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The 2050 target – achieving an 80% reduction including emissions from international aviation and shipping

Committee on Climate Change | April 2012

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 May 2009.

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, and will publish our fourth progress report in June 2012.

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, renewable energy ambition and a review of bioenergy. 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.

This report

This technical report sets out detailed analysis of how the UK's 2050 target to reduce emissions by at least 80% relative to 1990 levels could be achieved when emissions from international aviation and shipping are included in the target. It supports our advice published in April 2012 recommending that these emissions should be included in the UK carbon accounting framework: ***Scope of carbon budgets:*** *Statutory advice on inclusion of international aviation and shipping*.

The analysis follows on from our *Review of UK Shipping Emissions* in November 2011, our Bioenergy Review in December 2011, and our December 2009 advice '*Meeting the UK aviation target – options for reducing emissions to 2050*', as well as our 2008 and 2010 advice on carbon budgets.

Acknowledgements

The Committee would like to thank:

The team that prepared the analysis for the report. This was led by Mike Thompson and David Kennedy and included: Alice Barrs, Owen Bellamy, Russell Bishop, Ute Collier, Adrian Gault, Ibukunoluwa Ibitoye, David Joffe, Alex Kazaglis, Sarah Leck, Eric Ling, Nina Meddings, Meera Sarda, Stephen Smith, Kavita Srinivasan and Indra Thillainathan.

Other members of the Secretariat that contributed to the report: Neil Golborne, Swati Khare-Zodgekar, Anna Leatherdale, Jo McMenamin, Joanna Ptak and Emily Towers.

A wide range of stakeholders who engaged with us, provided advice, attended our expert workshops, or met with the Committee 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

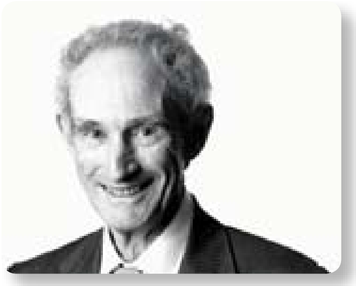
Professor Sir Brian Hoskins, CBE, FRS is the Director of the Grantham Institute for Climate Change at Imperial College and Professor of Meteorology at the University of Reading. He is a Royal Society Research Professor and is also a member of the National Science Academies of the USA and China.

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.

Chapter 1

Meeting the 2050 target – summary and overview

Introduction and summary

Our report *Scope of carbon budgets: Statutory advice on inclusion of international aviation and shipping* concludes that:

- Emissions from international aviation and shipping cause warming and therefore must be managed.
- The current approach to these sectors lacks legal underpinning and should be formalised in order to remove current uncertainties around the future interpretation of the 2050 target.
- Including these sectors in carbon budgets and the 2050 target would be the most transparent, comprehensive and flexible approach.
- Potential complexities that we previously identified (relating to design of the EU ETS cap for aviation and the accounting methodology for shipping) no longer exist.

In that report, we therefore recommend that international aviation and shipping should now be included in the accounting framework of the Climate Change Act.

This technical report supports that advice by showing how an 80% 2050 target can be achieved *inclusive of emissions from international aviation and shipping* based on currently identified measures and at a cost previously accepted.

It builds on previous work in our 2011 Bioenergy Review and in our advice on carbon budgets, adding a new approach and new analysis:

- **New approach.** Instead of using cost-optimising models (as in our previous work) we develop deployment ranges for key abatement measures in each sector based on detailed modelling of technology costs, deployment constraints and interactions within the energy sector, as set out in Chapters 2-6 of this report. We then combine these sectoral deployment levels to create economy-wide scenarios for 2050, identifying how an 80% reduction target including international aviation and shipping can be met when some deployment barriers cannot be overcome, or in the absence of key technologies.
- **New analysis.** We have undertaken detailed new analysis of abatement options to 2050 in the key emitting sectors (e.g. for battery costs for electric vehicles, district heating and electrification in industry).

In analysing ways to meet the 2050 target we are not seeking to specify now the precise mix of technologies and/or consumer behaviour change to achieve this target, which would be neither necessary, possible nor desirable. However, it *is* important to establish that plausible scenarios exist for reaching such a target and to consider their potential costs.

Our specific conclusions are:

- The 2050 target is stretching and will require action across the economy. There are various ways in which the target could be met based on currently identified measures, all of which require deep emissions cuts through energy efficiency improvements, decarbonisation of power generation, extensive electrification of heat and transport, and prioritised use of scarce bioenergy to reduce (or offset) emissions from applications with few alternative abatement options. There is scope for less than full uptake in one or two – but not all – sectors. Without CCS or with very limited availability of sustainable bioenergy the target becomes far more challenging although it could still be met within the technical abatement potential we identify. Scenarios for international aviation and shipping emissions set out in our statutory advice are feasible and desirable in the context of required reductions across the economy.
  - All our scenarios involve widespread deployment of energy efficiency measures and decarbonisation of the power sector (through a combination of nuclear, renewables and CCS), with low-carbon electricity used to meet energy demands from heat and surface transport. Significant abatement will also be needed from industry (e.g. through efficiency and CCS), from aviation (e.g. from more efficient planes and moderations to demand growth) and from measures to reduce emissions on farms and in waste disposal. Scarce bioenergy resources should be used where they can reduce emissions most effectively – in sectors where other abatement options are limited and in combination with CCS to generate negative emissions.
  - Our scenarios demonstrate that the target can still be met if deployment barriers prevent full delivery in some areas. For example, we show scenarios with significant but not full deployment of electric vehicles, with tighter constraints on heat pump applicability, with limited use of CCS in industry, or with stronger demand growth for aviation.
  - We include sensitivities where CCS is not available as an abatement option and/or where bioenergy availability is limited. These require very deep reductions from other available measures (e.g. electrification in industry), implying increased costs and delivery risks. We therefore reiterate a conclusion from our Bioenergy Review that successful development of CCS and access to bioenergy will be particularly important to achievement of the 2050 target.
  - Planning assumptions for 2050 aviation emissions at around 2005 levels, and shipping emissions roughly a third below 2010 reported levels, are appropriate in the context of reductions required across the economy.

- Our estimates of the cost of meeting the 2050 target are towards the low end of those previously accepted by Parliament when the Climate Change Act was legislated (i.e. 1-2% of 2050 GDP). A failure to accept this cost now could result in setting of insufficiently ambitious carbon budgets. These would imply either a weakening of climate ambition or higher costs further out in time (e.g. due to required scrapping of capital, rapid supply chain expansion, or purchase of increasingly expensive offset credits).
- The appropriate strategy now is to aim for full deployment of all options to prepare for deep emissions reductions across the economy. Decisions about where to focus effort can then be made as uncertainties over costs and barriers are resolved. This is consistent with the legislated fourth carbon budget and with the Government's approach as set out in the Carbon Plan.

We set out our analysis in detail in five sectoral chapters following this summary, which has six sections:

1. Current emissions and options for abatement
2. Reducing emissions to 2030
3. Achieving an 80% 2050 target including emissions from international aviation and shipping
4. Meeting the 2050 target with limited availability of key options
5. Costs of meeting the 2050 target
6. Summary and implications for policy approach

1. Current emissions and options for abatement

Current emissions

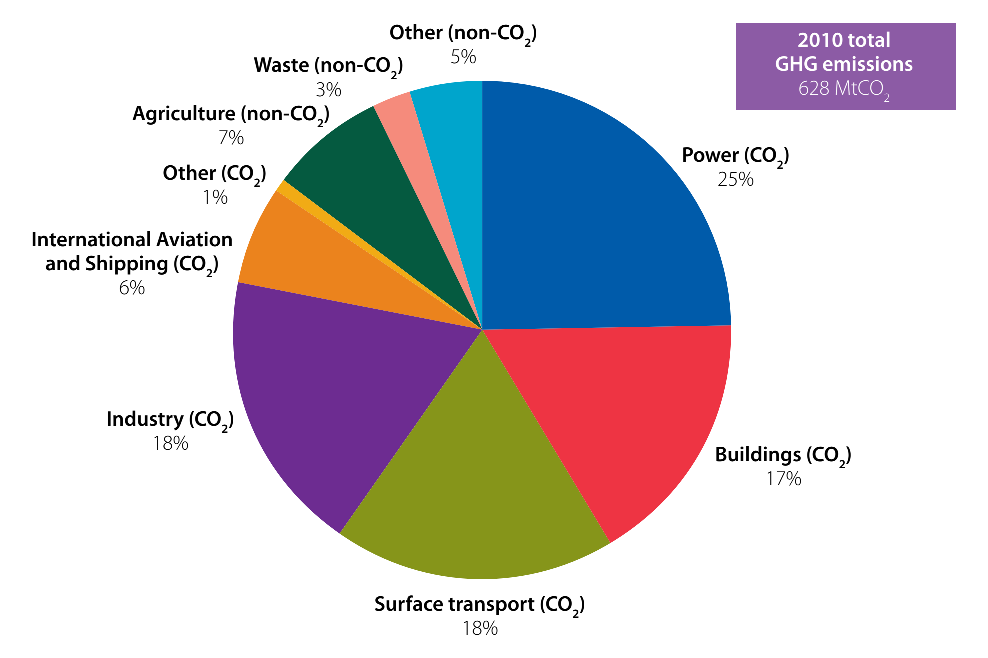
GHG emissions in 2010 were 628 $MtCO_2e$ including international aviation and shipping, comprising 85% CO_2 and 15% non-CO_2 (Figure 1.1).

- Emissions from the power sector accounted for 29% of CO_2 emissions, and direct emissions from buildings for 20%, industry for 21%, surface transport for 21% and international aviation and shipping for 7%.
- Key sources of non-CO_2 emissions were agriculture and waste, which accounted for 51% and 18% of these emissions.

Emissions in 2010 were already 21% below 1990 levels, driven by factors including the 'dash for gas' in the power sector in the 1990s, lower energy demand (as a result of restructuring) and fuel switching in industry, and significant reductions in non-CO_2 emissions (including methane from landfill, N_2O from industry and fugitive emissions from energy supply).

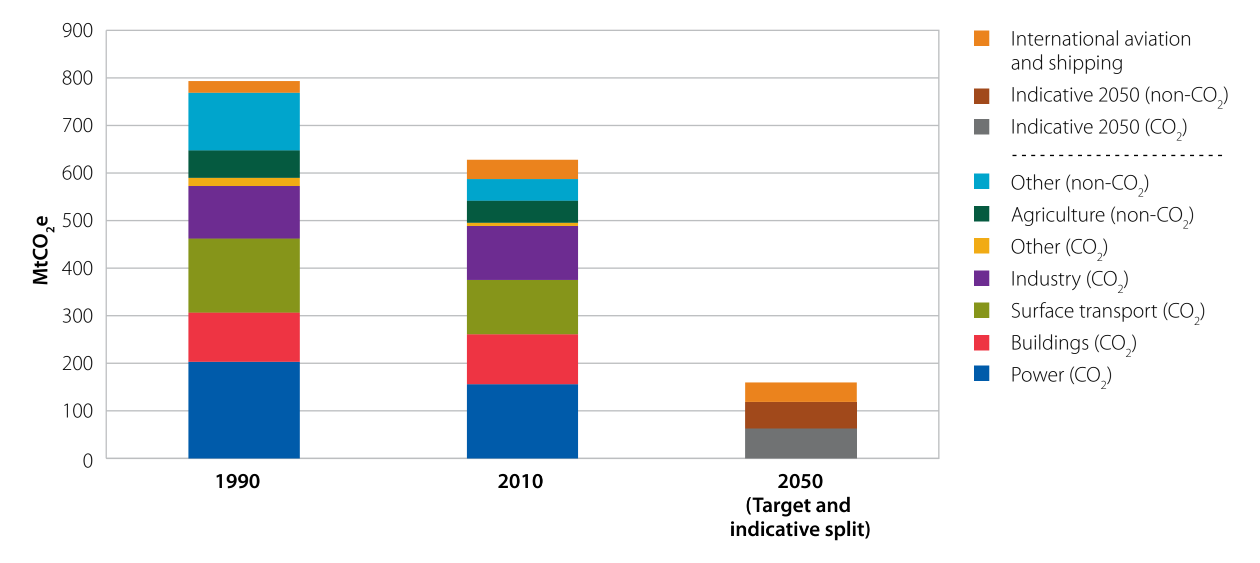
The 2050 target for an 80% reduction against 1990 levels therefore implies a 75% reduction against the 2010 level (Figure 1.2).

Figure 1.1: Greenhouse gas emissions in 2010



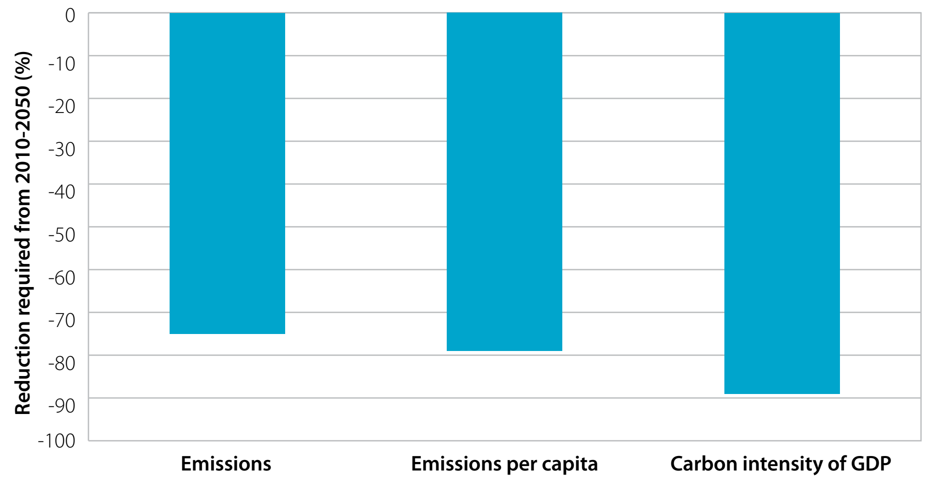
Source: NAEI (2012).
Notes: Other CO_2 includes CO_2 emissions from domestic and military aviation and shipping, agricultural energy use and LULUCF. Other non-CO_2 includes non-CO_2 emissions from waste, buildings, industry, energy supply and transport. Data are for UK and Crown Dependencies. However carbon budgets cover UK emissions only; UK emissions excluding international aviation and shipping were 586 $MtCO_2e$ in 2010 (versus 588 $MtCO_2e$ in this figure).

Figure 1.2: Required emissions reductions to 2050



Source: NAEI (2012); CCC analysis.
Note: Other CO_2 includes CO_2 emissions from domestic and military aviation and shipping, agricultural energy use and LULUCF. Other non-CO_2 includes non-CO_2 emissions from waste, buildings, industry, energy supply and transport.

Figure 1.3: Percentage reductions in emissions, emissions per capita and carbon intensity of GDP required by 2050



Source: NAEI (2012); HM Treasury (March 2012) *Pocket Databank*; OBR (Nov 2011) *Economic and Fiscal Outlook*; OBR (2011) *Fiscal Sustainability Report*; ONS (2011) *Population Projections*; CCC analysis.

Achieving this reduction in emissions will require a larger reduction in emissions per capita and carbon intensity of GDP, given expected rising population and incomes to 2050 (Figure 1.3):

- **Emissions per capita.** Emissions per capita in 2010 were 10 tCO_2e/person, given a UK population of 62 million. Under the latest ONS projections, the UK population will reach 75 million in 2050[1]. Emissions per capita will therefore need to fall by around 80% relative to the 2010 level in order to reach around 2 tCO_2e/capita identified as required on a path to tackling global climate change in our December 2008 report *Building a low-carbon economy – the UK's contribution to tackling climate change.*
- **Carbon intensity.** The carbon intensity of GDP in 2010 was 400 gCO_2e/£. Using the OBR's latest GDP projections to 2016 and assuming annual growth of 2.3% thereafter, GDP in 2050 will be around 150% higher than in 2010. The required 75% reduction in emissions from 2010 to 2050 thus implies around a 90% reduction in carbon intensity.

Achieving these radical reductions in emissions to 2050 will require major changes in the way energy is produced and used in the UK and in other emitting activities across the economy.

Options for reducing emissions

In our previous reports, we have identified a range of options for reducing emissions across the key emitting sectors of the economy. These reflect a combination of improved energy efficiency and behaviour change to reduce demand for emitting activities and increasing use of low-carbon sources of energy supply in place of unabated fossil fuels:

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[1] ONS (2011) Population projection – UK low migration variant

- **Power.** Nuclear, renewables and CCS all offer the potential to produce electricity without significant emissions. Some of these technologies (e.g. nuclear and onshore wind) will be cost-competitive with unabated gas by 2020 when including costs of the Government's carbon price underpin, while others have scope to become cost-competitive in the longer term as a result of learning and innovation (e.g. offshore wind, marine, solar, CCS). Responsive demand, interconnection to other power systems and various modes of storage offer the opportunity for low-carbon approaches to meeting demand peaks without emissions.
- **Buildings.** Energy demand can be reduced through improved building fabrics (e.g. loft and wall insulation), more efficient lights and appliances, and to some extent through behavioural measures such as more efficient use of heating controls. A range of options including heat pumps, district heating using waste heat from low-carbon power stations or local biomass resources, solar thermal heating and resistive electric heating, offer scope to meet remaining heat demand without emissions.
- **Surface transport.** Some emissions reductions are available through improved vehicle efficiency and sustainable biofuels in the near to medium term[2] together with demand-side measures (e.g. Smarter Choices and eco-driving). Electric and hydrogen vehicles offer the chance to avoid emissions completely for all vehicle types (when the electricity/hydrogen used is produced from low-carbon sources), and could be widely deployed and cost-effective from the 2020s.
- **Industry.** Options in industry differ by sector, and include: improved efficiency, application of CCS, electrification and use of bioenergy or hydrogen to replace fossil fuels. Over a long time period (e.g. to 2050) introduction of these measures can be aligned to capital replacement cycles. There may also be opportunities to reduce emissions through material efficiency and product substitution and as industry restructures to meet the demands of a low-carbon economy (e.g. with less requirement for fuel refining).
- **Non-CO_2 emitting sectors.**
  - Agriculture emissions can be reduced by changed farming practices (e.g. efficiencies in soil and nutrient management, improved animal fertility), reduced food waste and adjustment of diet towards less carbon-intensive foods.
  - Waste emissions are expected to fall as EU Landfill Directives divert biodegradable waste away from landfill.
  - Fugitive emissions in the energy sector will be reduced as fossil fuel use declines and gas pipes are replaced, and F-gases could be replaced by alternative coolants.
- **Negative emissions from bioenergy.** Our Bioenergy Review identified two potential routes to negative emissions through use of bioenergy in combination with CCS (for power generation, in energy-intensive industry or production of hydrogen or aviation biofuels) and through using wood in construction.

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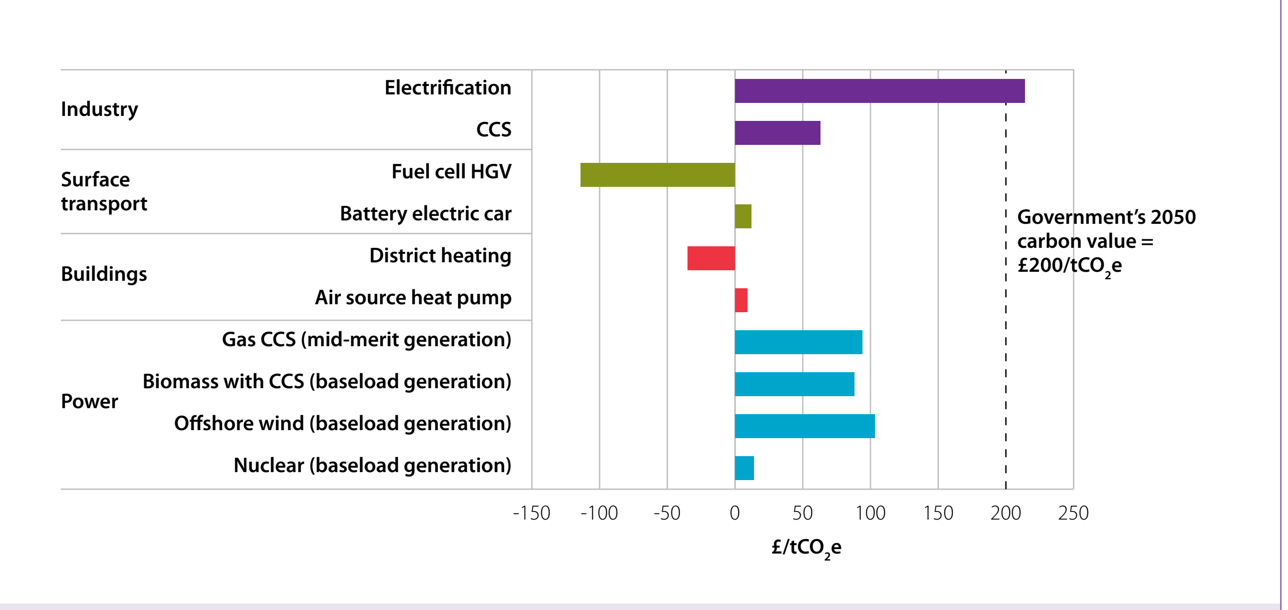
[2] Analysis for our December 2011 Bioenergy Review suggests that in the longer term, bioenergy feedstocks are likely to be most valuable in reducing emissions from sectors with few alternatives (energy-intensive industry, aviation and shipping) and/or in generating negative emissions to offset them through use in wood in construction or with CCS. This could be in a range of applications including power generation, heat in industry, or production of aviation biofuels or hydrogen for transport.

Figure 1.4: Costs of key abatement technologies versus carbon price in 2050



Source: CCC analysis.
Notes: Costs are measured relative to a reference technology (e.g. unabated gas generation in the power sector). Non-CO_2 measures (not shown) are diverse, but generally low cost or cost-saving. See Chapters 2-6 for a full set of measures, their costs and underlying assumptions.

Our analysis suggests that there is scope for the full range of these technologies to become cost-effective ways of reducing emissions relative to carbon price projections over the next decades (see Chapters 2-6, and Figure 1.4).

In meeting a climate objective, emissions from international aviation and shipping cannot be ignored. In previous work we have also identified options for emissions reduction in these sectors:

- **Aviation.** On the supply side, options include improvements in engine and aircraft efficiency, operational efficiency improvements and some use of biofuels. Further emissions reductions could be achieved through limiting demand growth (e.g. via carbon pricing and/or capacity constraints).
- **Shipping.** Abatement options in shipping include technological and operational improvements to fuel efficiency (including use of larger ships), together with some use of biofuels.

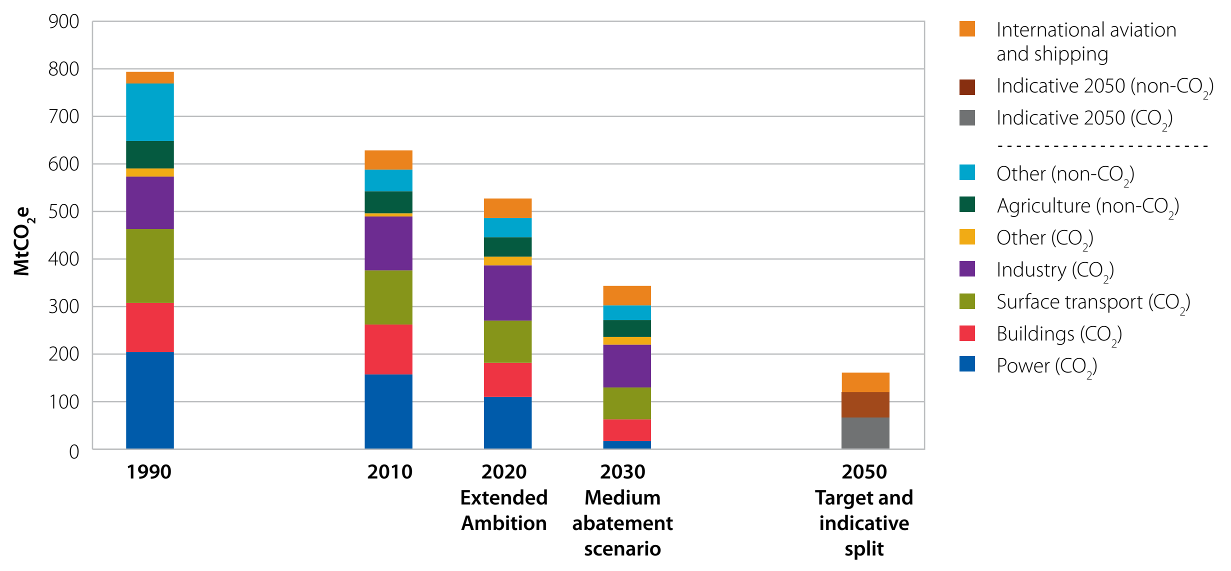
Options for emissions reductions exist across the economy. Different options will imply different costs and challenges in their deployment. We now consider how packages of options can be combined to reduce emissions to 2030 and 2050.

2. Reducing emissions to 2030

In our advice on the fourth carbon budget, we developed scenarios for reduction of emissions to 2030 in those sectors currently covered by carbon budgets (i.e. excluding international aviation and shipping).

The scenarios included measures which were feasible and cost-effective against rising carbon prices and/or required to prepare for the deep emissions cuts necessary by 2050.

Figure 1.5: Emissions reduction scenarios to 2030 and allowed emissions in 2050



Source: NAEI (2012), CCC analysis.
Notes: Other CO$_2$ includes CO$_2$ emissions from domestic and military aviation and shipping, agricultural energy use and LULUCF. Other non-CO$_2$ includes non-CO$_2$ emissions from waste, buildings, industry, energy supply and transport.

Under our central scenario, total emissions in 2030 are almost 50% below current levels, at 310 MtCO$_2$e (excluding international aviation and shipping). Sectoral reductions achieved in this scenario vary from over 90% on 2010 levels in power generation, to 57% in buildings (direct emissions) and 41% in surface transport to only 21% in industry and 24% in agriculture (Figure 1.5).

These emissions reductions are based on:

- **Power.** Investment in around 20 GW (baseload-equivalent) of additional low-carbon capacity to 2020, with a further 36 GW to 2030, resulting in emissions intensity of around 50 gCO$_2$/kWh in 2030, compared to average emissions of around 500 gCO$_2$/kWh in 2010. This reflects all baseload and some mid-merit generation coming from low-carbon sources.
- **Buildings.** Deployment of energy efficiency measures and low-carbon heat, including insulation of 90% of lofts and cavity-walled homes, and 3.5 million solid walls, together with uptake of heat pumps in 6.8 million homes. In non-residential buildings all cost-effective efficiency measures are taken up by 2030, and around 75% of heat is from low-carbon sources.
- **Industry.** Implementation of energy efficiency measures over the next decade, together with options in energy-intensive industry (e.g. refinery optimisation and clinker substitution in the cement sector), increasing use of bioenergy, and initial investment in CCS (where this would be cost-effective versus the Government's £70/tCO$_2$e carbon price assumption and in line with expected plant refurbishments).

- **Surface transport.** Widespread deployment of demand-side measures, continued use of biofuels in line with an 8% share in 2020, and improved efficiency of conventional vehicles to reach 80 gCO$_2$/km for cars and 120 gCO$_2$/km for vans. Electric vehicles reach 60% penetration for new cars and vans (of which two-thirds are plug-in hybrids and the rest battery electric). There is also an early role for hydrogen fuel cell vehicles in buses.
- **Non-CO$_2$.** Measures in agriculture, waste and other sources:
  - In agriculture, roll-out of on-farm measures to reduce emissions from soils and livestock.
  - In waste, diversion of biodegradable wastes away from landfill.
  - Reduced non-CO$_2$ energy emissions in line with scenarios for reduced fossil fuel use, and some abatement from replacing F-gases with alternative coolants.

This scenario excludes emissions from international aviation and shipping. Given 2030 emissions from those sectors of 41 MtCO$_2$e (see section 3), total UK emissions would be around 350 MtCO$_2$e.

Therefore to deliver the 2050 target of 160 MtCO$_2$e would require that emissions are slightly more than halved from 2030 to 2050. We now turn to how such reductions could be achieved.

3. Achieving an 80% 2050 target including emissions from international aviation and shipping

In this section we set out how the 2050 target could be met based on currently identified abatement options.

Our aim is to demonstrate that there are plausible scenarios for meeting the 2050 target at reasonable cost, rather than to specify what the optimal mix of technologies and consumer behaviours should be, which would be neither possible nor necessary.

Scenarios can also be useful for developing planning assumptions, which in turn can inform long-lived infrastructure decisions, technology policy and international negotiations and to enable costs and risks of meeting carbon budgets to be managed.

In section 4 we address questions raised in our Bioenergy Review over how the target could be met in the absence of key abatement options – without carbon capture and storage, and with very constrained bioenergy.

We present cost estimates in section 5.

We now consider:

(i) The need for domestic emissions reductions to meet the 2050 target

(ii) Approach to constructing scenarios for 2050 emissions

(iii) Emissions from international aviation and shipping

(iv) Options for emissions reductions across the economy to 2050

(v) Economy-wide scenarios to meet the 2050 target

(i) The need for domestic emissions reductions to meet the 2050 target

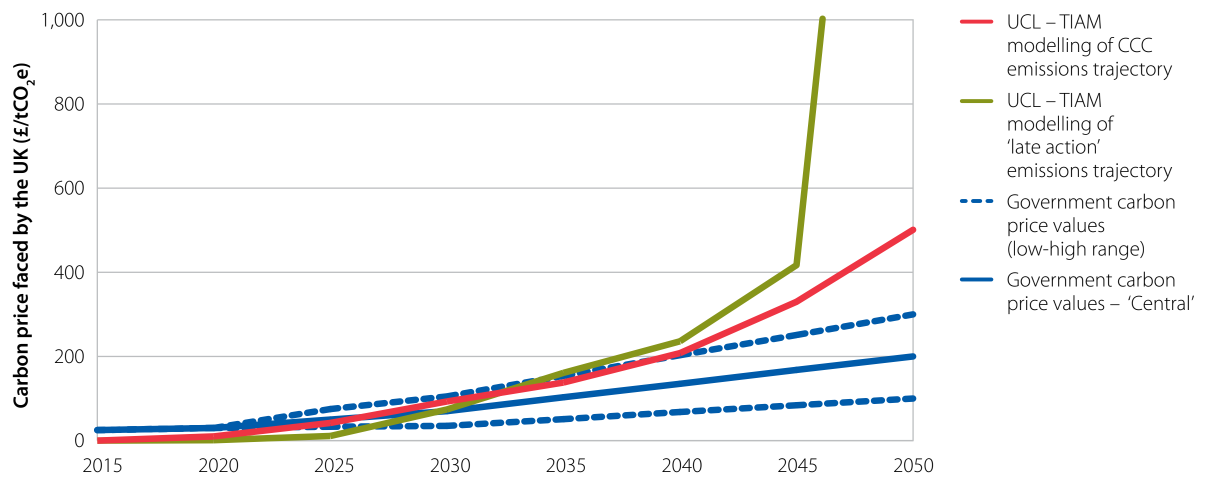
Scope for low-cost purchase of offset credits is likely to become limited over time, as all countries will need to be on a strong downward emissions path and so opportunities to exploit low-cost abatement opportunities overseas will reduce.

Therefore by 2050, while there may be some continued purchase of credits and carbon trading (e.g. reflecting rich-poor country trading, or aviation hubbing), it is not clear that low-cost abatement (and therefore low-cost credits) will remain in any sectors or countries.

This is borne out in global energy system modelling which suggests high carbon prices in scenarios consistent with tackling climate change (Figure 1.6):

- Modelling for the Committee by UCL suggests that carbon prices in 2050 could reach around US$750 (£500) per tonne even with an active global carbon market taking advantage of trading opportunities to minimise global abatement costs[3]. Prices are even higher with less benign assumptions, for example going above £1000/tCO_2e if weak early action requires even deeper 2050 emissions reductions.
- The Government's carbon price trajectory also implies high carbon costs in 2050, reaching £200/tCO_2e
- Estimates from the literature are often £100s/tCO_2e in 2050 for global emissions trajectories consistent with limiting warming to 2°C[4].

Figure 1.6: Global carbon prices are likely to be high in 2050



Source: UCL Energy Institute (2012) modelling for CCC, DECC (2011) *IAG guidance for policy appraisal.*

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[3] UCL Energy Institute (2012), *Modelling carbon price impacts of global energy system scenarios,* available for download at www.theccc.org.uk.

[4] For a review of results from various global models, see, for example, O. Edenhofer, B. Knopf, et al (2010), The Economics of Low Stabilization: Model Comparison of Mitigation Strategies and Costs, Energy Journal 31: 11-48.

The vast majority of emissions reductions should therefore be delivered through domestic action, and we develop scenarios consistent with all reductions being delivered through abatement action within the UK. When considering potential abatement measures for each sector we therefore consider options with costs up to £100s/tCO_2e.

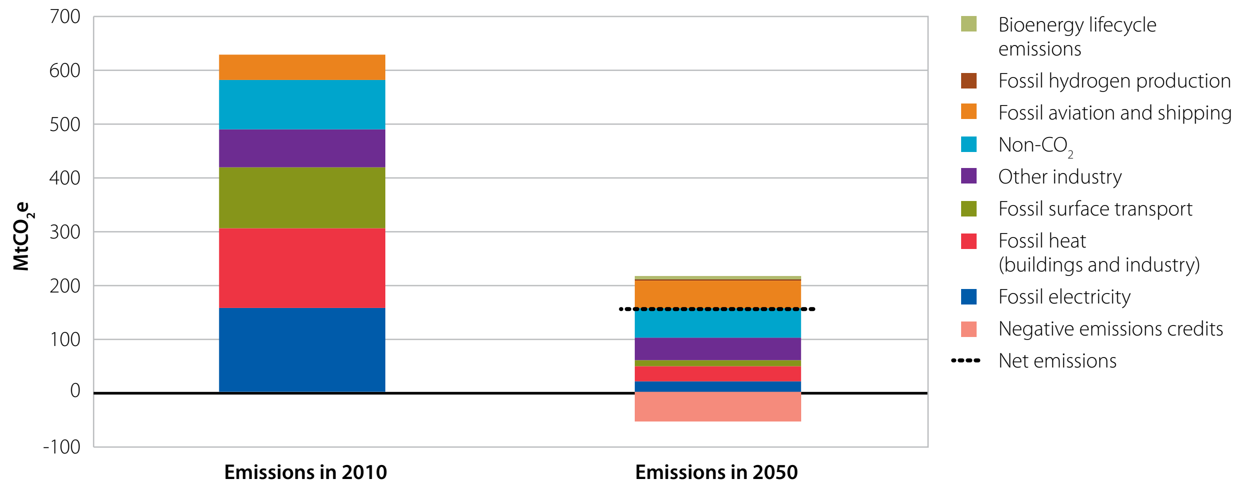
(ii) Approach to constructing scenarios for 2050 emissions

In our Bioenergy Review we used a cost-optimising model to develop scenarios consistent with the 160 MtCO_2e target under various scenarios for bioenergy and technology availability. In a scenario with a bioenergy share equal to 10% of total primary energy demand (our 'Extended Land Use' scenario) and with CCS available, the target is achieved through decarbonisation of power and electrification of surface transport and buildings, with remaining emissions concentrated in industry, aviation and shipping, and non-CO_2 emitting sectors (Figure 1.7).

