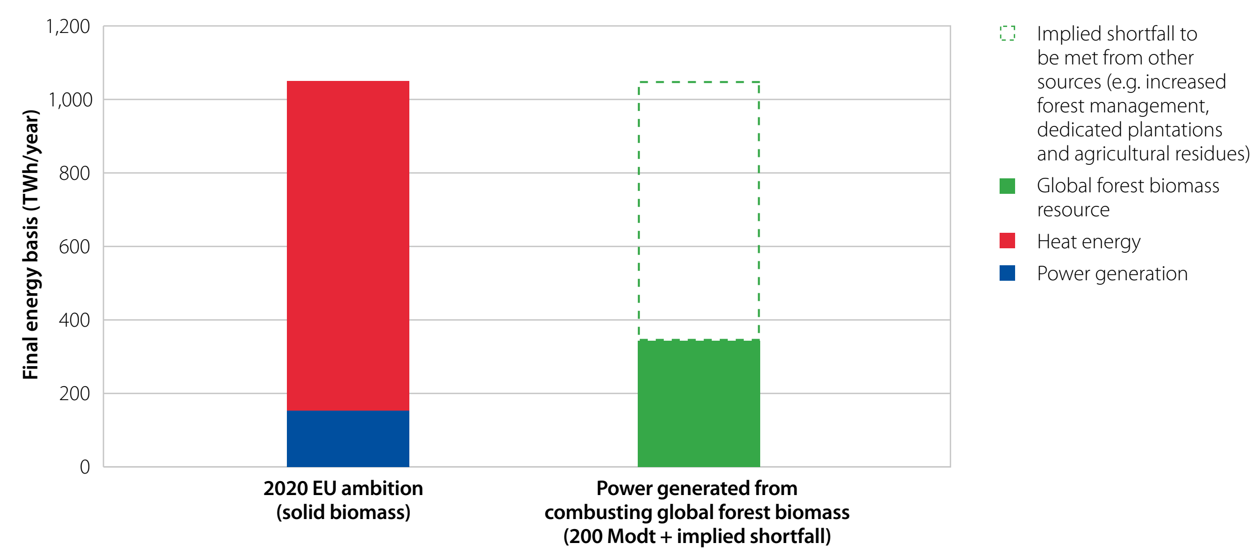
Measures are in place to try to ensure that the UK use of forest biomass is sustainable, but these provide limited confidence that significant emissions savings will ensue, and leave open the possibility that using biomass will actually increase emissions:

Figure 2.7: UK solid biomass ambition for heat and power in 2020 versus domestic forest biomass resource



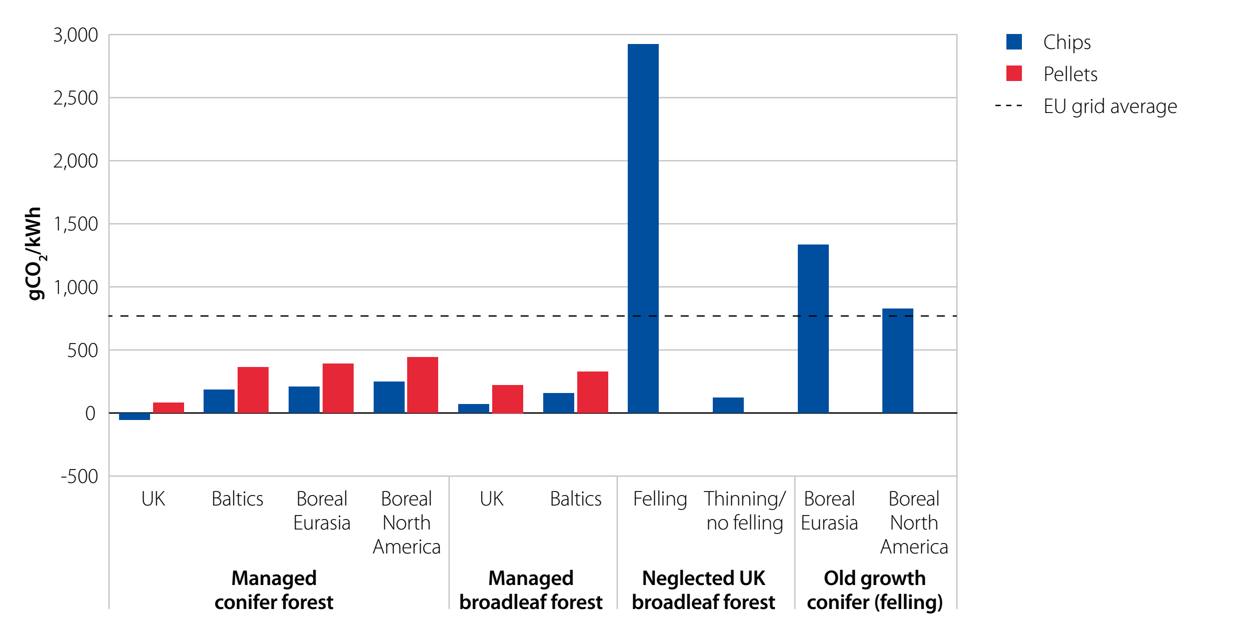
Source: UK Renewables Roadmap (2011); CCC (2010), Fourth Budget Report; CCC (2011), Renewables Review; AEA (2011), UK and Global Bioenergy Resource.
Notes: (i) Figures presented on a final energy basis assuming a conversion efficiency of 80% for heat and 36% for power. (ii) UK forest biomass resource reflects a medium scenario in AEA assessment (2011), reflecting a bioenergy price of £6/GJ and overcoming easy constraints. (iii) Pellets produced from forest biomass assumed to have a calorific value of 17 GJ/oven-dried tonne (odt) of feedstock.

Figure 2.8: EU solid biomass ambition for heat and power in 2020 versus global supply of forest biomass



Source: European Environment Agency (2011), Renewable Energy Projections as Published in the National Renewable Energy Action Plans of the European Member States; AEA (2011), UK and Global Bioenergy Resource.
Notes: (i) Figures presented on a final energy basis assuming a conversion efficiency of 80% for heat and 36% for power. (ii) Focuses on sustainable forest biomass (e.g. residuals of timber industry under AEA's business-as-usual assessment (2011)) rather than increased management of forests and dedicated plantations. Indicates a significant increase in sustainable supply over a relatively short time period is required to meet EU ambition. (iii) Forest biomass assumed converted to pellets, with a calorific value of 17 GJ/oven-dried tonne (odt) of feedstock.

Figure 2.9: Impact of forestry management practice on GHG emissions of biomass in power generation



Source: Environment Agency BEAT2.
Notes: Evaluated over a 20 year time horizon. BEAT2 uses a different methodology to the UK biomass sustainability criteria, and these differences will be important when results are close to the 60% threshold (e.g. 285 gCO_2e/kWh) under the UK sustainability criteria for biomass.

- There is a requirement that by 2013 biomass used to meet the RO must at a minimum meet an emission threshold of 285 gCO_2e/kWh.
- This represents a 60% saving relative to the EU grid average carbon intensity, which is much higher than that of the UK (i.e. around 700 gCO_2/kWh for the EU compared to around 500 gCO_2/kWh for the UK).
- As a result, emissions could be significantly higher than alternative forms of low-carbon power generation, and only slightly lower than those from gas-fired power generation.
- When risks of indirect deforestation are accounted for (see below), use of biomass could actually increase emissions relative to gas-fired generation (i.e. from a carbon perspective, it would be preferable to invest in gas generation rather than biomass, notwithstanding that gas generation is carbon-intense).

We therefore recommend that the threshold for use of biomass to meet the RO should be tightened to 200 gCO_2/kWh. This would represent a significant enough saving relative to gas-fired generation, allowing a margin for emissions from possible indirect deforestation. In addition, we recommend that this should be enforced by operators reporting on actual lifecycle emissions, rather than use of the EU default values, which are potentially inaccurate.

Limiting risks of indirect land use impacts

Although UK biomass sustainability criteria cover emissions from direct deforestation and forest management, they do not mitigate risks of indirect deforestation related to potential displacement of demand from other wood consuming industries:

- Total current wood demand in the UK is around 30 Mt, the majority of which is imported, and of which 0.7 Mt is used in power generation.
- Demand from power generation is expected to increase to 25 Mt in 2020 if the ambition set out in the Government's Renewables Roadmap is to be achieved.
- There is a risk is that this will displace existing demand from other wood consuming sectors, which might then be met from unsustainable sources. This risk is more pronounced given the sustainability framework in place under the RO and the lack of similar standards covering wood demand more generally.

There are also potential indirect land use impacts from the growth of energy crops and short rotation forestry for use in biomass power and heat generation (e.g. this could displace agricultural production to carbon-rich land).

Therefore ways should be found to provide confidence that there will be no direct or indirect deforestation, nor other land use impacts as a result of forest biomass use:

- Given that there is generally more certainty about the sustainability of UK-grown biomass, the aim should be to maximise UK supply without threatening supplies to other industries that use wood, through enhanced forest management, new woodland planting and growth of dedicated energy crops.
- The Government should include in its forthcoming bioenergy strategy an assessment of the global wood industry, with a view to understanding the demand-supply balance associated with increasing use of bioenergy in the UK and other countries. The key issues of interest here are whether there is currently enough supply from sustainably managed forests to meet demand for biomass in power and heat generation and from other industries which use wood, and whether in the event of excess demand there is scope for a rapid expansion of sustainable supply.
- There should be close monitoring of wood industry developments with a focus on supply expansion, and flexibility to change the biomass power ambition depending on the extent to which increased supply is or is not likely to be sustainable.
- Consideration should also be given to introducing a sustainability standard for all wood consumed in the UK, which would provide more confidence that the UK biomass strategy was not causing indirect deforestation.

- Indirect land use change emissions due to the growth of energy crops should be included in the UK's biomass sustainability framework (e.g. using ILUC factors from the EU's sustainability criteria for biofuels).

The risk of indirect land use impacts and deforestation through the increased use of biomass remains an important issue, and should be fully addressed in the Government's forthcoming bioenergy strategy, to be published early in 2012.

(v) Conclusions – is bioenergy low-carbon?

The evidence set out above suggests that bioenergy could be low-carbon in principle, but this may not always be the case in practice:

- **Lifecycle emissions from energy crops.** Our discussion above has highlighted the risk that near-term targets for liquid biofuels result in only small, or even negative, emissions savings when accounting for lifecycle emissions. This risk could be mitigated through limiting the types of crop and land used for bioenergy, which could be achieved through enhancing the EU's current sustainability framework to include indirect land use impacts, and in the longer term through a comprehensive global agreement to reduce emissions.
- **Lifecycle emissions from forest biomass.** Very ambitious targets for the use of biomass in the UK and the EU to 2020 could put pressure on sustainable supply, and result in direct and indirect land use impacts including deforestation. This risk could be mitigated through extending the UK's sustainability framework under the RO in the near term, and through a comprehensive global agreement to reduce emissions in the longer term.

Therefore the challenge is to ensure that regulatory frameworks are strengthened to provide confidence that bioenergy supply will be low-carbon. If sufficient low-carbon feedstock can be sourced, bioenergy has a potentially useful role in meeting carbon budgets and targets subject to other sustainability constraints being met.

(vi) Approaches to lifecycle emissions in assessing appropriate bioenergy use

Lifecycle emissions from crops

Our modelling of appropriate bioenergy use (Chapter 4) reflects emissions from cultivation, production and transportation of bioenergy. For example, we assume a different carbon intensity of bioenergy feedstocks depending on where they come from and the technology used to produce them. We also assume that land use change impacts are addressed either through a global agreement to reduce emissions, or through specific regulations. To reflect this and other sustainability concerns (e.g. tension with use of land to grow food, or biodiversity), we limit the land available for growing bioenergy crops.

The modelling includes an assumption that near-term targets for renewable transport fuels are achieved. However, in practice we believe that these targets should have a degree of flexibility, recognising the possibility that a robust sustainability framework could result in a lower level of ambition being achieved. Should this be the case, it would not change the long-term assessment of appropriate bioenergy use, which is the main focus of our modelling (e.g. a lower level of liquid biofuels penetration in 2020 would not change longer-term bioenergy supply and appropriate use).

Lifecycle emissions from forest biomass

When assessing appropriate use of bioenergy from forest biomass, we assume that a robust sustainability framework is introduced. In the near-term, we reflect the possibility of constrained sustainable supply when considering Government support for biomass power generation.

We now set out our assessment of long-term sustainable bioenergy supply – including from dedicated energy crops and forestry, reflecting lifecycle emissions and wider sustainability concerns – before considering where this might best be used to meet emissions targets, given other low-carbon technologies available.

Chapter 3

Sustainable bioenergy supply

In this section we develop scenarios for global bioenergy resources. We start by considering the scope for growing dedicated energy crops, where relevant factors include the demand for food, agricultural productivity, biodiversity, water stress, social and ethical issues (e.g. relating to property rights or the displacement of indigenous people). We then review estimates of tradable global bioenergy resources from forestry, forest residues, and agricultural residues and non-tradable domestic resource such as waste. Finally, we set out UK bioenergy scenarios which reflect our assessment of possible global and domestic resources, and which we then use in our modelling of appropriate bioenergy use.

Scenarios for global dedicated energy crops: approach and objectives

We now set out four scenarios for the future global supply of bioenergy from dedicated energy crops in 2050. We develop the scenarios from the bottom up in order to make our assumptions on the key supply drivers fully transparent. We then benchmark the scenarios against those from the literature.

In doing this, we are not attempting to predict the future. Instead, our aim is to illustrate a broad range of alternative assumptions about demand for food, agricultural productivity growth and land availability, and to explore sustainability constraints relating to food supply, biodiversity, water stress and social issues. Our scenarios then illustrate a range of possible futures for bioenergy contributions to meeting carbon budgets.

We do not assume major breakthroughs in technology or behaviour change, recognising that while these are possible, we do not consider them an appropriate basis for current planning, as they are highly uncertain.

Dedicated energy crops, food prices, and increasing food demand

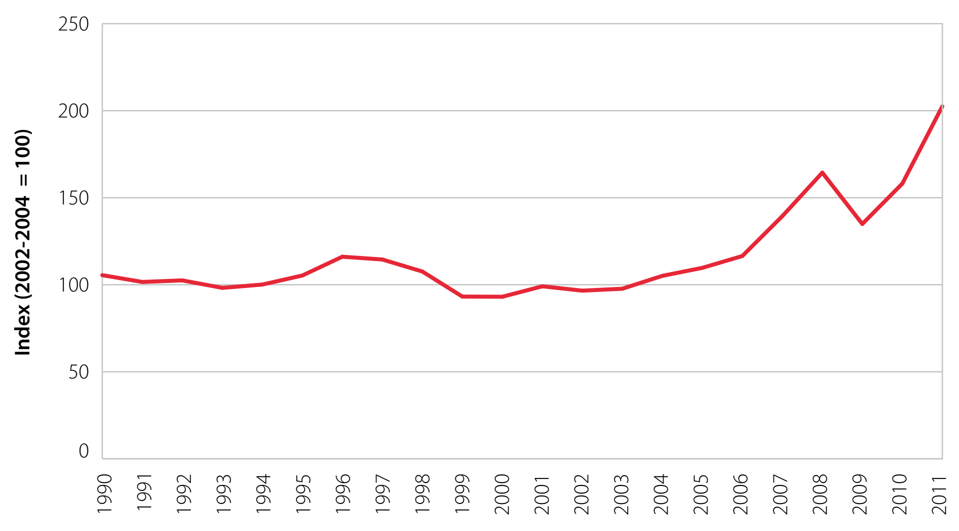
There is increasing concern over the impact of bioenergy on the availability of food. Given a fixed stock of land in the world, and acknowledging that providing enough food for people is a priority, this limits the amount of land available for growing dedicated energy crops. Even now, at a relatively low level of bioenergy use, there is some evidence to suggest a relationship between the use of land for growing conventional liquid biofuel feedstocks and food price spikes (Box 3.1).

Box 3.1: Bioenergy and food security

The rapid expansion of the biofuel industry over the last decade has triggered concerns over adverse effects on food prices – namely that biofuels cause food price inflation and increased volatility.

- High food price levels. After several decades of low and stable food prices, the price of many agricultural commodities has spiked twice in the last four years. Food prices began to rise sharply in 2006, peaking in 2008. Although they then fell in 2009, they remained higher than pre-crisis levels and once again rose sharply into 2010. In early 2011, food prices went even higher than the 2008 peak (Figure B3.1a).
- Increased volatility. High prices have not been the only concerning trend; after a period of relative stability for several decades, prices have been increasingly volatile in the last five years.

Figure B3.1a: Annual food prices from FAO Real Food Price Indices



Source: FAO Food Price Indices.

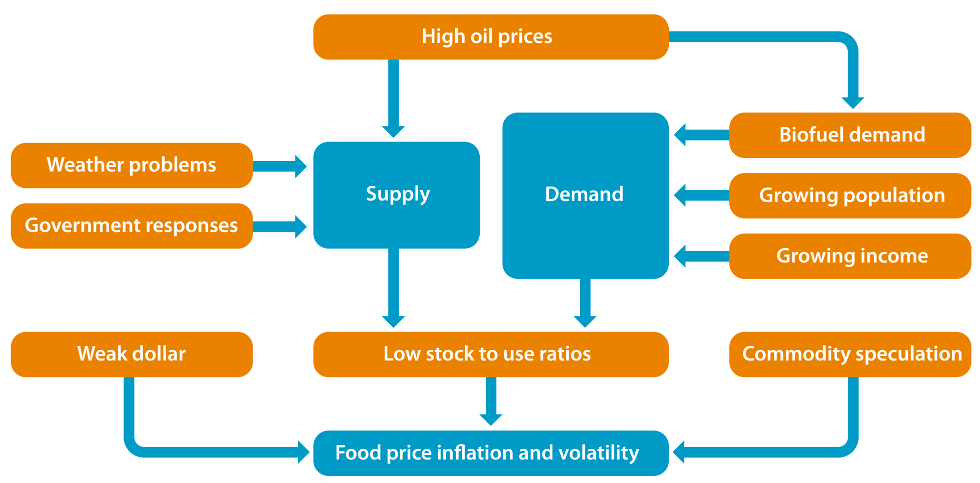
There is a broad consensus that the two recent price spikes have occurred due to the coincidence of a number of factors, including biofuels production (see Figure B3.1b and technical paper for more detail).

Box 3.1: Bioenergy and food security

- There are various quantitative studies of the impact of biofuels production on food prices, which find that biofuels may account for between 20-70% of maize price inflation in 2008.
- Other studies have played down the contribution of biofuels mandates in rising food prices, citing weather and commodity speculation as key factors.
- The balance of evidence suggests that biofuels were one amongst a number of significant factors in driving food price spikes.
- Given this evidence, multilateral organisations have argued that biofuels ambition should be lowered to protect food security[i].