However, there is a high degree of uncertainty around the extent to which the full potential to abate emissions could be delivered in practice, which would imply a divergence from the cost-optimised modelling. This relates to the fact that technologies are often at an early stage of development (e.g. CCS), to deployment barriers (e.g. potential consumer resistance to take-up of new technologies like heat pumps or electric vehicles), and to uncertainties over the level of sustainable bioenergy that will be available.

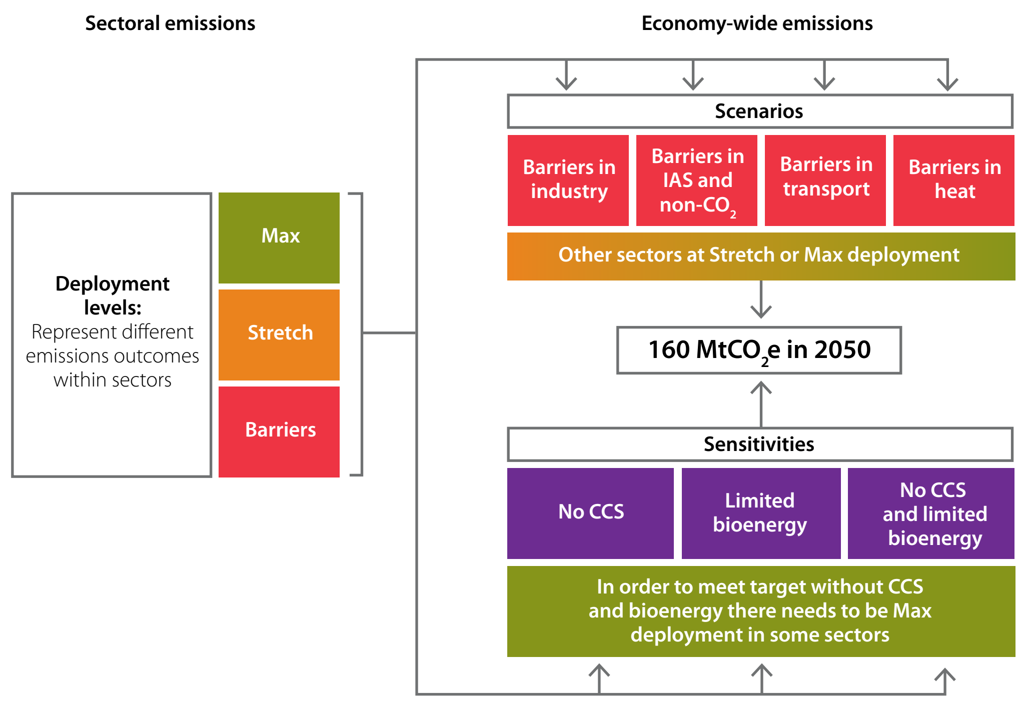
Therefore, for this report we have built on our previous analysis to develop plausible scenarios for meeting an 80% 2050 target that includes international aviation and shipping emissions under different assumptions about technology availability, and the extent to which available technologies are deployed (Figure 1.8):

Figure 1.7: Scenario for meeting the 2050 target developed for our Bioenergy Review using cost-optimising model



Source: NAEI (2012), CCC (2011) *Bioenergy Review.*
Notes: Non-CO_2 and Other industry emissions are outside the scope of the model. Other industry emissions include industrial process CO_2 emissions, emissions from refineries, other energy supply industries and other sources; these are assumed to be 42 MtCO_2 in 2050 incorporating 27 MtCO_2 of abatement potential from CCS on process emissions. Emissions from CHP are included in Fossil heat in 2010 and in Fossil electricity in 2050. Bioenergy availability is assumed to be 213 TWh in 2050. Bioenergy lifecycle emissions include overseas lifecycle emissions for imported bioenergy, as well as those occurring in the UK. Negative emissions from biomass with CCS and wood in construction.

Figure 1.8: Approach to scenarios



Source: CCC.

- We consider abatement potential from a range of options in each sector (see below).
- For each sector, we then define three levels of deployment resulting in three levels of sectoral emissions in 2050.
    - **Max.** In this case there is full take-up of all abatement measures identified as feasible and potentially cost-effective by 2050.
    - **Stretch.** Decarbonisation measures are still deployed very extensively, but the most uncertain and challenging measures are scaled back in this case.
    - **Barriers.** In this case deployment is constrained for some of the most costly measures, or for those with major barriers to uptake. Decarbonisation is still far beyond that assumed for 2030 in our fourth carbon budget advice, but some policy failure is implied, either in reducing costs of key technologies or in driving their uptake.
- We use these sectoral deployment levels as the building blocks for four economy-wide scenarios. The economy-wide scenarios each have total emissions of around 160 MtCO$_2$e in 2050, but are differentiated according to the sectors in which these emissions remain.
- We define three further economy-wide sensitivities illustrating how the 2050 target could be met without CCS and/or with limited sustainable bioenergy, which we identified in our Bioenergy Review as key risk areas.

- Our scenarios include growth associated with population and income growth (e.g. more households, more vehicle-kms, more power demand), but do not include entirely new sources of emissions (e.g. potentially arising from unconventional gas extraction) or potential emissions reductions from economic restructuring (e.g. a reduced requirement for fuel refining as transport decarbonises). Such factors are inevitably hard to predict and emphasise the importance of maintaining a flexible approach to emissions reduction.

We now set out scenarios for international aviation and shipping emissions in 2050, before turning to options for reducing emissions across the economy. We then combine these in economy-wide scenarios set out in section 3(v).

(iii) Emissions from international aviation and shipping

We set out scenarios for international aviation and shipping emissions to 2050 in our main advice on including these emissions in carbon budgets.

We show that international aviation emissions could return to 2005 levels by 2050 (i.e. 35 MtCO$_2$e). This would require improvements in engine and aircraft efficiency, operational efficiency improvements and possibly some use of biofuels and/or moderation in demand growth. It is in line with scenarios proposed in our 2009 aviation report, by Government (Department for Transport) and by the industry (Sustainable Aviation and IATA):

- In our aviation report, our 'Likely' scenario includes baseline demand growth of 115% from 2005 when exposed to a carbon price that reaches £200/tCO$_2$e in 2050. Emissions reductions are delivered through a 0.8% annual improvement in fuel efficiency, by meeting 10% of fuel demand with biofuels and by constraining demand growth to 60% from 2005 (75% from 2010, given that demand fell during the recession).
- DfT's central scenario (published in summer 2011) projects demand growth of 125% from 2010 when a carbon price is included (a 105% increase from 2005). Achieving 2050 emissions at 2005 levels can then be achieved through a 1.2% annual improvement in fuel efficiency, 10% biofuels use and a moderation of demand growth to 90% on 2010 levels.
- Sustainable Aviation has proposed a trajectory in which demand increases in line with DfT's 2011 analysis (i.e. a 125% increase from 2010), with offsetting savings based on a combination of improvements in engine and aircraft efficiency (combining to give a 1.2% annual improvement in fuel efficiency), improvements in aircraft operations and air traffic management, and an 18% emissions saving from use of biofuels.
- At the global level, IATA has set targets for carbon-neutral growth from 2020, and a reduction in CO$_2$ emissions of 50% on 2005 levels by 2050. IATA envisages that this target will be achieved through significant reductions in gross emissions, together with some purchase of offset credits in 2050.

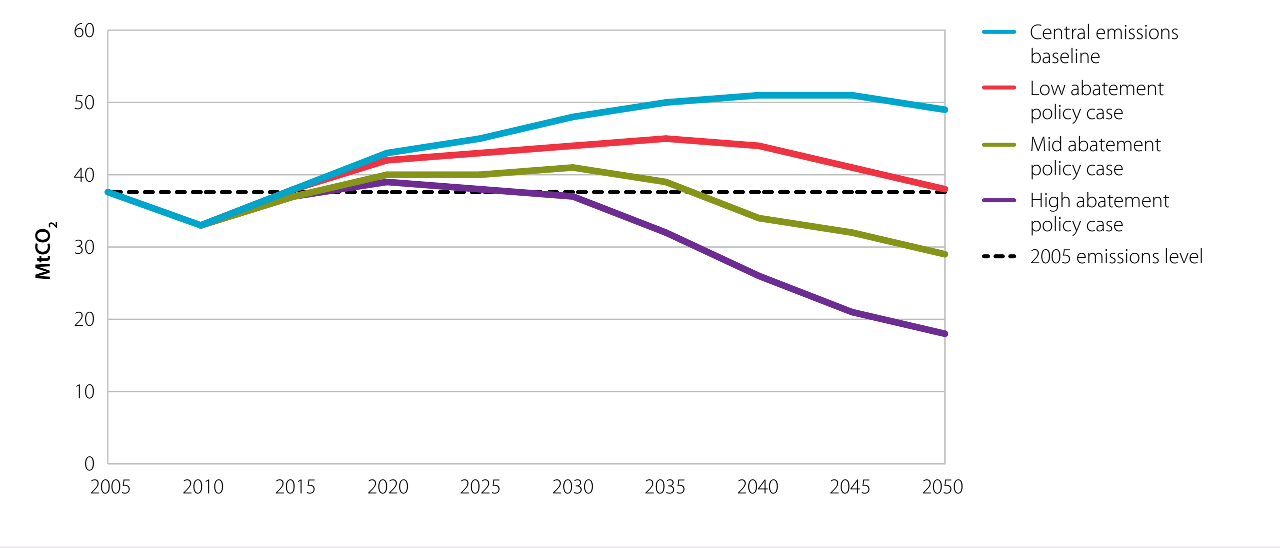
For international shipping we set out emissions scenarios from our Shipping Review. In the central scenario, emissions are roughly a third lower than today in 2050 (i.e. 6 MtCO$_2$e, on an activity basis), being cut through a combination of technological and operational improvements and limited use of biofuels.

Total emissions from international aviation and shipping would therefore be 41 $MtCO_2e$ in these scenarios. We suggest in our main report that this would be an appropriate planning assumption for emissions from these sectors in the longer term. This defines our Stretch deployment level for international aviation and shipping.

We also show that there is uncertainty around future emissions and illustrate scenarios that capture this:

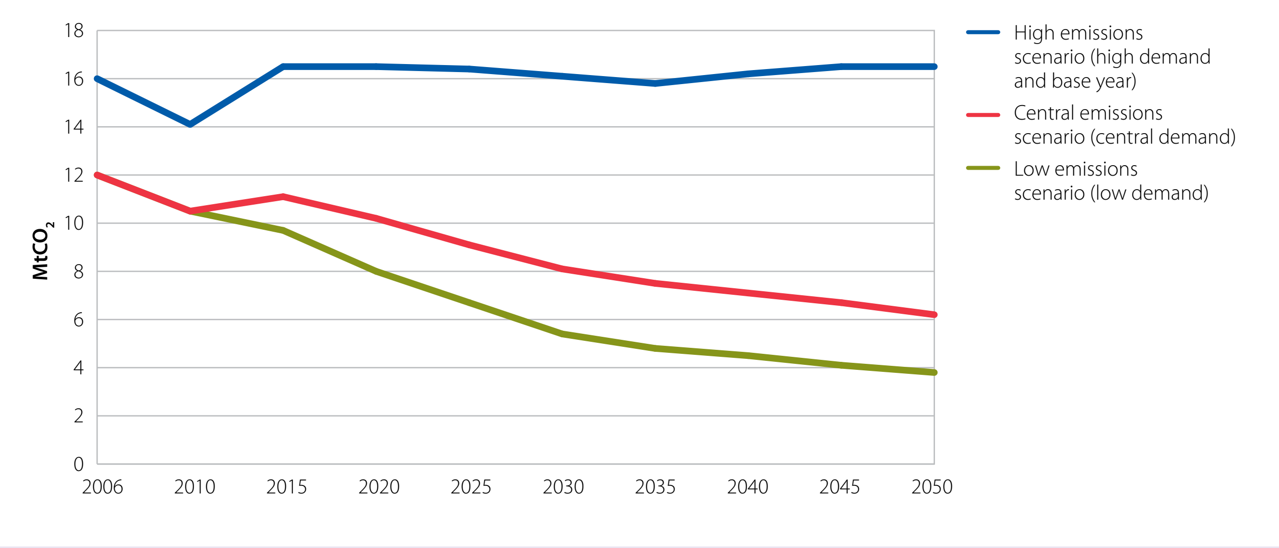
- For aviation (Figure 1.9), DfT's scenarios and abatement cost curves show a range of emissions in 2050. Their central baseline emissions scenario includes improvements in fuel efficiency of 0.9% p.a. and limited biofuel penetration; the level of emissions in this scenario is 47 $MtCO_2e$ and could also be consistent with our aviation report Likely scenario with no demand constraint. Their high abatement case reflects deep improvements in carbon intensity (e.g. from 1.9% annual improvement in fuel efficiency and 40% penetration of biofuels), combined with a moderation of demand to 85% above 2010 levels. With a lower level of biofuels (i.e. 10%), emissions in this scenario would be 27 $MtCO_2e$.
- For shipping (Figure 1.10), scenarios from our Shipping Review reflect uncertainty over both the appropriate methodology for estimating emissions and over future prospects for demand and carbon intensity. The low emissions scenario (4 $MtCO_2e$) reflects our low demand forecast and strong future policy action such that the full abatement potential is realised. The high emissions scenario (17 $MtCO_2e$) reflects our high demand forecast, limited abatement beyond the IMO's EEDI, and a high estimate of base year emissions (i.e. using our top-down trade based estimate).

Figure 1.9: DfT UK aviation emissions forecast with abatement potential to 2050



Sources: DfT (August 2011) *UK Aviation Forecasts*; EMRC/AEA (2011) *A MACC model for the UK aviation sector.*
Notes: Shows total UK aviation emissions (international and domestic). 2005 and 2010 are outturn emissions. Policy cases show total abatement potential and have the same set of measures but with increasing levels of ambition. The main abatement options include: improvements in fuel efficiency from ATM, operations and achievement of ICAO-CAEP technology goals; penetration of biofuels (10%, 20% and 40%); airport capacity constraints; early fleet retirement; behaviour change.

Figure 1.10: Future scenarios for UK international shipping emissions (2006-2050)



Source: CCC analysis.
Notes: Low emissions scenario excludes abatement from biofuels, reflecting a world with CCS where bioenergy resources are concentrated in CCS applications. Emissions from interntional shipping could be lower with use of biofuels.

In our economy-wide scenarios below, we include ranges to reflect the various uncertainties (e.g. over demand and scope for technological improvement), with 2050 emissions of 27-47 $MtCO_2e$ for international aviation and 4-17 $MtCO_2e$ for international shipping.

These ranges define our Max and Barriers deployment levels, under which emissions are 30 $MtCO_2e$ and 63 $MtCO_2e$ respectively in total for international aviation and shipping.

These ranges assume limited use of biofuels in aviation and shipping, reflecting a world where CCS is deployed in power and industry and bioenergy resources are concentrated in these applications. In a world without CCS, emissions from aviation and shipping could be further reduced below the lower end of these ranges, as bioenergy resources are diverted to non-CCS applications including aviation and shipping biofuels.

International aviation and shipping emissions of 41 $MtCO_2e$ in 2050 (as in our Stretch deployment level) would leave an envelope of around 120 $MtCO_2e$ for other sectors in order to meet the 2050 target (i.e. a reduction of 85% on 1990 levels on average in these other sectors), moving to 97 $MtCO_2e$ (an 87% reduction on 1990 levels) if IAS emissions were at the high end of the range and 130 $MtCO_2e$ (an 83% reduction on 1990 levels) if IAS emissions were at the low end of the range.

(iv) Options for emissions reductions across the economy to 2050

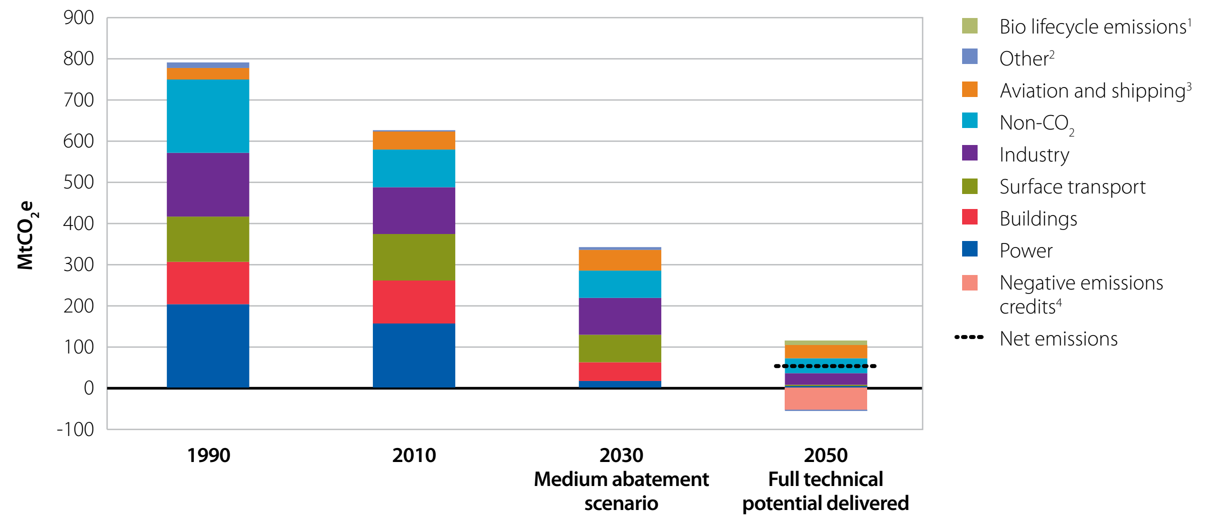
Full technical potential

We have identified a range of options for further reducing emissions across the key emitting sectors beyond the scenarios proposed in our fourth budget advice, and considered the technical abatement potential available from these options[5]. These options are set out in full in Chapters 2-6.

If all the opportunities in every sector were deployed then emissions could be reduced to very low levels across the economy. Full deployment of these options defines our Max deployment level for each sector:

- **Power.** Potentially all demand, including peak, could be met with low-carbon generation by 2050. This would require continued investment after 2030 in nuclear, renewables and CCS of the order 2-4 GW (baseload equivalent) annually, depending on the extent to which other sectors are electrified and the level of energy efficiency improvement achieved, together with measures to improve system flexibility (demand-side response, interconnection and storage). In addition, further storage options would be required to avoid peaking emissions (e.g. meeting peak demand with hydrogen that has been produced during off-peak periods or through novel applications of battery technologies at scale). With full deployment of these options, only 5 $MtCO_2$ of residual emissions from CCS generation remain.
- **Buildings.** Reducing buildings emissions beyond 2030 will require that new homes are designed to be zero-carbon, that further energy efficiency improvements are made to the existing building stock, and that low-carbon heat options are rolled out to remaining buildings. These include heat pumps, district heating using low-carbon sources, solar thermal and resistive electric heating. In a scenario where all these measures are fully deployed, direct buildings emissions could be reduced to zero by 2050.
- **Surface transport.** Rising carbon prices after 2030 would increase the cost-effectiveness of electric vehicles with larger battery capacity. This would ease range constraints, enabling full deployment of pure electric cars and vans by 2050. At the same time, fuel cell HGVs could become cost-saving by 2030 given technical innovation and rising oil prices; coupled with infrastructure development, roll-out from around 2030 could mean a near-100% hydrogen-fuelled HGV fleet by 2050. This effective elimination of liquid fuel demand from road transport could reduce emissions to close to zero in 2050.
- **Industry.** At the level of 90 $MtCO_2$ identified in our fourth budget analysis, industry would be one of the main emitting sectors in 2030. Options to reduce emissions to 2050 include further use of CCS and bioenergy, and fuel switching to electricity and hydrogen. A number of opportunities exist for CCS applied to refineries, blast furnaces in the iron and steel sector, process emissions in the chemicals and cement sectors as well as combined heat and power applications. Low-carbon grid electricity could replace both high-carbon autogeneration (i.e. generation of electricity onsite) and combustion of fossil fuels (e.g. for raising steam and for drying and separating materials). In a case where CCS and electrification are fully deployed, industry emissions in 2050 could be reduced to 28 $MtCO_2$.
- **Non-CO_2.** These emissions are expected to continue to fall as biodegradable waste is diverted from landfill and as fugitive emissions are reduced in energy. Further reductions are possible through a range of measures:
  - In agriculture, our previous analysis implies scope for further roll-out of supply-side measures to 2050. Along with demand-side options (including significant reduction of food waste, and some diet change away from red meat) this could reduce agriculture emissions to 26 $MtCO_2e$ in 2050.
  - In waste, diversion of *all* biodegradable waste from landfill from 2020 could reduce emissions to 3 $MtCO_2e$ in 2050.
  - Other non-CO_2 emissions could be reduced to 7 $MtCO_2e$ as fuel combustion is reduced across the economy and if HFCs can be phased out.

Figure 1.11: Full technical potential for emissions reductions to 2050



Source: NAEI (2012), CCC analysis.

Notes: [1]Bioenergy lifecycle emissions include overseas lifecycle emissions for imported bioenergy, as well as those occurring in the UK. [2]Other emissions include military aviation and shipping, emissions from hydrogen production via CCS, emissions removals from LULUCF, and abatement from injection of biogas from anaerobic digestion into the gas grid. [3]International and domestic. [4]Negative emissions credits are from use of bioenergy in combination with CCS or from use of wood in construction.

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[5] The theoretical maximum amount of emissions reduction that is possible from a particular technology (e.g. What would be achieved if every cavity wall were filled). This measure ignores constraints on delivery and barriers to firms and consumers that may prevent up take.

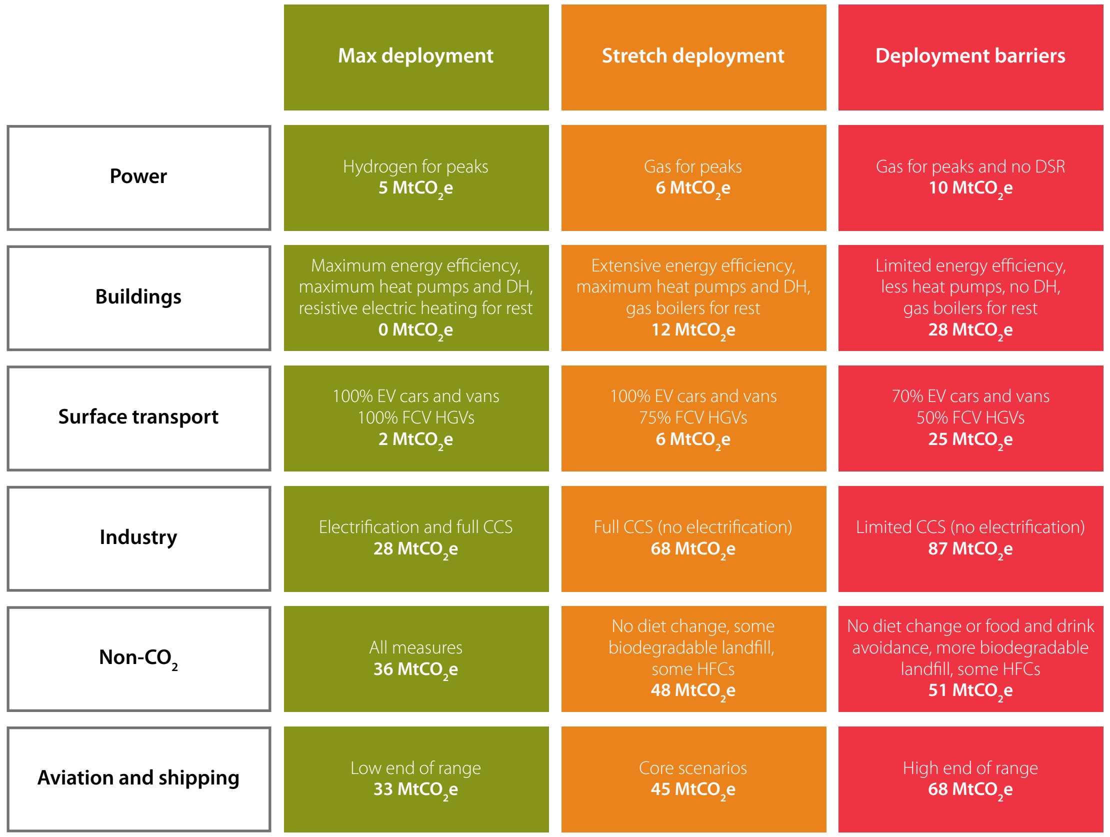
- **Bioenergy with CCS.** As set out in our Bioenergy Review, biomass could be combined with CCS to produce negative emissions (i.e. removals of CO_2 from the atmosphere). There is currently no mechanism to incentivise this (i.e. which gives credit to negative emissions) but we assume that one could be developed by 2050. Use of 150 TWh of biomass with CCS (e.g. in power generation, energy intensive industry, or production of biofuels for aviation or hydrogen for transport), could deliver negative emissions of up to -55 $MtCO_2$ in 2050.

If all of these abatement opportunities were delivered, this would result in economy-wide emissions, including international aviation and shipping at the low end of the range above, of around 55 $MtCO_2e$, or 93% below 1990 levels, which would significantly outperform the 80% 2050 target (Figure 1.11)

Sectoral deployment levels below full technical potential

As full delivery in every sector is neither likely nor required in 2050, we therefore consider two further sectoral deployment levels (Stretch and Barriers) that fall short of technical potential, reflecting the challenges in each sector (Figure 1.12):

Figure 1.12: Sectoral deployment levels



	Max deployment	Stretch deployment	Deployment barriers
Power	Hydrogen for peaks **5 $MtCO_2e$**	Gas for peaks **6 $MtCO_2e$**	Gas for peaks and no DSR **10 $MtCO_2e$**
Buildings	Maximum energy efficiency, maximum heat pumps and DH, resistive electric heating for rest **0 $MtCO_2e$**	Extensive energy efficiency, maximum heat pumps and DH, gas boilers for rest **12 $MtCO_2e$**	Limited energy efficiency, less heat pumps, no DH, gas boilers for rest **28 $MtCO_2e$**
Surface transport	100% EV cars and vans 100% FCV HGVs **2 $MtCO_2e$**	100% EV cars and vans 75% FCV HGVs **6 $MtCO_2e$**	70% EV cars and vans 50% FCV HGVs **25 $MtCO_2e$**
Industry	Electrification and full CCS **28 $MtCO_2e$**	Full CCS (no electrification) **68 $MtCO_2e$**	Limited CCS (no electrification) **87 $MtCO_2e$**
Non-CO_2	All measures **36 $MtCO_2e$**	No diet change, some biodegradable landfill, some HFCs **48 $MtCO_2e$**	No diet change or food and drink avoidance, more biodegradable landfill, some HFCs **51 $MtCO_2e$**
Aviation and shipping	Low end of range **33 $MtCO_2e$**	Core scenarios **45 $MtCO_2e$**	High end of range **68 $MtCO_2e$**

Source: CCC.

- **Power.** Our Stretch and Barriers deployment levels differ from Max deployment in the extent to which peak electricity is decarbonised. In Stretch deployment peak demand continues to be met with unabated gas generation reflecting uncertainty in low-carbon options (e.g. hydrogen or novel battery applications) for this role. In Barriers deployment, there is also a failure to deploy flexibility measures (e.g. demand-side response) reflecting the need for changes in consumer behaviour to deliver this. Both deployment levels still achieve full decarbonisation of baseload and mid-merit generation.
- **Buildings.** Under Stretch deployment, high costs of resistive electric heating (e.g. reflecting the need to upgrade distribution systems) and hassle factors associated with disruptive energy efficiency measures (e.g. solid wall insulation) reduce uptake, although other efficiency measures are still extensively rolled out, together with heat pumps. Our Barriers deployment level also sees tighter constraints on applicability of heat pumps such that (efficient) gas boilers continue to play a significant role in 2050 (e.g. meeting 30% of domestic demand). However, this still implies significant emissions reductions from 2030.
- **Surface transport.** Under Stretch deployment, barriers to full uptake of hydrogen HGVs limit roll-out to around 70% of the fleet in 2050 (e.g. there may be some types of vehicle or load that are not well-suited to hydrogen fuelling). Under Barriers deployment, uptake is further limited to around 45% of the fleet. In addition, risks to full uptake of electric vehicles (e.g. from high costs or consumer resistance) result in later take-up of battery electric vehicles, such that liquid fuels continue to be used for around 30% of car and van miles under Barriers deployment (this could also be consistent with a fleet dominated by PHEVs rather than pure electric or hydrogen vehicles). Both deployment levels still involve considerable roll-out of ultra low-carbon vehicles across the car, van and HGV fleets.
- **Industry.** Our Stretch and Barriers deployment levels in industry cover two key risks, relating to electrification and application of CCS. Electrification can reduce emissions from industrial combustion, but is likely to be relatively expensive (e.g. around £200/tCO_2); under Stretch deployment we assume that this prevents uptake, increasing emissions by 40 $MtCO_2$ relative to Max deployment. Under Barriers deployment, emissions are further increased by 18 $MtCO_2$ as CCS is limited to the most cost-effective applications (i.e. excluding refineries and industrial CHP). Both Stretch and Barriers deployment still involve extensive energy efficiency improvements together with roll-out of options in energy-intensive industry (e.g. refinery optimisation and clinker substitution in the cement sector).
- **Non-CO_2.** Under Stretch deployment, we assume that the most challenging/uncertain measures identified are not deployed (i.e. diet change away from livestock products, full diversion of biodegradable waste from landfill and replacement of HFCs). Under Barriers deployment we further assume that there is a failure to reduce food and drink waste, and there are no further reductions in waste and F-gas emissions beyond existing EU targets. Both deployment levels still require that these challenging EU targets are achieved, and both include on-farm measures to reduce emissions from soils and livestock.

While the Stretch and Barriers deployment levels are designed to reflect risks that delivery may fall short of technical potential, it is important to note that even the most constrained level is still very ambitious and will require that a significant number of barriers are overcome across all sectors:

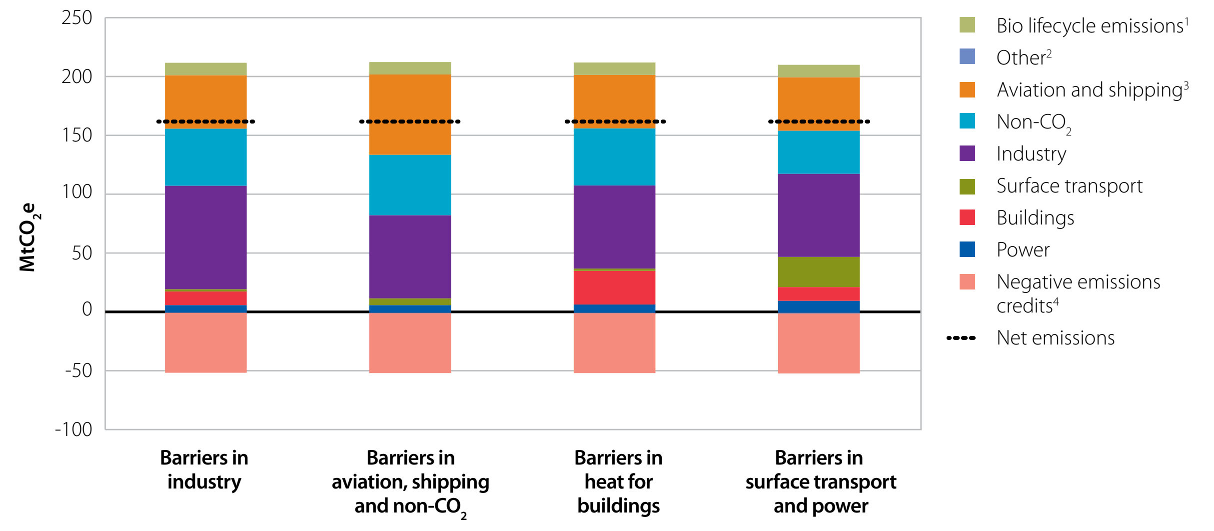
- In **power**, all deployment levels require that barriers to full decarbonisation are overcome, such that further cost reductions are achieved, additional plant sites are identified and upfront capital requirements are managed sufficiently to provide continued significant investment in low-carbon capacity (at the rate of up to 4 GW per year).
- In **buildings**, all deployment levels require that barriers to heat pump deployment are overcome such that consumer awareness and confidence is raised and the supply chain – relating both to equipment and installation – is developed.
- In **surface transport** all deployment levels require that barriers to mass deployment of electric and hydrogen vehicles are overcome, such that forecast battery and fuel cell cost reductions are achieved, itself requiring sufficient R&D and development of an early-stage market (e.g. through price support), and that appropriate charging/refuelling infrastructure is developed.
- In **industry**, all deployment levels require that barriers to investment are overcome, including high upfront capital requirements and long payback periods, and the need to align with refurbishment cycles when retrofitting measures, requiring planning and preparation well in advance. Roll-out of CCS to industry also requires that CO_2 transport and storage barriers are overcome (development of CO_2 pipelines, availability and viability of storage sites).
- In **non-CO_2** emitting sectors, all deployment levels require that effective policy measures are found to deliver on-farm measures in agriculture, that success is achieved in reducing waste from households and businesses and that different waste streams are collected separately and diverted to optimal treatment routes.
- In **aviation and shipping**, all deployment levels include technology innovation (e.g. to improve fuel efficiency or develop sustainable biofuels) which would require coordinated international action and investment, given that these industries are international.

Deployment is therefore challenging for all sectors in all scenarios and will require successful implementation of policies to overcome barriers and drive uptake.

(v) Economy-wide scenarios to meet the 2050 target

Our four economy-wide scenarios are built up based on different combinations of the deployment levels for each sector, reflecting different resolution of the risks and uncertainties. The scenario combinations are set out in Table 1.1, resulting in emissions as in Figure 1.13 and covering potential slippage in: industry; aviation, shipping and non-CO_2; heat for buildings; or surface transport and power.

Figure 1.13: Scenarios for meeting the 2050 target



Source: CCC analysis.
Notes: [1] Bioenergy lifecycle emissions include overseas lifecycle emissions for imported bioenergy, as well as those occurring in the UK. [2] Other emissions include military aviation and shipping, emissions from hydrogen production via CCS, emissions removals from LULUCF, and abatement from injection of biogas from anaerobic digestion into the gas grid. [3] International and domestic. [4] Negative emissions credits are from use of bioenergy in combination with CCS or from use of wood in construction.

Table 1.1: Combination of sectoral deployment scenarios in economy-wide scenarios

	Barriers in industry	Barriers in aviation, shipping and non-CO_2	Barriers in heat for buildings	Barriers in surface transport and power
Power	Stretch	Stretch	Stretch	Barriers
Buildings	Stretch	Max	Barriers	Stretch
Surface transport	Max	Stretch	Max	Barriers
Industry	Barriers	Stretch	Stretch	Stretch
Non CO_2	Stretch	Barriers	Stretch	Max
Aviation and Shipping	Stretch	Barriers	Stretch	Stretch

Source: CCC

- **Barriers in industry.** In this scenario emissions remain relatively high in industry as there is limited application of CCS and no electrification. Greater success is achieved in other sectors, with heat for buildings and power largely decarbonised (notwithstanding some residual gas use in both sectors), and all but the most challenging/uncertain abatement options deployed in non-CO_2 emitting sectors. Success is particularly strong in transport, where full technical potential is delivered including full deployment of hydrogen HGVs. Aviation and shipping emissions are in line with our proposed planning assumptions.

- **Barriers in aviation, shipping and non-CO_2.** In this scenario emissions remain relatively high in aviation and shipping and non-CO_2 emitting sectors. Power and surface transport are largely decarbonised and significant reductions are made in industry. Buildings in particular are fully decarbonised as resistive electric heating is deployed where heat pumps and district heating are not suitable.
- **Barriers in heat for buildings.** This scenario reflects a world where barriers remain to full decarbonisation of heat. As a result fewer energy efficiency measures are deployed, and there is more limited take-up of heat pumps and a failure to deploy low-carbon district heating, with gas boilers meeting remaining demand. Conversely, power is largely decarbonised, and significant reductions are made in industry and non-CO_2 emitting sectors, while transport in particular achieves full decarbonisation. Aviation and shipping emissions are in line with our proposed planning assumptions.
- **Barriers in surface transport and power.** In this scenario, barriers remain to full uptake of ultra-low carbon vehicles, with fossil fuels used for 30% of car and van miles, together with 50% of HGV miles. We also assume that there is less success in deploying flexibility mechanisms to decarbonise peak demand in power. Progress is strong in other sectors, with heat largely decarbonised and significant reductions in industry. In particular, very challenging measures are deployed in non-CO_2 sectors including some diet change away from livestock products and phasing out of HFCs. Aviation and shipping emissions are in line with our proposed planning assumptions.

Within each scenario there are potentially multiple technology choices that could result in the same sectoral emissions outcomes. For example, power sector decarbonisation could be mainly through nuclear, CCS *or* renewables, whilst cars and vans could be decarbonised using electric batteries *or* hydrogen fuel cells.

In practice, the choice between these, and other, scenarios would come down to differences in costs and specific barriers, including those relating to infrastructure requirements. Those factors are currently uncertain, but will become clearer as policies are introduced and measures are deployed.

In summary, even based on our central expectation for technology availability and development, there are multiple possibilities for how allowed emissions could be shared between sectors, and which technologies could be deployed to achieve those scenarios. However there are also a number of common themes which run through all of the scenarios including efficiency improvements, decarbonisation of power generation, extensive electrification of heat and transport, and prioritised use of scarce bioenergy to reduce (or offset) emissions from applications with few alternative abatement options.

The appropriate approach now is to deploy extensively across the measures identified, making decisions about where to focus effort as costs and barriers become clearer.

This is recognised in the Government's Carbon Plan published in December 2011, which includes a number of 2050 scenarios that meet the emissions target (i.e. an 80% reduction on 1990 levels, including emissions from international aviation and shipping), and proposes actions in the nearer term to develop those options (Box 1.1).

Box 1.1: Scenarios for meeting an 80% 2050 target including international aviation and shipping in the Government's November 2011 Carbon Plan

The Government's Carbon Plan set out four alternative 2050 'futures'. Three 'futures' are constructed using DECC's 2050 Calculator, benchmarked to a run of the MARKAL model, which is set up to align to the 80% 2050 target for all sectors including international aviation and shipping:

> *"The UK MARKAL model covers CO_2 emissions from energy use and does not model non-CO_2 greenhouse gases (GHGs), land use, land use change and forestry (LULUCF) and international aviation and shipping sectors. As a consequence, the 80% 2050 target covering all GHGs on the net UK carbon account was translated to a 'MARKAL equivalent' of a 90% reduction for the core MARKAL run."* (page 122)

The four 'futures' involve:

- In the '**Core Markal**' run, demand for energy is roughly halved via energy efficiency measures, electrification of heat and transport, and service demand reduction in response to cost increases. District heating and biofuels for transport also play a role. CCS is applied widely in industry. In electricity generation, there is a balanced generation mix across nuclear, CCS and renewables with unabated gas for system balancing.
- The '**Higher renewables, more energy efficiency**' future sees an even greater reduction in per capita energy demand through behaviour changes and uptake of efficiency measures, facilitated by smart new technologies such as heating controls. Heat, transport and industry are all mostly electrified. Major cost reductions for renewable generation alongside advances in storage capacity mean that renewable technologies including wind, solar, marine and others meet a large share of overall electricity demand. This future could be consistent with a world in which high fossil fuel prices or a global commitment to tackling climate change drive investment and innovation in renewables.
- The '**Higher CCS, more bioenergy**' future reflects a world in which CCS is successfully deployed at commercial scale in power generation and industry, and is relatively cheap due to availability of low-cost gas (e.g. shale gas). Plentiful, cheap resources of sustainable bioenergy are also available and can be used with CCS to generate negative emissions. These create headroom for some fossil fuel use in other sectors. As a result, district heating and CHP replace heat pumps for half of demand, which is higher due to less take-up of insulation measures. In transport around a third of vehicles still use liquid fuel, including more biofuels.
- The '**Higher nuclear, less energy efficiency**' future is one where innovation in newer technologies is less successful and the extent to which people change their behaviours and energy consumption patterns is lower. CCS is not commercially viable and major cost reductions in renewables are not achieved. This future thus relies heavily on nuclear generation to supply power, with unabated gas for meeting peak demand. On the demand side, there is less take-up of insulation measures and smart technologies to reduce energy demand, and people continue to travel by car for most journeys, although heat and transport are still largely electrified. Without CCS to generate negative emissions, bioenergy is key to reducing emissions in 'hard to reach' sectors in this scenario.

Therefore, as in our analysis, the Government has identified multiple scenarios consistent with meeting the 2050 80% target including international aviation and shipping. These scenarios also cover various possibilities for the sectors in which remaining emissions are concentrated, and the technologies that are deployed to reduce emissions.

Source: HM Government (2011) *The Carbon Plan: Delivering our low carbon future.*

4. Meeting the 2050 target with limited availability of key options

Our scenarios in section 3 are based on deployable or demonstrable technologies which are, or are likely to become, feasible and cost-effective by 2050. All of these options face some risks and barriers to their full uptake (e.g. technology development/performance, scope for cost reductions, consumer acceptability, planning approval).

In our Bioenergy Review we identified two options which are particularly important and particularly uncertain: CCS and use of bioenergy.

- **CCS.** Carbon capture and storage is yet to be demonstrated at large scale, so we cannot yet be certain of its long-term contribution. The demonstration and deployment of CCS is likely to be of particular importance because it could increase overall abatement potential in at least three areas:
  - In industry, where it can potentially be applied to various sources of CO_2 with no alternative abatement options (e.g. emissions from chemical processes).
  - In power generation to help to decarbonise mid-merit generation. CCS is likely to be the best-suited low-carbon option for this role given it has relatively lower capital costs and is likely to be more flexible than nuclear or many renewable options.
  - In combination with bioenergy to remove CO_2 from the atmosphere, which can offset emissions from fossil fuels in hard-to-reduce sectors.
- **Bioenergy.** The potential for the long-term sustainable availability of bioenergy depends on factors that are inherently difficult to predict now, such as global trends in diet, agricultural productivity and land-use patterns. Bioenergy is highly important to the overall emissions reduction strategy as it is able to provide abatement in applications with limited alternative low-carbon options (e.g. aviation), and can be used with CCS to generate 'negative' emissions.

In our Bioenergy Review we noted that without CCS, or with sustainable land-based bioenergy supply of less than around 10% of total energy demand, meeting the 2050 target could require technology breakthroughs in bioenergy (e.g. algae) or other areas (e.g. in 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). This could be in addition to the roll-out of more expensive mature technologies (e.g. resistive electric heating).

We have now considered these options further, in three economy-wide sensitivities for meeting the 2050 target: without CCS; with limited bioenergy; and both without CCS and with limited bioenergy (Table 1.2 and Figure 1.14). These sensitivities appear particularly challenging (requiring sectoral deployment levels of at least Stretch and in many cases Max) and involve significant escalations in the overall cost and challenge:

Table 1.2: Combination of sectoral deployment scenarios in economy-wide sensitivities

	No CCS	Limited bioenergy	Limited bioenergy and no CCS
Power	Stretch[1]	Stretch	Stretch[1]
Buildings	Stretch	Max	Stretch
Surface transport	Max	Stretch	Stretch
Industry	Max[2]	Stretch	Max[5]
Non CO_2	Stretch	Stretch	Max
Aviation and Shipping	Stretch[3]	Stretch[4]	Stretch[4]

Source: CCC

Notes:

[1] Additional renewables and nuclear compared to main Stretch deployment level

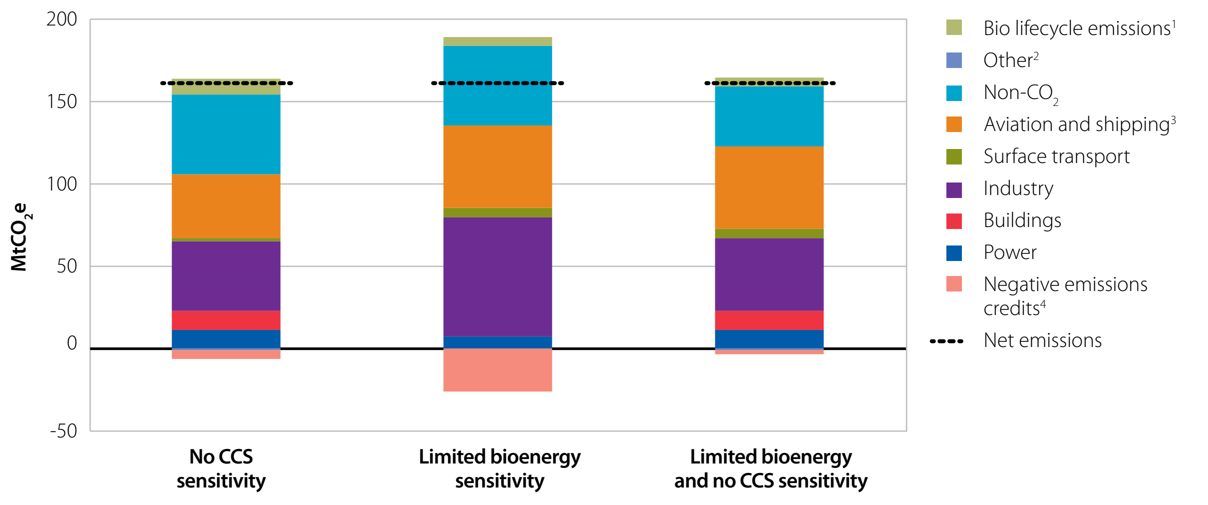
[2] More bioenergy and less electrification than main Max deployment level, as well as no CCS

[3] More biofuels than main Stretch deployment level

[4] As for main Stretch deployment level except no biofuels

[5] More bioenergy than main Max deployment level, as well as no CCS

Figure 1.14: Sensitivities for meeting the 2050 target with limited availability of key options



Source: CCC analysis.

Note: [1]Bioenergy lifecycle emissions include overseas lifecycle emissions for imported bioenergy, as well as those occurring in the UK. [2]Other emissions include military aviation and shipping, emissions from hydrogen production via CCS, emissions removals from LULUCF, and abatement from injection of biogas from anaerobic digestion into the gas grid. [3]International and domestic. [4]Negative emissions credits are from use of bioenergy in combination with CCS or from use of wood in construction.

- **No CCS sensitivity.** In power, additional renewables and nuclear capacity replace CCS, increasing costs as some peak and mid-merit generation is met with high-capital cost low-carbon plant, in addition to higher costs associated with managing more intermittent renewables (see Chapter 2). There may also be additional challenges associated with site availability and acceptability. Bioenergy that would have been used with CCS (to generate negative emissions) is diverted to energy-intensive industry and aviation and shipping, but with less emissions savings as a result. To compensate, greater reductions are (around 50 $MtCO_2e$) required elsewhere, requiring full decarbonisation of surface transport and high cost options such as electrification in industry.

- **Limited bioenergy sensitivity.** Availability of bioenergy is reduced from around 210 TWh (in line with the Extended Land Use scenario from our Bioenergy Review) to around 110 TWh (in line with the Constrained Land Use scenario). The limited bioenergy that is available is concentrated in CCS applications that generate negative emissions. In order to compensate for lost abatement from bioenergy (around 30 $MtCO_2e$), the majority of abatement potential from other measures must be delivered (e.g. all energy efficiency measures and resistive electric heating in buildings).
- **Limited bioenergy and no CCS sensitivity.** Without these two key options, meeting the 2050 target becomes very difficult and costly. The majority of technical abatement potential is required from the other options identified including high levels of electrification in industry and all measures in non-CO_2 emitting sectors. Additional renewable and nuclear replace gas/biomass CCS in power, at additional cost, and bioenergy that would have been used with CCS is instead used to reduce emissions in industry. In theory, further abatement potential could be delivered by applying capture equipment to relevant industrial plants that are no longer suitable for CCS, but instead diverting this CO_2 to mineralisation processes, or the production of algae or synthetic fuels. However these options are uncertain and potentially very expensive due to high energy input requirements (Box 1.2).

Box 1.2: Alternatives to CCS

For some sources of CO_2, such as those generated by chemical reactions in production of cement or steel, carbon capture and storage (CCS) is the key abatement technology envisaged as being available at reasonable cost. However CCS is not yet proven, and it is conceivable that potential sites for geological storage of CO_2 may turn out to be unviable or have insufficient capacity.

If CO_2 cannot be sequestered, alternative forms of abatement may be required to ensure that emissions targets are met. This may involve greater levels of electrification, for example in heat for buildings or industry, or changes in personal behaviour or industrial structure.

However, where significant volumes of CO_2 are still being produced (e.g. in carbon-intensive industries), carbon capture applied with alternatives to its geological storage could still play a role in providing abatement. There are three main alternative ways of gaining abatement by storing or recycling this CO_2:

- **Mineralisation.** The reaction of CO_2 with minerals to produce a solid carbonate product, which would store the carbon permanently (e.g. used as an aggregate or turned into a useful end product). The Energy Technologies Institute has an ongoing study to examine the availability and distribution of suitable minerals across the UK and technologies that could be used for mineralisation of CO_2.
- **Algae production.** Cultivation of micro-algae requires concentrations of CO_2 greater than those available from the air. Growing algae would fix the CO_2 from industrial sources, using sunlight to provide the energy for the resulting hydrocarbon fuel. However, it is not clear whether micro-algae production would be viable in the UK, given that the amount of sunlight available is less than that in lower latitudes.
- **Synthetic fuels.** Recycling CO_2 into production of hydrocarbon fuels, but using hydrogen instead of sunlight to provide the energy. This hydrogen, produced from renewable or nuclear energy, would be combined with the CO_2 to produce hydrocarbon fuels (e.g. aviation fuel or biomethane). It should be noted that this is a thermodynamically inefficient use of low-carbon electricity – using the same quantity of electricity directly in EVs displaces around four times the quantity of liquid fossil fuels as its use to produce synthetic fuels for surface transport – and would therefore be very expensive unless substantial quantities of low-carbon electricity were available at very low cost.

These options are either at the research or early demonstration stage, and are no closer to being proven than CCS. Of these, mineralisation may be the most promising alternative to CCS in the UK context, given the requirements for sunlight and low-cost electricity for algae and synthetic fuel production respectively.

We therefore reiterate our previous conclusion that successful demonstration of CCS technology remains important to the successful building of a low-carbon economy. We also note that at the global level CCS is likely to be even more important given the relatively larger stocks of recently built fossil-fired capacity globally compared to the UK (e.g. modelling of global emissions scenarios we commissioned from UCL showed that the cost of abatement in 2050 could increase dramatically in the absence of CCS).

5. Costs of meeting the 2050 target

We previously considered the cost of meeting the 80% 2050 target (including emissions from international aviation and shipping) in our 2008 report *Building a low-carbon economy*. There we found, based on analysis using the UK MARKAL model, that the 2050 target could be met at a cost in the order of 1-2% of GDP in 2050. We noted that this was consistent with estimates from other sources, including the Stern Review and the Intergovernmental Panel on Climate Change (IPCC).

We have now complemented that analysis by building on our detailed bottom-up modelling for our advice on the fourth carbon budget, to produce bottom-up estimates of the cost of meeting the 2050 target.

- Our estimates of costs as a proportion of GDP are based on resource cost estimates. These are derived by summing the incremental costs (on an annualised basis) of abatement measures in our 2050 scenarios relative to an appropriate reference technology in each case (e.g. unabated gas generation in power).
- Resource costs are likely to capture the most important elements of the GDP cost. Macroeconomic modelling for our December 2008 advice on the first three carbon budgets suggested a range of costs, and our resource cost estimate fell within this range.
  - HMRC's general equilibrium model suggested that the GDP cost would be slightly lower than our resource cost estimate
  - Cambridge Econometrics' macroeconomic model suggested it would be higher. However, as this model does not include any automatic mechanism for the economy to return to full resource use, we suggested in 2008 that some of the additional cost might be considered transitional.
- Where measures appear to be cost-saving (e.g. some energy efficiency measures in buildings and industry; some electric and hydrogen vehicles), we have conservatively included these at zero rather than negative cost in our estimates. This reflects general uncertainty around technology and fuel costs and the possibility that some cost-saving measures would be taken up anyway in the absence of policies to reduce emissions.
- While we include cost estimates associated with key infrastructure investments (e.g. for electricity transmission and distribution, for hydrogen distribution) we have not undertaken a detailed assessment of infrastructure costs more generally (e.g. we do not include potential costs from managing the gas network with significantly reduced throughput).

Under central assumptions for technology costs and fossil fuel prices we estimate that the scenarios outlined above could be delivered at a cost of 0.5-0.7% of 2050 GDP, rising to 0.6-0.9% of GDP if CCS were not available or sustainable bioenergy supply was very limited (Table 1.3).

- In power, costs relate mainly to decarbonisation of mid-merit and peak demand, with limited costs from decarbonising baseload. They include higher costs of generation compared with unabated fossil alternatives, together with additional network costs reflecting increased demand, demand peaks, and intermittent renewable generation.
- In buildings, 60-80% of the overall cost relates to provision of low carbon heat and 20-40% to more expensive energy efficiency measures (e.g. solid wall insulation). Other efficiency measures (e.g. loft insulation) are likely to be cost saving.
- In surface transport, abatement costs of electric cars appear to be close to zero by 2050, while electric vans appear to be cost-saving, as do hydrogen HGVs, due to the longer distances travelled and hence greater fuel savings which more than offset higher capital costs.
- In industry, energy efficiency measures and options in energy-intensive industry are assumed to be zero cost (and could potentially be cost-saving by 2050). CCS therefore accounts for the majority of costs in the four economy-wide scenarios. In the sensitivities without CCS, the majority of costs relate instead to electrification.
- In non-CO_2 emitting sectors, costs relate mainly to on-farm measures in agriculture (including measures to reduce CO_2 emissions from farm buildings and machinery). Total costs across these sectors are small given small amounts of abatement over and above the projected business-as-usual decline, together with low costs per tonne for many measures.
- In aviation and shipping, costs for aviation are relatively small reflecting the relatively small amount of abatement (bringing emissions back to 2005 levels, compared with the deep cuts required in other sectors). Abatement measures in shipping appear to be cost-saving.

Table 1.3: Cost of different scenarios for meeting the 2050 target including aviation and shipping

Costs (% of GDP)	Barriers in industry	Barriers in aviation, shipping and non-CO_2	Barriers in heat for buildings	Barriers in transport and power	No CCS	Limited bioenergy	Limited bioenergy and no CCS
Power	0.3%	0.3%	0.3%	0.4%	0.3%	0.2%	0.3%
Buildings	0.1%	0.3%	0.2%	0.1%	0.1%	0.3%	0.1%
Surface transport	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Industry	<0.1%	0.1%	0.1%	0.1%	0.3%	0.1%	0.3%
Non CO_2	<0.1%	<0.1%	<0.1%	0.1%	<0.1%	<0.1%	0.1%
Aviation and shipping	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%
TOTAL abatement costs	**0.5%**	**0.7%**	**0.6%**	**0.7%**	**0.9%**	**0.6%**	**0.9%**

Source: CCC analysis.
Notes: Costs for increased demand for low-carbon electricity from abatement options in end-use sectors (buildings, industry and transport) are allocated to those sectors (rather than the power sector).

We have also examined the impact of different fossil fuel prices (based on DECC's fossil fuel price projections, see Table 1.4) and technology costs on overall abatement costs. For the *Barriers in industry* scenario, costs vary from 0.1-1.0% of GDP under a range of assumptions for fossil fuel prices, and from 0.2-0.9% of GDP under different assumptions for technology costs (Table 1.5).

Table 1.4: DECC assumptions for 2050 fossil fuel prices.

	Low	Central	High
Coal ($/tonne)	80	110	157
Gas (p/therm)	44	70	100
Oil ($/bbl)	78	130	170

Source: DECC (October 2011) Fossil fuel price projections, DECC (October 2011) IAG guidance for policy appraisal.
Notes: 2011 real prices.

Table 1.5: Sensitivity of costs in the Barriers in industry scenario to fossil fuel prices and capital costs (2050)

Costs (% of GDP)	Central case	Low fossil fuel prices	High fossil fuel prices	High abatement technology costs	Low abatement technology costs
Power	0.3%	0.4%	0.1%	0.5%	0.2%
Buildings	0.1%	0.1%	0.1%	0.2%	<0.1%
Surface transport	0.0%	0.4%	-0.3%	0.2%	-0.1%
Industry	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%
Non CO_2	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%
Aviation and shipping	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%
TOTAL abatement costs	**0.5%**	**1.0%**	**0.1%**	**0.9%**	**0.2%**

Source: CCC analysis.
Notes: We use the Barriers in industry scenario as an illustrative case. In the central case we assume zero rather than negative costs for cost saving measures. However for transport we then include the change in abatement cost under different fossil fuel prices and technology cost assumptions relative to a case which includes negative costs for cost saving measures. Costs for increased demand for low-carbon electricity from abatement options in end-use sectors (buildings, industry and transport) are allocated to those sectors (rather than the power sector). Capex sensitivities are based on: power – ranges identified in modelling by Mott MacDonald for our Renewable Energy Review (2011); transport – ranges for battery costs and hydrogen fuel cells identified by Element Energy (2012) and AEA (2012) for this report; heat and industry – CCC assumptions of +/- 25%.

Our estimates therefore provide more confidence that a 2050 target including aviation and shipping emissions can be achieved at a cost of 1-2% of GDP, which was accepted at the time the Climate Change Act became legislation.

Our estimates consider costs as compared to a world with no carbon constraint. In a world that is carbon constrained our scenarios for emissions reduction in the UK are likely to be cheaper than an alternative with limited abatement that relies on expensive purchase of carbon credits to pay for emissions reductions in the rest of the world.

- For example, Government's trajectory of carbon costs assumes a cost in 2050 of £200/tCO_2 in a central case.

- If all of the emissions reduction from 2010 to 2050 in our scenarios was delivered through credit purchase at £200/tCO_2, total costs would be of the order 2.5% of GDP (i.e. higher than in our scenarios where abatement is delivered in the UK. In practice, business-as-usual emissions in 2050 would be likely to be higher than 2010 emissions so abatement costs (i.e. costs of reducing emissions to 160 MtCO_2e through credit purchase would be even higher.

Preparing for deep emissions reductions now is therefore the lowest cost strategy and best route to ensure the UK's continuing competitiveness internationally in an ever more carbon-constrained world. Including international aviation and shipping in the UK carbon budgets will clarify the value of such a strategy and ensure that the UK is planning robustly for the future.

6. Summary and implications for policy approach

We have set out plausible scenarios for meeting an 80% target in 2050 at reasonable cost including international aviation and shipping.

The level of abatement assumed in these scenarios does not exhaust the full technical potential of all options identified. However, given uncertainties, a sensible approach now would be to deploy extensively across the measures identified, making decisions about where to focus effort as risks and barriers are revealed and resolved over time.

This would ensure that options are sufficiently developed to maintain flexibility in two key areas:

- Flexibility to respond to new evidence around feasibility, costs and effectiveness of low-carbon options – both those discussed above and potential new options that may emerge.
- Flexibility to adjust overall effort in response to developments in scientific understanding, the international context and/or success in reducing emissions from aviation and shipping

We advised that such an approach was desirable in our previous advice, including on the fourth carbon budget, where we noted several areas of particular importance:

- **Decarbonising power.** Early investment in a range of low-carbon technologies is required to prepare for a much larger, fully decarbonised sector to meet the 2050 target. Specifically, there should be a portfolio approach, including competitive investment in mature technologies and additional support for less mature technologies where there is potential for UK deployment to drive down costs. This is recognised in the Government's plans for Electricity Market Reform (EMR), which includes both of these aspects. The Government's commitment to develop an Electricity Systems Policy as part of the EMR process is also appropriate, given the importance of flexibility options in decarbonising mid-merit and peak demand.
- **Developing the market for low-carbon heat.** There is a need to develop the full range of options for cutting heat emissions. This suggests that the Government's support for heat pumps under the Renewable Heat Incentive is appropriate and that the next phase of funding should be confirmed early on. It also highlights the need to ensure that this policy supports investment in both residential and non-residential sectors. More detailed assessments are required for other low-carbon options, in particular for district heating from low-carbon power generation and for resistive heating (i.e. to understand where this may be necessary and the implications for networks).
- **Developing the market for electric vehicles.** Early-stage development of electric and hydrogen vehicles will be required in order for these to achieve full fleet penetration by 2050. Government funding for ultra-low carbon vehicles under the current Spending Review period is therefore justified, with further funding likely to be required through this decade and possibly beyond. There is a need to develop a better understanding of infrastructure requirements (e.g. implications of battery charging for power networks) which can then be reflected in policy and regulatory regimes, with a possible need for additional funding in some cases (e.g. hydrogen networks).
- **Demonstrating and developing key emerging technologies.** Our analysis has reemphasised the importance of CCS in meeting the 2050 target, especially when combined with bioenergy to produce negative emissions. This implies a need to move forward with demonstration of CCS as a matter of urgency. Following recent changes in the competition framework, a clear timetable is required now for selecting and implementing the four power sector CCS demonstration projects to which the UK is committed. Beyond this, an approach should be developed linking these and international demonstration projects with roll-out to energy-intensive industry in the UK.
- **Reducing emissions in industry.** In addition to demonstration of CCS, there are a number of actions required now to develop technologies and improve the evidence base in industry. The RHI should help to increase penetration of sustainable bioenergy, but this should be closely monitored, and funding for the second phase confirmed to improve investor confidence. Improvements to the evidence base are required to establish more detailed cost estimates for electrification and hydrogen options, particularly given their large abatement potential. Beyond this, there is a need to better understand the implications of decarbonisation for the UK's industrial structure and to further explore scope for product substitution and materials efficiency. The Government's forthcoming industry strategy provides an opportunity for this assessment.
- **Other sectors.** It is also important that sufficient focus is placed on those sectors which are currently smaller sources of emissions, but which could become important by 2050. This includes agriculture, waste and other sources of non-CO_2, aviation and shipping. Specifically for aviation and shipping, the Government should continue to support global and EU approaches to reducing these emissions (e.g. the EU ETS for aviation) and support technology development aimed at improving the emissions intensity of new planes and ships.

The Government has taken an important step by setting out in their Carbon Plan scenarios for long-term emissions reductions and priorities to 2030 in preparing for these. They should now continue to develop and deploy policy measures to ensure take-up of abatement options and development of technologies towards the building of a low-carbon economy.

Chapter 2

Decarbonising the power sector

Introduction and key messages

Decarbonising the power sector is key to economy-wide decarbonisation, both because power is currently a major source of emissions and because low-carbon power can be used as a route to decarbonisation of other sectors (buildings, transport and industry – see Chapters 3, 4, and 5).

Power sector emissions were 158 MtCO$_2$e in 2010. We proposed a scenario in our advice on the fourth carbon budget where these emissions fell to 16 MtCO$_2$e in 2030, through reducing carbon intensity from 500g CO$_2$/kWh currently to around 50g CO$_2$/kWh.

In this chapter we consider opportunities to reduce emissions further, through ongoing investment in low-carbon baseload capacity, together with low-carbon investment to meet demand peaks.

Our key messages are:

- The assessment in this chapter reinforces our previous conclusions that power sector decarbonisation is key to economy-wide decarbonisation, that early investment in low-carbon technologies is appropriate and that a portfolio approach to technology development and deployment should be pursued.
- Emissions from the power sector can be reduced to around 5 MtCO$_2$ based on continued roll-out of low-carbon capacity and deployment of flexibility options to reduce demand for peaking generation. New low-carbon capacity is likely to continue to be needed beyond 2030 at roughly the same rate as we previously proposed for the 2020s (i.e. up to 4 GW baseload-equivalent each year).
- Emissions could potentially be reduced to close to zero if new storage mechanisms can be deployed at scale (e.g. meeting demand peaks with hydrogen generated during off-peak periods or with large-scale battery storage).
- Significant removals (i.e. negative emissions) of CO$_2$ could be achieved through use of biomass in combination with CCS in the power sector. Following our bioenergy review we include removals of up to 45 MtCO$_2$, achieved within the economy-wide constraint on bioenergy and demand for this resource from other uses.
- Power sector decarbonisation could cost of the order 0.5% of GDP in 2050.

We set out our analysis in six sections:

1. Power sector emissions and abatement options
2. Scenarios for power sector decarbonisation to 2030
3. Potential negative emissions from biomass CCS
4. Reducing power sector emissions further to 2050
5. Costs of power sector decarbonisation in 2050
6. Summary and implications for policy approach

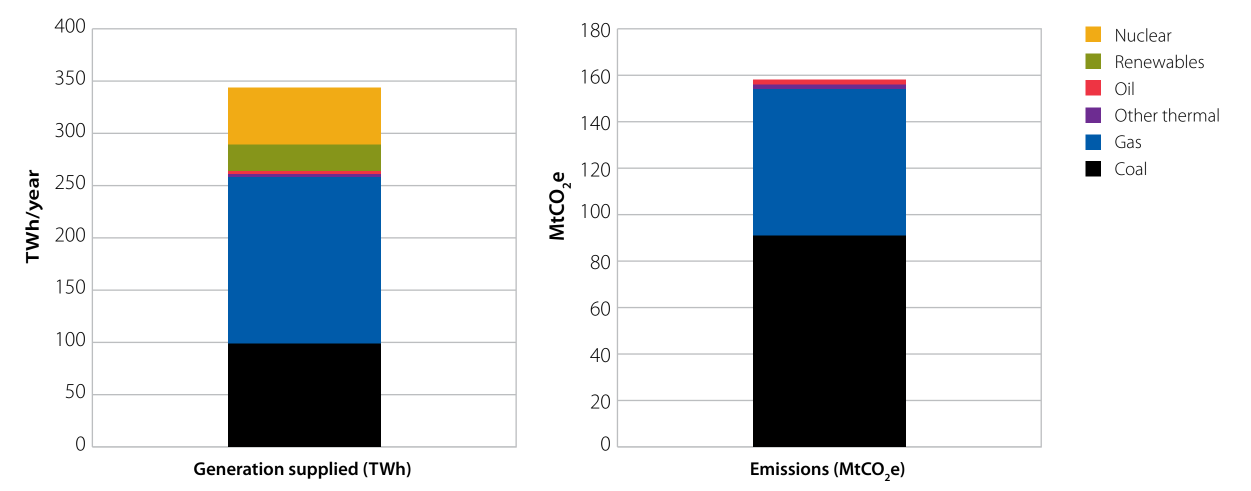
1. Power sector emissions and abatement options

Current emissions from electricity generation

In 2010, power sector emissions in the UK were 158 $MtCO_2$, accounting for around 25% of economy-wide emissions including aviation and shipping. Generation comprised 46% gas, 29% coal, 16% nuclear and 7% renewables, with gas and coal accounting for 40% and 58% of sector emissions respectively (Figure 2.1).

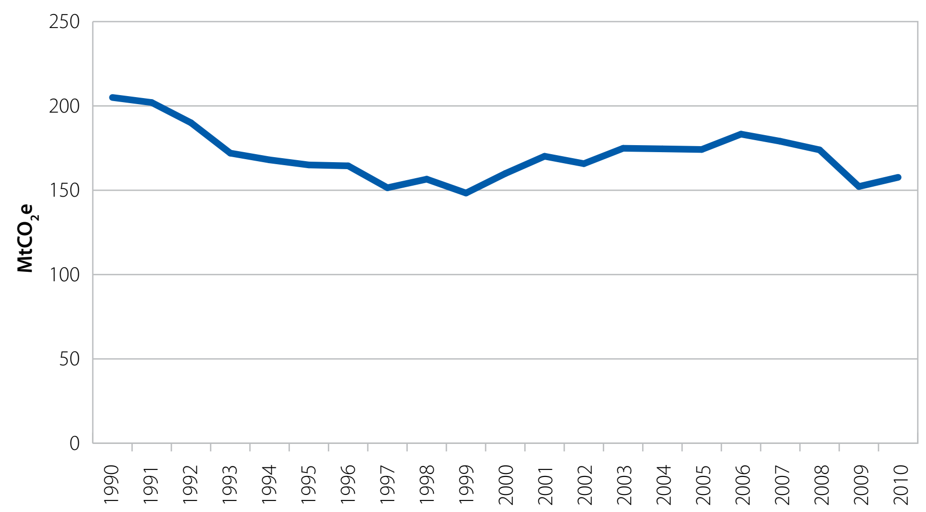
Emissions have fallen 23% since 1990, mainly as a result of the 'dash for gas' during the 1990s. (Figure 2.2).

Figure 2.1: Breakdown of generation and emissions from the power sector (2010)



Source: DUKES (2011) table 5.6, UK GHG emissions data (NAEI 2012).
Notes: Emissions include all GHGs from Power Stations, excluding emissions from autogenerators. Thermal generation from all Major Power Producers only; except 'other' thermal sources, and renewables (includes all generators). Generation is on a supply basis (i.e. excludes own use). Other thermal sources include coke oven gas, blast furnace gas and waste products from chemical processes.

Figure 2.2: Power sector emissions (1990-2010)



Source: NAEI (2012).
Note: Includes all GHGs from Power Stations, excluding emissions from autogenerators.

Options for reducing emissions from electricity generation

Given the combination of capital stock turnover and availability of low-carbon technologies which are or are likely to become cost-effective (i.e. cheaper than fossil fuel generation facing a carbon price), there is scope for significant reduction in power sector emissions over the next two decades and beyond.

We have previously set out detailed technical and economic assessments of the various low-carbon power technologies, both in our advice on the fourth carbon budget, and in our review of renewable energy.