Notwithstanding the uncertainty over the precise impact of biofuels production on food prices in recent years, it is clear that in the longer term there is likely to be a tension between growth of bioenergy and food production in a world where the land constraint is increasingly binding.

Figure B3.1b: Factors contributing to food price inflation and volatility



Notes: (i) Price Volatility in Food and Agricultural Markets: Policy Responses. Policy Report including contributions by FAO, IFAD, IMF,OECD, UNCTAD, WFP, the World Bank, the WTO, IFPRI and the UN HLTF.

The tension between using land for food, feed, and grazing versus growing bioenergy feedstocks is likely to continue in the future, given a rising global population and changing diets, and limited scope for further agriculture productivity improvement based on conventional technologies:

- **Population growth.** The United Nations central estimate is that the global population will increase from its current level of 7 billion to 9.1 billion over the next four decades in a central case, with a range of 8.7-11.3 billion.

- **Diet change.** It is likely that income growth will drive diet change in emerging economies, where demand for meat is expected to increase. Red meat and dairy production are particularly land intense, both as regards land for grazing and for growth of feed (e.g. the land requirement for cattle is around thirty times that of cereals to produce the same calorie content). Therefore increasing demand for meat and dairy products in emerging economies will result in increased demand for grassland and cropland for feed production.
- **Agricultural productivity growth.** In the past, agricultural productivity growth has been sufficient to provide food for a growing population without significantly increasing the amount of farmed land. However, a significant proportion of this productivity improvement has resulted from the use of carbon-intense fertilisers and irrigation. In future, scope for further such improvement may be limited in a carbon- and water-constrained world subject to a changing climate.

The FAO suggests that the combination of increasing population and changing diet could require an increase in agricultural production by 70% by 2050, resulting in a small increase in the amount of land required for growing food if all production were to be based on current best practice (Box 3.2).

Box 3.2: FAO agricultural outlook to 2050

FAO analysis projects that an additional 72 million hectares (a 5% increase in arable land) will be required to meet food demand in 2050. This analysis is based on an assessment of future population growth, diet change, and improvements in agricultural productivity.

Demand assumptions

The FAO analysis assumes a rising and increasingly wealthy global population, with both of these contributing to an increase in food demand of 70% over the next four decades:

- Population will grow from 7 billion now to over 9 billion by 2050, in line with UN projections.
- Average daily consumption per capita will rise to 3130 calories (kcal), representing an 11% increase between now and 2050.
- Meat consumption is projected to increase from an average of 37 kg/capita/day to 52 kg/capita/day between now and 2050. This increase is due to a move towards high protein Western diets in the developing world.
- 45% of projected cereal demand increase is for direct food consumption and 40% for livestock feeding (with the remainder for other uses, including industrial uses, seeds, etc.).

Agricultural productivity assumptions

A small increase in land required for food production is projected on the basis that increased demand can largely be met through productivity improvement:

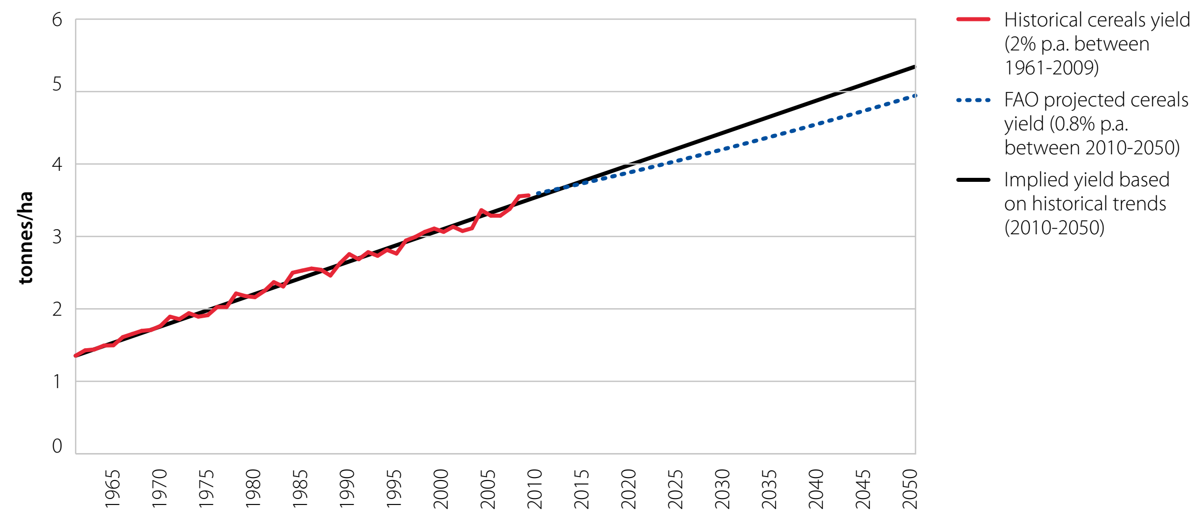
- Agricultural productivity increased by between 150 and 200% between 1960 and 2010 (e.g. global cereal yields grew by 2% per year), which allowed production to keep pace with growing demand without large amounts of new land being brought under production (e.g. the area of land under cultivation has increased by 12% while agricultural production has grown by 2.5 to 3 times).
- Much of this increase was fuelled by the 'green revolution' where advances in crop breeding, seed technology, and improvements in management practices allowed yields to improve, particularly in India and central Asia.
- The FAO notes that in many places productivity achievements have been associated with management practices that have degraded the land and water systems upon which food production depends.

Box 3.2: FAO agricultural outlook to 2050

- Growth in yields has therefore slowed recently and is forecast to be lower than historical increases (e.g. FAO modelling suggests global cereal yields will grow by 0.8% per year between 2010 and 2050) (Figure B3.2). This reflects scope for further improvement given productivity gaps across regions. For example, the global average cereal yield is 3.6 tonnes/ha, with Western Europe averaging 7.3 tonnes/ha and Africa averaging 1.3 tonnes/ha.
- The FAO suggests that largest contribution to increases in agricultural output will most likely come from existing agricultural land. This has to be achieved through sustainable intensification which makes more effective use of land and water resources (e.g. improving irrigation efficiency, maintaining ecosystem functions, enhancing carbon storage), In addition, innovative farming practices such as conservation agriculture, agro-forestry, and integrated crop-livestock systems hold the promise of expanding production efficiently.

We reflect the above assumptions (including land required for food production) in our scenarios for energy crops (set out below).

Figure B3.2: Historic and projected yield improvements for cereal crops



Sources: FAOSTAT (2011), FAO (2006), World agriculture: towards 2030/2050; Bruinsma, J. (2009) The resource outlook to 2050: by how much do land, water and crop yields need to increase by 2050?; FAO (2011), The State of the World's Land and Water Resources for Food and Agriculture; managing systems at risk.

We reflect the FAO analysis in two out of our four scenarios for dedicated energy crop supply:

- We assume demand for food and land required to meet this demand in line with the FAO, which means that there is very limited current agricultural land available for growth of dedicated energy crops in the longer term.
- We also assume that crops grown for energy are dedicated energy crops due to their potential suitability to poorer quality land, thereby minimising direct competition with food production.

We also include a scenario which reflects improvements in productivity over and above the FAO baseline/diet change to free up agricultural land.

Dedicated energy crops, biodiversity, water stress and social issues

Increased growth of dedicated energy crops could also have adverse impacts for biodiversity, exacerbate water stress, and compete with wider social and economic uses of land, particularly on land currently not used for commercial agriculture:

- **Biodiversity.** Although the importance of biodiversity has been recognised by the United Nations, which has targeted a significant reduction in the rate of biodiversity loss under the Convention of Biological Diversity, much land remains unprotected and biodiversity loss continues. Given a lack of protection, the risk is that increased growth of bioenergy crops could result in further biodiversity loss. This is a particular risk for land currently not used in agriculture, which often has a high biodiversity value.
- **Water stress.** This is a major issue in many parts of the world, where large-scale and inefficient use of water in agriculture has resulted in limited availability, both for ongoing use in agriculture and other sectors. This could both constrain water available for growing bioenergy crops and, where these are grown, exacerbate water shortages in other sectors. Water stress may be more of an issue in areas where there is potentially additional land available for growing arable and energy crops (e.g. sub-Saharan Africa), and may become more pronounced as a result of climate change. Where water is available, this may have an associated carbon cost penalty (e.g. depending on energy inputs for irrigation).
- **Ethical and social issues.** Much of the land identified as abandoned agricultural land (Box 3.3) is unlikely to be truly unused and may serve a variety of purposes, including subsistence farming and common grazing, which are not accurately captured in the estimates. It may still be appropriate to use some of this land for bioenergy, as long as land rights can be established and benefits shared with local communities.

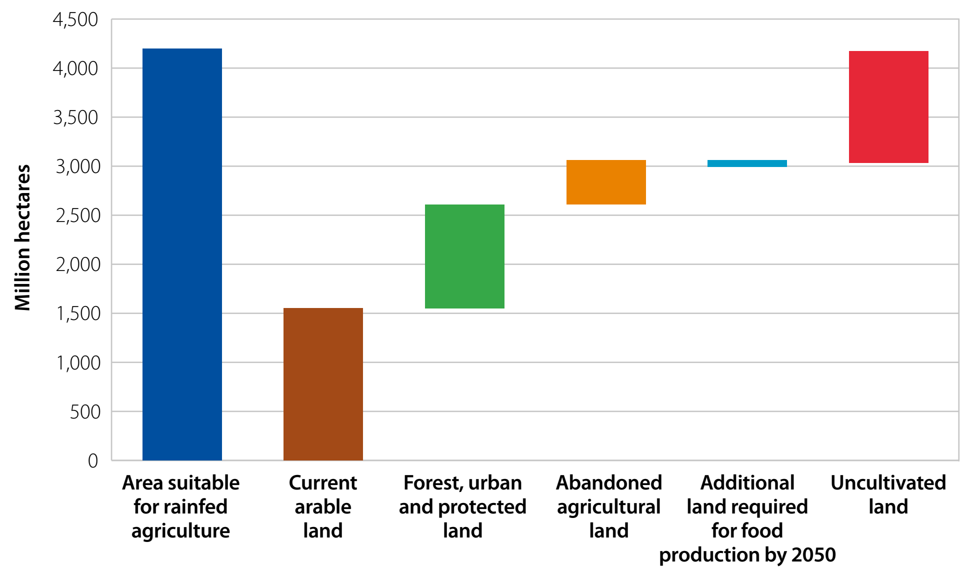
We reflect these environmental and social concerns to different extents in our scenarios for global energy crops.

Scenario drivers and descriptions: land availability, productivity and bioenergy shares

The key factors determining bioenergy supply are the land available for the growth of energy crops, which in turn depends on land required for growth of food, biodiversity, water stress, and the productivity of this land:

- **Available land.** Within land that is suitable for cultivation, we can be most confident that some abandoned agricultural land may be available for dedicated energy crops, with the possibility of additional land currently used for growing food crops, or previously uncultivated land, subject to significant uncertainties and concerns about productivity, biodiversity and water stress (Box 3.3, Figure 3.1).
- **Productivity**. There is a wide range of potential yields for dedicated energy crops, depending on the land type, with lower yields expected on abandoned agricultural land and higher yields on current arable land. Therefore land type and productivity will be key determinants of future bioenergy supply.
  - The literature suggests an average global yield of around 10 tonnes (dry matter)/ha, with a range from 5 tonnes/ha for low quality land and up to 15 tonnes/ha on high quality agricultural land incorporating improvements in yields over time[2].
  - These yield rates represent a range of perennial energy crops (e.g. miscanthus, short rotation poplar/willow, switchgrass) without specifying the exact mix of species grown.

Figure 3.1: Breakdown of available land



Source: Bruinsma (2009); FAOSTAT; Campbell, et al., (2008), CCC analysis.

2 Slade, *et al.*, (2011) Energy from biomass: the size of the global resource. Imperial College Centre for Energy Policy and Technology and UK Energy Research Centre, London.

Box 3.3: Land availability

- The total global land area (excluding Antarctica) is around 13,000 million hectares (Mha), of which around 4,200 Mha is regarded as being suitable for growing crops (i).
- Of this, around 1,550 Mha is currently used for growing arable crops, with a further 70 Mha required for crops by 2050 under FAO assumptions.
- This leaves around 2,550 Mha of suitable land, from which 1,060 Mha of forests, protected areas, and human settlements should be excluded (ii).
- Of the remaining 1500 Mha, around 500 Mha is accounted for by abandoned agricultural land, or land that has been previously used for cultivating crops or grazing but is no longer in production due to a variety of reasons (e.g. economic, political, water stress, soil degradation, etc.) (iii, iv), and the remainder (i.e. 1,000 Mha) by previously uncultivated land, which is likely to represent areas of natural habitat such as grassland ecosystems or current pasture land.
- Although FAO analysis (v) suggests that up to 700-800 Mha may be available for growing energy crops, this is highly uncertain given:
  - This land may be rich in carbon and biodiversity.
  - It may be used for grazing livestock or subsistence farming.
  - There is a high degree of uncertainty around productivity, including water supply. This may become more pronounced in a world subject to climate change.
  - For land where productivity is not prohibitively low, it is unclear whether growing dedicated energy crops would be economically viable, given limited experience of this to date.
- Given these concerns and uncertainties, the Government's Foresight Report *The Future of Food and Farming* concludes that we should plan for very limited additional agricultural land in future over and above currently abandoned agricultural land.
- Our approach is consistent with this conclusion, and with that of the FAO assumptions on land required for future food production. We focus on currently abandoned agricultural land for growing energy crops, with only limited (if any) use of land currently used for growing food crops or previously uncultivated land.

Sources: (i) Fischer, G., van Velthuizen, H., Shah, M. and Nachtergaele, F. (2002), Global Agro-ecological Assessment for Agriculture in the 21st Century: Methodology and results. IIASA. (ii) Bruinsma, J. (2009) The resource outlook to 2050: by how much do land, water and crop yields need to increase by 2050? (iii) Campbell, J. E., D. B. Lobell, R. C. Genova, and C. B. Field (2008), The global potential of bioenergy on abandoned agriculture lands, Environmental Science & Technology, 42(15), 5791-5794. (iv) Cai, X., Zhang, X. and Wang, D. (2011), Land availability for biofuels production, Environmental Science and Technology, 45, 334-339. (v) Fischer, G. (2009), World food and agriculture to 2030/50: how do climate change and bioenergy alter the long-term outlook for food, agriculture and resource availability?

The range of land covered in our scenarios is 100-700 million hectares (Mha), with a range for yield of 5-15 tonnes dry matter/ha, giving rise to bioenergy shares of primary energy demand in 2050[3] ranging from around 1 to 18% (Box 3.4):

- **Constrained Land Use (CLU).** In this scenario only a small proportion of abandoned agricultural land, with an assumed low level of productivity, is used for the growth of dedicated energy crops. This is designed to reflect a world where much of the abandoned agricultural land has prohibitively low productivity and/or where there are tight social and environmental constraints, and/or where land conversion would result in significant carbon release.

3 Approximately 186,000 TWh under the IEA's Blue Map Scenario; IEA (2010) Energy Technology Perspectives..

- **Extended Land Use (ELU).** This scenario relaxes productivity and sustainability constraints, allowing greater use of abandoned agricultural land for dedicated energy crops, but still very limited use of current agricultural land and previously uncultivated land.
- **Further Land Conversion (FLC).** We include two land conversion scenarios which are either highly uncertain (e.g. as regards agricultural productivity growth or behaviour change) or require ethical judgments to be made (e.g. around biodiversity loss), and which should therefore be used only as sensitivities and not as a basis for planning. These scenarios give the same bioenergy production but for different reasons:
  - **Agricultural Land Conversion.** This includes growth of dedicated energy crops on some land where food crops are currently grown. It therefore assumes either agricultural productivity growth beyond that envisaged by the FAO or diet change (i.e. a reduction in livestock consumption).
  - **Natural Habitat Conversion.** This has the same level of bioenergy supply as in the agricultural land conversion scenario, but under a different assumption that energy crops are grown on uncultivated land, which is likely to result in the conversion of a range of natural habitats. However, this scenario could involve high land use change emissions.

Without appropriate regulation, much higher levels of bioenergy penetration might ensue under a market-based approach and a rising carbon price (i.e. where bioenergy has a high market value and supply is allowed to adjust to reflect this). However, this would not be desirable from a sustainability perspective, given the impact on food supply, biodiversity, and soil carbon.

Therefore in order to limit dedicated energy crops to the levels in our scenarios, new regulatory arrangements would have to be introduced (e.g. limiting the types of land on which dedicated energy crops can be grown, and the extent to which these can be used to meet carbon targets). Confidence should be provided about regulatory arrangements before any new targets for the longer-term use of bioenergy are set.

Box 3.4: CCC bioenergy resource scenarios

Constrained Land Use

This scenario assumes 100 Mha or around 20% of estimated global abandoned agricultural land is used for dedicated energy crops by 2050.

- It reflects a world where there is a limit on scope for cultivation of abandoned agricultural land, and very limited scope for use of uncultivated land, either because this land is insufficiently productive, and/or due to water stress and concerns around biodiversity impacts, and/or where land conversion would result in significant carbon release.
- It assumes very limited use of current agricultural land, which continues to be used for growth of food crops to meet rising food demand.
- It assumes a crop yield at the low end of the range (5 tonnes/ha), reflecting the fact that abandoned agricultural land is likely to have low productivity.

Given such a yield, this land could produce around 2,600 TWh of energy, accounting for around 1.4% of the IEA Blue Map scenario global primary energy demand in 2050.

Box 3.4: CCC bioenergy resource scenarios

Extended Land Use

This scenario assumes 400 Mha of land is used for growing dedicated energy crops by 2050. It therefore relaxes the constraint on the proportion of abandoned agricultural land used for energy crops, reflecting a world where there is more land available of sufficient – albeit still low – productivity, and/or where there is less concern about biodiversity and water stress or between low-carbon and wider environmental objectives, and/or release of soil carbon from land conversion.

- It is an optimistic scenario because there is a high degree of uncertainty around how much abandoned agricultural land would be sufficiently productive to grow energy crops. Furthermore, there is a lack of confidence that concerns over biodiversity and water stress can be addressed.
- The assumptions on use of agricultural land and previously uncultivated land are the same as in the Constrained Land Use scenario (i.e. there is very limited use assumed).
- Therefore these assumptions on land use are fully consistent with the FAO analysis of land used for growth of food crops and the conclusions in the Foresight report about incremental land available.
- Yield assumptions are the same as in the Constrained Land Use scenario, reflecting that abandoned agricultural land is likely to have low productivity.

Resulting bioenergy potential is around 10,600 TWh (i.e. around 5.6% of the IEA's projected primary energy demand in 2050 under the Blue Map scenario).

Further Land Conversion

Agricultural Land Conversion

This scenario assumes 700 Mha of land is used for growing dedicated energy crops by 2050 (equivalent to around half of all land currently used to grow arable crops).