These assessments show that there are plausible scenarios where nuclear, renewables and CCS are feasible and cost-effective within the next two decades (Figure 2.3):

- **Nuclear.** This is currently technically feasible and is likely to be cost-effective based on central cost estimates inclusive of carbon costs (e.g. 8-9 p/kWh in 2020 under central capital cost estimates, compared to 8-9 p/kWh for gas CCGT under central gas prices and with carbon costs in line with the Government's carbon price underpin reaching £70/tCO_2 in 2030).
- **Renewables.** Onshore wind is a currently mature technology approaching cost-effectiveness. Although other renewable technologies are currently relatively expensive (i.e. offshore wind, solar) and some emerging technologies (e.g. marine) are very expensive, there is scope for cost reductions through learning and innovation.
  - **Onshore wind.** A well established technology with extensive global deployment. It is likely to be cost-effective in the UK by 2020 (i.e. 8-9 p/kWh), with some cost reduction expected thereafter. UK resource could be limited depending on planning constraints (e.g. we assume maximum achievable output of up to 70 TWh/yr, compared with around 7 TWh of generation in 2010).

  - **Offshore wind.** At an earlier stage of development to onshore wind, and less likely to be cost-effective by 2020 (11-16 p/kWh), but with continued development and deployment, costs could fall below 10 p/kWh. Benefits from a lower visual impact than onshore wind, and UK resource is very large – over 400 TWh/yr.
  - **Solar.** A mature technology, for which costs continue to fall rapidly (e.g. up to 50% reduction for UK domestic installations since mid-2011). Costs vary depending on size – small domestic installations (<4 kW) are currently eligible for up to 37.8 p/kWh, compared with 8.5 p/kWh for larger systems (>250kW). Feed-in tariffs for some UK installations have recently been reduced, and will be regularly reviewed. UK resource is theoretically large – around 140 TWh/yr on the basis of current technology, with more possible with technology breakthroughs.
  - **Marine.** The UK has played a key role in the global development of wave and tidal stream technology, for which it has significant potential resource (up to 40 TWh/yr for wave, and up to 200 TWh/yr for tidal stream, although there is some uncertainty over resource). Both technologies are yet to be demonstrated commercially and currently operate on a very small scale (e.g. less than 1 MW of wave and 1.55 MW of tidal stream was generating in the UK in 2010). Given its early stage, it is unlikely to be cost-effective within the next two decades, but with commercialisation and rapid cost reductions it could play a significant role as part of a diverse mix in the longer term.

- **Carbon capture and storage (CCS).** Unlike nuclear and renewables, CCS still involves some residual CO_2 emissions. We assume a 90% capture rate, resulting in emissions of around 90 gCO_2/kWh for coal CCS and 45 gCO_2/kWh for gas when allowing for the reduced efficiency of plants running CCS. Higher capture rates (and lower residual emissions) are plausible in the long term, depending on success in demonstration. Although CCS has not yet been demonstrated at scale, it is promising from technical and economic perspectives:
  - It could be particularly useful when used with gas plant to meet mid-merit and seasonal demand (for a definition of these concepts, see Box 2.2), and with coal to increase the diversity of the fuel mix.
  - Based on DECC's central view of fossil fuel prices and our analysis of potential costs and performance of CCS plants, we estimate costs for gas CCS could fall to around 9 p/kWh in 2030. Coal CCS could be more expensive due to higher capital costs and higher costs for residual emissions facing a carbon price, reaching 12 p/kWh in 2030 under our central assumptions.
  - In our 2011 Bioenergy Review, we also identified potential to combine CCS with the use of bioenergy to generate negative emissions. We set out our assumptions regarding biomass CCS in section 3[1].

Given these assessments we have previously recommended that a portfolio approach should be adopted under which each of the technologies above are developed.[2] This is appropriate given the scale of the challenge in decarbonising the power sector, cost uncertainties, scope for reducing costs of less mature technologies, and the potential constraints or risks around the deployment of individual technologies. It is reflected in the Government's approach, under which tailored support is or will be available for less mature low-carbon technologies (Box 2.1).

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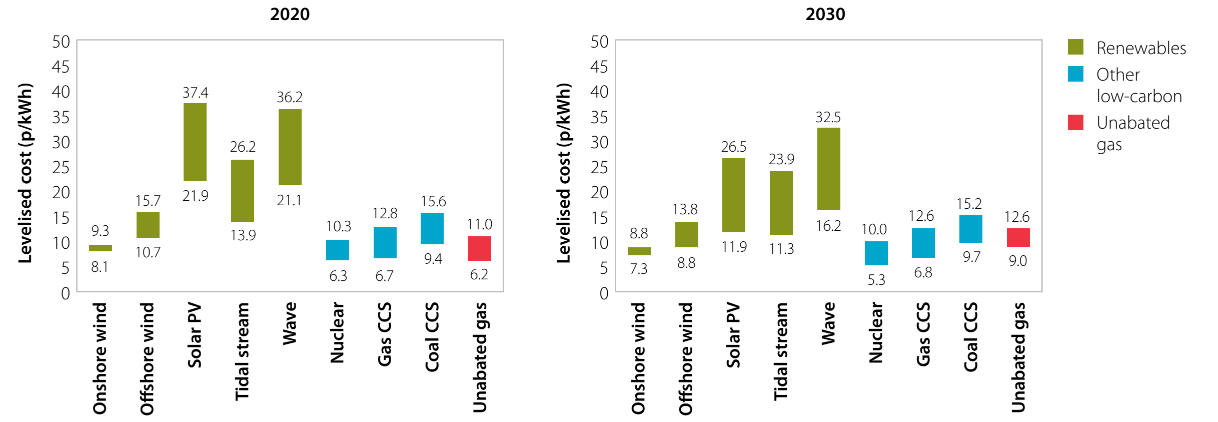
[1] In our Bioenergy review, we showed that use of biomass in power with CCS could provide the opportunity for negative emissions to offset emissions in 'hard to reduce' sectors (e.g. aviation). Without CCS, biomass in power would offer little long-term benefit relative to other forms of low-carbon power (e.g. nuclear, renewables), and would divert biomass from other uses where it is more highly valued.

[2] See our *Renewable Energy Review* (2011), where we argued that, given uncertainties over costs and technical constraints, a portfolio approach is appropriate, in which support is provided for less mature technologies to drive learning and cost reductions.

Figure 2.3: Levelised cost of unabated gas and a range of low-carbon technologies (2020 and 2030)



Source: CCC calculations based on Mott MacDonald (2011).
Notes: £2011. Levelised cost of technologies commencing operation in 2020 and 2030, using a 10% discount rate. Low range combines low fuel prices and low capex; high range combines high fuel prices and high capex. Includes carbon price consistent with the Government's proposed Carbon Price Floor, rising to £30/tCO_2 in 2020, £70/tCO_2 in 2030 and £200/tCO_2 in 2050.

Box 2.1: Support for CCS demonstration and renewables deployment

Support for renewable generation is currently provided through the Renewables Obligation, with capital funding also available for the demonstration of CCS. Under proposals to reform the electricity market, by 2020 support for new low-carbon projects will be provided via feed-in tariffs with contracts for difference (FiT CfDs).

Renewables Obligation

Electricity suppliers are required to surrender Renewable Obligation Certificates (ROCs) at a level consistent with an increasing share of demand over time (e.g. the target for 2011/12 is that 15.8% of electricity supplied should come from renewable sources). Developers of renewable generation receive income from ROCs on top of any earnings in the wholesale electricity market – in 2011 the value of a ROC was around £45-50/MWh. Under banding provisions, multiple ROCs are issued for each unit of generation for earlier stage technologies, recognising these have higher costs (e.g. offshore wind is currently eligible for 2 ROCs per MWh in England and Wales, whilst landfill gas is eligible for 0.25).

CCS demonstration

The 2010 Spending Review allocated up to £1 billion in capital funding for the demonstration of commercial-scale CCS in the UK. The process under which funding will be awarded for second, third and fourth demonstration projects via a competitive process is expected to be announced in the first half of 2012, with further funding potentially available for future projects and from Europe ('NER3000').

Electricity Market Reform – FiT CfDs

In July 2011, the Government published a White Paper[3] setting out proposals to reform the electricity market and the way support will be provided for new low-carbon generation. Under the proposals, support will be provided via long-term contracts, which will be linked to the wholesale electricity price which generators are able to receive in the wholesale market. The intention is for the first contracts to be signed in 2014, with FiT CfDs replacing the Renewables Obligation by April 2017. The new arrangements will take over from ROCs as the mechanism to deliver the UK's renewable energy target in the power sector, and could for example include higher payments for specific (less mature or higher cost) technologies.

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[3] DECC (2011) *Planning our electric future: a White Paper for secure, affordable and low-carbon electricity*, available at http://www.decc.gov.uk/en/content/cms/legislation/white_papers/emr_wp_2011/emr_wp_2011.aspx

2. Scenarios for power sector decarbonisation to 2030

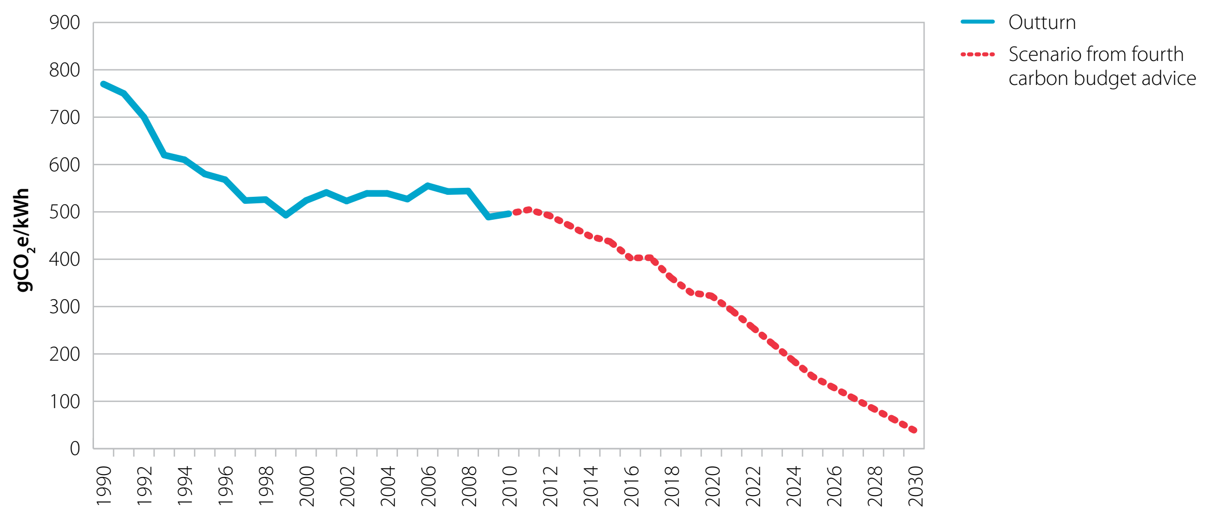
In our advice on the fourth carbon budget we developed scenarios for decarbonisation of the power sector. These included low-carbon investment judged to be cost-effective relative to the Government's carbon values, together with ongoing support for technologies that might not be cost-effective to 2030 but are likely to be required in the longer term. In our central scenario power sector emissions fell to around 16 $MtCO_2e$ in 2030.

The central scenario included investment in around 20 GW of (baseload-equivalent[4]) low-carbon capacity to 2020, with an additional 35 GW to 2030, which we identified as feasible based on an assessment of build constraints.

In our central scenario all baseload and some mid-merit generation would be from low-carbon sources. Remaining demand (5-10%) is principally met with unabated gas (at 400 g/kWh), resulting in emissions of around 50 gCO_2/kWh in 2030, compared to average emissions of around 500 gCO_2/kWh in 2010 (Figure 2.4).

In our review of renewable energy, we considered the generation mix in 2030 in more detail. Current uncertainties (e.g. over technology costs and deployment barriers) mean it is not possible now to predict what mix will best balance cost-competitive deployment of mature technologies, demonstration of new technologies and deployment of immature technologies aimed at driving their costs down the cost curve. In our renewables review we illustrated one possible mix in 2030 that balanced these factors, comprising around 40% nuclear, 40% renewables, 15% CCS and 5% unabated gas-fired generation for balancing the system (Figure 2.5). The most appropriate mix will become clear as new information about limits to investment in particular technologies and relative costs becomes available (e.g. we showed that mixes with 30-65% of electricity generated by renewables were plausible, with the remainder mainly to be met through some mix of nuclear and CCS).

Figure 2.4: Power sector emissions intensity per kWh of demand (1990-2030)



Source: CCC calculations based on DECC (2010) DUKES tables 5.3, 5.6, 7.4 and DECC emissions inventory.
Note: Intensity is based on energy supplied from major power producers and all renewable generators and is net of transmission and distribution losses.

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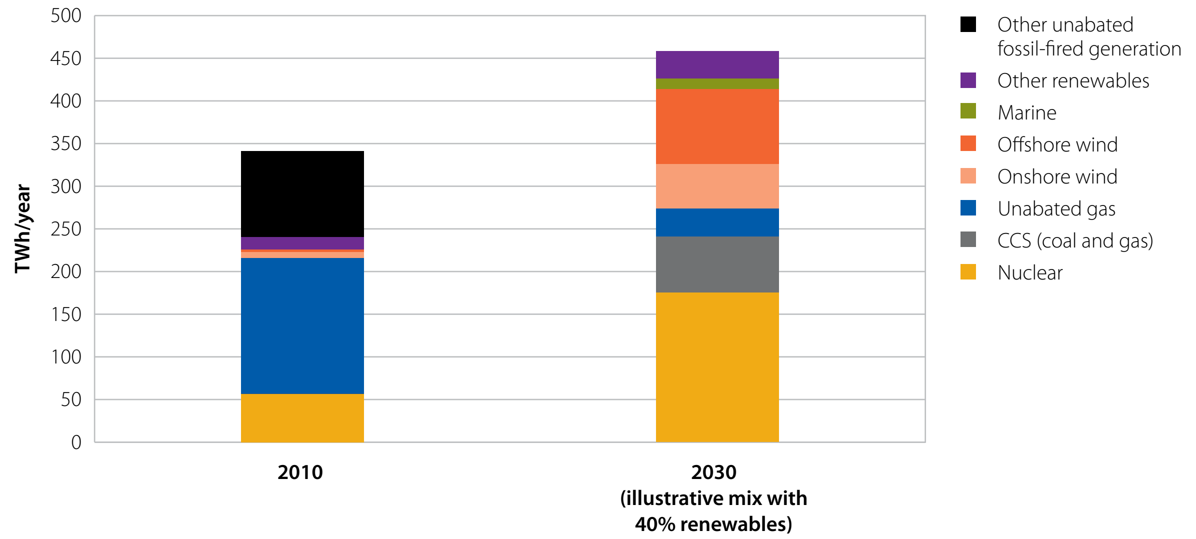
[4] Intermittent technologies (i.e. offshore wind, onshore wind, marine, solar) are adjusted in this figure by the difference between their average capacity factor and the availability of non-intermittent plants (e.g. nuclear, CCS) in order to put plants on an equivalent GW basis. For example, assuming non-intermittent plants are available to generate for 90% of the year, and offshore wind is able to generate at its maximum rated capacity for 42% of the year (i.e. capacity factor), 1 GW of offshore wind is equivalent to (42%/90%) * 1 GW = 0.47 GW of baseload-equivalent capacity.

Figure 2.5: Power sector generation mix (2010 and illustrative 2030 mix)



Source: DUKES (2011) Table 5.6, 7.4 and CCC calculations based on modelling by Pöyry Management Consulting for the Renewable Energy Review.
Notes: Generation from Major Power Producers only, except renewables (includes all generators). Generation is on a supply basis (i.e. excludes own use).
Other renewables includes biomass, solar PV, hydro. Other unabated fossil includes coal, oil.

3. Potential negative emissions from biomass CCS

One potential option that we did not consider in our advice on the fourth carbon budget is the use of bioenergy in combination with CCS. Our 2011 review of bioenergy identified the potential for the power sector to reach negative emissions through this technology as a particularly important use of bioenergy in the longer term.

The contribution that biomass CCS can make to emissions reductions to 2050 will depend on the effectiveness, deployability and cost of the technology, the availability of a supply of sustainable biomass and the relative attractiveness of biomass CCS compared to other potential uses.

Accounting for these factors, scenarios from our Bioenergy Review suggested that a major role for biomass CCS was likely to be appropriate if it is available:

- Technology availability is uncertain. It is dependent on successful demonstration and development of CCS more generally, as well as success in applying that to biomass specifically.
- Given successful demonstration of CCS, with plant costs in line with our assumptions for coal CCS, and with high-grade pelleted biomass (suitable for power generation) valued at 4.3p/kWh, the cost of generating electricity from biomass CCS would be around 17 p/kWh in 2050.
- Although this cost is higher than for some of the competing low-carbon technologies (e.g. nuclear, offshore wind), biomass CCS has the added benefit of sequestering carbon from the atmosphere. Assuming a 90% capture rate, the emissions intensity of a biomass CCS plant would effectively be negative 935 gCO_2/kWh.

- In our bioenergy review we included scenarios where the UK had access to 108-504 TWh of bioenergy resource. Our modelling of where this would best be used suggested that this was in applications with low efficiency losses in conversion and where either negative emissions could be achieved or low-carbon alternatives did not exist. Under our scenario with 213 TWh (our Extended Land Use scenario) of bioenergy resource, 171 TWh (80%) was used in conjunction with CCS in the power sector.

This is in line with other analysis that also assumes a major role for biomass CCS in 2050. For example:

- DECC's Carbon Plan includes a 'Higher CCS, more bioenergy' scenario, in which there is both successful deployment of CCS technology at commercial scale, as well as plentiful sustainable bioenergy resources. CCS is used with biomass to generate around 50 $MtCO_2$ of negative emissions.,
- The Energy Technology Institute is currently undertaking a high-level engineering study on biomass with CCS in order to assess the technology gaps and the likely time-scales for implementation. With the right technology they estimate biomass CCS as having the potential to remove 50-100 $MtCO_2$ from the atmosphere on an annual basis[5].

In our main 2050 scenarios (where CCS and sufficient bioenergy resource are available) we therefore include 4.3-6.1 GW of biomass CCS, generating 34-48 TWh of electricity (up to 8% of 2050 demand) based on a biomass input of 98-141 TWh and leading to negative emissions of 31-45 $MtCO_2$.

4. Reducing power sector emissions further to 2050

In this section we first set out the twin challenges from 2030 to 2050 of meeting increased demand and decarbonising demand peaks. We then consider how each of these challenges can be met, and consider the potential for negative emissions through application of CCS in combination with biomass. We conclude by setting out our scenarios for power sector decarbonisation in 2050.

We set out our analysis in four sections:

(i) The challenge from 2030 to 2050

(ii) The need for low-carbon capacity

(iii) Decarbonising peak demand

(iv) Remaining power sector emissions in 2050

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[5] ETI, Biomass to Power with *Carbon Capture and Storage (CCS) Flexible Research*. http://www.eti.co.uk/technology_programmes/bio_energy/

(i) The challenge from 2030 to 2050

The twin challenges for the UK power sector from 2030 to 2050 are to meet an increasing demand for low-carbon electricity, whilst also reducing emissions from mid-merit and peak demand:

- Our analysis of the end-use sectors (buildings, transport and industry – see Chapters 3-5) demonstrates that low-carbon electricity is likely to be an increasingly important energy source for wider economy decarbonisation to 2050. This is in line with the Government's scenarios from the Carbon Plan, which include an increase in electricity demand of 30-60% between 2007 and 2050[6].
- Our scenarios for low-carbon capacity deployment to 2030 decarbonise baseload demand, and some mid-merit demand. To further reduce emissions will require that all of mid-merit, and potentially peak demand, is also decarbonised. There are two options to achieve this, discussed further below – shifting demand (e.g. from peak to off-peak) and meeting more of peak and mid-merit demand with low-carbon generation operating at lower load factors.

We now turn to the first of these challenges – the need for new low-carbon capacity.

(ii) The need for low-carbon capacity

There will be scope for increased generation of low-carbon power beyond 2030 based on the same set of technologies to be demonstrated and deployed over the next two decades (i.e. nuclear, renewables, CCS), but at possibly lower cost (Figure 2.3).

The pace of investment beyond 2030 would be determined by demand growth and turnover of the capital stock:

- **Demand growth.** Investment in new capacity would be required to meet growth in overall demand.
  - Final electricity demand (excluding autogeneration and energy sectors) is currently around 330 TWh per year. In our core scenarios it rises to around 450 TWh by 2030 and 570 TWh by 2050, driven by the electrification of transport and heat (i.e. electrification accounts for 60% of growth between 2030 and 2050). Demand could be significantly higher if there is electrification of industry as well as heat and transport (e.g. in our scenario with constraints on CCS and bioenergy, demand would be above 700 TWh).
  - Much larger increases in demand are also possible, for example if electric heating is dominated by resistive heating (without storage) rather than heat pumps, if energy efficiency measures are not unlocked, or if inefficient synthetic fuels are required to substitute for bioenergy or CCS on industrial plants using fossil fuels. There are also major uncertainties over conventional demands, such as for new appliances or air conditioning.

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[6] DECC (2011), *The Carbon Plan: Delivering our Low Carbon Future*, available at http://www.decc.gov.uk/assets/decc/11/tackling-climate-change/carbon-plan/3702-the-carbon-plan-delivering-our-low-carbon-future.pdf

- **Capital stock turnover.** Further investments would be required in the 2030s and 2040s to repower or replace wind generation deployed during the 2010s and 2020s (i.e. at the end of the 20-25 year lives of these investments), and possibly to replace other low-carbon power (e.g. existing coal plants converted to burn biomass during the 2010s).

The total investment required in baseload-equivalent low-carbon capacity per decade could therefore be of the order 20-40 GW, compared to 20 GW in the 2010s and 30-40 GW in the 2020s. The required build will be determined by the degree of electrification and roll-out of energy efficiency, along with the degree to which increased total demand is reflected in peak requirements – see section 3(iii).

Insofar as CCS provides a significant proportion of generating capacity in 2050, increased demand will also translate to increases in residual emissions. Assuming that CCS makes up around 20% of low-carbon capacity (in baseload-equivalent terms) residual emissions from fossil CCS plants would be around 3-5 MtCO$_2$e in 2050.

(iii) Decarbonising peak demand

Demand variations across the year

Demand for power varies over the day (e.g. demand is typically highest at around 6pm during winter), over the week (weekday demand is generally higher than weekend demand) and over the year (winter demand is higher than summer demand, reflecting increased lighting demand on shorter days and increased heating demand from colder temperatures) – see Figure 2.6. It will also vary less regularly with temperature and special events (e.g. a popular television programme or event).

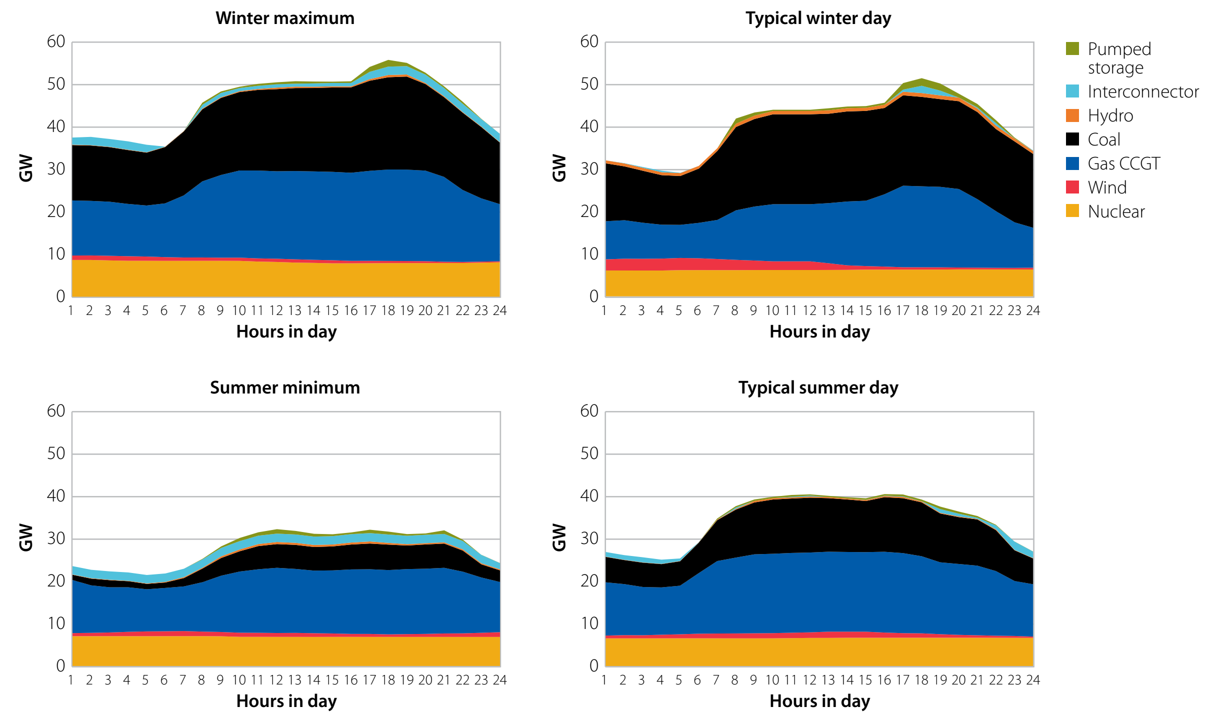
In our analysis we distinguish between peak, mid-merit and baseload demand (defined in Box 2.2), since different plants will be suited to meeting these demand types. We also identify potential changes in the overall demand pattern as new demands for electric heating and electric vehicles increase.

- Less than 5% of current demand relates to peaks, and could be met by plant operating at very low annual load factors (i.e. less than 20%). The majority (i.e. over two-thirds) of demand is baseload (i.e. could be met by plant operating for 90% of the year). The remaining 30% we define as mid-merit.
- Looking forward, we project offsetting effects on the demand profile:
  - Development of electric vehicle markets with overnight charging of batteries (see Chapter 4) and electrification in industry (see Chapter 5) will tend to increase baseload demand, reducing the share of peaking and mid-merit demand.
  - More widespread uptake of heat pumps and resistive electric heating (see Chapter 3) will increase seasonal demand, which will tend to increase mid-merit and peaking demand.

- In our 2050 scenarios these effects broadly offset, so that peaking and mid-merit demand would still be around 30-35% of all demand. However, we note that the future profile of demand and generation is uncertain, and may be affected by the impacts of climate change (e.g. warmer temperatures could lead to increased air conditioning and higher summer demand).
- Whilst baseload is likely to continue to dominate demand, emissions from plant meeting mid-merit and peak demand would also be significant if these are not decarbonised.

Given that a significant proportion of demand will continue to be mid-merit and peak, full decarbonisation of the power sector will require that this demand can be met with low-carbon generation.

Figure 2.6: Typical daily profiles over the year (2011)



Source: CCC calculations based on real electricity demand data for 2011 (Elexon Portal).
Notes: Flows out of the system (e.g. outflows under interconnector, pumped storage in pumping mode) is not shown. CCGT = Combined Cycle Gas Turbine.

Box 2.2: Definition of baseload, mid-merit and peak

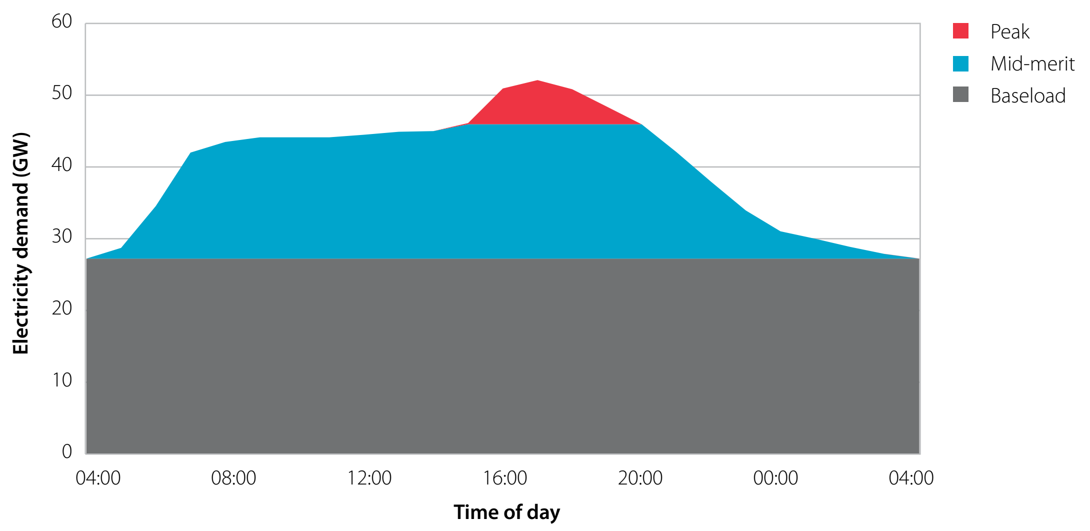
We define baseload, mid-merit and peak demand as follows, and as illustrated in Figure B.2.2 (based on an example day in 2011):

- **Baseload** is the part of total demand that is present throughout the year, and therefore can be met by capacity running continuously. Since most plants will need to shut down at some point during the year anyway (e.g. for maintenance), we define baseload as the minimum level of demand that is present throughout at least 90% of the hours of the year. This minimum level in the UK is generally associated with overnight periods in summer, for which the minimum was around 20 GW in 2011 (Figure 2.6). Since this demand is present throughout the year, it accounts for a large share of the total, making up 215 TWh (69%) of hourly generation in 2011[7]. It currently covers all nuclear generation and a significant share of renewables, unabated coal and gas generation.

- **Mid-merit** demand refers to those parts of demand that go beyond the levels covered by baseload, but do not reach the highest levels seen in a year. It typically occurs during the day in summer and throughout winter, reflecting use of electricity for heating during the coldest months of the year. We define mid-merit as being that part of demand greater than baseload and occurring in at least 20% of the hours in the year. In 2010, mid-merit covered hourly demand of around 25-40 GW, and made up 90 TWh (29%) of generation. Much of the UK mid-merit demand is currently met with unabated gas and coal generation, which are easily able to increase and decrease output within-day.

- **Peak** demand relates to those high levels of demand that occur only very infrequently in a year, typically during winter in evening. We define peak as those high levels (beyond baseload and mid-merit) that occur in no more than 20% of the hours in the year. In 2011, any hourly demand above 40 GW would have counted as peak demand, reaching 55 GW at the highest (winter maximum) level. Since this demand occurs relatively infrequently, it only totalled 2% of generation over the year in 2010. Generation that is able to quickly respond to the changing profile of demand by increasing or decreasing output is particularly suited to meeting peak (e.g. pumped storage and open cycle gas turbines).

Figure B2.2: Example profile of daily demand and baseload, mid-merit and peak demand



Source: CCC calculations based on real electricity demand data (Elexon Portal).

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[7] CCC calculations based on half- hourly data for 2011, from Elexon Portal www.elexonportal.co.uk

The impact of intermittent generation on demand shape

Currently the large majority of demand is met by despatchable capacity (e.g. fossil fuel and biomass plants that can ramp generation up and down as required to match supply with demand), with balancing ensured by the System Operator (i.e. National Grid – Box 2.3).

Box 2.3: Current arrangements for managing the system – balancing role of National Grid

In the UK, electricity is traded via bilateral contracts between suppliers and generators, based on expected demand and supply. Actual demand and supply may differ from expected due to unusually cold weather or a power station outage. It is the role of the System Operator (National Grid) to ensure that demand and supply of electricity are in balance on a second-by-second basis, for which a range of services are used:

- **Frequency response** through automatic controls on generators is provided within seconds.

- **Fast reserve** may be brought on within minutes and includes, for example, small variations in flexible plant output (which may be part-loaded in readiness), demand reduction, and pumped storage.

- **Standing reserve** is ready within 20 minutes, and may include open cycle gas turbines or back-up diesel generators.

Intermittent and inherently unpredictable generation (e.g. wind), can increase the fluctuations that have to be managed by the System Operator, and therefore the amount of reserve and response services required to maintain a balanced system.

By 2050 a large share of capacity is likely to be intermittent (e.g. wind capacity, that will generate depending on prevailing weather conditions and regardless of the level of demand). This creates an issue of peaks in net demand (i.e. the demand remaining to be met after accounting for generation from intermittent renewables), where the rest of the generation system will need to meet the balance of demand and intermittent generation.

The pattern of net demand in 2050 is likely to be significantly different from gross demand today (Figure 2.7):

- **Offshore wind** generation has a strong seasonal profile (i.e. generation is higher in winter), that will tend to offset the seasonality of heat demand.

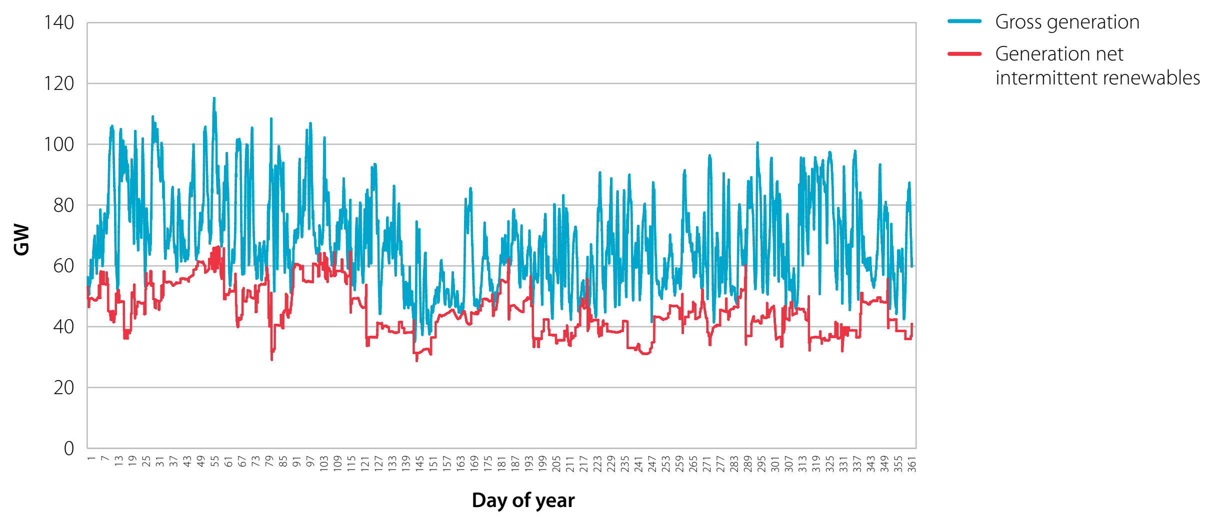
- **Wind** output (both onshore and offshore) has large day-to-day and within-day swings, which will tend to increase the short-term variability of net demand, compared to gross demand.

- **Solar** generation is higher in summer than winter and only during daylight hours.

- **Marine.** Tidal stream is driven by the ebb and flow of water according to tides, and therefore whilst intermittent is inherently predictable. Wave is less predictable, and positively correlated with wind speed offshore and therefore likely to generate more during the winter than summer.

Taken together, significantly increased intermittent generation is likely to imply that resulting net demand will be more volatile than gross demand.

Figure 2.7: Gross demand and demand net intermittent renewables (example from 2050)



Source: Modelling by Pöyry Management Consulting for the Renewable Energy Review (2011).
Notes: Hourly generation, based on observed weather patterns in 2009, scaled up to 2050 demand, c. 35% intermittent renewables. Chart shows gross generation, and gross generation minus output from intermittent technologies including wind, solar, wave and tidal.

Flexibility options for addressing intermittency

In our Renewable Energy Review we identified and assessed options for managing intermittency. This included three options to increase flexibility that would reduce the need for generation to meet peak net demand (Box 2.4):

- **Demand-side response.** Active management of demand (e.g. charging electric vehicles or running washing machines overnight when other demand is low) can help smooth the profile of demand and reduce the requirement for capacity during peak periods. Widespread deployment and use of smart technologies (such as smart meters) will facilitate increases in demand-side response given sufficient consumer engagement.
- **Interconnection.** Interconnection already provides a valuable source of flexibility to the UK, with around 3.6 GW of capacity with SEM (Ireland), France and the Netherlands. Flows are price-driven according to relative demand and supply, and to the extent that these differ across countries, will continue to be an important source of flexibility. Our modelling assumes up to 24 GW of connection in 2050, based on Pöyry analysis.
- **Storage.** Bulk storage, such as pumped storage, can be used both to provide fast response and to help provide flexibility over several days (providing supply at times of peak daily demand rather than continuously over a whole period).

There are clear challenges in implementing this flexibility, for example, a significant increase in demand-side response would require consumer acceptance of new technologies and behaviours, and new pricing models or approaches to aggregating disperse consumer demands. Construction and effective use of greater interconnection will require that appropriate conditions are in place not just in the UK, but also in interconnected (European) markets. In constructing our scenarios for power sector emissions we therefore include the possibility that deployment of flexibility options is more limited.[8]

However, given significant lead time to 2050, increasing value of delivering flexibility over time and existing plans to support these measures (e.g. smart meter roll-out planned to 2020), there is scope to overcome these challenges. Given extensive implementation of flexibility options the effects of intermittent generation would be mitigated. For example, for our Renewable Energy Review we modelled scenarios with up to 75% of generation coming from intermittent sources – with significant increases in demand-side response, interconnection and storage, the requirement for mid-merit and peaking demand remained at around 30-35% of total demand.

Box 2.4: Flexibility options in electricity generation

Options that improve flexibility in the power sector help match the profile of demand with supply, which is particularly important with increasing shares of intermittent and inherently unpredictable generation (e.g. wind). In 2010 we commissioned Pöyry[8] to identify and characterise flexibility options, which fall into three key categories:

- **Demand-side response.** Growth in demand from new sectors such as heat and transport provide an opportunity to change the profile of demand, by giving access to storage which facilitates the shifting of demand – for example, electric vehicles can be charged overnight even though they may be used at peak times during the day, and when deployed with storage heat pumps can also provide flexible 'charging'. A very simplified illustration of demand shifting is shown in Figure B.2.2, where demand (via, for example, a time of use tariff) that would have occurred at peak is moved to fill in the trough at mid-merit, thereby requiring less overall capacity to meet a given level of demand (within-day), and allowing that capacity to operate at higher load factor. As well as 'smoothing' the profile of demand, active demand management (i.e. using 'smart' systems with some element of centralised signal or control) can shift demand to respond to swings in wind generation. Pöyry's analysis suggests that based on our scenarios for increased electrification, and subject to roll-out of smart technologies and tariffs, around one-third of demand could be flexible, at least within-day, by 2050.
- **Interconnection.** Increased interconnection can increase flexibility by allowing trading of electricity to exploit differences in demand or in the output from intermittent sources of generation between the UK system and surrounding countries (e.g. reflecting that periods of high heating demand or low wind output in the UK could coincide with low air conditioning demand or high solar output elsewhere). For modelling interconnector flows Pöyry used a European-level model, based on weather and demand patterns in GB and Northern Europe (i.e. it allows for the probability that low wind output and high demand occur concurrently in UK and interconnected markets).
- **Bulk storage.** This includes pumped storage, which is well developed and in operation in the UK, as well as more novel applications such as batteries and compressed air storage (see Box 2.6). Pumped storage uses electricity to pump water into a high level reservoir, which is then released to generate electricity. This can provide very fast response (e.g. within minutes). The UK currently has 2.7 GW of pumped storage capacity, often used during the 'tea-time' peak (as shown in Figure 2.6). Pöyry estimate up to 4 GW of storage facilities could be in operation in 2050, with operating characteristics similar to pumped storage.

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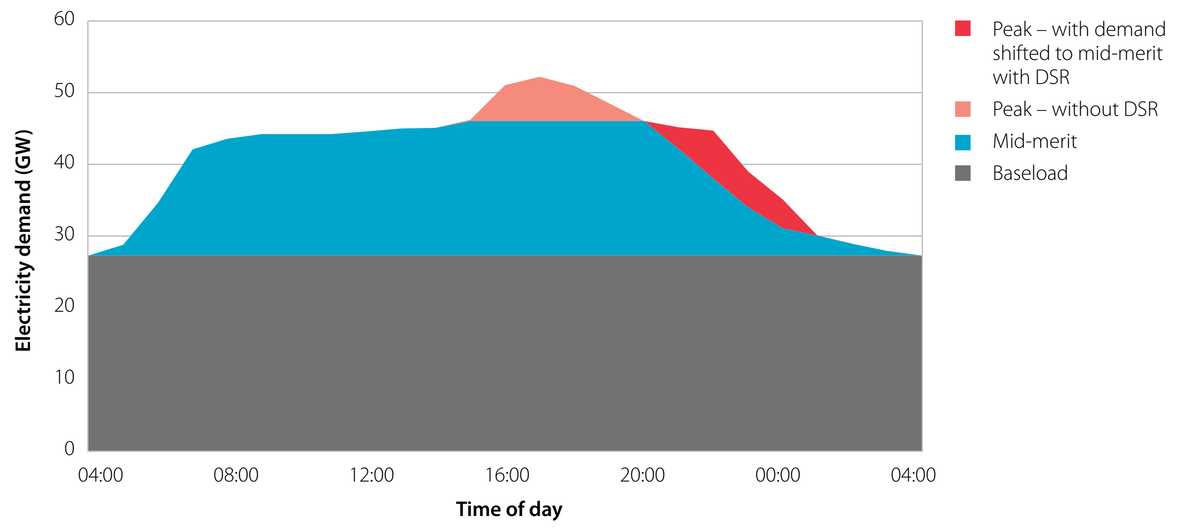
[8] Pöyry Management Consulting (2011) *Analysing technical constraints on renewable generation*, available at www.theccc.org.uk

Box 2.4: Flexibility options in electricity generation

We reflect these assumptions in our 2050 modelling for this report.

Figure B2.4: Simplified illustration of demand shifting and reduction in required capacity



Source: CCC calculations.
Note: DSR = demand side response.

Low-carbon options to meet remaining mid-merit and peak net demand

Even with significant roll-out of flexibility options, there will be a requirement for some balancing generation operating at low load factors. Some of peak and mid-merit demand could be met with low-carbon generation, although at higher cost than for baseload demand.

- To an extent, low-carbon technologies are able to fulfil a mid-merit and peaking role, since they can be configured to operate relatively flexibly from a technical perspective (Box 2.5).
- Whilst they are less suited to this role economically – reflecting high upfront costs and low operating costs compared to fossil-fired capacity – as the carbon price rises low-carbon options will be increasingly economic at low load factors. For example, at a carbon price of £200/tonne in 2050, gas CCS would be competitive with unabated gas at annual load factors as low as 10% based on our central cost assumptions (Figure 2.8), making it particularly suitable as a low-carbon option at mid-merit.
- There may also be opportunities for more extensive deployment of storage options for use at peak than considered in our Renewable Energy Review. This could, for example, be through meeting peak demand with hydrogen that has been produced during off-peak periods or through novel applications of electricity storage technologies at scale (Box 2.6).

Given these options we include in our deployment scenarios gas CCS at mid-merit, and two possibilities for peak demand – that only unabated gas is used to meet demand peaks (at annual load factors of 20% or below) and that peaks are met by low-carbon options (e.g. hydrogen or other storage).

Box 2.5: Operating low-carbon generation more flexibly

Flexible forms of generation used to keep the system in balance currently are predominantly fossil fuel fired, with unabated gas and coal providing diurnal mid-merit and some peak demand, requiring operational flexibility (e.g. ramping output up and down within a relatively short space of time). From a technical point of view it is possible for forms of low-carbon generation to provide flexible generation to some extent, with the possibility that they could go further with technological advances in new designs:

- **CCS** with fossil fuel (coal or gas) and biomass may offer a fairly high level of flexibility, with reasonably short minimum on and off times (e.g. six hours, suitable for mid-merit, within-day flexibility).
    - Pre-combustion CCS is most suitable for flexible generation, with the capture process running separately from generation thereby allowing the output of the pre-combustion process to be produced, stored and fed into the plant to generate electricity when required.
    - For post combustion CCS, the capture process itself could provide a source of flexibility as it is possible to turn off the capture equipment and increase the net capacity of the plant. However, this may incur severe penalties in terms of carbon emissions, and therefore may only be desirable infrequently and for very short periods.[9]
- **Nuclear.** Traditionally, nuclear plants in the UK have operated relatively inflexibly almost continuously throughout the year (with some planned maintenance, generally in the summer months). Although there are constraints preventing nuclear providing the same degree of flexibility as other options (e.g. minimum on and off times of 48 hours), it could offer more flexibility in the future:
    - French nuclear plants run fairly flexibly to support system balancing, at times operating at 10% of their rated output (i.e. part-loaded in readiness to increase or decrease output if necessary).
    - The new generation of nuclear plants planned for the UK (EPR and AP1000) offer improved flexibility on current operational designs, with shorter minimum on and off times, lower minimum stable generation levels and faster response rates.
    - Some flexibility requirements are longer-term (e.g. seasonal) and can be met without any short-term changes in generation or increased number of starts (e.g. nuclear could fulfil a mid-merit role by having a longer summer off-period than required for maintenance, rather than by flexing output up and down within each day).
- **Renewables.** Some renewables can potentially operate flexibly (e.g. hydro or tidal lagoons). Whilst many (e.g. wind) cannot choose when to generate, they can 'spill' output (i.e. stop generating at times of excess supply), which may be preferable to reducing output from nuclear in shorter timeframes. Biomass generation without CCS would also be relatively flexible, however, in our Bioenergy Review we concluded that without CCS biomass in power would offer little long-term benefit relative to other forms of low-carbon power, and would divert biomass from other sources where it is more highly valued.

It is worth noting that, as for all forms of generation, operating low-carbon plants at less than full load (e.g. repeated ramping up and down of output) could potentially have an impact on operating lifetime and operational costs (e.g. increased wear of components, requiring replacement). We have incorporated plausible assumptions about the flexibility of low-carbon generation in our 2050 modelling based on Pöyry analysis for our Renewable Energy Review.[10]

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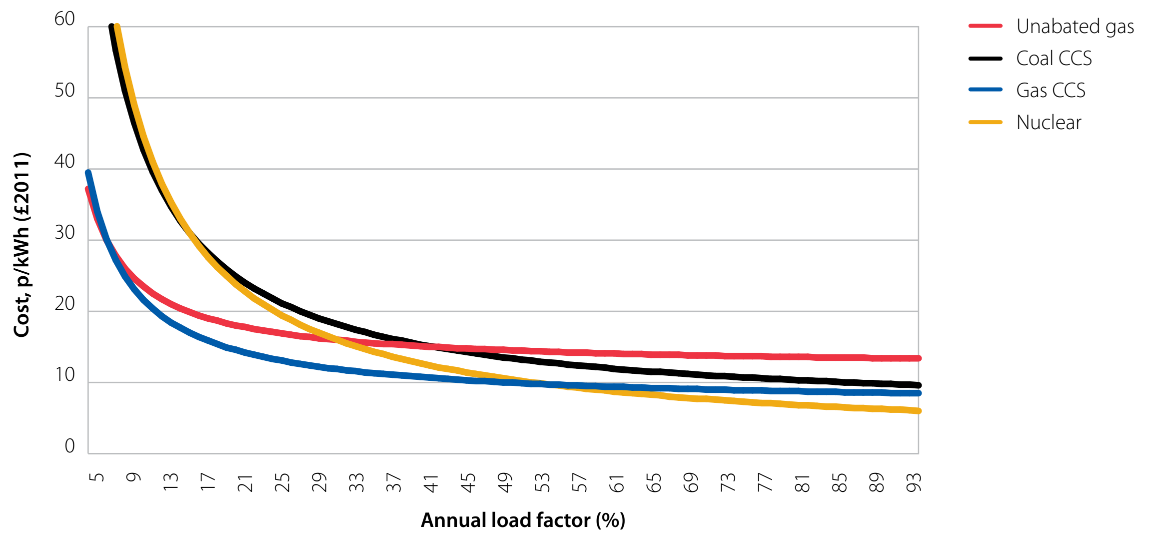
[9] We do not include this as an option in our scenarios.

[10] For further information on the characteristics of flexible generation, see Pöyry Management Consulting (2011) *Analysing technical constraints on renewable generation*. Modelling accounted for minimum stable generation and minimum on and off times for new nuclear and flexible CCS. Once running, these plants must remain on for a certain number of hours, and once shut down cannot restart for a period.

Figure 2.8: Levelised cost of generation at different load factors (2050)



Source: CCC calculations based on Mott MacDonald (2011). Costs for plants commencing operation in 2040. 10% discount rate.

Box 2.6: Using low-carbon options to meet peak demand

In order to maintain security of supply, there is a need to have sufficient generating capacity to meet demand during the periods of greatest electricity demand, which are likely to cover relatively few hours within the year (e.g. less than 20% of the time – Box 2.2). Demand at these times is usually met with generating options that have low capital costs, but often high running costs, such as open-cycle gas turbines.

By contrast, intermittent renewables, nuclear and most forms of CCS are relatively capital-intensive forms of electricity generation – using them to meet these peaks is neither technically feasible or economically sensible. There are a range of options which may be able to provide low-carbon electricity at peak times:

- **Electricity storage technologies.** These could include pumped storage, hydro power, batteries (including old EVs batteries when their performance is no longer sufficient for transport applications) or compressed air storage. These typically still have relatively high capital costs, but have relatively high 'round trip' storage efficiencies[11] (e.g. typically 70-80%) and are well suited to relatively short periods of storage and regular cycling of energy in and out.
- **Hydrogen.** Storage of hydrogen, for example in geological formations such as salt caverns, may have lower capital costs and be more suitable for storage on longer time scales. The hydrogen could then be used to generate electricity at peak times, using fuel cells or hydrogen turbines.
  - If the hydrogen is produced via electrolysis (using electricity to split water), this becomes an additional electricity storage option, with greater seasonal flexibility but lower 'round trip' efficiency than the options above (e.g. around 50%).
  - If the hydrogen is produced via pre-combustion CCS, this becomes a more flexible form of CCS generation (Box 2.5), able to decarbonise peak as well as mid-merit demand, although at higher cost.

We have only included these options to decarbonise the peak in our most ambitious level of deployment (Max), as their availability at reasonable cost is uncertain. However, we would not rule out that they could make a significant contribution to avoiding emissions at peak times, depending on technical developments (e.g. on geological hydrogen storage) and costs. Storage options are unlikely to be developed via market forces alone, suggesting regulatory measures (via the system operator) and/or deployment support may be required.

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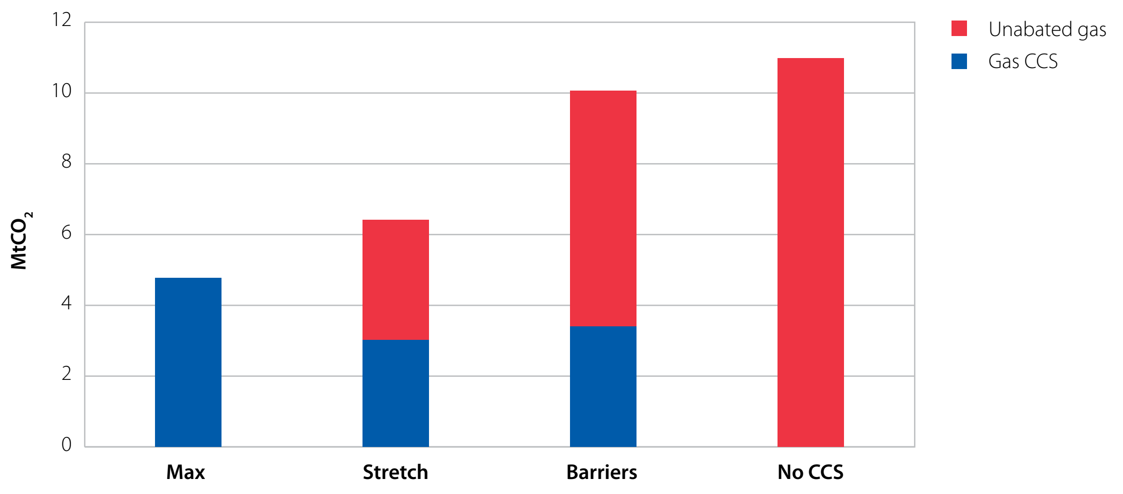
[11] Round-trip efficiency is the proportion of electricity output of a storage technology compared with the electricity input.

(iv) Remaining power sector emissions in 2050

Our analysis suggests scope to reduce power sector fossil emissions to close to zero in 2050, as captured in our three deployment levels (Figure 2.9):

- **Max.** Investment in low-carbon capacity continues, at the rate of up to 4 GW (baseload – equivalent) per year to 2050, met through a combination of nuclear, renewables and fossil plant operating CCS. Flexibility options are fully deployed to reduce the need for peaking demand, which is then met through low-carbon options (as in Box 2.6). In such a case, the only remaining emissions would be residual emissions from fossil CCS generation of around 5 $MtCO_2$ assuming a 20% share of low-carbon capacity.
- **Stretch.** There is still substantial investment in low-carbon capacity (as under Max deployment), but low-carbon sources of peak generation (e.g. hydrogen) are not available. Peak demand is therefore met by unabated gas generation, increasing fossil emissions to 6.5 $MtCO_2$.
- **Barriers.** In this case there is still full roll-out of low-carbon capacity, but less success in deploying flexibility measures , such that there is no shifting of demand away from peak periods, or into periods of high wind generation (i.e. all demand follows a fixed profile). As a result the requirement for peaking and mid-merit generation is higher, requiring more capacity to be built in total and increasing costs. We assume the increased need for peak generation is met with unabated gas, adding a further 3.5 $MtCO_2$ of fossil emissions, to reach 10 $MtCO_2$ in total.

Figure 2.9: 2050 power sector emissions from fossil fuel under Max, Stretch and Barriers deployment



Source: CCC calculations based on modelling by Pöyry Management Consulting.
Notes: Does not include negative emissions from biomass CCS, i.e. negative 35 $MtCO_2$ (except no CCS world).

Offsetting fossil emissions are negative emissions from biomass CCS. Where CCS and bioenergy are sufficiently available, depending on the availability of bioenergy in power (given deployment in other sectors) we include 4.3-6.1 GW of biomass CCS, leading to negative emissions of 31-45 $MtCO_2$. Together with fossil emissions, overall net emissions are in the range negative 39-21 $MtCO_2$.

A key risk for the power sector is if CCS were not to be available (see Chapter 1 on the implications of this across the economy). In this case we estimate emissions would increase up to 11 $MtCO_2$.

- We assume that there is some increase in renewables and nuclear capacity to replace CCS capacity for some parts of mid-merit demand, within the constraints implied by potential flexibility (e.g. nuclear annual load factors drop to 75-80%, although this could also be achieved at comparable cost by nuclear continuing to operate only at baseload with increased spilling of wind). Emissions are higher as a result, as more unabated gas generation is required to meet those parts of mid-merit demand that require significant flexibility in generation.
- There are no negative emissions from biomass with CCS, with the biomass resource diverted to other difficult-to-reduce areas of the economy (see Chapter 1).

Therefore, our economy-wide scenarios include fossil emissions from the power sector, from 5 $MtCO_2$ with full deployment of flexibility measures and low-carbon sources of peak generation, and up to 10 $MtCO_2$ if flexibility options are constrained, along with 45 $MtCO_2$ of negative emissions depending on how much biomass is available for use with CCS in the power sector. If CCS is not available emissions will be positive at 11 $MtCO_2$.

5. Cost of power sector decarbonisation in 2050

The cost of power sector decarbonisation in 2050 will depend on the generation mix, the extent to which costs of various low-carbon technologies fall, and the assumed fossil fuel prices that would be paid by conventional generation. To estimate costs, we have calculated investment and generation based on an assumed mix of around 45% renewables (35% intermittent), 40% nuclear and 15% CCS, with a very small amount (1-2%) of unabated gas generating at peak. The cost of decarbonisation is compared against a counterfactual, which we assume to be unabated gas (excluding the carbon price)[12].

Costs relate mainly to decarbonisation of mid-merit and peak demand, with limited costs from decarbonising baseload (Figure 2.10):

- If cost reductions suggested by our analysis are achieved, the implied costs of decarbonising baseload demand would be limited.

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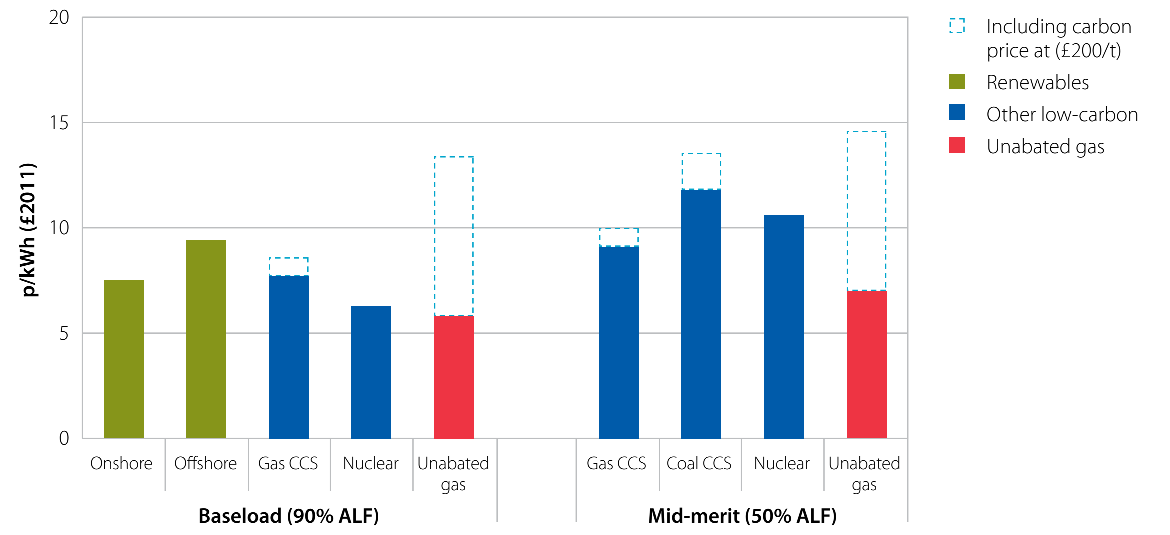
[12] We exclude the carbon price from our cost calculations, in order to determine the cost per tonne of carbon saved. This may then be compared costs in other sectors and to the traded cost of carbon in order to determine cost effectiveness.

Figure 2.10: Cost of unabated gas and low-carbon generation at baseload and mid-merit – central fuel prices (2050)



Source: CCC calculations based on Mott MacDonald (2011).
Notes: Costs for plants commencing operation in 2040. Gas price = 70p/therm. Coal = \$110/t (£71/t). ALF = annual load factor. 10% discount rate.

  - Under DECC's central fossil fuel price scenario (i.e. a gas price of 70 p/therm and a coal price of \$110/tonne in 2050) low-carbon generation costs to meet baseload demand would be broadly comparable to those of unabated gas-fired generation (i.e. around 6 p/kWh), and only slightly higher than unabated coal-fired generation (around 5.5 p/kWh).
  - Low-carbon generation at baseload could incur a cost penalty (relative to unabated gas) of around 2.5 p/kWh under low fossil fuel prices or offer a saving of around 1.5 p/kWh under high fossil fuel prices
- Similarly, the power sector costs of meeting new demands from transport and industrial heat through low-carbon power (as opposed to unabated gas) will be very limited where these demands can be treated as baseload (i.e. where the demands are fairly constant across the year and either constant or flexible over a day).
- For remaining mid-merit demand (which could include some new heat demand), the cost differential between low-carbon generation and unabated fossil fuel alternatives could be of the order 3 p/kWh, relating to around 70 TWh of generation. With only a small proportion of net peak demand being met with unabated gas (at no additional cost penalty), the implied additional cost of generation is around £15 billion annually (i.e. 0.4% of GDP in 2050).

- There are also additional costs associated with managing the system with increased demand and demand peaks, and to provide additional flexibility with intermittent renewables. These include additional annualised costs of around £0.7 billion for interconnection (assuming interconnection reaches 24 GW by 2050), £2 billion for transmission and distribution and £0.6 billion for additional peaking capacity and pumped storage. We do not add costs associated with smart grids and meters, reflecting an assumption that these will be offset by savings in metering costs and grid management and that much of the capital cost of installation will be incurred before 2020 and be written off by 2050.

Therefore in total, we estimate that the cost of power sector decarbonisation in 2050 would be of the order 0.5% of GDP, with a range of 0.2-0.7% of GDP under our range of assumptions for fossil fuel prices (see Chapter 1). The average wholesale cost per unit of electricity would be around 9.5 p/kWh (11.5 p/kWh including network costs), compared to around 5 p/kWh today, but significantly less than 14 p/kWh were all generation to come from unabated gas facing a £200/tonne carbon price. We would also expect a smaller impact on retail prices, given that the wholesale price makes up only a part of the retail price (e.g. 40% of the retail price in 2010).

6. Summary and implications for policy approach

In our economy-wide analysis in Chapter 1 we include fossil power sector emissions of 5-10 $MtCO_2$ in 2050, depending on how far options for flexible low-carbon generation are developed and deployed and including fugitive emissions from CCS. Where CCS is available, these are more than offset by up to 45 $MtCO_2$ of negative emissions from biomass CCS.

The cost estimate that we use in the economy-wide analysis is around 0.5% of GDP in 2050, based on the same possibilities and central fuel prices.

Emissions and costs could be significantly higher if CCS is not available, both as biomass CCS is ruled out and as more unabated gas is required for balancing generation. We reflect this risk in our sensitivities with constrained abatement options in Chapter 1.

The assessment in this chapter reinforces our previous conclusion, that early investment in a range of low-carbon technologies is required in order to make feasible almost full decarbonisation to meet the 2050 target. The alternative to set out on the decarbonisation path later would leave technologies insufficiently developed, and would require scrapping of capital and high build rates, in order to meet longer-term goals. Given the Government's carbon price underpin, investment in the cheapest low-carbon options (i.e. nuclear and onshore wind) during the 2020s is also likely to be cheaper than investment in gas.

This highlights the importance of the specific objective of Electricity Market Reform (i.e. the pace of emissions reduction that it is aimed at achieving) and the technology policy aspects of this policy (i.e. the support that it provides for less mature technologies).

In addition, our assessment highlights the need to develop options for meeting mid-merit and seasonal demand with flexible low-carbon generation. Gas CCS should be demonstrated as part of the Government's programme for CCS, and storage options should be further assessed and developed. More generally, this is an area where understanding is developing rapidly and the Government's commitment to develop an Electricity Systems Policy as part of the EMR process is appropriate.

In our next report to Parliament (in June 2012) we will present new analysis of the appropriate pace of power sector decarbonisation, and will monitor progress demonstrating CCS, and investing in low-carbon power technologies more generally.

Chapter 3

Reducing emissions from buildings

Introduction and key messages

Total buildings emissions were 219 $MtCO_2e$ in 2010, more than one third of current total emissions. We presented a scenario in our advice on the fourth carbon budget where these emissions fell to around 56 $MtCO_2e$ by 2030, based on energy efficiency and the roll-out of heat pumps, bioenergy and district heating.

In this chapter we focus on the around 50% (105 $MtCO_2$) of direct CO_2 emissions. We consider opportunities to reduce emissions further, including additional scope for energy efficiency, heat pumps, district heating based on low-carbon sources, solar thermal and direct electric heating.

Our key conclusions are:

- The assessment in this chapter reinforces our previous conclusions that buildings emissions should be reduced to very low levels by 2050 and that continuation of current and proposed policy options (i.e. the Renewable Heat Incentive) aimed at increasing uptake of low-carbon heat is therefore appropriate.
- Energy efficiency is important to achieving these reductions because it reduces heat demand, increases the suitability of buildings for low-carbon heating technologies and reduces broader energy system costs.
- Heat pumps could play a central role in achieving a low-carbon buildings sector as they can provide efficient delivery of low-carbon heat in up to 65 – 85% of the building stock.
- District heating could also play a substantial role in decarbonising heating, based on heat off-take from low-carbon power generation, large-scale heat pumps and bioenergy.
- Where both heat pumps and district heating are suitable, there is not a clear cost advantage for either approach. Therefore, the optimal balance between these two options will depend upon site-specific considerations (e.g. proximity to low-carbon power generation, concentration of heat demand) and the extent to which policy is developed to address the challenges of community-scale heat supply.
- Although solar thermal and electric resistive heating are relatively costly and inefficient in most buildings, there is a potential role in providing low-carbon heat in certain circumstances (e.g. new homes where electricity demand would be low and/or installation costs of solar are minimised).
- Scenarios with very low emissions can be achieved at a total cost of around 0.1 – 0.3% of GDP in 2050.

We set out our analysis in 4 sections:

1. Buildings emissions and abatement options
2. Scenarios for reducing building emissions to 2030
3. Scope for further cuts in buildings emissions beyond 2030
4. Summary and implications for policy approach

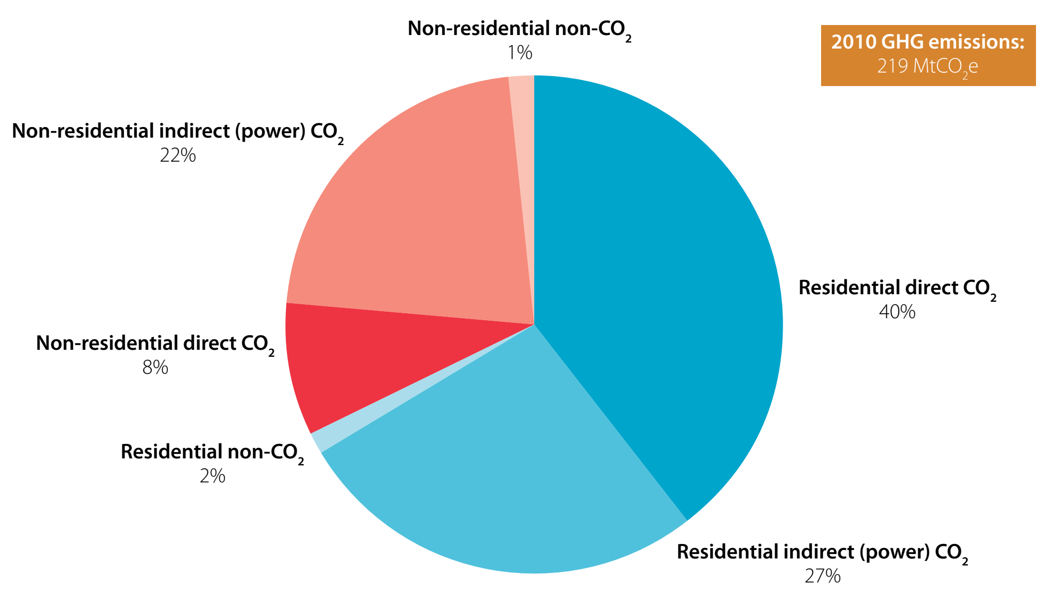
1. Buildings emissions and abatement options

Current emissions from buildings

CO_2 emissions from buildings were around 212 $MtCO_2$ in 2010 (Figure 3.1), of which 69% are residential and 31% are non-residential. Overall, half of the emissions are direct (i.e. related to burning of fossil fuels for heat) and half indirect (i.e. electricity related):

- In the residential sector, 87 $MtCO_2$ of emissions are direct and 59 $MtCO_2$ are indirect.
  - Direct emissions relate to space heating (77%), water heating (21%) and cooking (2%).
  - Indirect emissions relate to lighting and appliances (75%), water heating (6%), cooking (5%) and electrically heated households (14%).
- In the non-residential sector, 18 $MtCO_2$ of emissions are direct and 48 $MtCO_2$ are indirect.
  - Direct emissions relate to lighting and computing (33%), heating (32%), catering (12%), hot water (7%), cooling (6%) and other (10%).
  - Indirect emissions relate to lighting and computing (47%), heating (14%), catering (13%), cooling (9%), hot water (4%) and other (13%).

Figure 3.1: GHG emissions in buildings (2010)



Source: NAEI (2012).
Note: This figure includes emissions from non-CO_2. This chapter focuses on CO_2 only. Non-CO_2 emissions from buildings are covered in Chapter 6.

Options for reducing direct buildings emissions

In previous reports we have identified two main opportunities for reducing direct building emissions without relying on bioenergy. These are further energy efficiency improvement and the deployment of low-carbon heat, in particular heat pumps:

- **Energy efficiency improvement.** This offers scope to reduce energy demand and therefore CO_2 emissions in buildings but cannot by itself yield a zero carbon system:
  - **Residential buildings:** Potential improvements to the building fabric include loft and cavity wall insulation, and higher-cost measures such as solid wall insulation and double glazing. Emissions can be reduced further through the upgrading of existing technologies (e.g. efficient boilers) and changes in behaviour (e.g. through turning down the thermostat by 1 degree). However, even for new buildings where the most energy efficient construction standards (e.g. Passivhaus standard) can reduce space heating demand by 90% compared to existing buildings, some heating and hot water demand remains. In existing buildings (which are expected to make up around 80% of the housing stock in 2050), it is very difficult and expensive to achieve this level of reduction.
  - **Non-residential buildings:** Energy savings can be achieved through efficient building control systems. There is an opportunity for fabric measures in non-residential buildings, but these can be expensive to retrofit in some commercial buildings (e.g. those with large glass facades).
- **Heat pumps.** Given current carbon intensity of grid electricity, these can reduce emissions (e.g. compared to oil boilers), and may be regarded as low-carbon when using low-carbon power generation. They are technically feasible in many residential and non-residential applications, and therefore offer the opportunity for deep cuts in building emissions over the next decades. They are currently cost-effective in some applications and are likely to become cost-effective in others over the next 10-20 years.
  - **Air source heat pumps (ASHPs):** ASHPs extract heat from the outside air, in the same way a fridge extracts heat from the inside. There are two types of ASHPs: an air-to-water heat pump heats water for underfloor heating and radiators and an air-to-air heat pump delivers warm air directly into the room.
  - **Ground source heat pumps (GSHPs):** GSHPs extract heat from the outside ground to heat water and air. As ground temperatures are relatively stable throughout the year, GSHPs are generally more efficient than ASHPs.
  - **Heat pumps with storage:** Heat pumps used in combination with storage are able to generate heat during off-peak periods (e.g. overnight) thereby making use of spare low-carbon power generation capacity. However, with current storage options (i.e. large hot water tanks) these units are limited to installation in larger premises only.