- It therefore includes growth of energy crops on all abandoned agricultural land, together with some growth on land currently used for food crops (e.g. around 300 Mha).
- This would be compatible with meeting increased food demand given agricultural productivity improvement going beyond that assumed by the FAO (e.g. increases of 100% to 2050 rather than 65% in the FAO analysis), or it could be achieved through change to less carbon intense diets (e.g. a 18% reduction in livestock consumption).
- Yields in this scenario are assumed to be 5 tonnes/ha for abandoned agricultural land, and 15 tonnes/ha (i.e. at the high end of the range) for current agricultural/previously uncultivated land.

Resulting bioenergy potential is around 34,300 TWh (i.e. around 18.4% of the IEA's projected total primary demand in 2050).

Natural Habitat Conversion

This scenario also assumes 700 Mha of land is used for growing dedicated energy crops. It includes growth of energy crops on currently abandoned agricultural land, together with expansion onto productive, previously uncultivated land (e.g. around 300 Mha).

- This scenario would result in the conversion of natural habitats, e.g. unprotected woodland or grassland, and may have significant environmental impact in terms of biodiversity loss and loss of soil carbon.
- Yields in this scenario are assumed to be 5 tonnes/ha for abandoned agricultural land, and 15 tonnes/ha (i.e. at the high end of the range) for current agricultural/previously uncultivated land.

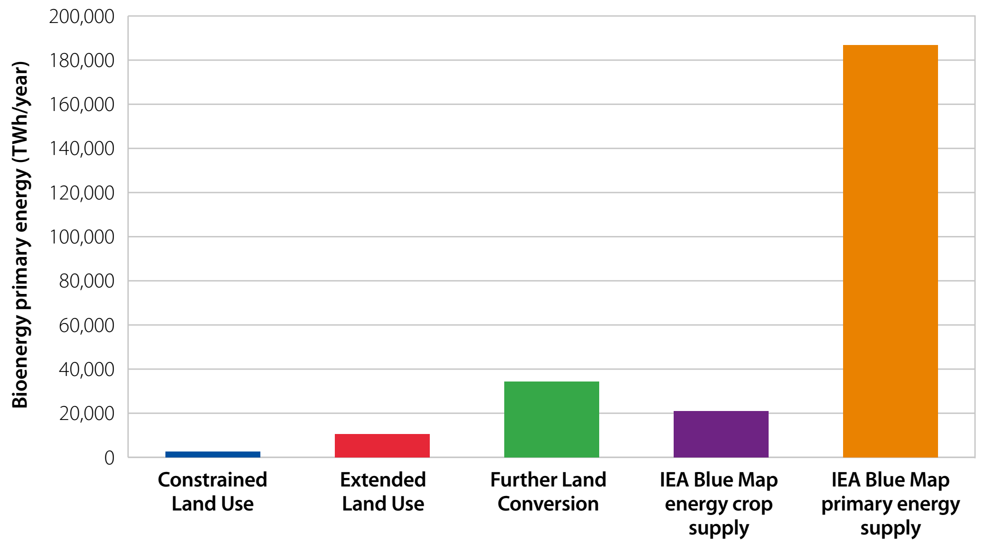
Resulting bioenergy potential is around 34,300 TWh (i.e. around 18.4% of the IEA's projected total energy demand in 2050). Although this is similar to that of the agricultural land conversion scenario, yields on uncultivated land are more uncertain.

These scenarios range around the IEA Blue Map scenario which assumes 11% of total primary energy demand could be met by energy crops in 2050, compared to 1.4% in our CLU scenario, 5.6% in the ELU scenario and 18.4% in the FLU scenarios (Figure 3.2). More generally, there are many studies which suggest a similar range for bioenergy supply (Figure 3.3).

There are some studies which include significantly higher scenarios for potential supply as they assume higher levels of land availability. However, these studies make overly optimistic assumptions about agricultural productivity improvement and breakthroughs in bioenergy technologies, as well as loosening sustainability constraints which make them an inappropriate basis for low-carbon strategy for at least three reasons:

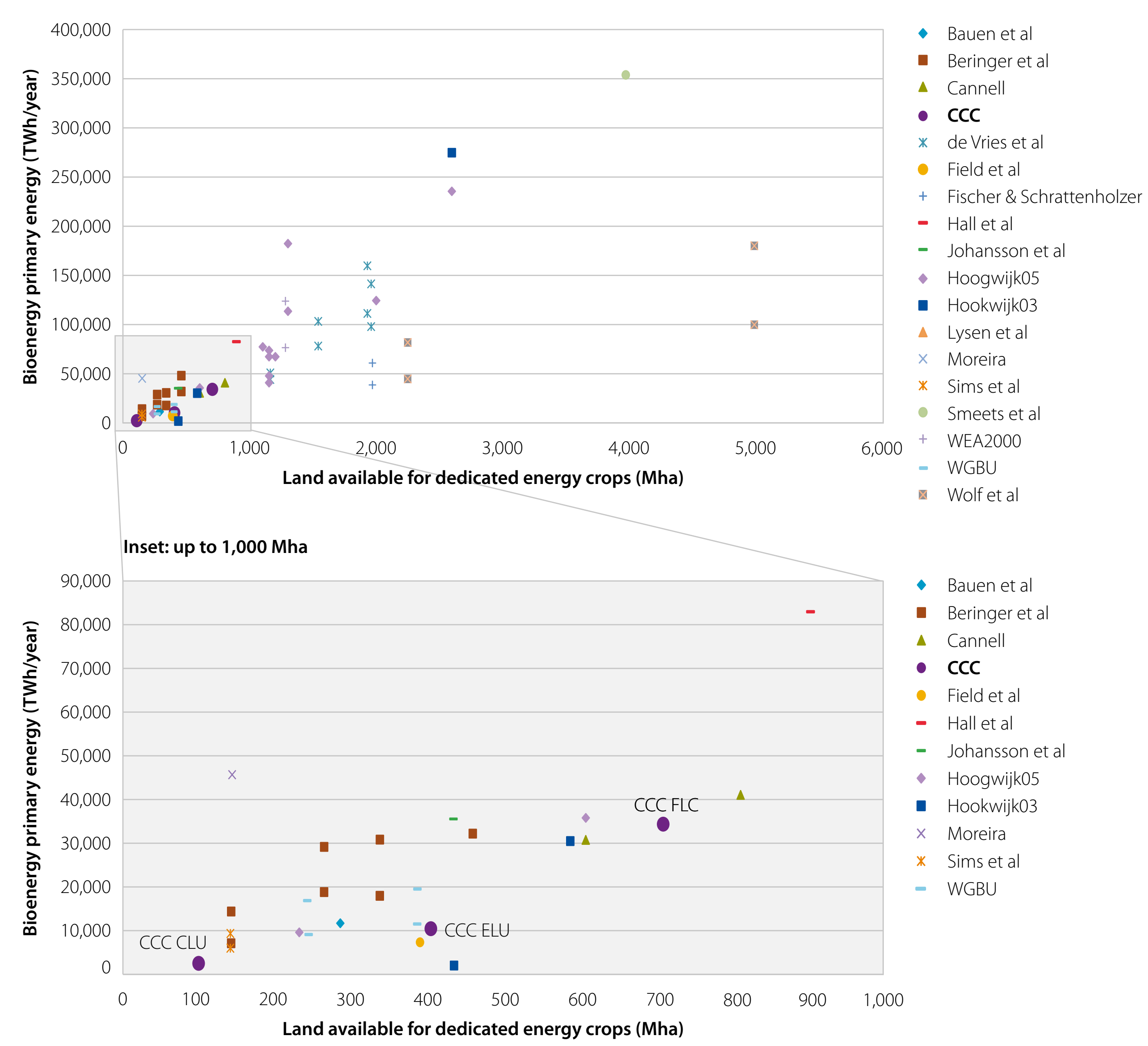
- Such scenarios are predicated on very high rates of agricultural productivity growth, which are likely to require increased use of fertiliser and could therefore be incompatible with achieving carbon targets.
- Alternatively, high rates of agricultural productivity growth would require major breakthroughs in advanced crop breeding. While this should not be ruled out, given the degree of uncertainty, such breakthroughs should not be the basis for low-carbon strategy.
- Scenarios with higher levels of energy crops also have higher associated risk of indirect land use impacts and associated emissions (i.e. there is a higher likelihood of displacing agricultural production to soil carbon rich land as competition between use of land for energy crops and food increases).

Figure 3.2: CCC global energy crops scenarios in 2050 compared with IEA Blue Map scenario



Source: OECD/IEA (2010); CCC calculations.
Notes: Primary energy accounted for on the 'physical energy content' method, as used by DECC, the International Energy Agency and Eurostat. This method counts the heating value of combustible fuels (bioenergy, fossil fuels), the heat produced by nuclear and geothermal facilities (which is then used, at an assumed 38% efficiency, to generate electricity) and the electricity output of non-thermal renewable generation such as wind and hydro. Primary energy required to meet demand varies depending on the technologies used; this method tends to under-represent the contribution of non-thermal renewables (e.g. wind) and of heat pumps, for which the electricity input is counted and where primary energy can therefore be 3-4 times lower than heat output."

Figure 3.3: CCC scenarios within range of recent studies



Sources: Adapted from Slade, et al., (2011); CCC Calculations.
Note: For full list of references, see Slade, et al., (2011).

We use the range in the four scenarios above as inputs to our assessment of where scarce bioenergy should best be used, while reiterating that the Further Land Conversion scenarios are to be used as sensitivities and are not currently an appropriate basis for planning.

Bioenergy from forestry, agricultural residues and waste

In addition to dedicated energy crops, we assume that there will be some bioenergy resource available from forestry management and forest residues, agricultural residues and wastes. Some of this resource is tradable and can be deployed on a large scale (e.g. pellets from forest biomass) while some feedstocks, such as wastes, are non-tradable and could serve local markets (e.g. biofuel from used cooking oil).

There is a wide range of estimates in the literature of the potential resource derived from these feedstocks. Our estimates are largely drawn from analysis commissioned by the Department of Energy and Climate Change (AEA, 2011) and by the Department for Transport (E4tech, 2011), which attempt to construct a sustainable picture of future supply that is constrained by market, logistical and environmental factors[4]:

- **Forestry and forest residues:** We use estimates ranging from 1,100 to 1,600 TWh of sustainable biomass in 2050, after allowing for use of timber for industrial wood, paper and pulp, as well as for fuelwood. The bulk of the forest resource is likely to come from North America, Europe and Russia. We assume that part of this resource (300 to 450 TWh, representing the small roundwood resource) could alternatively be used as wood in construction.
- **Agricultural residues:** Although there is a potentially high level of agricultural residues (e.g. according to the IPCC between 5,000 and 20,000 TWh in 2050), much of this will not be available internationally for bioenergy use, given the lack of suitability for export, and competition from other uses (e.g. for nutrient recycling and soil stability). We use estimates ranging from 300 to 1,800 TWh of agricultural residues potentially available in the global market in 2050.
- **Wastes:** Although there is significant potential bioenergy supply from waste, this is unlikely to be traded internationally. Therefore we reflect this potential in our analysis through including estimates of potential for domestic bioenergy from waste in our UK energy scenarios below. The availability of wastes suggests that there are many niche markets.

Taking these categories together, they could add around 1,500 to 3,300 TWh to the global bioenergy resource, compared to 2,600 to 34,300 TWh in our scenarios for dedicated energy crops.

The resulting total bioenergy resource (i.e. from dedicated energy crops, forest biomass, agricultural residues and wastes) is at the low end of the range recently suggested by the Intergovernmental Panel on Climate Change (IPCC)[5]. This reflects the cautious approach in our land use scenarios, which we believe is appropriate given sustainability concerns.

4 AEA, including Oxford Economics, the Biomass Energy Centre and Forest Research (2011), UK and Global Bioenergy Resource and E4tech (2011) and E4tech (2011), Modes Project 1: Development of illustrative scenarios describing the quantity of different types of bioenergy potentially available to the UK transport sector in 2020, 2030 and 2050. The ranges reflect overcoming a number of constraints and barriers under energy prices ranging from £4-£10/GJ.

5 IPCC SRREN, (2011). However, it is important to note that our assessment of the global resource focuses on those feedstocks which are likely to be traded on the international market and therefore exclude a not insignificant amount of resource considered by the IPCC which could be used locally in each country (i.e. straw and biodegradable waste).

UK bioenergy scenarios

We derive UK bioenergy scenarios – inputs to our modelling of appropriate bioenergy use – from global scenarios for tradable bioenergy feedstocks and estimates of UK domestic production of non-tradable feedstocks:

- **Globally tradable feedstocks.** We assume that the UK will receive a pro-rata share of tradable feedstocks:
  - Tradable feedstocks include energy crops as in our Constrained Land Use, Extended Land Use and Further Land Conversion scenarios, together with forest biomass and some agricultural residues, for which we assume supply in the centre of the range of estimates in the above subsection.
  - In the long run, all countries are likely to compete for these tradable feedstocks, and we reflect this competition in our analysis:
    - Of the various methodologies for allocating global supply of tradable bioenergy (e.g. equal per capita, pro-rata GDP share), a bioenergy share reflecting the UK's share of total energy consumption best proxies the likely outcome under a market-based allocation of bioenergy. This assumes that the UK economy has a broadly similar structure to the global economy. We consider the resulting share as a proxy for what we might be able to use rather than an entitlement.
    - In reality, the UK share may be lower. This is due to its relatively low share of energy-intensive industry in GDP, and the high value of biomass in energy-intensive industry, as well as its relatively low share of domestic bioenergy production in higher penetration scenarios, suggesting relatively high costs of transporting bioenergy feedstocks and products.
- **Non-tradable feedstocks:** The main non-tradable bioenergy feedstocks are derived from waste sources and wet agricultural residues (e.g. animal manures), for which there is significant potential in the UK. Analysis by AEA (2011) and Defra (2011) suggests that this could account for 50 to 60 TWh in 2050, or up to 3% of total UK primary energy demand in 2050, subject to new approaches to collecting waste and significant investment in anaerobic digestion (AD) and other appropriate technologies.

Combining our estimated shares of global tradable resource with the domestic non-tradable resource gives a range of 100 to 500 TWh of UK bioenergy supply, or a bioenergy share representing 5, 10 and 22% of primary energy demand in 2050 in our Constrained Land Use, Extended Land Use and Further Land Conversion scenarios respectively (Figure 3.4). More detail on our assumptions about the path to 2050, both as regards overall bioenergy penetration and composition of feedstocks, is set out in Box 3.5.

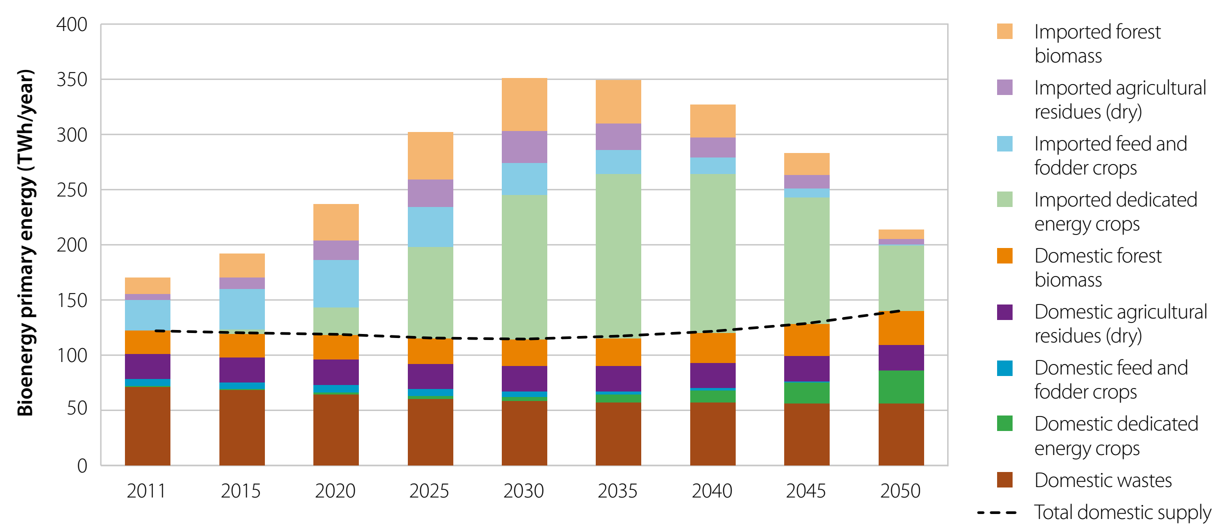
Of total bioenergy supply, domestic production of energy crops, forestry, forest residues and agricultural residues, together with waste could account for 100%, 65%, and 38% in our Constrained Land Use, Extended Land Use and Further Land Conversion scenarios (Box 3.6).