There are also bioenergy options which could in principle be used to cut building emissions. These include the use of biomass boilers, and use of biogas as a substitute for natural gas. However, analysis in our 2011 Bioenergy Review suggested that in the long-term, higher value may be placed on use of bioenergy in other sectors (e.g. energy-intensive industry, aviation, applications with CCS). Therefore, the use of bioenergy in providing heat for buildings may be limited to niche applications (e.g. using locally-sourced bioenergy in district heating systems).

Given uncertainty over the scope for deployment of heat pumps, we have identified district heating based on low-carbon sources of heat, solar thermal water heating and resistive electric heating as possible options for further decarbonisation. We consider these options in Section 3 below.

Options for reducing indirect buildings emissions

There is scope for reducing indirect emissions in the residential and non-residential sectors through the implementation of a range of energy efficiency measures:

- In the residential sector, there is considerable scope for improved lighting and appliance efficiency. For example, efficient appliances (with an A+ or better rating) currently constitute a very small proportion of the stock (e.g. less than 1% of cold appliances are currently A++). They are widely available, without requiring any significantly increased upfront cost.
- In the non-residential sector, opportunities for increased energy efficiency exist in lighting, air conditioning, appliances and building control management.

Together these measures could reduce buildings electricity demand by around 30 TWh (12%) over the next decade.

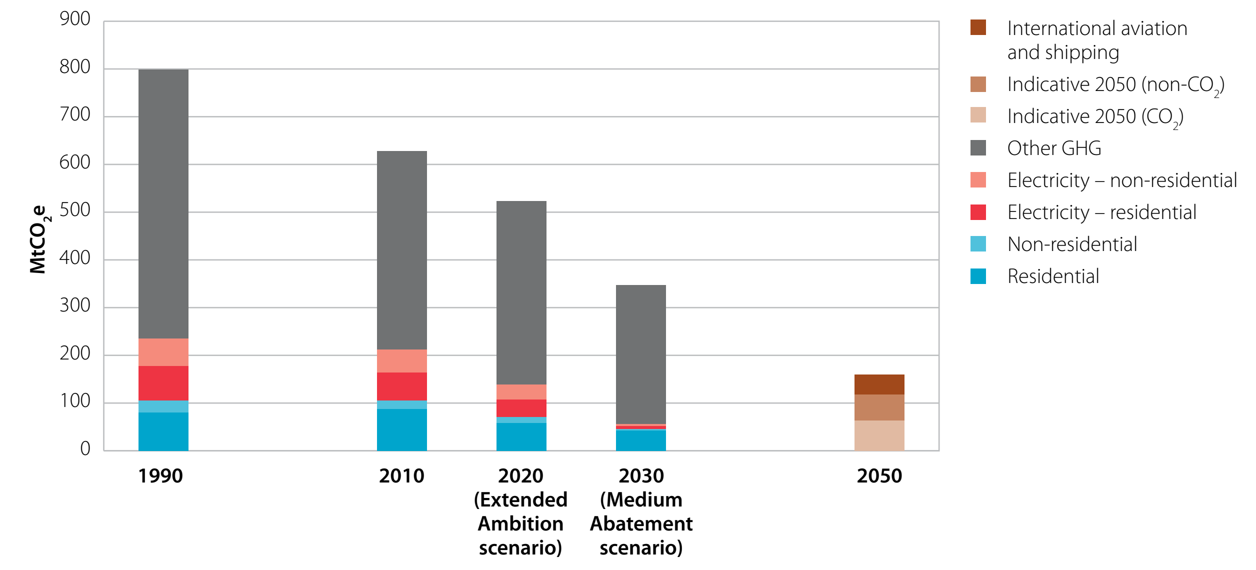
Furthermore, on the electricity supply side, there is significant scope for reducing indirect emissions through investment in a range of low-carbon technologies; we consider scope for reducing power sector emissions in Chapter 2. However, even with supply-side decarbonisation, efforts to reduce demand are important for both reducing the overall cost of the energy system and in reducing peak demand that is particularly expensive to meet with low-carbon capacity.

2. Scenarios for reducing building emissions to 2030

We developed scenarios for decarbonising buildings to 2030 in our advice on the fourth carbon budget. These were designed to include the deployment of cost-effective measures (i.e. measures that reduce emissions at lower cost than the Government`s projected carbon price, which reaches £70/tCO_2 in 2030) subject to feasibility constraints (e.g. space constraints on heat pump deployment in the residential sector, see section 3 below). In our central scenario, total CO_2 emissions from buildings fall 74% to 56 MtCO_2 in 2030 (46 MtCO_2 of which are direct), due to energy efficiency improvement and deployment of low-carbon heat (Figure 3.2):

- In the residential sector, we assumed that new policies deliver significant energy efficiency improvements to the UK housing stock, including the insulation of 90% of lofts and cavity walls and around 45% (3.5 million) of solid walls. Additionally, we assumed the widespread take-up of energy efficient appliances and deployment of low-carbon heat (in particular heat pumps) to serve 34% of domestic heat demand.
- In the non-residential sector, the scenario assumes high take-up of cost-effective energy efficiency measures by 2020, with some further improvement in non-heat electricity efficiency by 2030. On the basis of cost-effectiveness, we also assumed that the majority (74%) of heat demand in the sector will be met from low-carbon heat.

Figure 3.2: Buildings emissions in the context of UK GHG emissions (1990-2030 and 2050)



Source: CCC modelling; NAEI (2012).

This scenario underpins the fourth carbon budget that we recommended and that was subsequently legislated. Its delivery will therefore be required, in broad terms, if the budget is to be achieved through domestic emissions reductions. This is recognised in the Government's Carbon Plan, which envisages significant levels of energy efficiency improvement and deployment of low-carbon heat over the next two decades.

In this scenario, remaining direct emissions from buildings in 2030 would be very low for non-residential buildings (4 MtCO_2) and for residential buildings they would be cut significantly to 41 MtCO_2. These direct emissions are the focus of the rest of this chapter. Remaining indirect emissions would be 10 MtCO_2, with scope to cut these further through our scenarios for power sector decarbonisation in Chapter 2.

3. Scope for further cuts in buildings emissions beyond 2030

Reducing building emissions beyond 2030 will require that new homes are designed to be zero carbon, that further energy efficiency improvements are made and that low-carbon heat options (i.e. heat pumps, district heating based on low-carbon heat sources, solar thermal and resistive electric heating) are rolled out to the existing building stock. We now consider those issues in turn, before setting out our scenarios for remaining emissions in 2050 and associated costs.

Ensuring new homes are zero carbon

From current levels to 2050 the UK population is projected to increase by around 20%. The increase in the number of homes could be slightly larger, given trends towards reduced occupancy per household. To avoid increased emissions, it will therefore be important that these homes are designed to use zero carbon heating systems. This is likely to be easier than reducing emissions from existing homes:

- **Radiator compatibility:** Heat pumps have a higher performance when installed in conjunction with large radiators or underfloor heating (which are more prevalent in new buildings) because this allows for a lower temperature heat to be used which heat pumps generate more efficiently.
- **Optimised building fabric:** A higher level of energy efficiency is possible in new buildings where insulation can be incorporated into the building fabric during construction.
- **Avoided hassle costs:** The hassle costs associated with installing insulation and low-carbon heat technologies for occupied properties are absent.
- **Low capital cost technologies:** Efficient new buildings with minimal heat demand could be suitable for direct electric heating which has low capital costs compared with a heat pump.

The Government is already committed that all new homes in England should be net zero carbon from 2016 (with the devolved administrations expressing similar aspirations), although this definition can include positive emissions with offsetting measures (e.g. gas or oil boilers could be consistent with regulations on new buildings). Energy efficient new homes with gas or oil boilers may be good candidates for resistive heating, particularly if heating demand is very low (e.g. new flats, see below).

In the years from 2030 to 2050 the turnover of the existing stock also could also play a role, with a fraction of existing residential buildings and non-residential buildings demolished by 2050, creating an opportunity to replace them with zero carbon new builds.

Further deployment of energy efficiency measures in the existing building stock

Low-cost efficiency measures, such as cavity wall insulation and loft insulation, should be taken up prior to 2030. They were included in our fourth budget scenarios and so do not offer further opportunity to reduce emissions

Significant scope for increased roll-out of other efficiency measures remains beyond 2030.

- **Solid Wall Insulation**: 3.5 million in 2030, and could increase up to 6.7 million in 2050.
- **Double Glazing**: 15.2 million in 2030, increasing up to 22.3 million in 2050 (total housing stock is 38 million in 2050).
- **Draught Proofing**: 17.2 million in 2030, increasing up to 22.3 million in 2050.

These further measures are relatively high cost but can be implemented in the course of other refurbishments, and become more attractive and cost-effective as emissions targets tighten (e.g. the Government`s carbon values increase from £70/tCO_2 in 2030 to £200/tCO_2 in 2050). While these measures are important, total thermal energy demand increases in all our scenarios due to the growth in households.

More radical efficiency measures also exist (e.g. adoption of retrofit zero carbon standard) similar to new build but require major refurbishment or demolition of the existing housing stock and as a result are very costly.

Opportunities for further deployment of heat pumps

There is scope for further deployment of heat pumps in residential and non-residential sectors beyond the level we envisage in 2030, as gas boilers added in the 2010s reach the end of their life.

Heat pumps could become increasingly cost-effective, both as the projected carbon price increases, and given scope for innovation and cost reduction after 2030 (Box 3.1). We expect that investment in heat pumps will become cheaper than the high-carbon alternative (i.e. efficient gas boilers) in the 2020s, when carbon savings are valued in line with the Government's projected carbon price (i.e. rising to £70/tCO_2 in 2030).

Box 3.1: Performance and cost of heat pumps

Performance

The performance of heat pumps is described in terms of its Coefficient of Performance (COP), or the amount of heat that the heat pump produces compared to the total amount of electricity needed to run it. The higher the COP, the lower the electrical energy required to deliver a given amount of heat, and therefore the better the performance. The performance of heat pumps depend on a range of factors, including the type of heat pump, building insulation levels, type of heating systems and weather conditions.

- Previous analysis conducted for the Committee by NERA and AEA (2010)[1] suggested that current COPs are around 2.5, and that COPs could increase towards levels in the 2020s of 3.5-5.5 (up to 4.5 in residential applications and 5.5 in non-residential).
- The results of the first large-scale trial of heat pumps were published by the Energy Saving Trust (EST), and covered 83 sites in the UK. In the trials, GSHPs had a mid range COP of around 2.3-2.5, with the highest figures above 3.0. The mid range of COPs for ASHPs was around 2.2, with the highest figures over 3. A key finding was that heat pump performance can vary considerably between installations, and is particularly sensitive to installation and commissioning practices and customer behaviour.
- Given uncertainty around current and future COPs, the analysis conducted for this report assumed COPs increasing to 2030 but staying flat thereafter:
  - **Residential:** up to 2.75 for ASHP and 3.85 for GSHP.
  - **Non-residential:** up to 4 for ASHP and 4.25 for GSHP.

Performance monitoring of heat pumps has been conducted under the Heat Pump Premium Payment scheme, and further field trials are being conducted by the Energy Savings Trust. Whilst the results of these trials are not yet available, these studies will improve the evidence base regarding the performance of heat pumps in the UK.

Costs

The NERA and AEA analysis suggested that cost reductions for heat pumps could be around 40% by 2030. For the analysis in this report we take a conservative approach and assume no further cost reductions beyond 2030. This leads to a capital cost in 2030 for ASHPs of around £4,660 and GSHPs of £7,220 in domestic applications (with slightly lower costs in non-domestic applications).

Given these cost reductions and COPs, heat pumps are potentially cost-effective in 2030 compared to a gas boiler including a carbon price of £70/tCO_2. In 2050, the cost of an ASHP and GSHP are £86/MWh and £85/MWh respectively, comparable to the cost of £81/MWh for a gas boiler (assuming a gas price of around 70p/therm) and cheaper than a gas boiler when facing a carbon price of £200/tCO_2 (£120/MWh).

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[1] NERA and AEA (2010), *Decarbonising heat: Low-carbon heat scenarios for the 2020s*. Available at www.theccc.org.uk

Given their favourable economics, the relevant factor in determining the role of heat pumps is likely to be the presence of deployment barriers, for example relating to suitability, space and noise:

- In the context of the Fourth Carbon Budget Report (2010), we commissioned analysis from NERA which assessed the suitability of heat pumps in different building types. This assessment highlighted the difficulties of installing heat pumps in poorly insulated buildings where the temperature differential between indoors and outdoors is too great for heat pumps to operate efficiently.
- For some properties, adequate outdoor space for locating ground loops for a GSHP is not available. Space is also a consideration for the installation of an ASHP. However, given that ASHPs can be scaled down to meet smaller demands, it is unlikely that this is a constraining factor in most cases.
- Where buildings are located in dense urban areas, the noise generated by heat pumps could be a nuisance.

For this report we commissioned Element Energy and AEA (2012)[2] to consider these factors. They conclude that the technical potential for heat pumps in 2050 is in the range 65% to 85% of the building stock.

In order to achieve these greatly increased levels of take-up, some barriers to near-term market deployment must be overcome:

- Given limited deployment of heat pumps to date and therefore low visibility, there is a lack of consumer awareness and limited confidence regarding the operation of heat pumps.
- The supply chain for heat pumps is under-developed in the UK, with potential bottlenecks relating to both equipment supply and installation.

Analysis conducted by Element Energy and NERA[3] in the context of our Renewable Energy Review (2011) assessed the extent of near-term barriers to heat pumps. This assessment concluded that whilst uptake could be significantly constrained if these barriers were not addressed, policy measures (e.g. accreditation of installers and integration of renewable heat and energy efficiency policies) could overcome these barriers if implemented.

In the analysis conducted for this report we have assumed that these near-term barriers will be addressed in order to achieve the full technical potential. Nevertheless, given the potential for a significant part of the building stock to be unsuitable for heat pumps, other options for buildings decarbonisation are required.

Scope for low-carbon district heating

Use of district heating is currently limited in the UK, but widespread in other countries (e.g. Scandinavia and Eastern Europe). District heating offers opportunities for low-carbon heat when based on low-carbon sources. In particular, it offers an opportunity in areas of concentrated heat loads (e.g. urban environments) where heat pumps are less suitable but where distribution costs for district heating can be minimised.

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[2] Element Energy and AEA *(2012), Decarbonising heat in buildings: 2030 to 2050.* Available at www.theccc.org.uk

[3] Element Energy and NERA *(2011), Achieving deployment of renewable heat.* Available at www.theccc.org.uk

The Element Energy and AEA analysis commissioned for this report also considered scope and costs for district heating using low-carbon generation sources (Box 3.2). This analysis identified cost-effective potential for district heating to meet up to 40% of demand. Most of this potential overlaps with areas that are suitable for heat pumps and could be implemented if the uptake of heat pumps is constrained (e.g. if heat pumps turn out to be more expensive or if delivery barriers cannot be overcome). However, it is also likely that district heating would be more suitable than heat pumps in some areas (e.g. dense urban areas where there are space and noise constraints) although the precise extent to which this is the case is not yet clear.

Box 3.2: Scope and costs for district heating

The relevant factors in assessing the potential for district heating are the availability of low-carbon heat supply, and the feasibility and cost of heat transmission and distribution:

- **Low-carbon heat supply:**
  - **Heat off-take from power stations:** Extracting heat from steam turbines is an attractive option for low-carbon heating because much of this heat would otherwise be wasted. Whilst heat extraction does reduce the power output, approximately 8 units of heat can be extracted for each unit of power forgone. This leads to a relatively attractive efficiency of heat generation (i.e. around 800%), compared with between 250%-350% for heat pumps.
  - **Heat Pumps:** Whilst large-scale heat pumps could be a source of heat for district heating, this is less attractive than use of heat off-take from power stations due to the lower efficiency.
  - **Gas-fired CHP DH:** Emissions from gas-fired CHP are equivalent to those from heat delivered by efficient gas boilers and power delivered at around 200 g/kWh. This implies more emissions than other options for low-carbon heat and is therefore unlikely to play a major role in decarbonising buildings by 2050.
  - **Bioenergy:** Given the limited availability and preference for use in other applications (e.g. in combination with CCS in power generation), sustainable bioenergy is unlikely to form a significant source of supply for district heating networks. However, local sources of bioenergy (e.g. municipal waste) could be appropriately used in local district heating systems as this avoids the need for transport over longer distances.
- **Transmission and distribution:**
  - **Transmission pipes:** As costs rise proportionally with distance, buildings in remote locations and others not close to sources of low-carbon heat are unlikely to be suitable candidates for district heating.
  - **Distribution network:** The costs of piping heat from the transmission network directly into buildings depend on the degree of concentration of the heat demand, and rise steeply if buildings are dispersed.

Using a spatial model of heat demand, Element and AEA identified around 40% of UK heat[4] demand as located sufficiently close to sources of low-carbon heat and concentrated as to be potentially cost-effective for the deployment of district heating networks. This assessment was based on the location of existing power stations, as many of these sites are also likely to be the location of future low-carbon power generation. However, if low-carbon power plants were to be located at greater distances from clusters of heat demand, the costs of transmission could rise. Conversely, location of new plant close to heat clusters could make more buildings suitable for district heating.

The cost of district heating assuming a penetration of 40% is around £80/MWh (with a carbon price of £200/tCO$_2$ in 2050), of which 70% is sourced from waste heat from low-carbon power generation. This is cost-effective relative to a gas boiler in 2050 (£120/MWh).

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[4] In this chapter, heat demand includes residential and commercial buildings only. Industrial buildings are accounted for in Chapter 5.

However, there are a number of barriers to implementing low-carbon district heating:

- **Location of low-carbon heat supply:** If networks are to be low-carbon, sufficient decarbonised heat supply is required. Whilst some of this could be provided by large-scale heat pumps and biomass, the most efficient source of heat is off-take from power stations. The development of district heating systems will therefore potentially be limited by the location of new low-carbon power generation.
- **Transmission infrastructure:** Connecting clusters of heat demand to low-carbon heat supply would require significant roll-out of transmission pipelines for heat. This would be a challenge both in terms of the distances and the number of connections required in urban areas, requiring the digging up of many roads. Local opposition and planning constraints could therefore be a problem.
- **Demand uncertainty:** Given that district heating could provide heat directly into homes using existing systems there may not be significant barriers to roll-out from the perspective of the consumer. However, investors may be averse to raising the high capital required for installation unless there is a degree of certainty that sufficient heat demand will be connected once the network is in place.

We conclude that district heating offers a promising opportunity for significant additional emissions reduction in buildings or to provide an alternative to heat pumps. However, there are challenges with respect to the location of low-carbon heat supply, transmission infrastructure and securing adequate heat demand in advance.

We therefore assume a range for uptake of district heating. At the low end uptake is limited to the availability of local sources of bioenergy (around 2% of heat demand). At the high end we assume this could increase to a significantly greater share (around 40%) as part of a decarbonised building sector. In order to develop this option further, new policies and approaches will be required that focus on addressing the challenges we have identified.

Scope for solar thermal

Solar thermal provides a further option for decarbonising heat in buildings. The challenges it faces concern costs and generation of sufficient heat at the times when it is most needed:

- In the majority of installations, heat generated is insufficient to meet winter space heating demand. Hot water demand can usually only be fully met in the summer, while in the winter a supplementary heat source is needed (i.e. an electric immersion heater).
- Owing to high capital costs, solar thermal is more expensive than other heating technologies in 2050 (around 150 £/MWh compared with around £90/MWh for heat pumps and £120/MWh for gas boilers, assuming a carbon price of £200/tCO$_2$).

However, analysis conducted by Element Energy suggests that there are opportunities for reducing installation costs in new build properties such that costs could become competitive with gas boilers. This suggests a possible role for solar thermal in niche circumstances (e.g. in meeting hot water demand and in some new build properties).

Scope for resistive electric heating

A potentially low-carbon way to meet remaining demand would be through using resistive electric heat technologies. These technologies are widely deployed today (currently meeting 9% of heat demand from buildings) and potentially applicable in all buildings, but will generally have higher operating costs than low-carbon alternatives and if deployed at large scale could pose problems for the power sector and/or electricity distribution network:

- **Power sector investment.** If half of 2050 domestic heat demand were met by resistive heating, this would increase peak electricity demand by 90 GW (e.g. around 150% of current peak capacity). This would increase the challenge for power sector decarbonisation considerably and would be particularly difficult if CCS is not shown to be a viable technology (e.g. it would require total investment in low-carbon power generation going well beyond currently identified nuclear sites and at very high build rates through the 2030s and 2040s).
- **Distribution grid strengthening.** For individual homes, replacement of gas-based heating with electric heating could increase overall electricity consumption by around 70% (depending on the specific characteristics of the house in terms of occupancy, build type, quality of insulation, etc). This is likely to require some strengthening of the distribution network, which is both costly and subject to significant delivery barriers.

Therefore, whilst it may have an important role in buildings unsuited to heat pumps and district heating, it could be problematic if resistive heat were to be deployed widely.

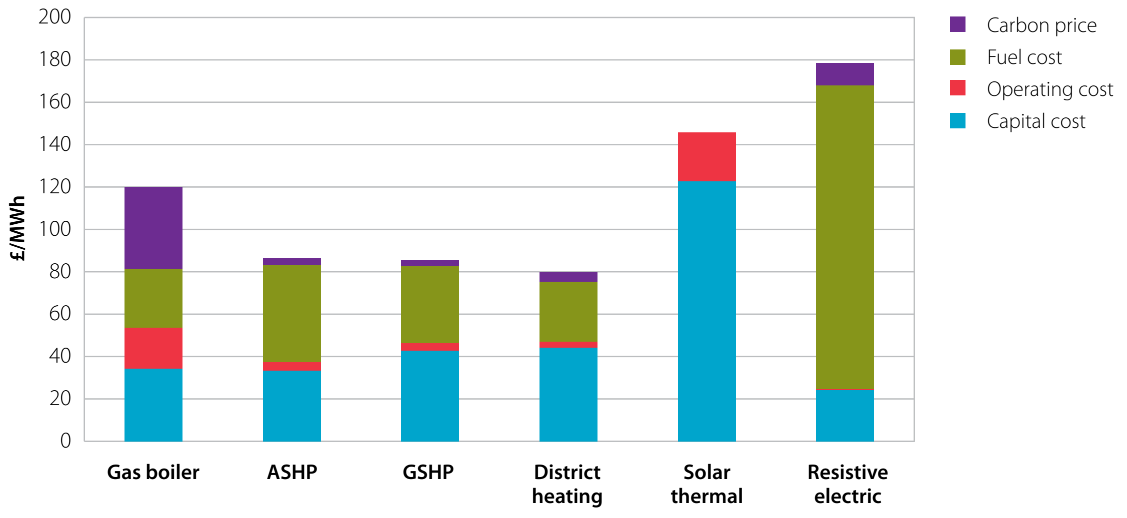
It could, however have a role to meeting some of the around 15% of thermal demand that remains after roll-out of heat pumps, district heating and solar thermal. There are two key options for resistive electric heating:

- **Storage heaters:** These are currently the dominant form of electric heating, comprising 95% of electric heat in buildings. Storage heaters take advantage of off-peak electricity tariffs and slowly release heat throughout the day.
- **Electric boilers:** Electric boilers comprise most of the remaining electric heat demand**.** They are more responsive than storage heaters, but will tend to require peak electricity.

Other niche direct electric options exist including panel heaters, fan heaters, electric towel rails, and electric under-floor heating.

Resistive electric heating is characterised by relatively low capital costs (e.g. compared to heat pumps), but high running costs. The high operating cost of resistive heating is due to both high cost of electricity and its relative inefficiency: resistive heating operates at around 90% efficiency, compared to 250% in heat pumps and around 800% in district heating using heat off-take from power stations.

Figure 3.3: Cost for low-carbon heat technologies compared to gas boilers (2050)



Source: CCC modelling; Element Energy (2012).
Note: Carbon price assumed at £200/tCO_2. The carbon intensity of electricity is assumed to be equivalent to that of gas CCS generation i.e. Around 50gCO_2/kWh.

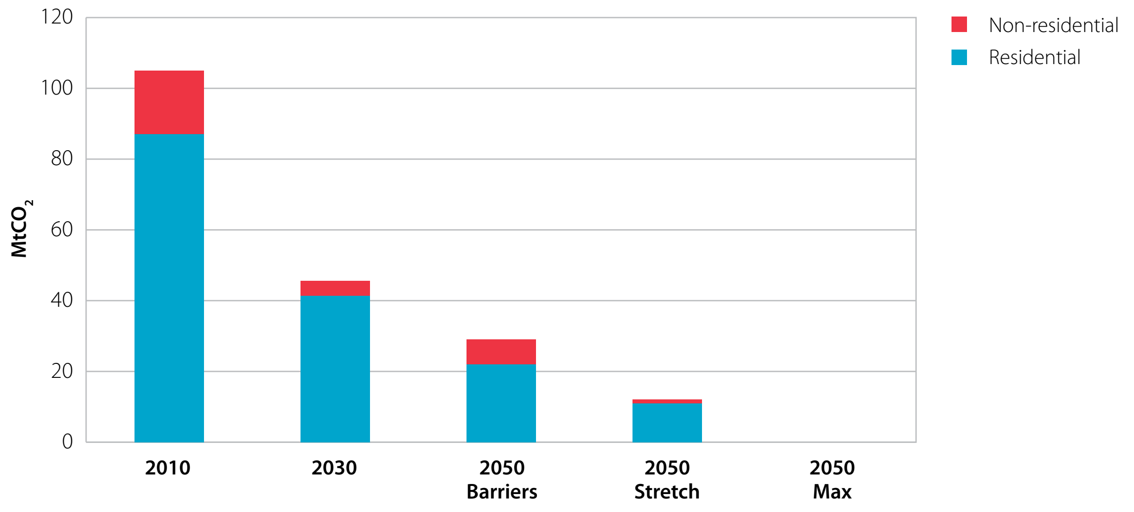
The Element Energy/AEA analysis conducted for this report suggests a heating cost of the order £180/MWh for resistive heating, compared to £90/MWh for heat pumps, and gas-based heating at £120/MWh including carbon costs at £200/tCO_2 (Figure 3.3). The carbon price would have to rise to above £600/tCO_2 for resistive heating to be cost-competitive for retrofit to the average home.

However, in buildings with low thermal demands (e.g. new highly insulated flats, or in tandem with solar thermal with thermal demands less than 5 MWh/yr) the ongoing running cost savings may not be sufficient to justify the additional capital cost of a heat pump (relative to direct electric heating).

Resistive heating therefore provides an option to reach full decarbonisation of the buildings sector or to provide an alternative to cheaper low-carbon options should their deployment be constrained (subject to the power sector being fully decarbonised). However, given its high costs in most applications and potential difficulties implied for electricity generation and distribution, it should only be pursued when other options for reducing buildings emissions and those elsewhere in the economy have been fully deployed.

Therefore in our scenarios for heat decarbonisation we assume that current resistive electric heating installations are replaced by heat pumps and district heating where suitable, and only include an increase in ambition (i.e. beyond the existing 9%) in the maximum deployment level.

Figure 3.4: Remaining direct emissions for residential and non-residential buildings (2010, 2030 and 2050)



Source: CCC modelling; NAEI (2012).
Note: Direct emissions only.

Remaining direct emissions from buildings in 2050

Based on the analysis summarised above, for our economy-wide scenarios we include three potential levels of deployment in 2050 for the buildings sector covering both residential and non-residential (Figure 3.4):

- **Max:** This scenario features heat pumps with optimistic assumptions regarding suitability (82% of thermal demand), and a high level of ambition on energy efficiency based on all low-cost measures (e.g. loft and cavity wall insulation) and a high level of ambition on high-cost measures (e.g. around 7 million installations of solid wall insulation). This is taken together with district heating based on availability of local sources of bioenergy (2%) and solar thermal for hot water in new buildings (3%). Subject to the resolution of uncertainties regarding district heating, it is also possible to deliver similar emissions savings with a higher level of ambition for district heating based on bioenergy and heat off-take from power stations (up to 40%, with a corresponding lower level of heat pumps at around 44%). All of the remaining demand is met by electric resistive heaters rather than gas and oil boilers (13%). This leads to zero direct emissions in 2050.
- **Stretch:** This scenario involves optimistic roll-out of heat pumps (82%), and a moderate level of ambition on energy efficiency based on all low-cost measures and some high-cost measures in hard-to-treat homes (e.g. 6 million installations of solid wall insulation). This is taken together with district heating based on availability of local sources of bioenergy (2%) and solar thermal for hot water in new buildings (3%). As in Max, subject to the resolution of uncertainties, a higher level of deployment of district heating is also possible. Remaining demand is met by gas and oil boilers (13%) and a minimal level of electric resistive heaters (1%) as they are considered too expensive. This leads to remaining emissions of 12 $MtCO_2$.

- **Barriers:** In this scenario we assume that roll-out of heat pumps is somewhat constrained due to limited suitability and acceptability (but still reaches 65% of demand). We also assume a lower level of energy efficiency based on installing all low-cost measures (e.g. loft and cavity wall insulation) and limited roll-out of more challenging measures (e.g. solid wall insulation in only 1 million homes). This is taken together with district heating based on availability of local sources of bioenergy (2%) and solar thermal for hot water in new buildings (2%). Remaining demand is met by gas and oil boilers (29%), and a minimal level of resistive electric heating (3%). This leads to remaining emissions of 28 $MtCO_2$ in 2050.

All these levels of deployment imply extensive decarbonisation to 2050, whilst recognising the risk that barriers could prevent a full roll-out of more difficult measures. We reflect this range in our economy-wide scenarios in Chapter 1.

Cost of cutting building emissions

In our advice on the fourth carbon budget, we estimated the cost of decarbonising heat in buildings to be 0.1% of GDP in 2030 at most, with the majority of this due to increasing penetration of heat pumps in the 2020s. Between 2030 and 2050, our scenarios require a phasing-out of remaining unabated gas-fired generation, and electricity supply for heat pumps to come solely from low-carbon power generation. This is relatively expensive for low-load factor plant – required due to the seasonality of heat demand – and increases the costs associated with heat pumps deployed before 2030.

From 2030 we do not assume any further reduction in capital cost of low-carbon heat technologies. Heat pumps will comprise the majority of the additional cost as deployment rates continue at similar levels to the 2020s.

The costs associated with decarbonising heat to 2050 are 0.1-0.3% GDP, of which 0.1-0.2% GDP is the provision of low-carbon heat and 0-0.1% relates to energy efficiency measures. We use these figures when estimating economy-wide costs of meeting an emissions target with aviation and shipping emissions included. The balance between district heating and heat pumps does not significantly affect overall cost.

4. Summary and implications for policy approach

All our scenarios involve very extensive deployment of heat pumps, which provide a means to reduce emissions where applicable at minimal cost. We identify district heating as another potentially low-cost option that could substitute for heat pumps where not applicable. We consider lower buildings emissions from the use of resistive electric heating which is widely applicable but likely to be expensive. We conclude in Chapter 1 that all of these options could be needed in the context of the 2050 economy-wide target.

This suggests that the Government's support for investment in heat pumps under the Renewable Heat Incentive (RHI) is appropriate and highlights the need to ensure that this policy supports investment in both residential and non-residential sectors. This should be closely monitored and policy adjusted in the event of under-investment in either of these sectors. It reinforces the message in our Renewable Energy Review (2011) that the next phase of funding for the RHI (i.e. from 2014/15) should be confirmed early on, and that additional policy levers are required to overcome barriers to delivery (e.g. accreditation of installers and integration of renewable heat and energy efficiency policies).

Our deployment levels involve significant heat pump penetration, but we do not rule out a larger proportion of district heating displacing some of these. In particular there could be a major role for district heat using heat off-take from low-carbon power generation (e.g. up to 40% under our highest assessment of feasibility).

Finally, there are questions regarding the infrastructure required to deliver these scenarios. In particular there are challenges for heat pumps and electric heating in the delivery of sufficient transmission and distribution infrastructure. High levels of low-carbon heat imply a significantly reduced demand for gas, which has implications for the economics of gas networks. These are areas where it is important to improve understanding in order to accurately reflect the costs and barriers to low-carbon heat.

Chapter 4

Decarbonising surface transport

Introduction and key messages

Surface transport emissions in the UK were 113 $MtCO_2$ in 2010, accounting for 18% of UK greenhouse gas emissions.

In our advice on the fourth carbon budget we proposed a scenario where these emissions fell to 67 $MtCO_2$ in 2030, based on improved efficiency of conventional vehicles, increased take-up of ultra-low emission vehicles, biofuels, behaviour change and freight efficiency improvement.

Achieving further reductions to 2050 will require uptake of ultra-low emission (electric or hydrogen fuel cell) vehicles across the car, van and HGV fleets. We explore those opportunities and challenges in this chapter.

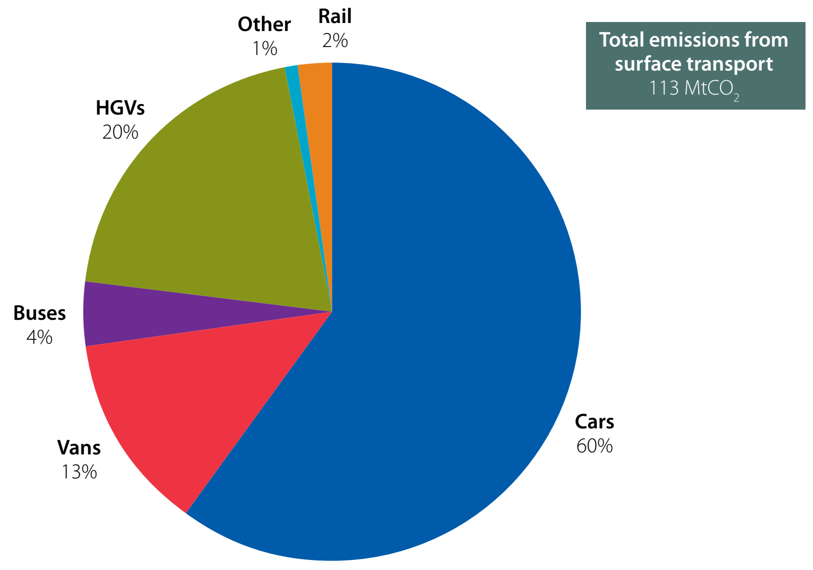
Our key conclusions are:

- Near-total decarbonisation of surface transport is possible by 2050 based on a near-100% share of zero-emission (battery electric, hydrogen) vehicles, with minimal reliance on bioenergy.
- By 2050, the total cost of owning and operating battery electric and hydrogen vehicles is likely to decrease to a level comparable to or below conventional vehicles, such that scenarios with very low emissions can be achieved without incurring any overall GDP cost in 2050 (i.e. higher capital costs of low-carbon vehicles are offset by lower operating costs).
- Key challenges relate to:
  - Development of the market for electric vehicles; this requires innovations in battery technology and manufacturing processes to reduce vehicle costs and improve range, and appropriate incentives to ensure consumer take-up while vehicle costs and range constraints remain significant.
  - The coordination of development of hydrogen vehicles with development and deployment of hydrogen production capacity, and hydrogen distribution and fuelling infrastructure.
- Our new analysis therefore supports the recommendation from our fourth budget advice that Government should support development of the market in electric vehicles and demonstration of hydrogen technologies.

We set out this chapter in four sections:

1. Current emissions and abatement options for surface transport.
2. Scenarios for surface transport emissions to 2030.
3. Scope for further surface transport emissions reduction to 2050.
4. Summary and implications for approaches to reducing surface transport emissions.

Figure 4.1: Breakdown of surface transport CO_2 emissions by mode (2010)



Source: NAEI (2012).
Note: 'Other' includes mopeds and motorcycles, liquefied petroleum gas emissions (all vehicles), and other road vehicle engines.

1. Current emissions and abatement options for surface transport

Current emissions

Surface transport emissions in the UK were 113 $MtCO_2$ in 2010, accounting for 18% of UK greenhouse gas emissions. The largest components were emissions from cars (67 $MtCO_2$), vans (15 $MtCO_2$), and HGVs (23 $MtCO_2$) (Figure 4.1). Emissions in 2010 were 3% above 1990 levels, but have been falling since 2007, as a result of vehicle efficiency improvements, reduced distance travelled and increased penetration of biofuels.

Options for reducing emissions from surface transport

There is scope for reducing surface transport emissions through measures on both the demand side and the supply side, based on a set of technologies and opportunities that exist today:

- **Demand-side measures.** These include implementation of Smarter Choices programmes, eco-driver training, enforcement of the speed limit on motorways and dual carriageways and improved freight logistics.
  - **Smarter Choices.** This approach encourages reduction of car journeys through measures including modal switch, car pooling and working from home. Evidence from pilot projects suggests that this has the potential to reduce car travel by around 5%.
  - **Eco-driving training.** This encourages people to drive in a manner which is fuel efficient, for example, through gentle acceleration and braking and not travelling with excess weight in the car. We assume (conservatively) that eco-driving reduces fuel consumption by 3-4%.
  - **Speed limit enforcement.** The speed limit on motorways is 70 mph. In 2010, around 50% of car and van drivers exceeded this limit, with around 15% exceeding the limit by over 10%. These increased speeds are damaging for fuel efficiency (e.g. for a typical car there is a 13% efficiency penalty as speed increases from 70 to 80 mph). Enforcement of the current speed limit could reduce emissions by around 1.4 $MtCO_2$ in 2020.
  - **Freight logistics.** A number of options provide opportunities for emissions reduction. These include modal shift from road to rail or water; supply chain rationalisation (e.g. optimising distribution centre locations); improved vehicle utilisation such as load sharing (different firms sharing the same vehicle) and backloading (re-loading of vehicle and transport of additional freight on the return trip). Evidence from case studies and scenarios produced by freight logistics experts and by DECC support potential for significant reduction (McKinnon and Piecyk (2010)[1], DECC (2011)[2]).
- **Supply-side measures**. These include more efficient conventional vehicles, ultra-low emission vehicles, and use of biofuels.
  - **More efficient vehicles.** There is scope for significant improvement in the fuel efficiency of cars, vans and HGVs through measures such as powertrain efficiency improvements, improved aerodynamics, reduced rolling resistance and light-weighting.
    - EU targets reflect this potential, requiring average new car emissions to fall to 95 gCO_2/km by 2020 compared to the 2010 fleet average of 144 gCO_2/km, and new van emissions to fall to 147 gCO_2/km compared to the 2010 fleet average of 196 gCO_2/km.
    - Comparable options exist to reduce emissions from HGVs, including flywheel, hydraulic and conventional hybrids.
    - Ultimately there are limits to how efficient conventional vehicles can become. This suggests that even in the very long term, emissions intensity of conventional (including hybrid) vehicles will not fall below around 60 gCO_2/km for cars, 85 gCO_2/km for vans or 550 gCO_2/km for large HGVs[3].
  - **Ultra-low emission vehicles.** These offer the opportunity for low or zero emissions if power generation for battery charging and/or hydrogen production is low- or zero-carbon. Within the broader category of ultra-low emission vehicles we identify three distinct types:
    - **Battery electric vehicles (BEVs):** Vehicles powered by an electric motor, with all energy supplied by a battery. Due to their relatively high cost and weight, batteries are not considered suitable for very heavy vehicles with high range and energy storage requirements, like large HGVs.
    - **Plug-in hybrid electric vehicles (PHEVs):** Vehicles powered by an electric motor, with energy supplied by a battery up to a limited range (e.g. 65 km), beyond which an internal combustion engine takes over (parallel hybrid) or powers a generator that continues to power the electric motor (serial hybrid).

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[1] McKinnon, A. and Piecyk, M. (2010), Logistics 2050: Moving Freight by Road in a Very Low Carbon World.
[2] DECC (2011), 2050 Calculator.
[3] AEA (2012): A review of the efficiency and cost assumptions for road transport vehicles to 2050.

  - **Hydrogen fuel cell vehicles (FCVs):** Vehicles powered by an electric motor, with energy supplied by a hydrogen fuel cell. Plug-in hybrid electric vehicles using hydrogen fuel cells (FC-PHEVs) are also a possibility. Unlike BEV and PHEV cars and vans, which are now ready for early-stage deployment, hydrogen FCVs have not yet reached the commercialisation stage.

- **Biofuels.** Subject to sustainability criteria being met, these offer the opportunity for near- to-medium term emissions reduction in surface transport, with more limited scope for longer-term use as bioenergy demand increases in other sectors (as suggested in our 2011 Bioenergy Review).

This set of options, both as regards demand and supply side measures, is typically cost-effective now (i.e. able to yield carbon savings at lower cost per tonne than the Government's carbon price assumptions), with many measures estimated to have negative cost (i.e. result in cost savings).

An important exception here is take-up of ultra-low emission vehicles, which are based on less mature technologies, and which therefore have relatively high costs at present. However, over time we expect that there will be significant reduction in costs of ultra-low emission vehicles (see section 3(i) below), such that these will become cost-effective in the 2020s.

2. Scenarios for surface transport emissions to 2030

In our advice on the fourth carbon budget we developed scenarios for surface transport emissions. These were designed to include measures that are cost-effective and measures required on the path to meeting the 2050 target (i.e. ultra-low emission vehicles). They covered cars, vans, HGVs and buses, and included demand and supply-side measures:

- **Cars.** Our central scenario for car emissions included widespread deployment of demand-side measures, increasing efficiency of conventional vehicles and increasing penetration of ultra-low emission vehicles.
  - The scenario included full roll-out of Smarter Choices programmes across the UK, with eco-driving training for 20% of drivers by 2030, and enforcement of the current speed limit on motorways and dual carriageways.
  - CO$_2$ emissions intensity of new cars decreased to 95 gCO$_2$/km in 2020 in line with the EU target, and decreased further to 52 gCO$_2$/km by 2030 (80 gCO$_2$/km excluding the impact of electric and plug-in hybrid vehicles).
  - Ultra-low emission car penetration reached 60% by 2030 (i.e. 60% of new cars purchased in 2030 are ultra-low emissions vehicles). We assumed that 70% of these would be plug-in hybrid electric vehicles, and the remaining 30% pure battery electric vehicles.

- **Vans.** Our scenario included increasing efficiency of new vans to 147 gCO$_2$/km in 2020 in line with the EU target and 80 gCO$_2$/km in 2030 (120 gCO$_2$/km excluding the impact of electric and plug-in hybrid vehicles), with increasing penetration of ultra-low emission vans to 60% of new vans by 2030.
- **HGVs.** Our scenario included increasing efficiency of new HGVs by around 12% between 2010 and 2020, and a further 18% between 2020 and 2030.
- **Buses.** We included a small role for hydrogen in the bus fleet. Buses are well suited to uptake of hydrogen given the limited infrastructure requirements of depot-based fuelling. Early deployment in this sector provides an opportunity to develop the option of hydrogen vehicles for deployment in other vehicle categories (e.g. HGVs, and potentially cars and vans as an alternative to electric vehicles).
- **Biofuels** penetration (for total fuel use across all vehicle types) reaches 31 TWh (8% by energy) by 2020 in line with levels identified as being potentially sustainable in the Gallagher Review, and remains at this absolute level to 2030.

We estimate that there would be a surface transport emissions reduction of around 41% relative to 2010 levels through implementation of this set of measures, such that emissions from surface transport in 2030 would be 67 MtCO$_2$.

3. Scope for further surface transport emissions reduction to 2050.

By 2030, we expect that the vast majority of technical potential to reduce emissions from demand-side measures and fuel efficiency improvements to conventional vehicles will have been exploited.

In addition, and as set out in detail in our Bioenergy Review, use of biofuels in surface transport is likely to decline in the 2030s, given increasing demand for scarce bioenergy in other sectors, and the existence of alternative abatement options in surface transport.

Therefore decarbonisation of surface transport beyond 2030 is likely to require further take-up of ultra-low emission vehicle technologies. As set out in section 1, ultra-low emission vehicle technologies include battery and hydrogen technologies for cars, vans and small HGVs, and hydrogen technologies for larger HGVs. We now consider options for cars and vans, followed by options for HGVs.

(i) Further cuts in emissions from cars and vans

The challenge from 2030 to 2050

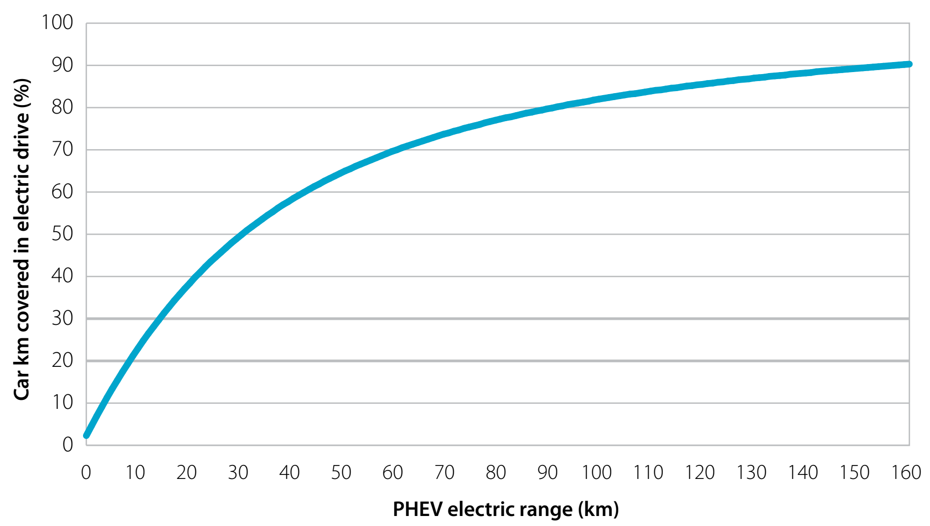
Our 2030 scenario for cars and vans was designed to be consistent with purchase of ultra-low emission vehicles rising to 100% of new vehicles by the mid-2030s, which we assessed would be both cost-effective and necessary in the context of meeting the 2050 target.

A key barrier to high levels of take-up would be the range constraint of battery electric vehicles (e.g. the range of current electric cars is under 100 miles). Given expected range constraints in 2030 we assumed that most people buying an ultra-low emission car or van at this time would choose a plug-in hybrid rather than a pure battery electric vehicle (range is not an issue for plug-in hybrids, which operate in internal combustion engine (ICE) mode once the electric range is exhausted).

If this pattern were to continue, then even with full take-up of PHEV cars and vans, there could still be significant emissions from cars and vans in 2050 from journeys travelled in ICE mode:

- We assumed the range for the electric engine of a plug-in hybrid would be around 65 km (40 miles) in 2030.
- A substantial proportion (46%) of total car travel distance is accounted for by cars covering a total of less than 65 km on the day of travel. Of the remainder, a further 26% is accounted for by the first 65 km covered on the day of travel. Therefore, full roll-out of plug-in hybrids with a 65 km range would cover around 70% (i.e. 46% plus 26%) of total distance in electric mode (Figure 4.2).
- At around 70 gCO_2/km (i.e. the emissions intensity of an efficient plug-in hybrid in conventional mode), this would result in car emissions of 13 MtCO_2 in 2050, given car km assumed to increase from around 400 billion car km today to around 500 billion in 2050.

Figure 4.2: Distance covered in electric drive by plug-in hybrid vehicles



Source: National Travel Survey 2008.

- Assuming a similar distribution of emissions by journey length for vans (data on van travel is not available), emissions from PHEV vans would be around 4 MtCO_2 in 2050.

This level of emissions could be problematic from the perspective of meeting the economy-wide 2050 target, given remaining emissions in other sectors. Therefore the challenges in moving from 2030 to 2050 are both to reach full penetration of ultra-low emission vehicles across the fleet, and to ensure that emissions from longer journeys are kept to a minimum.

Scope for battery cost reduction and range extension

A key barrier to the uptake of electric vehicles is the high cost, as a result of the cost of the battery[4]. This will ease over time as battery costs fall, and as rising carbon costs feed through to higher running costs for conventional vehicles.

For this report we commissioned Element Energy to assess scope for reduction in battery costs. Element concluded that there was scope for significant reduction in battery costs (e.g. the cost of BEV battery packs could decline from over $700/kWh in 2011 to around $200 in 2030, see Box 4.1). The implications of Element's forecast costs are that both PHEVs and lower-range BEVs are likely to be cost-effective by 2030, with higher BEV range becoming cost-effective by 2050, by when BEVs are expected to be lower-cost than PHEVs (Box 4.5 below summarises costs of low-carbon cars and vans):

- Despite the relatively high expected costs per kWh of PHEV batteries, PHEVs are likely to be cost-effective by 2030.
- BEV cars with a range of 240 km (around 150 miles) would be cost-effective by 2030. By 2050, rising carbon prices would justify higher battery capacity, such that longer range cars with a range of 320 km (200 miles) would be cost-effective.
  - A range of 200 miles would mean that a BEV could cover all travel undertaken in a single day on 97% of days for the average driver without the need to recharge, and even the longest journeys would only need a single recharge en route for a fully charged vehicle.
  - This is true even for low-mileage users (who still face the high upfront cost but benefit less from low running costs).
- Longer range BEVs would be cheaper than PHEVs given the existence of a carbon price. This is because while BEVs and PHEVs would have broadly comparable vehicle and operating costs, PHEVs would incur a carbon cost penalty due to the liquid fuel used in ICE drive.

Therefore, the Element analysis suggests that BEVs are likely to be preferred on grounds of cost, and that deployment of 60% of new car and van sales in 2030, 100% in 2035, and a fleet dominated by BEVs in 2050 is a cost-effective solution (i.e. cheaper than an ICE fleet when carbon costs are included at £70/tCO_2 in 2030 and £200/tCO_2 in 2050).

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[4] The use of lithium and cobalt in electric vehicle batteries and the rare earth metal neodymium in permanent magnets used in electric vehicle motors (and wind turbines) has prompted some concern about the availability of sufficient resources to meet the requirements of electrifying the global car and van fleet. However, potential barriers relating to resource constraints are likely to be surmountable. See: Gruber, et al. (2011), Global Lithium Availability: A Constraint for Electric Vehicles?; Stockholm Environment Institute (2012), Metals in a Low-Carbon Economy: Resource Scarcity, Climate Change and Business in a Finite World; Economist (2011), Nikola Tesla's revenge, available at: http://www.economist.com/node/18750574; Element Energy (2012), Cost and performance of EV batteries. We will revisit the issue of resource constraints in our future analysis.

In principle full roll-out of BEVs could eliminate the need for liquid fuels in cars and vans completely (e.g. with a motorway fast-charging or battery swap network providing recharges for longer journeys), or at least support a large share of pure electric cars (Box 4.2).

Box 4.1: Forecast cost and performance of electric vehicle batteries

We commissioned Element Energy, in collaboration with Axeon and Prof. Peter Bruce of EastChem to investigate the future trajectory of battery costs and performance. Element provided forecasts for both the medium-term (2010-2030) and long-term (post-2030), for BEV and PHEV cars and vans.

Element developed a bottom-up component-based approach to battery cost modelling, comprising factors relating to cell production (cell design, material consumption, manufacturing cost, factory throughput and overheads) and pack production (physical supports, environmental control, wiring, Battery Management System (BMS) and power electronics).

For the medium-term (2010-2030), Element focused on advanced lithium-ion batteries and identified two main cost drivers:

- The improvement in material properties delivering higher energy densities, resulting in less material per kWh and fewer cells to monitor.
- The scaling up in production of large cell formats.

Assuming sufficient R&D to overcome remaining technical challenges and sufficient uptake of electric vehicles to drive the required investment in new battery production capacity, the medium-term forecast to 2030 is:

- BEV car (C/D class) battery pack costs decrease from $726/kWh in 2011 to $212 in 2030.
- BEV van battery pack costs decrease from $587/kWh to $171.
- PHEV car battery pack costs decrease from $1,327/kWh to $422.
- PHEV van battery pack costs decrease from $746/kWh to $263.

The higher cost of PHEV battery packs is due to higher power requirements, as sufficient power needs to be generated by a smaller battery. As a result, some pack components are more expensive, particularly the thermal control (e.g. liquid cooled in a PHEV versus air cooled in a BEV).

For the long-term (post-2030), Element modelled costs of lithium-air (Li-Air) batteries, which present the greatest energy density potential among possible technologies. Element's forecast for the long-term is that:

- Li-Air battery pack costs reach $215- $250/kWh beyond 2030.
- No significant cost reductions are expected for lithium-ion batteries beyond their 2030 cost.

Li-air batteries are therefore not expected to offer a cost reduction on the pack level compared to the advanced lithium-ion batteries expected to be developed by 2030. Whilst Li-Air batteries may bring cost savings at the cell level, their requirement for more air management (the cells are air breathing), and the increased cost of BMS arising from the lower cell voltage, incur a cost penalty. However, Li-Air batteries would deliver a significant weight saving which would bring other benefits such as reduced chassis weight and better vehicle performance.

The implications of these battery cost estimates for the overall cost-effectiveness of electric vehicles are set out in Box 4.5.

Box 4.2: Options for long-distance travel with an electric car fleet

BEV cars with a range of 320 km (200 miles) should be cost-effective by 2050. A range of 200 miles would mean that:

- A BEV could cover all travel undertaken in a single day on 97% of days for the average driver without the need to recharge
- Even the longest journeys would only need a single recharge en route for a fully charged vehicle.

Options for those 3% of days (11 days per year for the average driver) on which a BEV could not cover all travel undertaken in a single day are:

- **Re-charging en-route.** This would require a charging infrastructure that is sufficiently widespread (nationwide coverage), fast (so that charging did not significantly increase journey times), and capable of using low-carbon electricity. A 200 mile range for a BEV might facilitate a relatively sparse infrastructure, for example along motorways for long distance travel rather than greater density over the entire UK road network.
- **Battery swapping en route.** This would require a similar number of facilities to fast-charging.
- **Use of a conventional car or plug-in hybrid** for travel over 200 miles in a single day. This would result in a small increase in remaining emissions in 2050.
- **Behaviour change.** This would involve drivers switching to public transport or selecting an alternative to travel.

Therefore, whilst a 200 mile range would not cover every journey made, plausible mechanisms exist to cover the small number of longer journeys, such that full take-up of EVs could be achieved.

A role for hydrogen cars and vans?

Although our scenario to 2030 focused on increasing penetration of electric cars and vans, we also highlighted a potential role for hydrogen fuel cell vehicles.

In the near to medium term, these do not appear to be as promising as electric cars and vans, partly because they are likely to be relatively expensive, and also because there are currently a number of challenges relating to hydrogen infrastructure for production, transportation and storage.

However, over time these challenges could be overcome and the costs of hydrogen vehicles reduced:

- Analysis we commissioned for this report from AEA suggests that by 2030 hydrogen cars and vans could be available at a similar cost to electric vehicles (Box 4.3).
- A coordinated approach to incentivising the parallel development of hydrogen vehicles and the required infrastructure would reduce the risk to developers that the market for hydrogen vehicles and fuels will not materialise (Box 4.4)

Box 4.3: Costs of hydrogen cars and vans

Hydrogen fuel cell vehicles are powered by an electric motor, with the electricity produced by a hydrogen fuel cell stored onboard the vehicle. Hydrogen vehicles are similar to battery electric vehicles, with a hydrogen fuel tank and fuel cell instead of a battery.

At present, only a small number of prototype hydrogen fuel cell vehicles have been produced, at very high cost due to the very small scale of production of the fuel cells themselves. Analysis we commissioned for this report from AEA indicates that there is potential for the costs of hydrogen fuel cells to decrease from around £800 per kW output as observed in prototype vehicles today, to £75 in 2030 and £48 in 2050. This would result in the cost of a hydrogen fuel cell car decreasing from around £100,000 today to around £20,000 by 2030, with comparable costs and cost reductions for vans.

Source: AEA (2012): A review of the efficiency and cost assumptions for road transport vehicles to 2050.

Box 4.4: Infrastructure challenges to development of a hydrogen transport system

In addition to hydrogen vehicles, a hydrogen transport system requires hydrogen production capacity and infrastructure for hydrogen distribution and fuelling.

The appropriate hydrogen production processes are likely to depend on whether 'pre-combustion' carbon capture and storage (CCS) is successful, with different distribution requirements in each case.

- Given the successful demonstration of pre-combustion CCS, hydrogen could be co-produced with electricity at large-scale directly from fossil fuels. The plant could produce electricity at peak times and hydrogen for transport off-peak (e.g. overnight). This method of hydrogen production would result in hydrogen being produced at relatively large scale at power plant sites. This would therefore require either considerable infrastructure (e.g. dedicated hydrogen pipelines) or hydrogen liquefaction for distribution by road to areas of demand. Hydrogen pipelines are capital-intensive and expensive for long distances and/or small volumes, and may face challenges relating to planning, while hydrogen liquefaction technology is expensive and energy-intensive.
- Without successful demonstration of pre-combustion CCS, hydrogen would need to be produced by electrolysis using low-carbon electricity. Hydrogen production in this way is less efficient and therefore more costly, though has the advantage that the hydrogen could be generated when low-carbon generating capacity is underutilised, and would imply a more distributed system of hydrogen production without the requirement for costly distribution infrastructure.

There are therefore technical and economic challenges relating to production, and distribution and fuelling, as well as the vehicles themselves. The risks to investors implied by these challenges are compounded by the fact that each element is likely to be supplied by different firms in different industries: auto manufacturers, power companies, and fuel companies. Without reasonable certainty that all elements will be in place and the market for hydrogen vehicles and fuel will develop sufficiently, the risks to a firm investing in any single element will be prohibitively high.

The parallel development of hydrogen vehicles, production capacity and distribution and fuelling infrastructure therefore requires a coordinated approach to provide a degree of confidence in the development of a market for hydrogen vehicles and fuel. This would reduce risks to investors, and ensure that sufficient incentives are in place for research and development, demonstration and deployment of each of these elements.

Therefore, in a world where there is limited battery innovation such that cost and range of BEVs do not improve to the degree required for commercialisation, and/or where investment in a national fast-charging or battery swap infrastructure is prohibitively expensive, hydrogen cars and vans could become an attractive zero carbon alternative to electric vehicles, and one that might be required to meet the economy-wide 2050 target.

The development of options for hydrogen fuel cell and battery electric vehicles could be complementary, as they both imply a shift to electric power-trains. Furthermore, the advantage of hydrogen in providing extra range suggests long-term potential for the development of hydrogen plug-in hybrid vehicles, using both a battery and fuel cell.

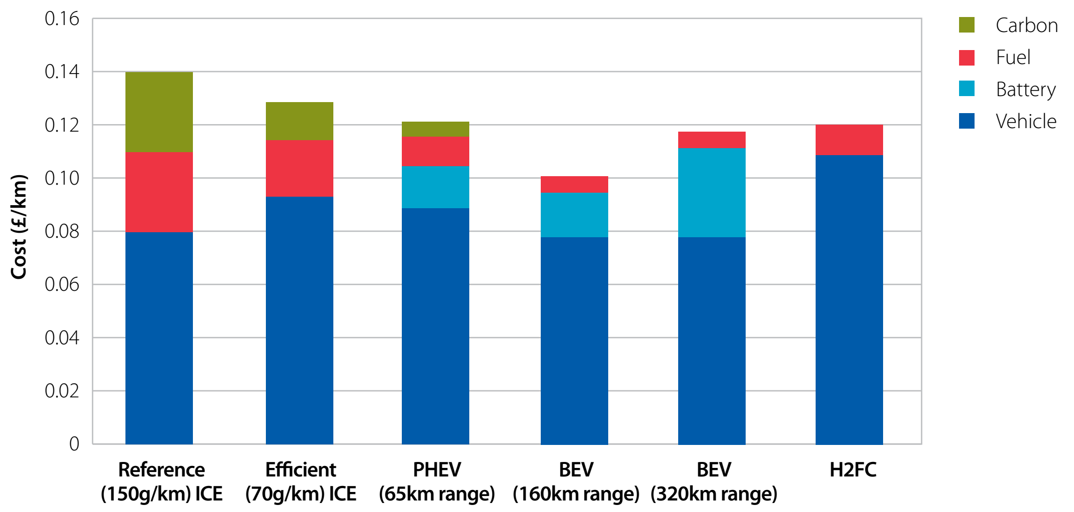
Summary of opportunities for ultra-low emission cars and vans

Box 4.5 sets out the abatement cost (the cost per tonne of reducing CO$_2$ emissions) of different car and van technologies in 2030 and 2050. These costs indicate that:

- By 2030, the majority of low-carbon vehicle technologies will be cost-effective:
  - PHEV and BEV cars represent cost-effective abatement opportunities relative to the Government's carbon values; hydrogen fuel cell cars are not expected to be cost-effective by 2030.
  - PHEV, BEV and hydrogen fuel cell vans represent cost-effective abatement opportunities by 2030.
- By 2050, all car and van technologies represent cost-effective abatement opportunities.

Figure 4.3 sets out the cost of travel per km for the range of car technologies considered, broken down into basic vehicle costs, battery costs (where applicable), fuel costs and carbon costs. Figure 4.3 indicates that, inclusive of carbon costs, battery electric vehicles and hydrogen fuel cell vehicles are likely to be the most cost-effective car technologies for reducing emissions, with a significant reduction in total costs for drivers whose requirements can be met with shorter range vehicles.

Figure 4.3: Cost per km of car technologies (2050)



Source: AEA (2012): A review of the efficiency and cost assumptions for road transport vehicles to 2050; CCC analysis.
Note: Carbon costs calculated at £200/tCO$_2$ in line with the Government's central case carbon values.

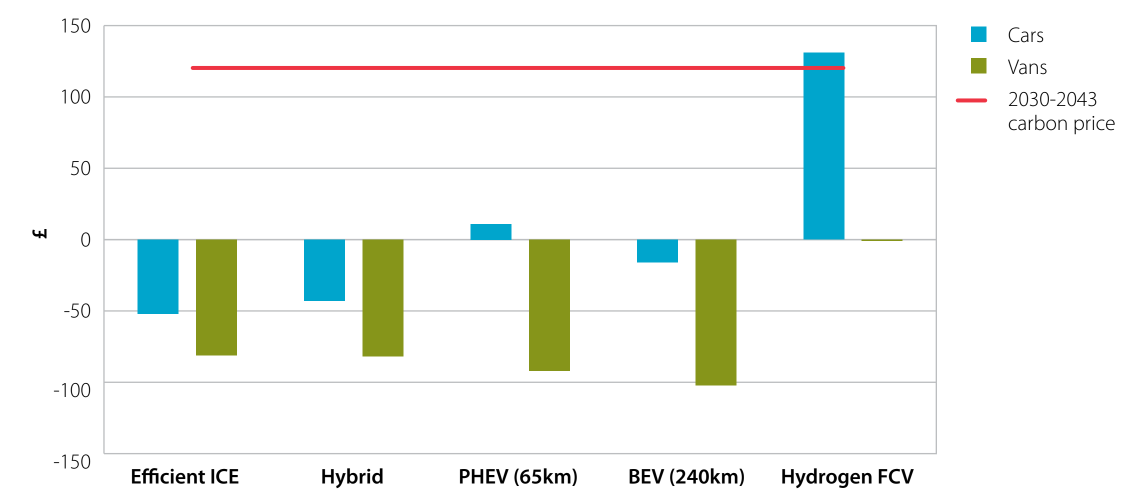
Box 4.5: Car and van costs in 2030 and 2050

We have estimated the costs of different car and van technologies in 2030 and 2050 using the following assumptions:

- Battery costs decrease as forecast by Element Energy (2012) (see Box 4.1)
- Capital costs decrease as set out in AEA (2012).
- Vehicle energy consumption decreases as set out in AEA (2012).
- Petrol and diesel costs are in accordance with DECC forecasts (see Table 1.4 in Chapter 1) with an oil price of $130/bbl in 2030 and beyond.
- Electricity costs are 2.7 p/kWh in 2030, consistent with the low level of transport electricity demand in our scenario met with off-peak low-carbon generating capacity, and 5.7 p/kWh in 2050, consistent with 50% of transport electricity demand met with existing off-peak low-carbon generating capacity, and the remaining 50% requiring new low-carbon generating capacity.
- Hydrogen is co-produced with electricity at large-scale directly from fossil fuels during pre-combustion CCS (Box 4.4), at a cost of £61/MWh (based on £78m capital cost of a 0.5 TWh per year steam methane reformation plant with CCS).

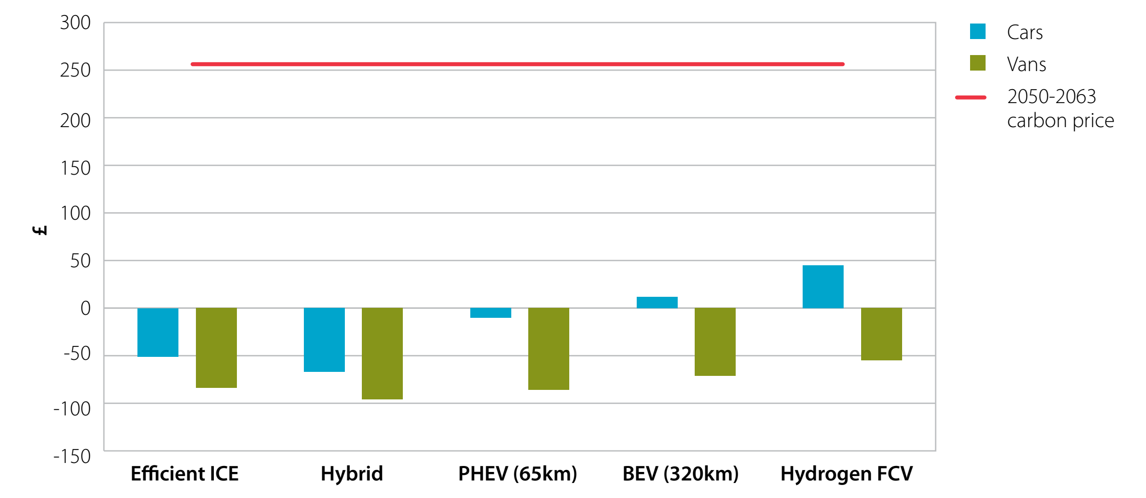
Figures B4.5a and B4.5b set out the abatement cost of each car and van technology in 2030 and 2050 based on these assumptions.

Figure B4.5a: Car and van abatement costs in 2030



Source: AEA (2012): A review of the efficiency and cost assumptions for road transport vehicles to 2050; CCC analysis.
Note: Carbon price is average price over lifetime of vehicle purchased in 2030.

Figure B4.5b: Car and van abatement costs in 2050



Source: AEA (2012): A review of the efficiency and cost assumptions for road transport vehicles to 2050; CCC analysis.
Note: Carbon price is average price over lifetime of vehicle purchased in 2050.

Remaining emissions from cars and vans in 2050

We reflect the potential for battery innovation and/or hydrogen cars and vans in our range for remaining emissions in 2050:

- The low end of the range reflects scope for reducing emissions from cars and vans to close to zero. This could be through the vast majority of people purchasing pure battery electric vehicles, which become acceptable as range constraints are eased; or with range extension provided through development of a national fast-charging infrastructure. Alternatively, it might involve a major role for hydrogen vehicles, which would be near-zero carbon given appropriate processes for hydrogen production. In such a scenario the negligible role of liquid fuels would preclude significant use of transport biofuels.
- The high end of the range reflects a scenario in which full take-up of zero-emission vehicles is not achieved, either due to failure to resolve barriers relating to consumer acceptance, or failure to achieve sufficient technological or cost breakthroughs. This scenario could reflect that the majority of cars and vans are PHEVs with electric range of 65 km (40 miles) rather than zero-emission vehicles, or that only 70% of cars and vans are BEVs or hydrogen fuel cell vehicles while the remaining 30% are conventional internal combustion engine vehicles. Emissions from cars and vans in this case are around 17 MtCO_2 in 2050. Given the remaining level of liquid fuels in such a scenario, there may be a role for transport biofuels if they can offer comparable total GHG reductions at similar costs to other bioenergy applications (e.g. in aviation or industry).

Our range for emissions from cars and vans in 2050 is therefore 1-17 MtCO_2, compared to 2010 emissions of 82 MtCO_2.

This is consistent with analysis in the Government's Carbon Plan, which suggested that almost all cars and vans would be ultra-low emission vehicles by 2050.

Costs of reducing emissions from cars and vans

In our advice on the fourth carbon budget, we estimated a cost associated with decarbonisation of cars and vans at around 0.1% of GDP in 2030, with the majority of this due to increasing penetration of electric vehicles, to reach around 30% of the car and van fleets.

From 2030, we would expect a broadly similar upfront cost of electric vehicles, with battery cost reductions translating to increased battery capacity and vehicle range rather than overall vehicle cost reductions. Hydrogen fuel cell vehicles (and plug-in variants) are likely to be available as an alternative to battery electric cars and vans, at similar cost.

Since our fourth carbon budget advice the oil price has continued to rise, and DECC's forecast long-term petrol and diesel prices have risen. This more than offsets the small cost estimated for 2030. Therefore we estimate that a zero-carbon car and van fleet can be delivered at no cost in 2050 with a fleet dominated by BEVs.

If only 70% of cars and vans are BEVs or hydrogen fuel cell vehicles while the remaining 30% are conventional internal combustion engine vehicles, emissions from cars and vans would be 17 MtCO_2, with comparable (i.e. zero) cost in 2050.

(ii) Reducing emissions from HGVs

Over the next two decades, there is scope for emissions reduction for HGVs. Opportunities exist to improve efficiency, increase biofuels penetration and to reduce miles travelled (e.g. by improving vehicle utilisation and supply chain rationalisation). There is the possibility of the introduction of hydrogen vehicles depending on the extent to which technical challenges can be addressed and whether there is investment in refuelling infrastructure.

Going beyond 2030, there is limited scope for continued CO_2 reduction through conventional and hybrid HGVs. There is also limited scope for further emissions reduction through increased biofuels penetration because of constraints on available sustainable supply, and a high degree of uncertainty over whether there is scope for additional reduction in miles travelled. Although battery technologies are promising for cars, vans and smaller HGVs, these are not feasible for larger HGVs, because of the cost and weight of the batteries required to power these vehicles for their required range.

Therefore the main option for reducing HGV emissions beyond 2030 is through increasing penetration of hydrogen vehicles. Whereas in the near- to medium-term challenges around technical development and vehicle cost may be prohibitive and investment in refuelling infrastructure limited, it is likely that these barriers can be addressed in the longer term (see Box 4.4 above).