Box 3.5: The path to 2050: bioenergy penetration and composition over time

Although our scenarios focus on the long term, our modelling of appropriate use (Chapter 4) covers the period to 2050, and requires assumptions on the level and composition of bioenergy on the path to the levels in our 2050 scenarios:

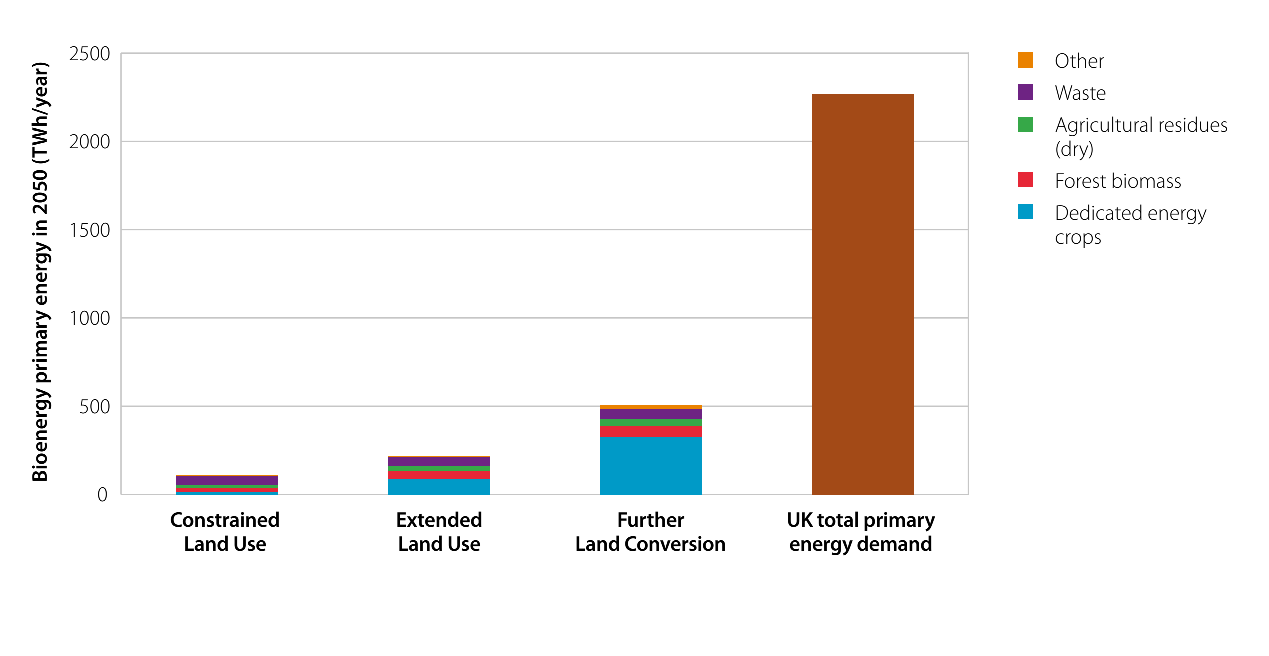
- Total bioenergy penetration. The UK and the EU are currently net importers of bioenergy. We assume that this continues to be the case, and that the UK consumes around 5% of global tradable bioenergy in 2020, dropping to 4% in 2030. By 2050 we have assumed that there will be greater competition for scarce bioenergy supplies and that the UK's share should be based on the projected share of primary energy demand under a low-carbon pathway. Therefore in 2050, the UK share of global bioenergy falls to 1.2%.
- Composition of bioenergy.
  - We assume that in the longer term dedicated energy crop feedstocks are a mix of fast growing trees and grasses with a high lignin content. We make this assumption for three reasons: these crops are likely to be suited to land of low productivity in our energy crops scenarios, they have low lifecycle emissions, and they can be converted for use across the range of sectors.
  - This does not preclude a transitional role for food and fodder feedstocks, which we envisage making an important contribution in the near- to medium-term, subject to concerns about lifecycle emissions and food security being addressed. Any longer-term role for food and fodder feedstocks (e.g. into the 2030s and beyond) would have to be predicated on evidence that:
    - These feedstocks can be grown on currently abandoned agricultural land.
    - Cultivation has lifecycle emissions comparable to those from other energy crops.
    - Conversion routes to appropriate uses are available and viable.
  - Imported and domestic forestry, forest residues and agricultural residues, as well as domestic wastes will also contribute significantly, representing 60% of the UK's bioenergy supply in 2050 under the Extended Land Use scenario.

Figure B3.5: Trajectory of feedstock groups under Extended Land Use scenario



Source: AEA (2011); E4Tech (2011); CCC analysis.

Figure 3.4: CCC scenarios compared to 2050 energy demand



Source: CCC analysis.
Notes: 'Other' includes food and fodder feedstocks and macroalgae. Primary energy based on modelling presented in Chapter 4, including energy efficiency and demand growth at levels consistent with those in the CCC 4th carbon budget analysis and accounted for on the 'physical energy content' method, as used by DECC, the International Energy Agency and Eurostat. This method counts the heating value of combustible fuels (bioenergy, fossil fuels), the heat produced by nuclear and geothermal facilities (which is then used, at an assumed 38% efficiency, to generate electricity) and the electricity output of non-thermal renewable generation such as wind and hydro. Primary energy required to meet demand varies depending on the technologies used; this method tends to under-represent the contribution of non-thermal renewables (e.g. wind) and of heat pumps, for which the electricity input is counted and where primary energy can therefore be 3-4 times lower than heat output.

Box 3.6: UK domestic supply

The UK can produce a variety of bioenergy feedstocks with a potential resource of 108 to 208 TWh in 2050, which represents between 38% and 100% of our UK bioenergy supply scenarios. While UK bioenergy resource can make a meaningful contribution to decarbonising large-scale power, industry, and transport, the dispersed nature of the resource and the challenges to harvesting, storing and transporting large quantities suggest a particularly important role for certain domestic feedstocks in regional applications (e.g. domestic boilers, anaerobic digestion and district heating and power).

A breakdown of potential sources of UK bioenergy and ranges of estimates is provided below, as well as key barriers to market development. More detail can be found in the technical paper accompanying this report.

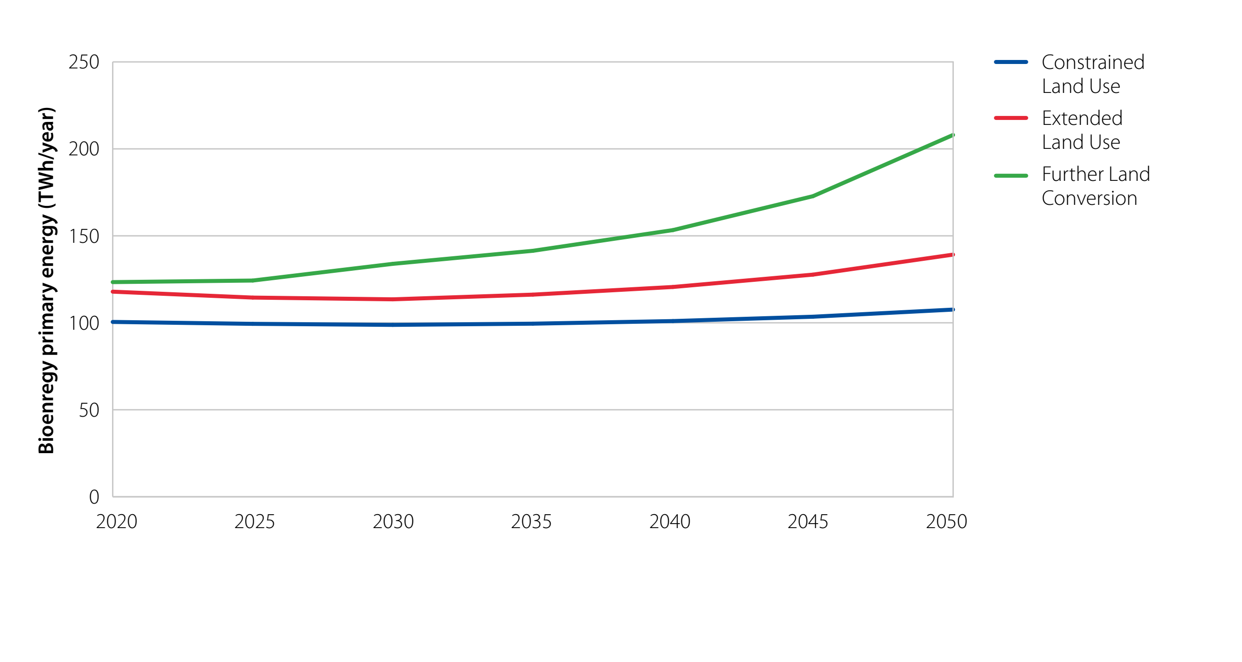
- **Food and fodder crops:** Biofuel produced from wheat, sugar beet and oil seed rape crops could reach 7 TWh in 2020 but reduces to zero by 2050, given sustainability concerns related to land use and biofuels meeting greenhouse gas savings criteria.
- **Dedicated energy crops:** Bioenergy produced from growing a mix of miscanthus and SRC willow on poorer quality and/or on some arable land released from agriculture could range from 3 to 13 million (oven-dried) tonnes, or 15 to 70 TWh in 2050. This range reflects the planting of crops on 0.3 to 0.8 Mha hectares, which would represent 5 to 13 percent of arable land in the UK. Key sustainability concerns associated with growing dedicated energy crops in the UK include land availability (and the potential for direct and indirect land use change and affiliated emissions), biodiversity impacts, and water stress. As for global energy crop development, additional land could become available in the UK through improved agricultural productivity, diet change (which would reduce pressure on land for feed production and grazing), and/or changes in production systems (e.g. agro-forestry).

Box 3.6: UK domestic supply

- **Forestry and forest residues:** A potential for 4 to 9 million (oven-dried) tonnes, or 19 to 47 TWh in 2050, which could arise from increased management of forests, sawmill industry residues, tree surgeries, and short-rotation forestry plantations. Key constraints to developing forest biomass supply include a lack of infrastructure, storage and transport facilities, the dispersed nature of the resource, and convincing private landowners to manage forests for bioenergy. Competition for feedstock (e.g. by the wood panel manufacture industry, for horticultural woodchips and animal bedding) may also impact the availability of the resource.
- **Agricultural residues (dry):** The main dry agricultural residue available in the UK is straw. There are a number of constraints that are likely to restrict the availability of dry agricultural residues for energy purposes including the dispersed nature of the resource, the value of straw as a fertiliser and competition (e.g. from animal bedding and feed markets). Agricultural residues could provide around 21 to 26 TWh in bioenergy by 2050.
- **Wastes:** A number of wastes could be diverted for bioenergy use, including waste wood, food waste, other solid waste, sewage sludge and used cooking oil. At present, wastes are used to generate landfill gas, incinerated with energy recovery and some biogas is generated from sewage sludge digestion. The energy available from waste is likely to decline over time as waste is diverted away from landfill into re-use and recycling to meet landfill and recycling targets. There is scope to increase the quantities of waste incinerated with energy recovery or sent for anaerobic digestion to generate biogas. However, this will require investment in the necessary infrastructure and separate collection of some wastes. Wet agricultural residues (e.g. livestock manures) are also a potential bioenergy feedstock and can be digested to produce biogas. The total resource available in 2050 could range from 50 to 60 TWh. Key constraints include the dispersed nature of the resource, establishment of new processing facilities and the requirement for some waste-streams to be collected separately (e.g. food waste, used cooking oil).

A summary of potential UK domestic resource is provided in Exhibit B3.6 below.

Figure B3.6: UK domestic bioenergy resource under CCC scenarios



Notes: 1 oven-dried tonne of feedstock assumed to have a calorific value of 19 GJ or 5.3 TWh
Sources: CCC analysis; AEA (2011); E4tech (2011), Defra. Source: AEA (2011); E4Tech (2011); CCC analysis

Chapter 4

Appropriate use of scarce bioenergy

In this section we consider where the scarce bioenergy resources identified in our scenarios might best be used to reduce emissions, given alternative low-carbon technologies and associated costs (Box 4.1 summarises specific questions that we try to answer).

Box 4.1 Appropriate use questions

- How much bioenergy may be required to meet emissions targets given other low-carbon technologies that are available or likely to be available?
- Is it plausible that there would be use of bioenergy in power generation without CCS in the long term?
- To what extent should we plan to achieve aviation emissions reductions through the use of liquid biofuels?
- Is there a widespread role for the use of liquid biofuels in surface transport?
- Is it more sensible to use woody biomass feedstocks in construction rather than in power or industrial heat?
- What is the role of biomass for heating buildings?

Our approach is first to consider at a high level what can be inferred from a comparison of our bioenergy scenarios with projections of energy demand. We then set out detailed analysis of appropriate bioenergy use based on a model of the role of bioenergy within the UK energy system. This analysis provides insights that are relevant both to the UK and – in a world where other countries also have increasingly tight carbon constraints – more generally.

Building on the insights from this modelling, we draw out implications for approaches in specific sectors. In doing this, our aim is not to set out a blueprint for decarbonising the economy. Rather, we identify technology options (bioenergy and other low-carbon options) which are robust to uncertainties and should be developed with a view to meeting future carbon budgets, the balance between which can be determined at a later date as current uncertainties are resolved.

We set out this analysis in 8 sections:

(i) High-level assessment of appropriate use

(ii) Detailed analysis of appropriate bioenergy uses

(iii) Implications for power sector decarbonisation

(iv) Implications for industry decarbonisation

(v) Implications for use of biomass for heat in buildings

(vi) Implications for the role of biogas

(vii) Implications for aviation and shipping emissions

(viii) Implications for surface transport decarbonisation

(i) High-level assessment of appropriate use

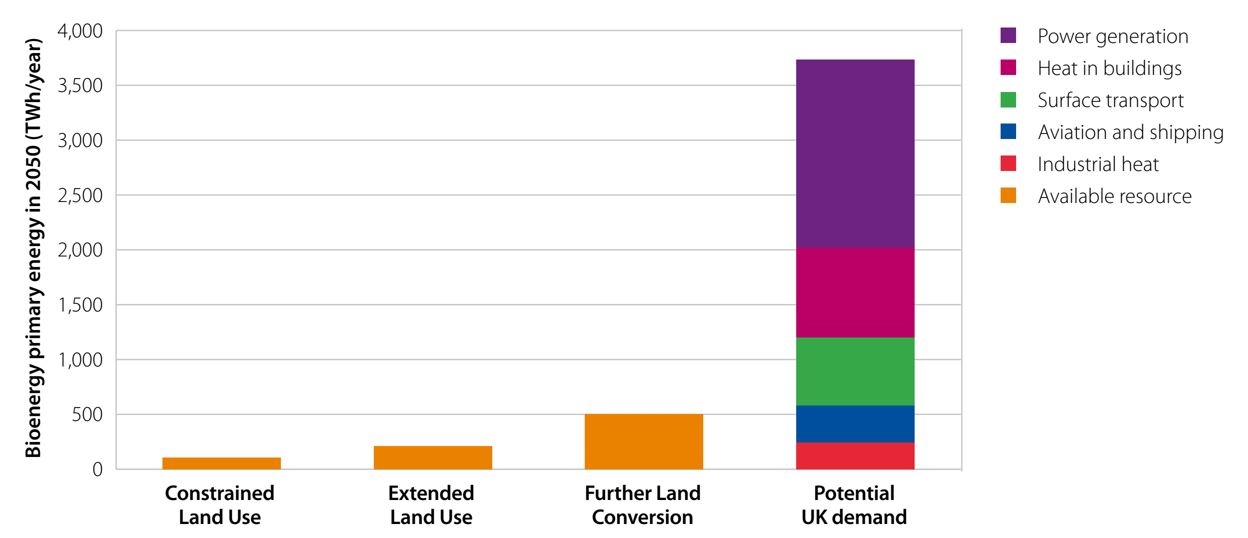
In previous reports we have assumed that bioenergy use is likely to be concentrated in areas in which there are very limited options for decarbonisation (i.e. energy-intensive industry, aviation, and shipping).

Our assessment of land use in this report reinforces our previous assumptions, and suggests that there is unlikely to be sufficient bioenergy available for the full decarbonisation of energy-intensive industry, aviation and shipping, and that widespread use of bioenergy in surface transport is highly unlikely to be feasible:

- In order to meet demand from energy-intensive industries, aviation and shipping in full, land in excess of 850 Mha would be required for growing bioenergy crops, compared to 400 Mha in our Extended Land Use scenario.
- To meet demand from surface transport in addition, the area of land required would increase to around 1,500 Mha, equivalent to the area currently planted with arable crops. This is implausible given the need for food.

It is therefore clear that bioenergy supply is likely to be limited relative to potential demand and that there will have to be trade-offs between uses across sectors, both globally and in the UK (Figure 4.1). In the following sections we set out our analysis of the benefits of using a limited supply of bioenergy in different ways.

Figure 4.1: Bioenergy supply scenarios versus potential demand in 2050



Source: CCC modelling, using model developed by Redpoint Energy and Ecofys.
Note: Calculations of potential UK demand assume that all 2050 energy use is met from energy crops, in the most cost-effective manner. Projected demand assumes energy efficiency and demand growth at levels consistent with those in the CCC 4th carbon budget analysis and the modelling presented later in this Chapter. This calculation of potential bioenergy demand differs from the primary energy calculation presented in Chapter 3, as primary energy input depends on the technology used – some technologies (e.g. wind generation and heat pumps) require substantially lower primary energy input per unit of output, under standard primary energy accounting conventions.

(ii) Detailed analysis of appropriate bioenergy uses

Appropriate use modelling approach

This section summarises results of our detailed analysis of appropriate planning assumptions for the use of scarce bioenergy resources to meet emissions targets. In the near term, bioenergy use will be driven by UK obligations under EU renewables legislation. In particular, the overall bioenergy ambition will be determined by the EU's target to achieve a 20% renewable share of final energy by 2020, as part of which the UK should achieve a 15% share, including a 10% penetration of renewable energy in surface transport. The choice that has to be made here is about the best means to meet renewable energy targets, for example through use of biomass in power generation versus surface transport.

In the longer term, the choice relates to both the quantity of biomass and where this should be used in order to meet emission targets. Our analysis aims to identify robust strategies across the range of abatement options (energy efficiency, bioenergy and other low-carbon technologies) and uncertainties (e.g. for bioenergy supply, technology costs, fossil fuel prices). Our analysis draws on a model developed for us and DECC by Redpoint Energy and Ecofys:

- The model focuses on CO_2 emissions. The target to reduce all greenhouse gas emissions in 2050 by 80% on 1990 levels requires that CO_2 emissions (including international aviation and shipping) are reduced from current levels of around 540 $MtCO_2$ to 105 $MtCO_2$ in 2050 assuming a 70% reduction in non-CO_2 levels versus 1990.
- The model identifies least-cost means to achieve emissions targets and the 2020 renewables target for a given available bioenergy supply and a set of assumptions about other technologies to reduce emissions and energy efficiency improvements.
- It includes the full range of options for energy efficiency improvement in buildings, industry and transport.
- It takes as given the level of available bioenergy supply (i.e. as in our scenarios above).
- It considers alternative uses across sectors (e.g. as biomass for heat generation in industry, or – via various processes – as liquid biofuels for use in surface transport or aviation).
- It uses assumptions on technology characteristics developed for our previous advice (e.g. the fourth carbon budget report), complemented with estimates for bioenergy technology characteristics from E4tech.
- It includes emissions associated with the production of bioenergy, whether or not these would actually occur in the UK or in other countries (e.g. as embodied emissions in imported biofuels).
- In effect, the model simulates a carbon-constrained world with scarce supplies of sustainable bioenergy, which are allocated via a market and a price mechanism.

We have worked pro-actively in developing and using the model, with a focus on technology availability and cost inputs, and ensuring that energy demand projections fully reflect all opportunities for cost-effective energy efficiency improvement. Our aim is to assess the likely best use of increasingly expensive bioenergy across sectors in the long term, both within and across scenarios (i.e. to model the range of uncertainties), and then to draw out implications for near- to medium-term low-carbon strategy.

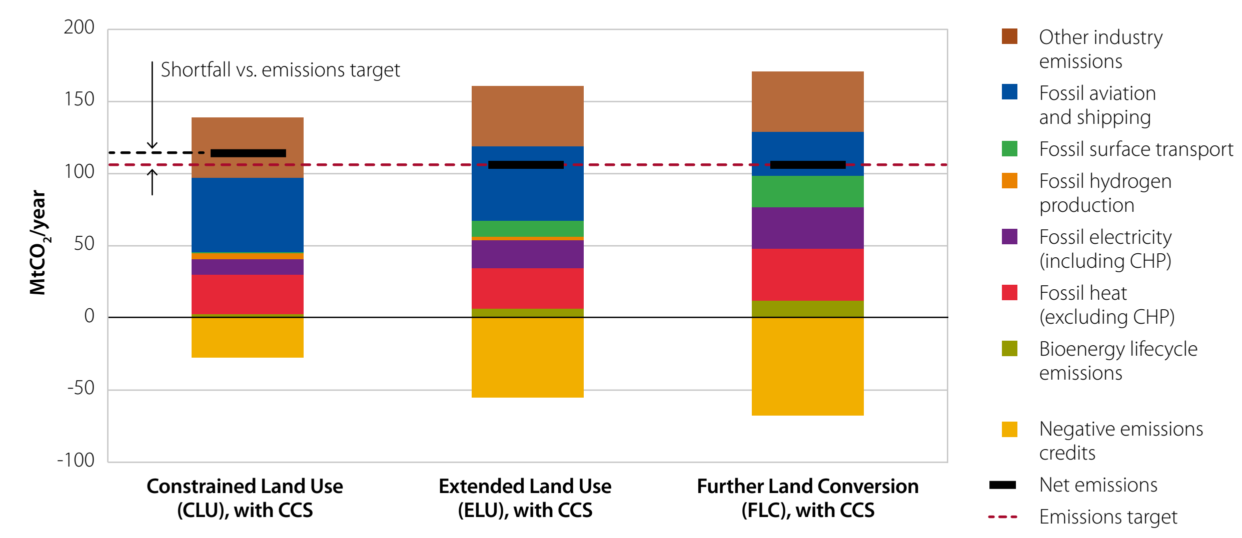
Appropriate long-term bioenergy use

Key results on appropriate use

Considering first the long term (i.e. to 2050), a key result from our analysis is that emissions targets will be very difficult to meet without some – albeit limited – bioenergy penetration, together with the use of CCS technology.

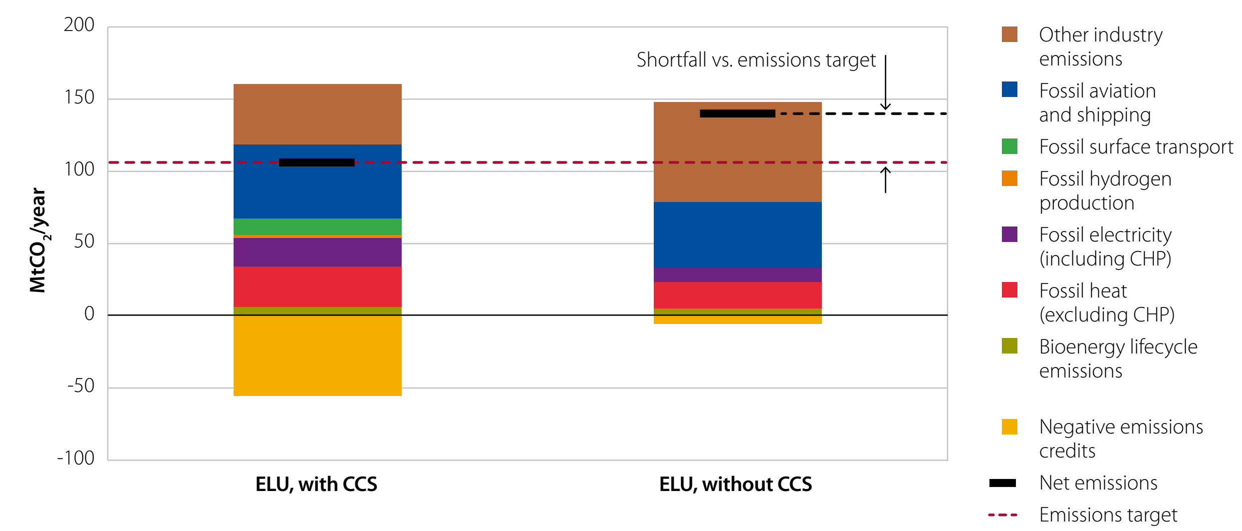
- It will be difficult to meet the overall 2050 emissions target unless bioenergy can account for around 10% of total UK primary energy (i.e. as in our Extended Land Use scenario) and CCS is a feasible technology (Figure 4.2). This reflects the fact that there are a small number of specific economic activities where alternatives to hydrocarbons may either be infeasible (e.g. in aviation) or have not yet been identified (e.g. in iron and steel).
- Scenarios for land use which take account of required food production suggest that a reasonable UK share of sustainable bioenergy could extend to 10% (i.e. as in our Extended Land Use scenario). However, it would be unsafe at present to assume any higher level of sustainable bioenergy supply, and even the 10% level might require some trade-offs versus other desirable environmental and social objectives (e.g. through encroaching on land of high biodiversity value).
- If CCS is not available at the scale envisaged, the amount of bioenergy required to meet the 2050 target would have to be significantly higher than 10% of primary energy demand (Figure 4.3), and would imply land use change exceeding reasonable currently estimated sustainability limits. This highlights the importance of CCS and other sequestration options (e.g. use of wood in construction), which offer the opportunity for negative emissions through a combination of carbon storage, displacement of fossil fuels, and reduced process emissions from chemical reactions in industry (Box 4.2).
- Therefore if CCS does not prove a viable technology and/or if subsequent developments in food or energy crop productivity suggest that the land use required to achieve 10% bioenergy penetration is unsustainable, achieving the 2050 target will then require bioenergy technology breakthroughs (e.g. algae), or breakthroughs in other areas (e.g. production of iron and steel without hydrocarbons, or to allow product substitution), further reductions in non-CO_2 emissions, or changes in consumer behaviour (e.g. in relation to diet or travel behaviour).

Figure 4.2: CO_2 emissions in 2050 under a range of scenarios for bioenergy supply, assuming availability of CCS



Source: CCC modelling, using model developed by Redpoint Energy and Ecofys.
Notes: Allowed emissions of 105 $MtCO_2$ based on 2050 target of 160 $MtCO_2e$, adjusted for 55 $MtCO_2e$ non-CO_2 emissions which are outside the scope of the model. Availability of CCS is assumed. Other industry emissions include industrial process CO_2 emissions and CO_2 emissions from other energy supply industries which are also outside the scope of the model; these are assumed to be 42 $MtCO_2$ incorporating 27 $MtCO_2$ of abatement potential from CCS on process emissions. Bioenergy lifecycle emissions include overseas lifecycle emissions for imported bioenergy, as well as those occurring in the UK. Negative emissions credits result from carbon storage in CCS or wood in construction. Where the model is unable to meet the 2050 target, it reduces emissions to the lowest level possible. In these results, Further Land Conversion (FLC) denotes specifically our Agricultural Land Conversion scenario, in which there are negligible land use change emissions (see Chapter 3).

Figure 4.3: CO_2 emissions in 2050 in scenarios with and without CCS



Source: CCC modelling, using model developed by Redpoint Energy and Ecofys.
Note: Extended Land Use scenario. Allowed emissions of 105 $MtCO_2$ based on 2050 target of 160 $MtCO_2e$, adjusted for 55 $MtCO_2e$ non-CO_2 emissions which are outside the scope of the model. Other industry emissions include industrial process CO_2 emissions and CO_2 emissions from other energy supply industries which are also outside the scope of the model; these are assumed to be 69 $MtCO_2$ in the scenario without CCS and 42 $MtCO_2$ in the scenario with CCS based on previous analysis for our fourth carbon budget report which identified 27 $MtCO_2$ of abatement potential from CCS on process emissions. Bioenergy lifecycle emissions include overseas lifecycle emissions for imported bioenergy, as well as those occurring in the UK. Negative emissions credits result from carbon storage in CCS or wood in construction. Where the model is unable to meet the 2050 target, it reduces emissions to the lowest level possible.

Box 4.2 Long-term abatement from different uses of bioenergy feedstocks

Sustainable biomass absorbs carbon in the growth stage and releases it during conversion or combustion of the final fuel. The emissions released are likely to be at least great as emissions from use of fossil fuels. For example, a new biomass power plant would release around 1000 gCO_2 per kWh generated, compared with around 800 g/kWh for a new unabated coal power plant.

Avoiding this release through sequestering of carbon potentially offers significant emissions reduction benefits, often referred to as 'negative emissions'. It is therefore important to assess the combined benefits of bioenergy from sequestration of carbon and/or displacement of fossil fuels (Figure B.4.2a):

- **Use of wood in construction**. This offers the opportunity both to sequester carbon and to displace the use of carbon-intense construction materials. Benefits are greater than those associated with use of CCS, given that all of the carbon in wood is sequestered as well as there being a significant reduction in industrial emissions from avoided production of iron, steel and cement.
- **Biofuels production**.
  - The fact that a significant amount of the carbon in biofuels feedstocks is released at the conversion stage suggests an opportunity for using CCS in conjunction with biofuels plants. Aviation biofuels produced with CCS would then reduce emissions both through displacement of fossil fuels and through sequestration of carbon.
  - However, use of CCS in plants for producing surface transport biofuels would not offer the same savings. While there would be an emission reduction due to sequestration, surface transport biofuels would not further reduce emissions through displacing fossil fuels, given alternatives for moving to a low-carbon surface transport system (i.e. battery electric and hydrogen vehicles).
- **Power generation**.
  - Use of CCS with biomass in power generation would not displace significant fossil emissions, given other low-carbon alternatives (e.g. nuclear, wind generation). However, it would provide the opportunity for negative emissions to offset emissions in 'hard to reduce' sectors. Depending on the relative CO_2 capture rates[6] this could offer greater overall emissions savings than producing biofuels with CCS for aviation and shipping.
  - However, use of biomass in power generation without CCS would offer no long-term benefit relative to other forms of low-carbon generation, and would divert biomass from other uses where it is more highly valued.
- **Hydrogen production**. The production of a zero-carbon energy carrier from biomass with CCS offers negative emissions benefits similar to those for electricity generation. While the future use of hydrogen is uncertain, it potentially offers an important route for decarbonising heavy-duty vehicles (e.g. buses and heavy goods vehicles) where battery electric vehicles are unsuitable.
- **Industry**. There may be an opportunity to increase emissions reductions through using CCS in conjunction with burning biomass in energy-intensive industries. The use of biomass with CCS results in emissions reductions both through displacement of fossil fuels which would otherwise be used (e.g. coal), and through sequestering the carbon in biomass.
- **Biochar**. Alternatively, biochar, or a solid charcoal produced via the pyrolysis of biomass (e.g. crops, straws or wastes) can be applied to agricultural soils with the potential benefits of a near permanent increase in soil carbon, as well as stabilisation of soil structure, suppression of other GHGs (e.g. N_2O emissions arising from fertiliser use) and enhanced fertiliser-use efficiency. These effects have yet to be widely demonstrated, although recent trials in the UK have indicated modest benefits.

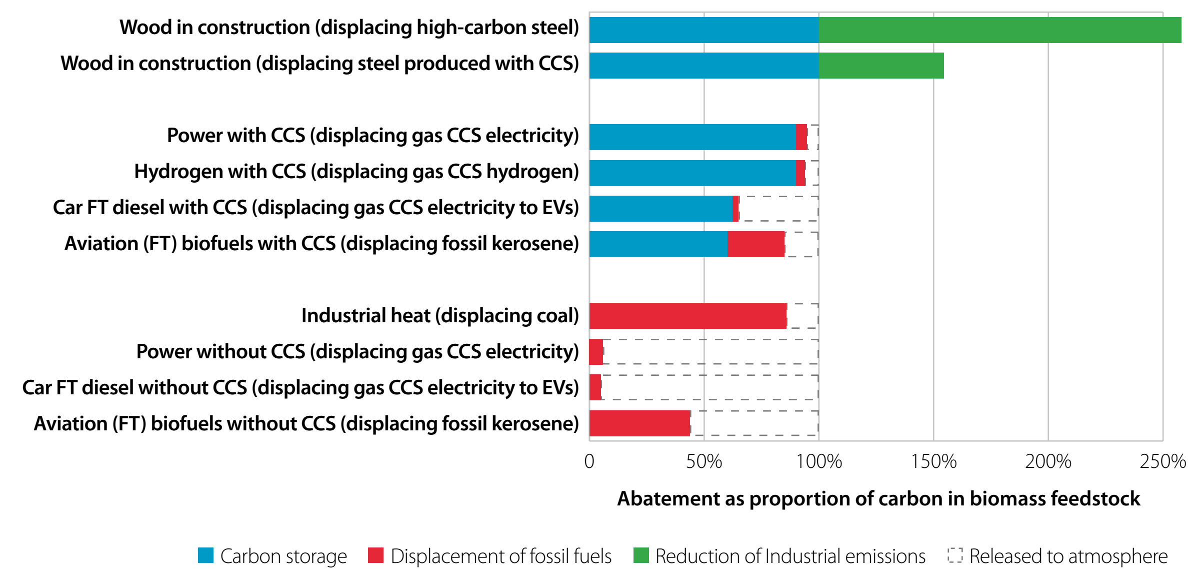
6 The application of CCS will generally sequester a large proportion, but not all, of the CO_2 that would otherwise be emitted to atmosphere. The proportion of the available CO_2 stream that is captured and stored is known as the capture rate and is expected to be around 90% (but in the range 80% to 95%, depending on the application).

Box 4.2 Long-term abatement from different uses of bioenergy feedstocks

Therefore to maximise emissions reductions – which should be the objective over time as emissions constraints are increasingly tight – the focus should be on use of bioenergy in applications which offer opportunities to capitalise on the combined benefits from carbon sequestration and/or the displacement of fossil fuels. These key applications are the use of wood in construction and the use of CCS across a range of applications: in energy-intensive industry, power generation, hydrogen production and biofuels production for aviation/shipping. The precise balance of bioenergy use with CCS across these applications is difficult to predict, and will be determined by their relative economics and technology performance.

This suggests that the main value of CCS may not be that it allows continued use of fossil fuels, but that it offers opportunities when used with biomass for negative emissions reductions, which significantly reduce costs and risks around meeting long-term emissions targets.

Figure B4.2a: Combined benefits from sequestration of carbon and/or displacement of fossil fuels for a range of bioenergy applications in 2050



Source: CCC analysis, based on data in model developed by Redpoint Energy and Ecofys.
Notes: Calculations track the carbon contained in solid biomass, assumed to have a carbon-intensity of 356 gCO_2 per kWh of primary energy. Does not include cultivation or transportation emissions; these are likely to be similar for a given feedstock across the range of applications. CO_2 capture rate for CCS applications assumed to be 90% in electricity and hydrogen generation and 80% in biofuel production. FT refers to Fischer-Tropsch biofuel production.

In considering specific long-term uses, it is therefore essential to distinguish between worlds with and without CCS (Figure 4.4):

- CCS technology is currently promising but uncertain from technical and economic perspectives. If it turns out to be the case that CCS is not viable, our analysis suggests that the most appropriate use of bioenergy from crops and waste would be to generate high grade industrial heat, and as liquid biofuels in aviation and shipping. It is important to note that the key point illustrated by Figure 4.4 is the extent of CCS use rather than its specific application to electricity and hydrogen production, which could equally be biofuel production for aviation and shipping, depending on feasibility and relative cost.
- Where CCS is proven to be a viable technology, our analysis suggests that bioenergy from crops and waste should, where possible, be used in applications with CCS (e.g. power and heat generation, or production of liquid biofuels for use in aviation and shipping). It is important to note that the key point illustrated by Figure 4.4 is the extent of CCS use rather than its specific application to electricity and hydrogen, which could equally be biofuel production for aviation and shipping, depending on feasibility and relative cost.
- In either world, there appears to be a very limited role for the use of liquid biofuels in surface transport. This reflects the fact that premium markets for bioenergy emerge and it therefore becomes expensive (Figure 4.5).
- A second implication of the increasing value of bioenergy over time is that use of biomass in power generation becomes relatively very expensive compared to other low-carbon alternatives, suggesting any role for use in power generation without CCS should only be transitional, and that in the longer term biomass should be used where it is more highly valued (i.e. CCS power generation or use in other sectors).

Sensitivity analysis: bioenergy supply, technology costs, fossil fuel prices

The results above are based on analysis assuming our Extended Land Use bioenergy supply scenario.

However, they hold for sensitivities around technology availability and costs, fossil fuel prices, and for scenarios with higher penetration of bioenergy (Figure 4.6):

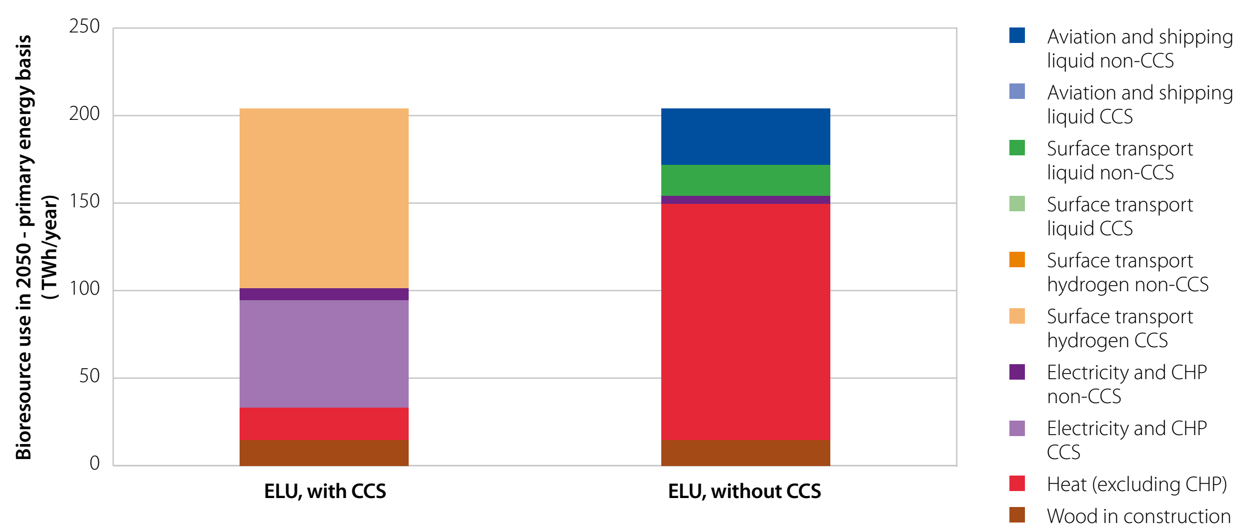
- Much higher bioenergy technology costs and lower fossil fuel prices would change decarbonisation costs rather than the role of bioenergy, given that the need to maximise abatement in the long term to meet the challenging 2050 target.
- Even in our Further Land Conversion scenarios use remains focused in energy-intensive industry, aviation and shipping and applications with CCS, with only niche use in surface transport.

This provides confidence in the options identified as an appropriate use of bioenergy versus those uses where other low-carbon options are more promising (i.e. power without CCS, surface transport).

Demonstration of CCS and broader low-carbon strategy

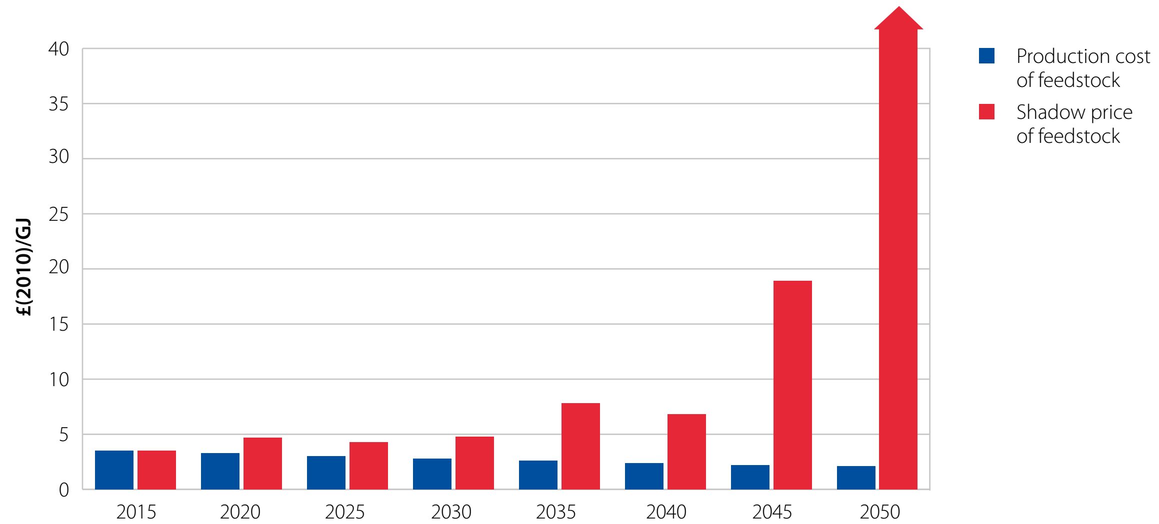
Our analysis highlights the need to demonstrate CCS technology as a matter of urgency, given its potentially crucial role in providing a negative emissions option when used with bioenergy.

Figure 4.4: Bioresource use in 2050 in scenarios with and without CCS



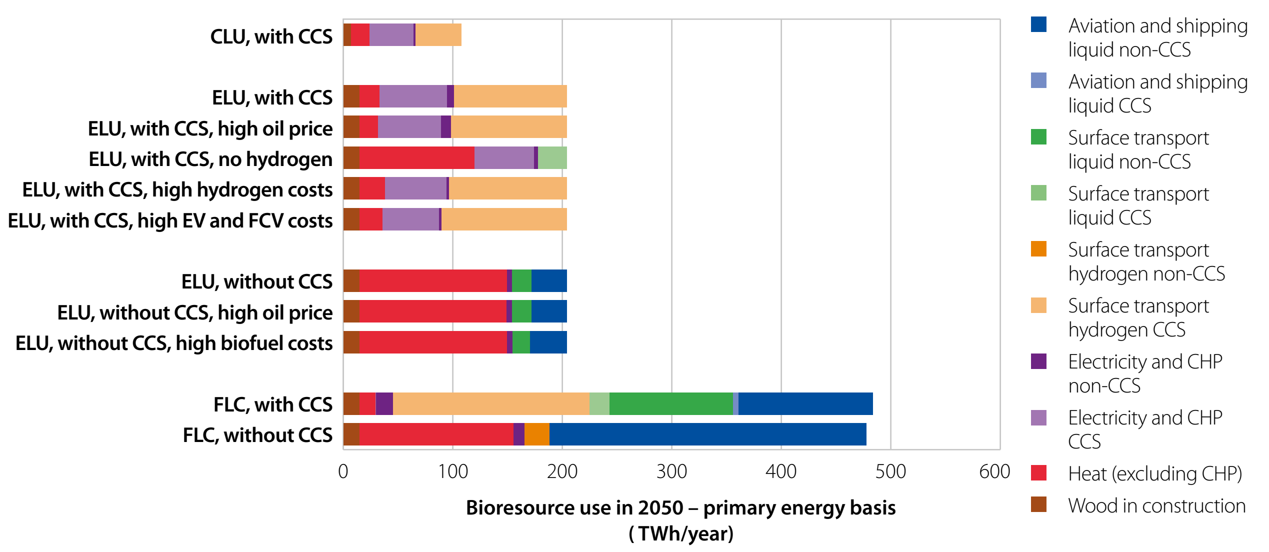
Source: CCC modelling, using model developed by Redpoint Energy and Ecofys.
Note: Extended Land Use scenario. In these results, power and hydrogen production with CCS are selected. In practice however, a range of CCS applications may be appropriate, with the balance dependent on relative technology performance and economics (see Box 4.2). This could result in a higher penetration of aviation and shipping biofuels if these are produced with CCS.

Figure 4.5: Increasing value of UK bioenergy crops over time



Source: CCC modelling, using model developed by Redpoint Energy and Ecofys.
Note: Bioenergy production costs are CCC calculations based on E4tech data, and are inputs to the model; shadow prices are model outputs, and represent the 'traded value' of the feedstock as a result of competition between different potential uses; run using DECC central fossil fuel prices, Extended Land Use bio-resource scenario, CCS assumed to be available.

Figure 4.6: Bioresource use in 2050 under a range of scenarios



Source: CCC modelling, using model developed by Redpoint Energy and Ecofys.
Notes: In these results, Further Land Conversion (FLC) denotes specifically our Agricultural Land Conversion scenario, in which there are negligible land use change emissions (see Chapter 3). EV denotes battery and plug-in hybrid electric vehicles. FCV denotes fuel cell and fuel cell plug-in hybrid vehicles. The model can choose whether or not to use the full available bioenergy resource; in the FLC scenarios there are small amounts of unused resource. In these results, power and hydrogen production with CCS are selected. In practice however, a range of CCS applications may be appropriate, with the balance dependent on relative technology performance and economics (see Box 4.2). This could result in a higher penetration of aviation and shipping biofuels if these are produced with CCS.

More generally, it suggests the need to develop a range of bioenergy options, and to pursue bioenergy paths that offer flexibility regarding their future role (e.g. biomethane injection into the gas grid, gasification pathways for ligno-cellulosic feedstocks).

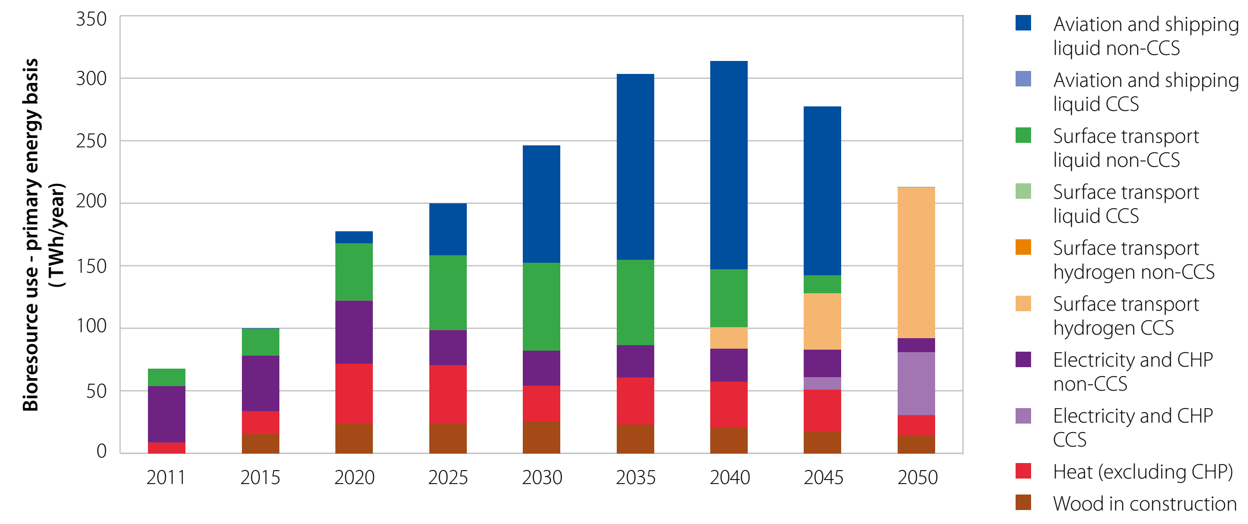
Going beyond bioenergy, our analysis suggests a clear role now for investment in nuclear and wind power generation, energy efficiency improvement, electric forms of heat in buildings, and battery and hydrogen electric vehicles (i.e. these are very unlikely ever to be displaced by bioenergy). We consider approaches in these and other specific sectors in more detail in sections (iii)-(viii) below.

Appropriate medium-term use of bioenergy

Our analysis suggests a path to 2050 characterised by the transitional use of bioenergy resources in non-CCS power generation and surface transport, and ongoing use in industry and construction. There is a strong role for aviation and shipping biofuels in the medium term, with the extent to which this continues dependent on availability of CCS (Figure 4.7, 4.8):

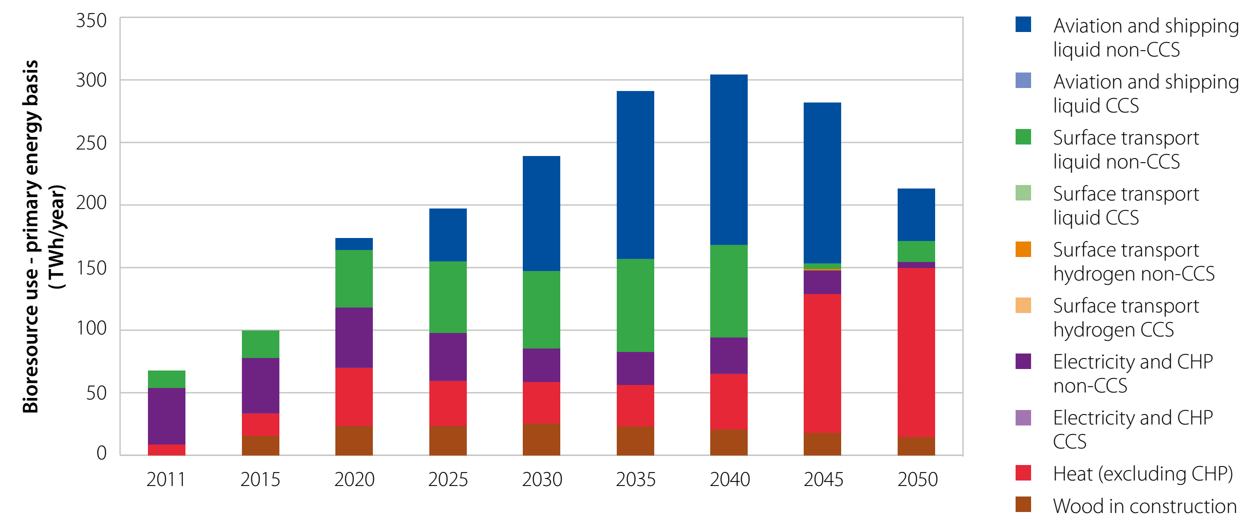
- To 2020: bioenergy resources are used across the range of available applications including construction, heat and power generation (see section (iii) below) and surface transport, with some early deployment in aviation.
- To 2030: there is continued use of biomass in construction, industrial heat, AD and CHP, and biofuels in surface transport, with increasing use in aviation and shipping.
- To 2040: there is continued use in construction, industrial heat and CHP. Use in surface transport starts to decline as this sector electrifies, while there is increased use in aviation/shipping and applications with CCS where available.

Figure 4.7: Bioresource use over time assuming availability of CCS



Source: CCC modelling, using model developed by Redpoint Energy and Ecofys.
Note: Extended Land Use scenario. In these results, power and hydrogen production with CCS are selected. In practice however, a range of CCS applications may be appropriate, with the balance dependent on relative technology performance and economics (see Box 4.2). This could result in a higher penetration of aviation and shipping biofuels if these are produced with CCS.

Figure 4.8: Bioresource use over time assuming CCS is not available



Source: CCC modelling, using model developed by Redpoint Energy and Ecofys.
Note: Extended Land Use scenario.

- To 2050: use in construction and industrial heat continues, with almost all remaining bioenergy used in CCS applications where available. Without CCS, there is ongoing use of aviation/shipping biofuels and increased use in industrial heat.

These paths for bioenergy use raise questions about near-term approaches to bioenergy investment which we now consider.

(iii) Implications for power sector decarbonisation

A transitional role for biomass?

Our analysis suggests that there may be an important long-term role for the use of biomass in large-scale power generation where CCS is available, in which case associated emissions could be negative. However, without CCS, there does not appear to be a longer term role in large-scale power generation, given available alternative low-carbon technologies.

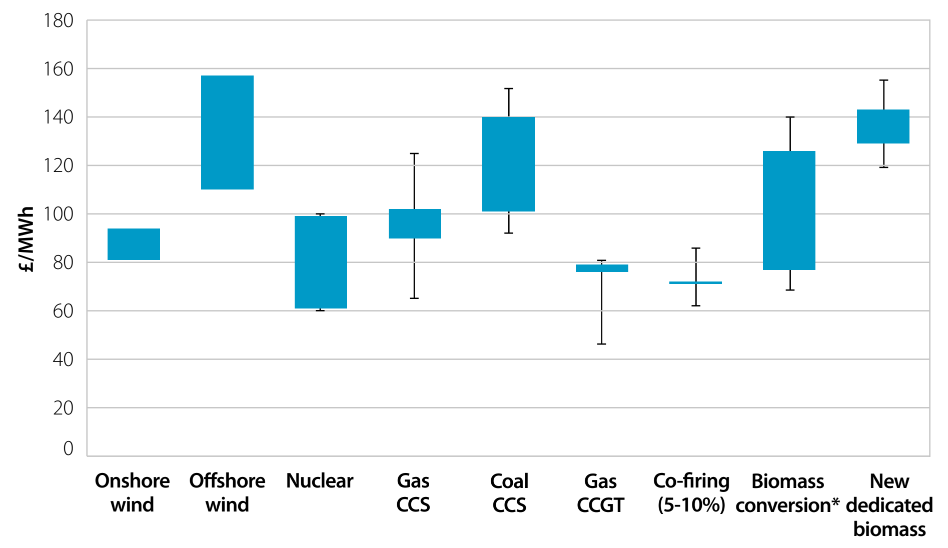
This raises a question about the possible transitional use of biomass in power generation, and the extent to which near-term investment is compatible with longer-term constraints on the availability of biomass supply. Such a role is envisaged by the Government in its Renewable Energy Roadmap, which includes 32 to 50 TWh/year of biomass generation in 2020, compared to current levels of around 12 TWh/year. Whether this ambition is appropriate depends on economics and technical feasibility, in addition to the availability of sustainable biomass supply.

Economics of co-firing, conversion and new dedicated biomass

Analysis we have commissioned for this review from Mott MacDonald (MML) suggests that biomass co-firing and conversion of existing coal-fired power plants to solid biomass are cost-effective options for near-term power sector decarbonisation and meeting renewable energy targets. However, this is unlikely to be the case for new dedicated biomass power plants:

- The MML modelling suggests that the conversion of existing coal-fired plants, most of which are scheduled to come off the system in the next decade, offers the opportunity for biomass power generation at a cost of around £80-90/MWh under central fuel price assumptions. Similarly, co-firing of solid biomass at low levels (e.g. 5-10%) is likely to cost around £70/MWh and enhanced co-firing (e.g. 50%, requiring some capital expenditure) around £80-90/MWh (Box 4.3).
- This can be compared to the cost of gas-fired generation with a carbon price, and the cost of more mature low-carbon technologies such as nuclear power and onshore wind, where we estimate in a central case that costs in 2020 may be of the order £80/MWh (Figure 4.9).
- Therefore subject to there being sufficient sustainable resource, co-firing and conversion may be regarded as cost-effective options both for meeting renewable energy targets and contributing to required power sector decarbonisation through the 2020s.
- In contrast, our analysis suggests that adding new dedicated solid biomass to the system could cost around £130-145/MWh (Box 4.4), which is a similar order of magnitude cost to offshore wind (Figure 4.9). While there are technology policy arguments to justify support for offshore wind, these are less relevant in the case of biomass, which is a more mature technology with a limited long-term role.

Figure 4.9: Cost of large-scale biomass power and other low-carbon technologies

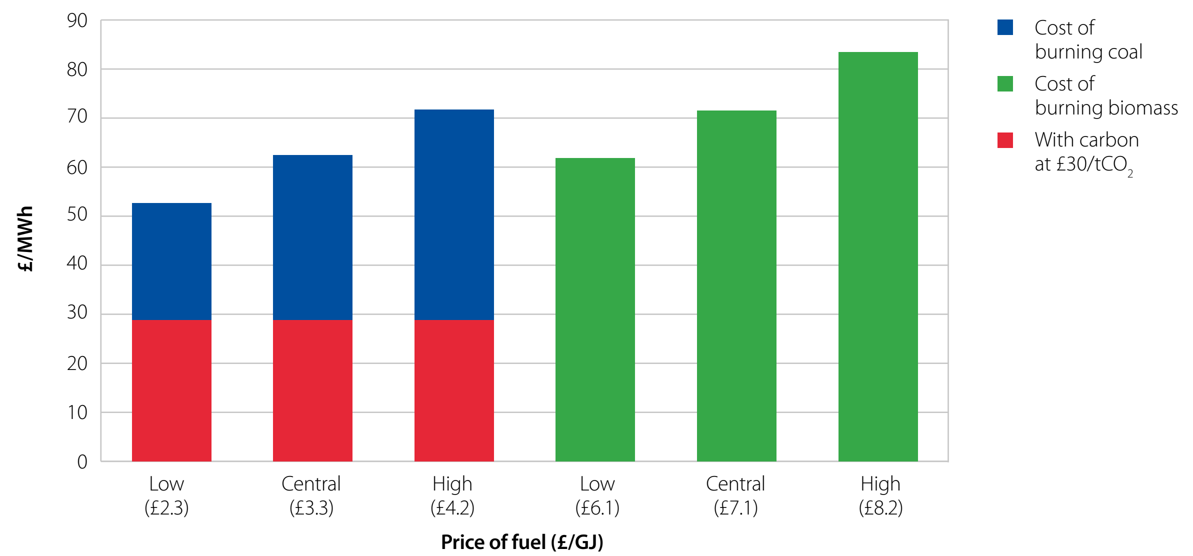


Source: CCC calculations based on Mott MacDonald data.
Notes: £2010. Costs are for projects starting in 2011. 10% discount rate. Solid bars represent the high/low capex figures, thin extending lines show sensitivity to combined high/low capex and fuel prices. Includes a carbon price rising to £30/tCO_2 in 2020. *Solid bar shows range under central prices for 17 of 18 plants considered.

Box 4.3: Biomass conversion and co-firing of solid biomass

Co-firing of solid biomass with fossil fuels at low levels (e.g. 5-10%) may not incur any capital cost (capex) requirements and is driven purely by fuel costs (i.e. £60-80/MWh). This is comparable with the cost of burning coal facing a carbon price of £30/tCO_2 (Figure B4.3a) consistent with the Government's carbon price floor trajectory for 2020. However, the potential from co-firing is limited, given constraints on fossil generation over the next decade (e.g. due to environmental legislation – Large Combustion Plant Directive (LCPD) and Industrial Emissions Directive (IED)).

Figure B4.3a: Cost of co-firing



Source: CCC calculations.

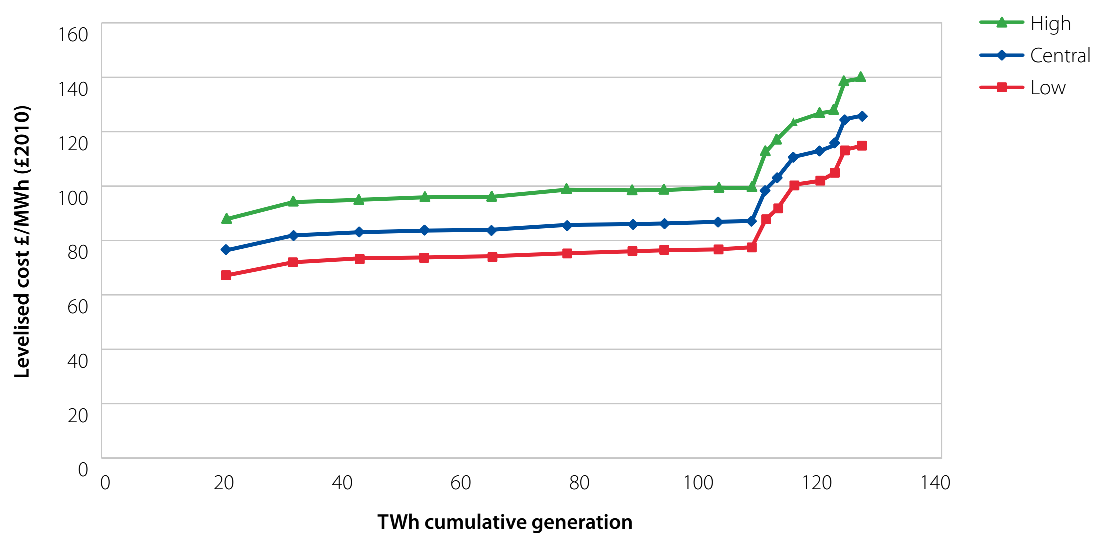
Box 4.3: Biomass conversion and co-firing of solid biomass

Capital spend will be required to unlock more potential, for enhanced (e.g. 50%) co-firing or conversion of existing coal power plants to 100% biomass. Conversion on this scale will require modifications to fuel handling (including storage) and new primary air equipment, and costs will vary on a case by case basis.

The analysis we commissioned from Mott MacDonald (MML) assesses at a high level the costs of converting existing coal plants to 100% biomass ('full conversion') as well as enhanced co-firing (50%). The analysis suggests that the capital cost of full conversion (including compliance with environmental legislation) could amount to around £200/kW for a 1 GW station, with a variation of ±25% and small economies of scale.

Given the lower volumetric energy density of biomass relative to coal, conversion leads to a de-rating of capacity and a small reduction in the efficiency of the base plant. Taking these into account, Figure B4.3b shows the levelised cost of conversion of 17 of the 18 plants considered in the MML study, plotted against cumulative TWh of generation (assuming LCPD opted-in plants run at baseload).

Figure B4.3b: Supply of biomass conversion



Source: CCC calculations based on Mott MacDonald (2011).
Notes: £2010 prices. 10% discount rate. Assumes LCPD opt in plant run at baseload (90%).

This shows that, under central fuel prices for plants opted in to the LCPD, there is a large amount of generation (over 100 TWh/year – close to the target for total renewable generation in 2020) available at between £80-90/MWh. Plants opted out of the LCPD have a higher cost (i.e. over £100/MWh), given their limited lifetime (i.e. closure by 2016).

Figure B4.3b excludes any allowance for the earnings that would have accrued to plant had it operated as a coal plant (i.e. the 'residual value') which may amount to around £10/MWh assuming that it operates at peak or mid-merit. Even allowing for any residual value, these costs are considerably lower than the cost of new dedicated plant.

Support for new biomass generation?

Therefore there is a strong case for supporting co-firing (including enhanced co-firing) and conversion, while supporting investment in new dedicated biomass generating plant appears less cost-effective.

Support for investment in new solid biomass could possibly be justified to meet renewable energy targets if the technical potential for conversion of existing plants were limited.

However, the pursuit of short-term targets may be in tension with longer term carbon reduction goals, particularly under the current sustainability framework (e.g. it would be preferable to pay slightly more for offshore wind, and to gain a much higher carbon benefit).

Moreover, the MML analysis suggests that biomass generation from converted plants and co-firing could amount to a significant portion of the Government's ambition for additional biomass power generation (i.e. 32-50 TWh/year in 2020), and could be significantly higher (i.e. over 100 TWh/year, Box 4.4).

Box 4.4: Economics of large-scale solid biomass power generation

In estimating the cost of new dedicated plant, in a central scenario, we have assumed a high quality (i.e. 17 GJ/t) woodchip/pellet feedstock at £7/GJ (delivered), with a high/low range of £6-8/GJ. Capex for a new plant (based on one 150 MW unit) are currently in the region of £2,000-2,400/kW, with a conversion efficiency of around 36%.

Based on these assumptions, at a 10% discount rate we estimate the levelised cost of new large-scale solid biomass plant for a project starting today and coming on the system in 2017 in the region of £120-155/MWh (Figure 4.9), with a central estimate of £130-145/MWh. This compares with £152-165/MWh by Ernst and Young in their recent assessment for DECC.

Given that the technology is reasonably well established, capital costs are not expected to decline significantly over time. The key driver of costs within this range and over time will therefore be fuel costs.

Given this potential, together with limits to sustainable biomass, there is a risk that these alternatives would compete for fuel supply and that investment in new dedicated biomass plant could displace investment in significantly cheaper biomass conversion, resulting in unnecessary costs and electricity price escalation.

Therefore unless clear evidence emerges that there is abundant supply of sustainable biomass, or a much lower potential for biomass conversion, there should be a very limited role for large new dedicated solid biomass capacity.

The focus within new dedicated should be on small-scale plant, especially those which supply combined heat and power (CHP), accessing locally sourced woodchips or wastes (e.g. incineration of municipal solid waste or AD of food wastes) which cannot be used for co-firing or converted plants (these both primarily require higher-grade pelletised feedstock).

The Government's proposals for supporting biomass generation

The Government has stated that its focus will be on co-firing and conversion, and has proposed levels of support in its Renewables Obligation Certificates (ROC) banding consultation for England and Wales that are broadly consistent with the underlying economics of these options. However, it has also proposed a very significant premium for new dedicated biomass generating plants (i.e. 1.5 ROCs, worth around £140-145/MWh for new plant, versus 1 ROC, worth around £120-125/MWh for co-firing/conversion).

Our analysis suggests that this could be sufficiently high to bring forward investment in new large-scale plant (it would give revenue of around £140-145/MWh compared to our estimated range for costs of £130-145/MWh), of which there is around 3.7 GW currently in the project pipeline. At the rates of support proposed, one outcome could be competition with co-firing and conversion for scarce fuel supply, with possible displacement of these options at an annual consumer cost of £175 million/GW/year of new plant added.

Alternatively, and if investment in new dedicated biomass were to be additional to co-firing and conversion, this could displace investment in offshore wind. The financial saving would be very low at levels proposed in the ROC banding review (e.g. around £20-25/MWh) but emissions reductions could be over 80% lower than from offshore wind under current sustainability criteria.

Given these risks, we strongly recommend that the Government should explicitly state that ROC support for new dedicated biomass power plants will be limited to small-scale plants. Alternatively, any support for new large-scale dedicated biomass should be limited to a very small number of projects.

The Scottish Government has recognised risks associated with investment in large-scale biomass power generation, ruling out support for large-scale biomass power plants in its recent ROC banding proposals, suggesting that the focus should instead be for use of biomass in heat only or CHP plants.

(iv) Implications for industry decarbonisation

Biomass product substitution

The use of wood in the construction industry is not common in the UK (except in Scotland), but is widespread in other countries. For example, in Finland 84% of the housing stock is built from wood. Our analysis of appropriate uses of biomass feedstocks highlights the opportunity to reduce emissions through using wood in construction. This is because of avoided emissions from the displacement of carbon-intense products such as steel and cement, and because wood is a carbon store, therefore reducing emissions relative to burning of biofuels (see Box 4.2).

The characterisation of opportunities for the use of wood in construction in our modelling is based on more detailed analysis of scope for product substitution that we commissioned from Pöyry. This analysis suggests that there is significant technical potential for using wood in the construction industry, and that this is likely to be cost-effective compared to the projected carbon price. Given the potential benefits of product substitution and use of wood in the construction industry in particular, but also the limited current evidence base about the resource, this is something that the Government should consider further as part of its low-carbon strategy. In this context, areas of focus should include technical and economic potential, and whether stronger incentives (e.g. financial or regulatory) are needed to encourage product substitution.

Use of biomass for energy in industry

Although potentially an appropriate use of biomass feedstocks, substitution of construction materials will be limited to wood, leaving 90+% of bioenergy supply in our scenarios available for other uses. Our analysis suggests that this bioenergy is of high value when used as a substitute for coal in energy-intensive industries. This reflects the limited alternatives for decarbonisation in these industries, and the high efficiency and limited processing costs and emissions associated with using biomass for industrial heat versus other applications. It applies whether CCS is available or not and therefore appears to be a low-regrets option for use of biomass.

Ambitious targets for biomass heat in industry in the Government's Renewable Energy Strategy are consistent with the longer term paths suggested by our analysis, justifying support provided under the Renewable Heat Incentive (RHI). However, support has only been confirmed to 2014, resulting in a high degree of investor uncertainty. It is therefore crucial that funding for the next phase of the RHI (from 2014/15) is confirmed.

We will continue to monitor development of the support framework, and use of biomass in energy-intensive industries, in our annual progress reports to Parliament.

Use of CCS in energy-intensive industry

Our analysis of appropriate bioenergy use also highlights the important role for the use of CCS technology in energy-intensive industry in the long term, especially in sectors such as cement and steel production, where there are emissions both from heat generation and from chemical reactions (e.g. blast furnace reactions in iron and steel production). CCS may be used alone or in conjunction with biomass, offering scope for industry to significantly reduce emissions and – where biomass with CCS is available – to contribute negative emissions.

Therefore with CCS the very tight emissions constraint for the rest of the economy is eased, allowing higher emissions in hard to treat sectors where emissions reductions are difficult and/ or expensive. Conversely, meeting emissions targets without CCS will be more challenging and expensive.

Given this potentially beneficial role, the challenge now is to demonstrate large-scale CCS application in energy-intensive industry, to resolve significant uncertainties over its technical and economic performance. While the Government has made commitments to demonstrate CCS in conjunction with power generation, this is not the case for energy-intensive industry. Therefore the Government should develop an approach to CCS demonstration, either here or in cooperation with EU partners, which would allow deployment from the 2020s as required to meet carbon budgets.

(v) Implications for use of biomass for heat in buildings

Our analysis suggests that the role for use of biomass in heating buildings is likely to be relatively limited in the longer term, given alternative low-carbon options such as air-source and ground-source heat pumps. Where these are not feasible, there may be opportunities for district heating using waste heat from large-scale low-carbon thermal power plants (potentially including biomass CCS) or CHP using local waste or biomass, and for biomass boilers using local biomass in rural homes.

This suggests the need to focus now on energy efficiency improvement, which will require strong incentives under new polices such as the Energy Company Obligation and the Green Deal, and to develop low-carbon heat options. Key challenges for Government strategy in this respect are to confirm the long-term funding (at least to 2020) for the RHI, and to develop an approach to deploying heat pumps in the residential sector. We are further considering the options for decarbonisation of heating out to 2050 in the context of our advice on inclusion of international aviation and shipping emissions in carbon budgets, to be published in 2012.

In the near term, there is a potential transitional role for use of biomass to provide heat in buildings, as set out in our advice on the fourth carbon budget. This is reflected in the Government's approach, which offers support for use of biomass in non-residential buildings through the RHI, with support for use in residential buildings expected from 2012.

(vi) Implications for the role of biogas

Biogas can be produced through AD plants or other gasification technologies making use of a range of feedstocks, including carbon-rich waste streams. It can be used locally in small-scale power and/or heat generation or, where feasible, upgraded and injected into the gas grid and used where this has most value (e.g. power generation with CCS, heat generation with or without CCS, compressed natural gas vehicles).

Analysis for this report supports our previous conclusions (e.g. in the context of advice on the fourth carbon budget) that biogas is a cost-effective low-carbon option, and should form part of low-carbon strategy in both the near and longer terms.

The potential for biogas to contribute to the 2020 renewables target is a product of the quantity of gas production, together with the efficiency with which it can then be turned into final energy. Therefore efficient local CHP plants, use in compressed natural gas vehicles and biomethane grid injection offer the biggest contribution, whereas relatively inefficient local power-only biogas plants are less desirable.

In the near term, there is a clear case for investment in AD plants, supported by the RHI. We considered proposed support for AD under the RHI in our Renewable Energy Review, where we concluded that this is set at broadly appropriate levels, with a question about support for small installations without a heat load.

In the near and longer terms, increased collection of suitable wastes to use in AD will be required if the full potential for sustainable supply is to be exploited. This remains a policy challenge, given current low collection rates (e.g. separate weekly collections of food waste are provided to only 3 million households out of 22.5 million in England).

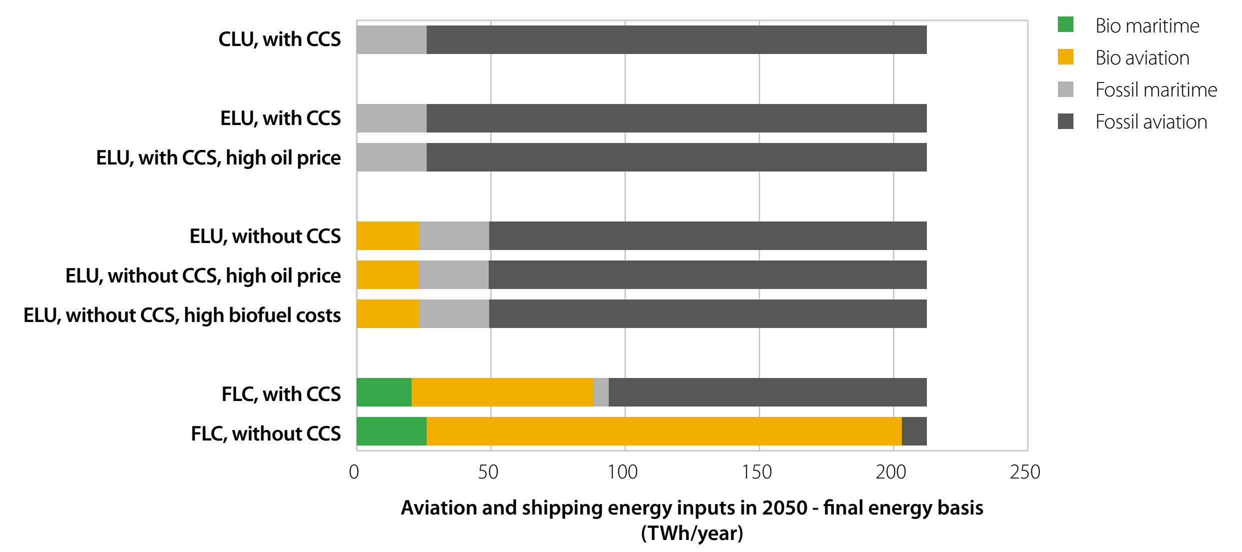
(vii) Implications for aviation and shipping emissions

Aviation emissions

Our analysis suggests that some use of biofuels in aviation could be desirable in the long term, depending on availability of CCS and its applicability to production of biofuels (Figure 4.10):

In a world without CCS, the use of biofuels in aviation is desirable given the need in this case to maximise abatement by prioritising resources in applications where there are few alternatives for decarbonisation.

Figure 4.10: Penetration of biofuels in aviation and shipping in 2050 under a range of scenarios



Source: CCC modelling, using model developed by Redpoint Energy and Ecofys.
Note: In these results, Further Land Conversion (FLC) denotes specifically our Agricultural Land Conversion scenario, in which there are negligible land use change emissions (see Chapter 3).

In a world where CCS is available, this could be used in a range of applications, including production of aviation biofuels:

- One strategy would be to use biomass with CCS for production of power, hydrogen or heat rather than for the production of biofuels, effectively offsetting rather than directly reducing emissions in aviation.
- An alternative strategy would be to use CCS in the production of biofuels for aviation and shipping, where feasible, as an alternative to CCS power generation, in which case higher rates of biofuels penetration in these sectors could be achieved.
- It is currently unclear which of these strategies would be desirable, and will remain so until uncertainties about technology feasibility and costs, as well as fossil fuel prices are resolved.
- In order to reflect this uncertainty, any near term investment in biofuels plants with a payback period of more than twenty years should be designed to allow for possible CCS retrofit.

In either case (i.e. with or without CCS), the level of biofuels penetration suggested as an appropriate planning assumption in our 2009 review of aviation emissions (e.g. around 10%) remains broadly appropriate under our Extended Land Use scenario.

However, whereas we previously assumed that lifecycle emissions savings would only be around 50%, analysis in this report suggests a much higher saving in the longer term assuming land use change emissions are minimised.

Meeting the target to reduce aviation emissions in 2050 to 2005 levels will require a combination of biofuels, technology and operational efficiency improvements, and constrained demand growth.

Shipping emissions

Our analysis suggests a similar approach for the use of biofuels in shipping. Specifically, in a world without CCS, there is likely to be some use of biofuels in shipping. In a world with CCS, this could be used for producing biofuels for ships depending on feasibility and cost relative to other CCS applications.

As for aviation, the level of biofuels penetration proposed in our recent shipping review (e.g. up to 15%) remains an appropriate basis for planning under our Extended Land Use scenario. For both aviation and shipping, planning assumptions should be revisited periodically as uncertainties are resolved, including - but not limited to - whether CCS is feasible.

The precise balance of biofuels use between aviation and shipping is uncertain, and will depend on the relative costs of use in these sectors. In addition, use will be determined by the policy instruments covering the sectors, both as regards the strength of incentives under these policies, and the timing of their introduction (e.g. aviation in the EU will shortly be subject to a carbon price, whereas there are no firm plans for the introduction of a carbon price in shipping). If the balance were to differ from that suggested above (e.g. with more biofuels in aviation and less in shipping), this would not have an impact as regards meeting carbon budgets, given that emissions would be the same in either case.

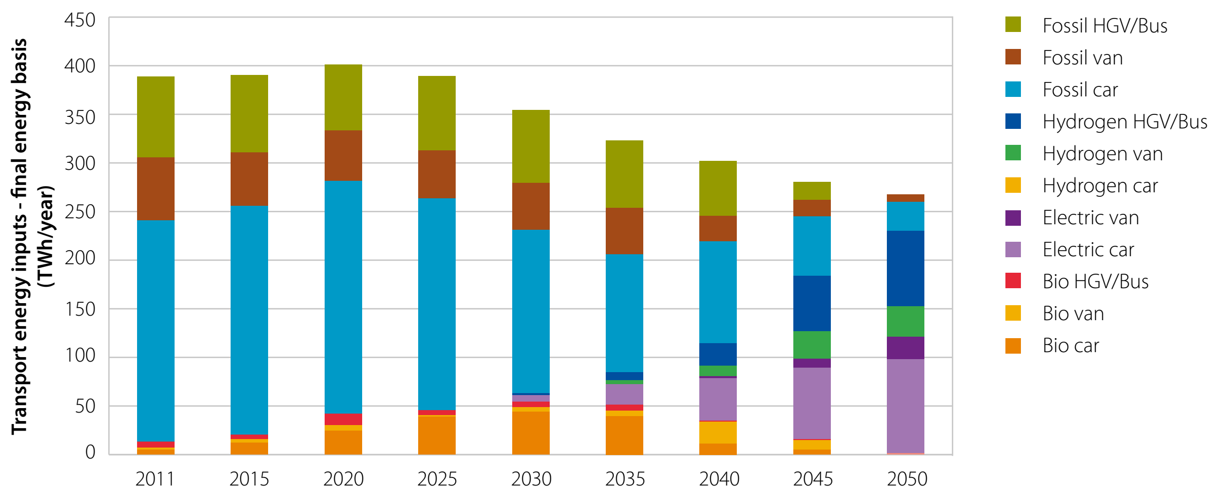
(viii) Implications for surface transport decarbonisation

Long-term use of biofuels in surface transport

Our analysis suggests that there may only be a niche use of biofuels in surface transport in the longer term, with sustainable bioenergy supply likely to be orders of magnitude lower than would be required to support more widespread use in cars and vans.

Our modelled surface transport biofuels share of 0-6% in 2050 under the Extended Land Use scenario reflects a world where the vast majority of surface transport is based on electric and hydrogen vehicles rather than conventional vehicles (including a possible role also for fuel cell plug-in hybrids, with hydrogen replacing the fossil fuel). Therefore the challenge in surface transport over the medium term is to continue to drive emissions reduction from conventional internal combustion engine vehicles whilst developing electric vehicle markets for a range of electric vehicle types (including hydrogen fuel cell vehicles). (Figure 4.11).

Figure 4.11: Surface transport fuels over time



Source: CCC modelling, using model developed by Redpoint Energy and Ecofys.
Notes: Extended Land Use scenario. This chart is on a final energy basis; as electric vehicles use less energy per kilometre than conventional vehicles, electric vehicles appear under-represented on the chart; total final energy also appears to decline from 2030 to 2050 due to this effect, despite continuing growth in kilometres driven.

Near-term use of biofuels in surface transport

The EU RED, enacted in 2009, requires Member States to ensure that the share of energy from renewable sources in all forms of transport is at least 10% of final consumption in 2020. The RED transport sub-target allows a flexible approach, permitting a lower than 10% share from biofuels through a contribution from renewable electricity and multiple credits for advanced biofuels.

We have previously accepted the findings of the Gallagher Review, which argued that a requirement for the 10% target to be met solely with biofuels could result in unacceptable ILUC impacts, and suggested a lower 2020 target with a maximum target of 8% triggered only if biofuels are shown to be demonstrably sustainable, including the avoidance of ILUC ILUC. The Government seems to have accepted this recommendation by including an assumption in its latest emissions projections that biofuels penetration is 8% rather than 10%.

Given the sustainability risks associated with the 10% target, approaches to delivering it should provide flexibility. For example, at the UK level, the RTFO should not allow the use of unsustainable biofuels, but allow a buy-out of the obligation if sustainable supply is not sufficient to achieve 10% biofuels penetration. At the EU level the target should be defined to allow such a buyout.

Whether biofuels penetration is 8% or 10% by volume in 2020, our analysis suggests that this should decrease in the long term as bioenergy is diverted to sectors where it is more highly valued. This raises questions about the economics of investment in biofuels plants (e.g. these should pay back by the early 2030s rather than over the technical life of a plant, or should around this time be based on advanced conversion processes and be deployed in the expectation that sales will shift to other markets such as shipping or surface transport in other countries based on advanced conversion processes).

Chapter 5

Summary of conclusions and recommendations for low-carbon strategy

This review has highlighted the significant degree of uncertainty about bioenergy, in terms of emissions reductions, the availability of sustainable supply and the appropriate use in different sectors.

We have reviewed the literature on lifecycle emissions, and make recommendations on strengthening the regulatory framework to ensure that emissions reductions do actually ensue from the use of biofuels and biomass over the next decade and beyond.

We have presented analysis which shows the need for some bioenergy, without which it will be very difficult for the UK to meet longer-term emissions targets, unless there is significant behaviour change or currently unforeseen technology breakthroughs.

We have characterised at a high level how the economy could be decarbonised to 2050. We recommend using scarce supplies of sustainable bioenergy in those sectors where there are limited alternatives for reducing emissions (e.g. industry, aviation), or in CCS applications where the resulting negative emissions create headroom for residual emissions in other sectors.

We have drawn out the implications of our analysis for the development of technology options – bioenergy and other – to decarbonise the various emitting sectors, and which are robust across uncertainties relating to bioenergy supply and technology availability and costs.

Our analysis has highlighted the importance of bioenergy generally in meeting carbon budgets, and of bioenergy with CCS as an option for negative emissions. Therefore CCS should be demonstrated as a matter of urgency, particularly given this potentially crucial long-term role.

More generally, the approach should now be for the Government to support investment in currently cost-effective options (e.g. energy efficiency improvement, low-carbon power generation) and the development of bioenergy and other low-carbon options identified, which together would give a technology portfolio which would allow us to meet long-term emissions targets.

Specific conclusions and recommendations based on the analysis presented in this report are:

Sustainability

- **Indirect land use impacts from bioenergy crops.** There is a risk of significant ILUC emissions under the current EU sustainability framework, which should be addressed through including these emissions via crop-specific ILUC factors or caps on the use of feedstocks with associated ILUC risks. Although existing near-term liquid biofuels targets may be achievable when ILUC emissions are included, approaches should allow for lower biofuels penetration where sustainable supply is not forthcoming.
- **Emission impacts from forest biomass.** The current UK sustainability criteria for forest biomass should be strengthened to 200 gCO_2/kWh. Furthermore, there is a risk of indirect land use impacts including deforestation as a result of increasing demand for biomass. In order to mitigate this, there should be a focus on the use of biomass from jurisdictions with best-practice sustainability safeguards, equivalent to or better than those in the UK.
- **Tensions between food and bioenergy.** Given risks that energy crop growth could displace food production, and possible impacts on biodiversity and water supply, it is appropriate now to plan for limited use of land for dedicated energy crops (e.g. abandoned agricultural land).
- **Increasing sustainable supply.** Options for increasing the sustainable supply of bioenergy should be developed, including measures to increase agricultural productivity (e.g. support for research into advanced crop breeding of dedicated energy crops and better management practices), measures to increase the use of domestic resource such as waste for energy (e.g. through separate collections of municipal food waste), and support for research into advanced biofuels.

Sectoral

- **Power.** Given the relative economics of different biomass generation options, and the limited longer term role for large-scale biomass power generation without CCS, Government support through the RO should be tailored to burning biomass in existing coal-fired plants through conversion and co-firing, and smaller-scale plants using local resources, with safeguards introduced to ensure that support for new dedicated biomass capacity is very limited, if any.
- **Industry.** Scope for using wood in the construction industry should be considered further, including possible new incentives to encourage this. In addition, there is an important role for the use of sustainable biomass for heat in energy-intensive industry, as recognised by the Government in its Renewable Energy Strategy, and the RHI. Longer term RHI funding (at least to 2020) should be confirmed to provide investor certainty. Complementing this, the use of CCS in industry could result in negative emissions from this sector, reducing risks and costs of meeting economy wide emissions targets. The Government should therefore develop an approach to the demonstration and deployment of CCS in industry.
- **Heat in buildings.** The role of bioenergy in heating buildings is likely to be limited (apart from some smaller-scale, local uses), with a longer term focus on other low-carbon alternatives (e.g. electric technologies, waste heat from low-carbon thermal power generation). There is a need to further develop approaches to deploying these technologies in the near term.
- **Aviation and shipping.** It is unlikely that these sectors can be decarbonised using biofuels alone. Although limited biofuels may be available, other levers will be required to reduce emissions in aviation and shipping, highlighting the need for technology and operational efficiency improvements, and possible constraints on demand growth with implications for infrastructure planning and development. To be certain about a future for biofuels in aviation, the option of producing them with CCS needs to be developed.
- **Surface transport.** Our analysis suggests that the decarbonisation of surface transport will largely be achieved through the use of electric vehicles and possibly fuel cell HGVs. In order to develop the electric vehicle option, support for near-term electric and hydrogen technology and market development is required.

In the coming months the Government will set out its approach to the use of bioenergy in power generation (in the ROC banding review, to be published in December 2011) and aviation (in its new strategy, to be published in 2012). It will be important here that approaches reflect sustainability concerns and that scarce bioenergy is appropriately targeted. More generally, targeted use of sustainable bioenergy, together with the development of other low-carbon technologies, will provide us with low-cost opportunities to meet our carbon goals and enjoy the wider benefits that this will bring.

Glossary

Abandoned agricultural land

Land that has been previously been used for cultivating crops or grazing but is no longer in production for a variety of reasons (e.g. economic, political, climatic, water stress, soil degradation).

Anaerobic Digestion (AD)

A treatment process breaking down biodegradable material, particularly waste, in the absence of oxygen. Produces a methane-rich biogas that can substitute for fossil fuels.

Advanced biofuels

Biofuels produced through application of advanced conversion processes to dedicated energy crops and the lignocellulosic parts of residues, or using novel feedstocks such as algae and bacteria.

Agricultural residues

The by-products from crops, such as wheat straw and seed husks, as well as other agricultural by-products including slurry and manure.

Biodiversity

Biological diversity, as defined under the UN Convention on Biodiversity, means the variability among living organisms from all sources including, inter alia, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems.

Bioenergy

Energy generated by combusting solid, liquid or gas fuels made from biomass feedstocks which may or may not have undergone some form of conversion process.

Biofuel

A fuel produced from biomass feedstocks.

Biomass

Biological material that can be used as fuel or for industrial production. Includes solid biomass such as wood, plant & animal products, gases and liquids derived from biomass, industrial waste and municipal waste.

Biomethane

Pipeline quality methane of biological origin (effectively renewable natural gas), generally produced either by cleaning up the biogas that results from anaerobic digestion or via a 'methanation' process to produce methane from the synthesis gas resulting from biomass gasification.

Carbon Capture and Storage (CCS)

Technology which involves capturing carbon dioxide, transporting it and storing it in secure spaces such as geological formations, including old oil and gas fields and aquifers under the seabed.

Co-firing

Combustion of two materials at the same time. For example, biomass can be co-fired in coal power plants.

Co-products

The production of bioenergy can involve the generation of co-products during cultivation, harvesting (e.g. straw) and processing of the crops into biofuel (e.g. rape meal). The RED uses the method of energy content to apportion resource inputs and upstream emissions between the co-product(s) and main bioenergy product.

Conventional biofuels

Biofuels typically derived from crops and waste using current conversion processes. Examples include bio-ethanol from sugar cane and biodiesel from cooking oil.

Dedicated energy crops

Crops not grown for food but that are being targeted for energy use. Examples include fast-growing trees and grasses with a high lignocellulosic content such as miscanthus and willow, and oil crops such as jatropha.

Direct Land Use Change

The conversion of land from one use to another (e.g. from unmanaged forest to cropland, or between two different crop types).

Feedstocks

Crops or products, like waste vegetable oil, that can be used to produce bioenergy.

Fermentation

The use of micro-organisms (e.g. yeasts, bacteria) to break down organic substances; fermentation is used to convert sugars into alcohol to produce bioethanol.

Fischer-Tropsch (FT) process

Production of liquid hydrocarbons, such as synthetic diesel and gasoline, by catalytic conversion of gas.

Forestry and forest residues

Forest sector by-products including residues from thinning and logging (e.g. treetops, limbs, slash and small round wood) and secondary residues including sawdust and bark from wood processing. Forestry and forest residues can also include dead wood from natural disturbances, such as fires and inset outbreaks, biomass grown in forests that are not required for timber production, and biomass from dedicated plantations (e.g. short- and long-rotation forestry).

Food and fodder crops
The edible parts of sugar, starch and oil plants traditionally developed and grown to produce food for humans and animals. Food crops being used for fuel include wheat, maize, soya, palm oil and sugar cane.

Gasification
Process in which solid materials are partially combusted to produce a 'synthesis gas', which typically contains a mixture of hydrogen, carbon monoxide, carbon dioxide and various other hydrocarbons. This mixture can be used to generate electricity and/or heat or to produce other fuels such as methane, biodiesel (via the Fischer-Tropsch process) or pure hydrogen.

Greenhouse Gas (GHG)
Any atmospheric gas (either natural or anthropogenic in origin) which absorbs thermal radiation emitted by the Earth's surface. This traps heat in the atmosphere and keeps the surface at a warmer temperature than would otherwise be possible.

Indirect Land Use Change (ILUC)
Indirect land use change occurs when land for an existing activity (e.g. food or timber production) is converted to grow bioenergy feedstock or a food crop is used for bioenergy (e.g. divert maize to ethanol), which results in the relocation of that displaced activity to another area that is converted.

Kilowatt hour (kWh)
A unit of energy, equal to the total energy consumed at a rate of 1,000 watts for one hour. Related units are: Megawatt hour (MWh) = 1,000 kWh, Gigawatt hour (GWh) = 1,000 MWh and Terrawatt hour (TWh) = 1,000 GWh. The kilowatt hour is equal to 3.6 million joules.

Kyoto Protocol
Adopted in 1997 as a protocol to the United Nations Framework Convention on Climate Change (UNFCCC), the Kyoto Protocol makes a legally binding commitment on participating countries to reduce their greenhouse gas emissions by 5% relative to 1990 levels, during the period 1998-2012. Gases covered by Kyoto Protocol are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), sulphur hexafluoride (SF_6), hydroflurocarbosn (HFCs) and perfluorocarbons (PFCs).

Lifecycle emissions
The emissions generated for a product system or service from its cradle to grave (i.e. over its entire life-time).

Lignocellulosic feedstock
Woody feedstocks with significant cellulose and hemi-cellulose content. Advanced conversion processes are required to break down the cellulose and hemi-cellulose for conversion to liquid biofuels.

Methanation
Process to produce methane of high quality from a mixture of chemical compounds, especially the products of gasification ('synthesis gas') and fermentation. The methane produced – often known as synthetic natural gas – can then be injected into the natural gas grid, or used in applications such as power generation and production of high-temperature heat for industry.

Microalgae
Single-cell, photosynthetic organisms known for their rapid growth and high energy content. They include a wide variety of photosynthetic microorganisms capable of fixing CO_2 to produce biomass more efficiently and rapidly than terrestrial plants.

Pellets
Pellets can be manufactured from woody, energy crop and agricultural residue feedstocks and used as fuel for electric power plants and biomass boilers. Pellets are very dense and have a low moisture content.

Pyrolysis
Similar to gasification, pyrolysis is the thermal decomposition of organic material at high temperatures, in the absence of oxygen. It produces gas and liquid products and leaves a solid residue richer in carbon content; the liquid products can be potentially used directly in ships or upgraded for a variety of transport applications, while the gaseous products can be used in a similar way to the products of gasification.

Renewable Energy Directive (RED)
A European directive that sets targets for all member states, such that the EU will reach a 20% share of energy from renewable sources by 2020 and a 10% share of renewable energy specifically in the transport sector.

Renewable Energy Roadmap
A comprehensive action plan published in 2011 by the Department for Energy and Climate Change to accelerate the UK's deployment and use of renewable energy, and put the UK on a path to achieve its 2020 target, while driving down the cost of renewable energy over time.

Renewable Energy Strategy (RES)
Government plan to meet the European target of 15% of energy (including electricity, heat and transport) from renewable sources by 2020).

Renewable Heat Incentive (RHI)
Provides financial assistance to producers (householders and businesses) of renewable heat.

Renewable Obligation Certificate (ROC)
A certificate issued to an accredited electricity generator for eligible renewable electricity generated within the UK. One ROC is issued for each megawatt hour (MWh) of eligible renewable output generated, which can be purchased by suppliers to meet their commitments under the Renewables Obligation.

Renewables Obligation (RO)
This is the primary support scheme for renewable electricity generation in the UK, and places an obligation on electricity suppliers to source an increasing proportion of their electricity from renewable sources.

Renewables Transport Fuel Obligation (RTFO)
UK legislation requiring fossil fuel suppliers to ensure that a specified percentage of their fuel for road transport in the UK – rising from 3.5% in 2010/11 to 5% by volume in 2013/14 – comes from renewable sources.

Soil organic carbon (SOC)
Carbon captured in soils from decomposing organic matter such as leaves and root tissues which can accumulate over decades and centuries. Globally, SOC holds about 1,500Gt of carbon, making it the second largest carbon pool after the ocean.

Uncultivated land
Land currently not used for crop production and likely to represent areas of natural habitat such as grassland ecosystems or current pasture land but which may have some potential for growing energy crops.

Wastes
Includes food waste, wood waste, sewage and other biological waste from homes or industry, which tend to otherwise be discarded, as well as livestock manures.

Abbreviations

AD	Anaerobic digestion
CCC	Committee on Climate Change
CCS	Carbon capture and storage
CHP	Combined Heat and Power
CLU	CCC “Constrained Land Use” energy crop scenario
DECC	Department for Energy and Climate Change
Defra	Department for Environment, Food and Rural Affairs
DDGS	Dried Distillers Grains with Solubles (bioethanol co-product)
DfT	Department for Transport
EU	European Union
ELU	CCC “Extended Land Use” energy crop scenario
FAO	Food and Agriculture Organization of the United Nations
FLC	CCC “Further Land Conversion” energy crop scenario
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GJ	Gigajoule
IEA	International Energy Agency
IED	Industrial Emissions Directive
ILUC	Indirect land use change
IPCC	Intergovernmental Panel on Climate Change
kWh	Kilowatt hour
LCPD	Large Combustion Plant Directive
Mha	Million hectares
MJ	Megajoule
Modt	Million oven-dried tonne
ODT	Oven-dried tonne
RED	Renewable Energy Directive
RO	Renewables Obligation
ROC	Renewables Obligation Certificate
RTFO	Renewable Transport Fuels Obligation
SRC	Short rotation coppice
TWh	Terawatt hour

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