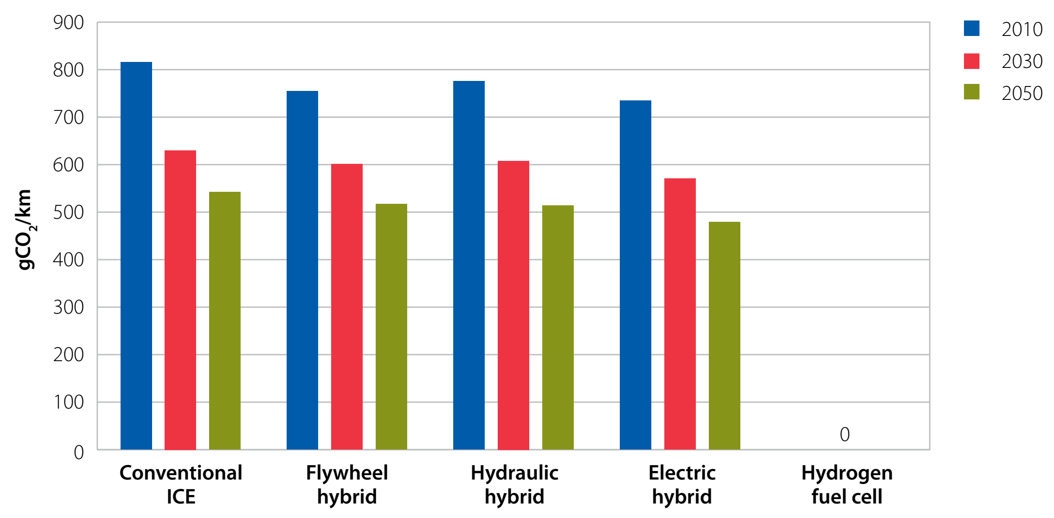
Box 4.6: HGV costs in 2030 and 2050

We have estimated the costs of different HGV technologies in 2030 and 2050 using the following assumptions:

- Capital costs decrease as set out in AEA (2012).
- Vehicle energy consumption and CO_2 intensity decreases as set out in AEA (2012).
- Fuel prices are as set out in Box 4.5

With the above assumptions, every HGV abatement technology is expected to be cost saving by 2030. Therefore a shift to hydrogen HGVs would eliminate tailpipe emissions (Figure B4.6a) and reduce costs, even with no value placed on the emissions saving.

Figure B4.6: Large rigid HGV technology vehicle CO_2 trajectory



Source: AEA (2012): A review of the efficiency and cost assumptions for road transport vehicles to 2050; CCC analysis.
Note: Real-world tailpipe emissions.

If this is the case, then the use of hydrogen in the context of HGVs becomes attractive from an economic perspective. Costs are likely to be lower for HGVs than for cars and vans because the efficiency of fuel cell vehicles and the large distances covered by HGVs mean that fuel cell HGVs deliver very significant fuel cost savings compared with conventional vehicles (Box 4.6).

Our cost estimates for hydrogen use in HGVs therefore suggest that this would be a very cost-effective (i.e. negative cost) option by 2030, and that hydrogen offers a potential means for reducing emissions from HGVs to close to zero in 2050 or shortly thereafter.

We set out three potential deployment levels for hydrogen HGVs:

- If infrastructure development and roll-out were to begin around 2030, then it is possible that roll-out could reach 100% of new vehicle sales by 2040, with over 90% of the HGV fleet hydrogen-fuelled by 2050, given vehicle lifetimes. Remaining HGV emissions would be around 1 $MtCO_2$ in 2050.
- Given moderate barriers to full uptake (e.g. there may be some types of vehicle or operation that are not well-suited to hydrogen fuelling), we also include the possibility that roll-out is limited to 75% of new vehicle sales by 2040, or around 70% of the fleet by 2050. Remaining HGV emissions would be around 5 $MtCO_2$ in 2050.
- Given more significant barriers to full uptake, or slower reductions in fuel cell costs we also include the possibility that roll-out is limited to 50% of new vehicle sales by 2040, or around 45% of the fleet by 2050. Remaining HGV emissions would be around 9 $MtCO_2$ in 2050.

These different deployment levels for hydrogen HGVs in 2050 imply a range for remaining emissions of 1-9 $MtCO_2$ in 2050. We estimate that moving to hydrogen HGVs for the majority of the fleet can be delivered at no cost in 2050 (our modelling suggests negative costs, as higher capital costs are more than offset by fuel cost savings).

(iii) Reducing emissions from other modes of surface transport

Additional surface transport emissions are generated by other modes:

- Buses and coaches: 5 $MtCO_2$ in 2010;
- Mopeds and motorcycles: 1 $MtCO_2$ in 2010;
- Rail: 2 $MtCO_2$ in 2010;
- Miscellaneous vehicles (LPG vehicles, other road vehicle engines, aircraft support vehicles): 1 $MtCO_2$ in 2010.

We estimate that much of the emissions from these sources could also be avoided by 2050 through electrification and/or use of hydrogen:

- The bus and coach fleet can be almost entirely converted to hydrogen fuel cell vehicles by 2050. Initial deployment of hydrogen buses and coaches from 2021, rising to 50% of new buses in 2030 (17% of new buses and coaches) as set out in our fourth carbon budget scenario) and to 100% of all new buses and coaches in 2040, would result in bus emissions of 0.2 $MtCO_2$ in 2050, at negligible cost.

- Analysis we commissioned for this report from AEA indicates that the motorcycle and moped fleet can be almost entirely electrified by 2050, at negligible cost (AEA (2012))[5].
- In our Fourth Carbon Budget report we noted that while the total costs of electrifying the entire rail network are uncertain, estimates of average cost per single track km suggest that electrification could cost around £160/tCO_2. Given minimal barriers, we assume that the entire rail network is electrified and rail emissions reduced to zero in our deployment scenarios. We also reiterate our recommendation in the Fourth Carbon Budget report that the total costs of electrifying the entire rail network are established to confirm that this measure is appropriate, and to identify any routes that cannot be electrified cost-effectively.
- Evidence is lacking on options to decarbonise miscellaneous vehicles. Given opportunities to reduce emissions from vehicles in major modes to zero through electrification or take-up of hydrogen technologies by 2050 at negligible cost, we assume similar opportunities are available for other modes, and that emissions are reduced to zero in our deployment scenarios.

Therefore emissions from other modes of surface transport should be reduced to low levels in 2050. Given the small size of these sectors, the GDP impact of their decarbonisation will be relatively marginal (around 0.01% of GDP).

4. Summary and implications for approaches to reducing surface transport emissions

Based on the analysis above, for our economy-wide scenarios we include three potential levels of deployment in 2050 for the surface transport sector:

- **Max.** For cars, vans and HGVs, 100% of new vehicles are zero-emission (battery electric or hydrogen fuel cell vehicles) by 2040 (near-100% of the fleet by 2050). Total surface transport emissions would be 2 MtCO_2 in 2050.
- **Stretch.** There is still very substantial decarbonisation, but with lower take-up of hydrogen fuel cell HGVs. For cars and vans, 100% of new vehicles are zero-emission by 2040 (near-100% of the fleet by 2050). For HGVs, 75% of new vehicles are hydrogen fuel cell vehicles by 2040 (around 70% of the fleet by 2050). Total surface transport emissions would be 6 MtCO_2 in 2050.
- **Barriers.** In this case we assume barriers to uptake (e.g. poorer than expected technology cost reductions, failure of policy to incentivise sufficient uptake) prevent full roll-out of ultra low emission vehicle technologies. For cars and vans, this could result from 70% of new vehicles being zero-emission by 2040 (near-70% of the fleet by 2050) or 100% of new vehicles being plug-in hybrid by 2040 (near-100% of the fleet by 2050). For HGVs, 50% of new vehicles are hydrogen fuel cell vehicles by 2040 (around 45% of the fleet by 2050). Total surface transport emissions would be 26 MtCO_2 in 2050.

2050 emissions under these levels of deployment are set out in Figure 4.4.

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[5] AEA (2012): A review of the efficiency and cost assumptions for road transport vehicles to 2050.

All these levels of deployment imply extensive decarbonisation to 2050, whilst recognising the risk that barriers could prevent full roll-out of more difficult measures.

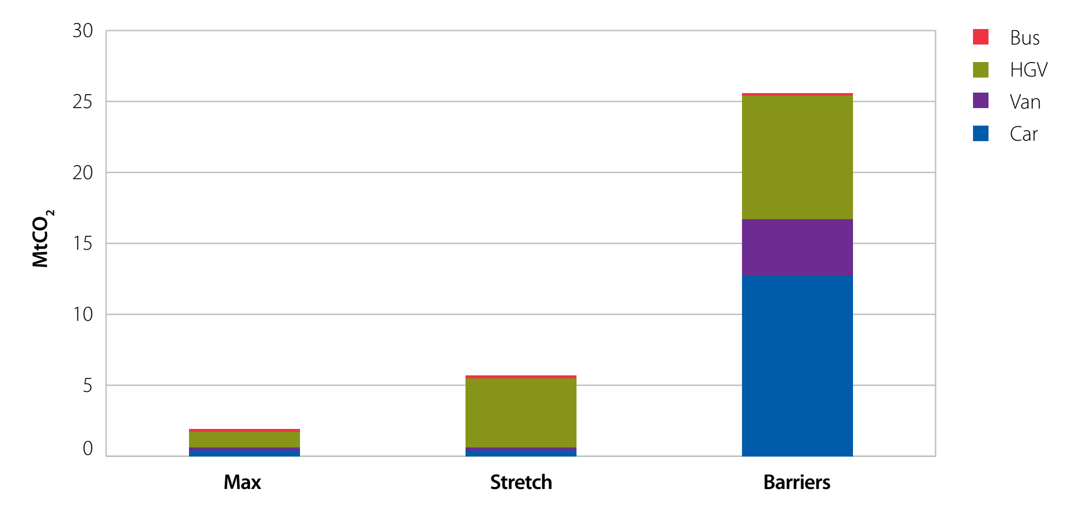
We estimate that each level of deployment can be delivered at zero cost in 2050 (our modelling suggests negative costs, as higher capital costs are more than offset by fuel cost savings).

In order that the long-term futures set out in this chapter remain feasible it is important now to implement low-cost measures on both the demand and supply sides, and to develop options for emissions cuts based on electric and hydrogen technologies. Consequently, there is a need for continued support for electric vehicle market development, and for development of hydrogen vehicles.

Achieving major cost reductions and full fleet penetration will require extensive deployment of ultra-low emission vehicles by 2030 (e.g. the 60% share of new cars and vans in the Medium Abatement scenario proposed in our Fourth Carbon Budget advice) and substantial progress by 2020 (e.g. to reach 16% of new cars and vans as assumed in our progress indicators).

We will continue to monitor progress in each of these key areas – demand measures, vehicle efficiency improvement, electric and hydrogen vehicle market development – in our annual progress reports to Parliament.

Figure 4.4: Remaining emissions by deployment level in 2050



Source: CCC analysis.

Chapter 5

Reducing emissions from industry

Introduction and key messages

Industry currently accounts for around a third (197 $MtCO_2e$) of total emissions. In this chapter we focus on around 60% (114 $MtCO_2$) of direct CO_2 emissions, given that we expect indirect emissions to fall as the power sector is decarbonised. Direct emissions will have to be reduced to meet the economy-wide target (i.e. 160 $MtCO_2e$), within which there must be headroom to accommodate emissions from hard-to-treat sectors such as agriculture, aviation and shipping.

We presented a scenario in our advice on the fourth carbon budget where direct CO_2 emissions from industry fell to 90 $MtCO_2$ in 2030, based on a combination of incremental energy efficiency, significant efficiency improvements in energy-intensive industry, bioenergy and a limited roll-out of carbon capture and storage (CCS).

In this chapter, we consider opportunities to reduce emissions further through CCS and bioenergy, together with additional options for decarbonising industrial heat through the use of electrification and hydrogen. Our key messages are:

- The new assessment of options reinforces our previous conclusions that the decarbonisation of industry is likely to rely heavily on the development of CCS and/or availability of bioenergy. In addition to its use in providing heat for industrial processes, there is further scope for using biomass to substitute for carbon-intensive products (e.g. using wood in construction of buildings). This is an attractive option for abatement as it displaces a carbon-intense industrial product and can lock up carbon (e.g. in the fabric of a building).
- A significant proportion of fossil fuels in industry (around 40%) are used to produce heat, primarily to raise steam and to provide high and low temperature process heat. Given availability of low-carbon electricity, there is a significant opportunity for abatement through electrification and use of hydrogen in these processes. However, much of this potential is relatively high cost.
- Taken together, along with energy efficiency, by 2050 these options can reduce emissions from industry to within the range 28-87 $MtCO_2$, at a cost of up to 0.3% of GDP in 2050. If CCS does not develop, abatement potential reduces significantly, and even with full deployment of all other options emissions would still be a 42 $MtCO_2$ in 2050.
- The existing set of policy measures is unlikely to encourage sufficient low-carbon investment in industry, as it does not address the barriers to implementation associated with key low-carbon opportunities (e.g. there is no well-developed strategy for CCS in energy-intensive industry that addresses the high capital cost and long asset lifetimes). Therefore, new policy will be required to address these barriers, possibly based on long-term sector agreements and financing.

We set out our analysis in 4 sections:

1. Current industry emissions and abatement options
2. Scenarios for industry emissions to 2030
3. Scope for further emissions reduction after 2030
4. Summary and implications for approaches to reducing industry emissions

1. Current industry emissions and abatement options

Current industry emissions

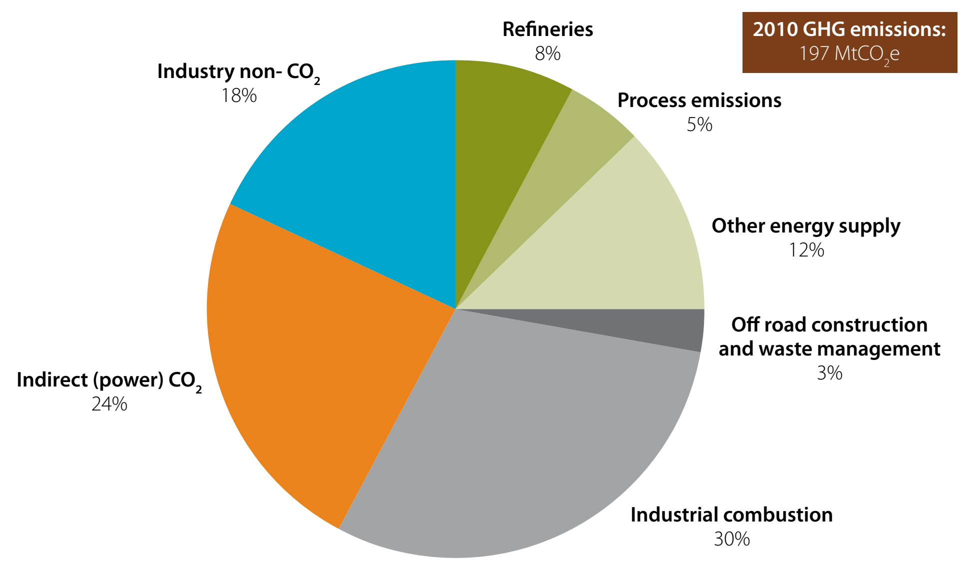
Emissions from industry were 197 $MtCO_2e$ in 2010, accounting for 31% of economy-wide emissions of 628 $MtCO_2e$. Emissions have fallen 44% since 1990, primarily a reflection of fuel switching and industry restructuring.

Industry emissions comprise 114 $MtCO_2$ direct emissions (which are the focus of this chapter), 47 $MtCO_2$ indirect emissions and 36 $MtCO_2$ e of non-CO_2 emissions (Figure 5.1).

- Direct emissions mainly relate to the production of heat and emissions due to chemical processes (e.g. the calcination of limestone in the production of cement).
- Indirect emissions mainly derive from industrial processes in some specific sectors (e.g. electric arc steelmaking and aluminium smelters, motors and a range of different mechanical applications across industry).

Energy-intensive industries covered by the EU Emissions Trading System (ETS) account for approximately 70% of total industry CO_2 emissions.

Figure 5.1: GHG emissions from Industry (2010)



Source: NAEI (2012).
Notes: This figure includes emissions from non-CO_2. The chapter focuses on CO_2 only. Non-CO_2 emissions from industry are covered in Chapter 6.

Reducing industry emissions

Options that we have previously assessed for reducing emissions include energy efficiency improvement, use of bioenergy and CCS, each of which could be cost-effective relative to the Government`s projected carbon prices of £70/tCO_2 in 2030 and £200/tCO_2 in 2050:

- **Incremental energy efficiency improvement.** Our analysis has previously focused on cost-effective, short pay-back options such as improvements to the efficiency of motors. The ENUSIM model used by Government suggests scope for reducing industry emissions by around 2 $MtCO_2$ in 2020 through such measures. We have previously noted questions about the robustness of this model. Whilst there clearly is an opportunity in this area, we have not identified further abatement from this type of measure through the 2020s.
- **Radical improvements in energy-intensive[1] industry.** Analysis conducted for the Committee by AEA[2] in the context of the Fourth Carbon Budget Report (2010) assessed the feasibility and cost-effectiveness of a range of technologies that require a more racial change to the industrial process (e.g. optimisation of refineries). There are however substantial challenges to adoption such as uncertainties around future demand, uncertain costs and site-specific constraints. Taken together, these opportunities could provide an additional 7 $MtCO_2$ savings in 2030.
- **Use of bioenergy.** There is potential to reduce industry emissions through the use of biomass and biogas:
  - **Biomass:** A high proportion of industrial heat load could potentially be met from biomass use, notwithstanding that some applications are unsuitable (e.g. clean burning fuels are required for ceramic kilns).
  - **Biogas:** Heat from biogas is suitable for the majority of industrial heat demand, including applications which require a high quality of gas (where biomass may be unsuitable). This biogas could come from anaerobic digestion and gasification of biomass.
- **Carbon Capture and Storage (CCS).** There are currently no examples of scale application of CCS in industry. However, analysis we previously commissioned led by Element Energy (2010)[3] has suggested that CCS could be widely applicable and cost-effective in energy-intensive industry. They identified a total potential for CCS to reduce emissions by 36 $MtCO_2$ by 2050, through application in energy intensive industry (e.g. iron and steel, cement, refineries).

Further options which could provide scope for additional emissions reduction, or an alternative to deliver emissions reductions if CCS were not to become viable, include electrification of heat and possible fuel switching to hydrogen sourced from low-carbon production. We consider these in Section 3 below. There are also options such as materials efficiency and reducing consumption of materials, but these currently lack a robust evidence base for both costs and abatement potential.

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[1] In this study energy-intensive industry was defined to be the 6 most energy and carbon-intensive sectors: iron and steel, cement, refineries, chemicals, food and drink, glass.

[2] AEA (2010), *Analysing the Opportunities for Abatement in Major Emitting Industrial Sectors.* Available at www.theccc.org.uk

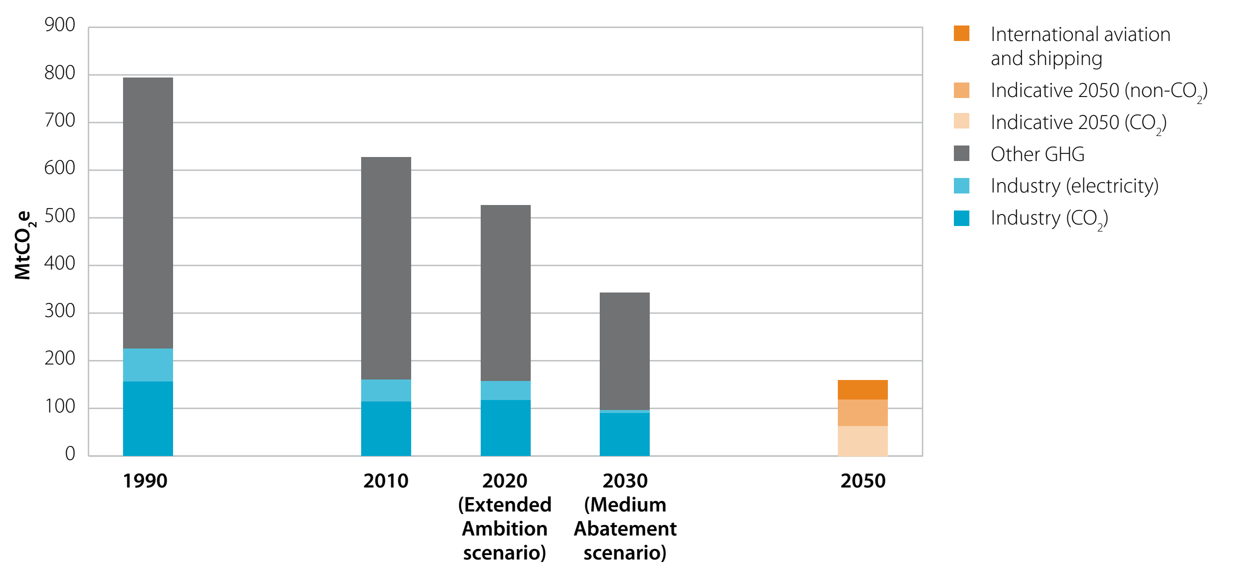
[3] Element Energy, Carbon Counts and AMEC (2010), *Potential for the application of CCS to UK industry and natural gas power generation.* Available at www.theccc.org.uk

2. Scenarios for industry emissions to 2030

In our advice on the fourth carbon budget, we developed scenarios for industry emissions to 2030. In our Medium Abatement scenario, implementation of energy efficiency measures over the next decade, radical options in energy-intensive industry, increased use of bioenergy, and limited investment in CCS, result in direct[4] industry emissions 21% below current levels, at 90 $MtCO_2$ (Figure 5.2).

We noted in the fourth budget advice the high degree of uncertainty over baseline emissions, reflecting uncertainty about the relationship between GDP growth and the carbon intensity of production, together with the future structure of UK industry; and we highlighted the need for further research on other industry abatement options.

Figure 5.2: GHG emissions from Industry in the context of total UK emissions (1990-2030 and 2050)



Source: CCC modelling; NAEI (2012).

Since our fourth budget advice, DECC have updated their projections for industry output, energy demand and emissions. These revisions reflect:

- Lower GDP growth assumptions as a result of the recession.
- A new forecasting methodology based on statistical relationships of past trends of sub-sector growth.

Taken together with our Medium Abatement scenario, the new projections suggest a reduction in the expected level of UK industry emissions relative to our fourth budget scenario, such that those would be 82 $MtCO_2$ in 2030, of which 77 $MtCO_2$ are direct and 5 $MtCO_2$ are indirect emissions (Figure 5.3). We reflect the revised projections in our scenarios and will return to this as part of the Fourth Budget Review due in 2014.

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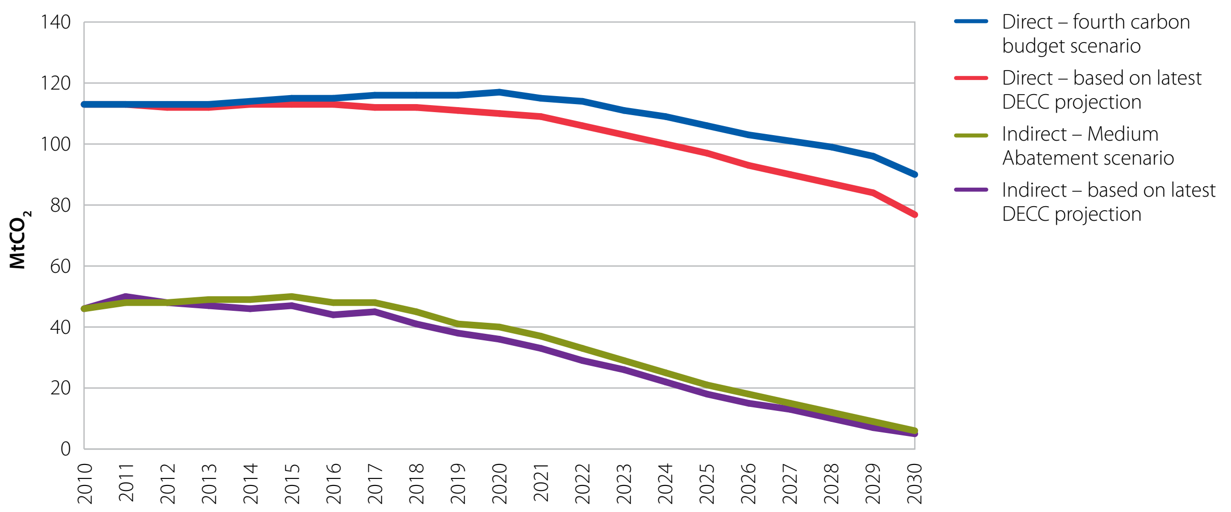
[4] Indirect emissions fall in line with power sector decarbonisation, see Chapter 4.

Figure 5.3: Direct and indirect Industry emissions using different baseline projections (2010-2030)

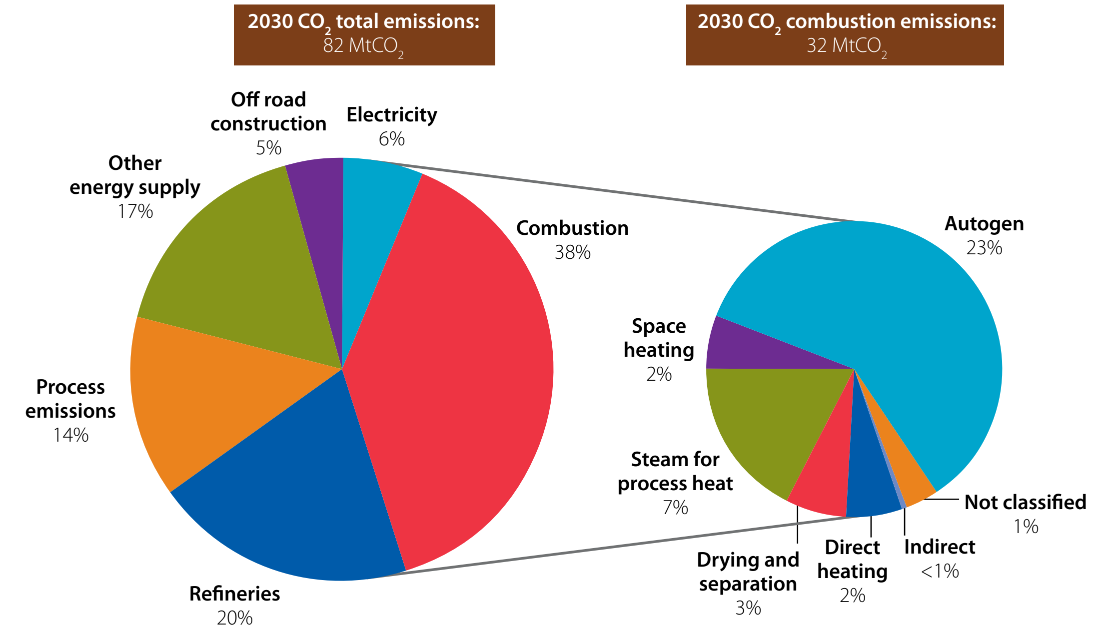


Source: CCC modelling; DECC (2011).
Notes: The data shown is the Medium Abatement scenario using two different "baseline" projections. The first (2010) was the baseline used in the fourth budget report. The second (2011) uses the October 2011 DECC emissions projection.

3. Scope for further emissions reduction after 2030

At 77 $MtCO_2$ of direct emissions, industry would be one of the main emitting sectors of the economy in 2030, accounting for around 25% of emissions. Remaining emissions in our 2030 scenario are from a combination of chemical processes and heat (in the form of steam or direct heating, Figure 5.4). Further reductions are necessary to contribute towards achieving the economy-wide 2050 target of an 80% reduction on 1990 levels.

Figure 5.4: Remaining emissions by use in fourth budget Medium Abatement Scenario (2030)



Source: CCC modelling.
Note: This reflects the CCC fourth budget scenario with updated baseline projection.

We now turn to the options for delivering further reductions: extending the use of CCS and bioenergy, as well as fuel switching to electricity and hydrogen. We also assess the possibility that a shift to a low-carbon economy will change industrial demands more generally (e.g. the implication of not using petroleum-based fuels in transport for emission from the refineries sector).

Further scope for use of CCS and bioenergy

Whereas we envisage limited deployment of CCS in the 2020s, there is scope for rolling-out this technology to energy-intensive industries after 2030. This could cut remaining emissions from energy-intensive industry by 36 $MtCO_2$ to 2050, including:

- In the iron and steel sector, CCS on emissions from the blast furnaces at Port Talbot, Scunthorpe and Middlesbrough (10 $MtCO_2$).
- In the refineries sector, CCS across the 8 major refineries in the UK (9 $MtCO_2$).
- CCS across 45 installations of industrial combined heat and power (CHP) (9 $MtCO_2$).
- CCS on the process emissions from the cement and chemicals sector (8 $MtCO_2$).

The Element Energy analysis of CCS indicated that abatement costs range from £33-82/tCO_2, which is cost-effective relative to the Government`s projected carbon price of £200/tCO_2 in 2050. The higher end of the range reflects less concentrated sources of CO_2 (e.g. the refineries sector) and the lower end of the range is concentrated sources of CO_2 (e.g. the chemicals sector).

This implies that high levels of abatement can be achieved with CCS. Owing to the uncertainty in costs we adopt a range for the deployment of CCS, with the full potential being deployed in the most ambitious case (Max) and with CCS only available to concentrated sources of CO_2 in lower levels of ambition. In all our deployment levels, key barriers must be overcome relating to the development of CO_2 pipeline infrastructure and availability of storage sites.

In our 2011 Bioenergy Review we showed that bioenergy could also play a major role, albeit this is likely to be a scarce resource and should be allocated where it can maximise abatement:

- Use of bioenergy and CCS together would result in negative emissions. This could be applied in industry or in the power sector and could offset emissions from hard-to-treat sectors such as aviation and agriculture. An assessment of the costs option conducted in the context of the 2011 Bioenergy Review suggests that the use of bioenergy in industrial CHP CCS would be cost-effective at around £72/tCO_2 (in addition to the costs of CCS on industrial CHP plant at around £65/tCO_2).
- The use of wood in construction is an effective use of the resource as it displaces materials from energy-intensive sectors and locks up carbon. It also requires relatively little material to provide the same level of service as steel, brick and cement. As a result of these benefits this option is highly cost-effective (less than £0/tCO_2).
- There are some applications for bioenergy in industry to displace coal and oil, and where there is no scope for other decarbonisation options.

The bioenergy resource could provide up to 23 $MtCO_2$ of abatement in industry, the bulk of which are negative emissions (19 $MtCO_2$) and are accounted for in Chapter 1. There is the potential for even further abatement with bioenergy in industry if more resource were made available to this sector (e.g. in the no-CCS scenario in Chapter 1).

Scope for electrification and use of hydrogen in industry

We have not previously considered the role of fuel switching to electricity and hydrogen, reflecting an uncertain evidence base regarding the different uses of fuels in some parts of industry. We commissioned AEA (2012)[5] to consider the combustion of fuels in industry and based on this we have investigated the potential for electrification and the use of hydrogen substitutes.

The analysis takes account of costs and technical potential, and incorporates practical constraints where evidence permits (e.g. it assumes that technologies are only replaced at end-of-life where lifetimes are known). The potential for the uptake of electrification and hydrogen options in industry could lead to up to 40 $MtCO_2$ further abatement over and above abatement from CCS and bioenergy:

- The assessment showed that the majority of the emissions associated with the combustion of fuels in industry (around 60%) is for autogeneration – the creation of electricity onsite. Low-carbon electricity from the grid could be used to replace this technology.
- A further 18% of combustion emissions is for the creation of steam for high temperature heating purposes. This demand could be met by electric boilers, amongst other electric or hydrogen technologies.
- A further 7% of fuel combustion is for the drying and separation of materials, which can be replaced by heat pumps as this is a relatively low grade of heat required.

The AEA assessment suggests that the costs of electrification and hydrogen options are uncertain due to the site-specific cost of rebuilding plant that may be required to install these new technologies but could be of the order of £200/tCO_2 (assuming sensible investment strategies i.e. aligned with refurbishment cycles of existing plant).

Therefore, given low-carbon electricity, there is a significant opportunity for electrification and hydrogen options to decarbonise combustion emissions. However it is uncertain (our new evidence requires more detailed assessment to improve confidence) and is likely to be high cost (i.e. around £200/tCO_2 or above). We therefore include these options only in our most ambitious deployment level (Max).

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[5] AEA (2012), *Potential for post-2030 emissions reduction from industry.* Available at: www.theccc.org.uk

Implications of decarbonisation for the structure of industry in 2050

Decarbonisation of the UK economy implies changes in the levels of consumption of some industrial commodities and fossil fuels, which may in turn impact on UK production emissions. For example, decarbonisation of surface transport could reduce demand for UK refinery output and therefore reduce refinery sector emissions.

Assessing the likely change in emissions is complex due to the many factors that affect levels of production (e.g. the level of demand for imported and exported products). However, it is likely that decarbonisation would imply some secondary reductions in emissions in production:

- **Refineries:** Refinery emissions are projected to be 19 $MtCO_2$ in 2030. However, in a decarbonised scenario the demand for petroleum for surface transport would be almost eliminated suggesting many of these emissions could be avoided. However, owing to the multiple co-products produced at refineries (e.g. bitumen and lubricants) , minimal change in aviation and shipping demand and the changing import/export balance of demand for refined products, it is difficult to determine the likely reduction in refinery production.
- **Other energy industry:** Energy industry emissions are projected to be 14 $MtCO_2$ in 2030, of which around 2% is associated with running the gas grid. Demand for the gas network in a decarbonised scenario could be very low (e.g. if the role of CCS gas is low and if heating is fully decarbonised), and this would imply some impact on emissions.

Reflecting the uncertainties, we adopt a conservative approach and do not allow for these potential savings in our 2050 scenarios.

Remaining industry emissions in 2050

Based on the analysis above, for our economy-wide scenarios we include three potential levels of deployment in 2050 for the industry sector (Figure 5.5):

- **Max:** This reflects a world where CCS is rolled out to all major emitting sectors of industry, relatively high-cost electrification options are pursued, available bioenergy is deployed (in combination with industry CCS) and radical improvements are made in energy-intensive industry. This would lead to remaining direct emissions of 28 $MtCO_2$.
- **Stretch:** This case also involves very substantial decarbonisation with CCS rolled out to major emitting sectors of industry, bioenergy and radical improvements in energy-intensive industry are deployed. High-cost electrification options are excluded. This would lead to remaining direct emissions of 68 $MtCO_2$ (Figure 5.6).
- **Barriers:** In this case, CCS is available to major emitting sectors of industry but the potential is constrained to a few concentrated sources of CO_2, bioenergy is rolled out where appropriate and radical improvements to energy-intensive industry are implemented. This would lead to remaining direct emissions of 87 $MtCO_2$[6].

The range for industry emissions in 2050 is therefore 28-87 $MtCO_2$, a cut of 24-76% relative to current levels.

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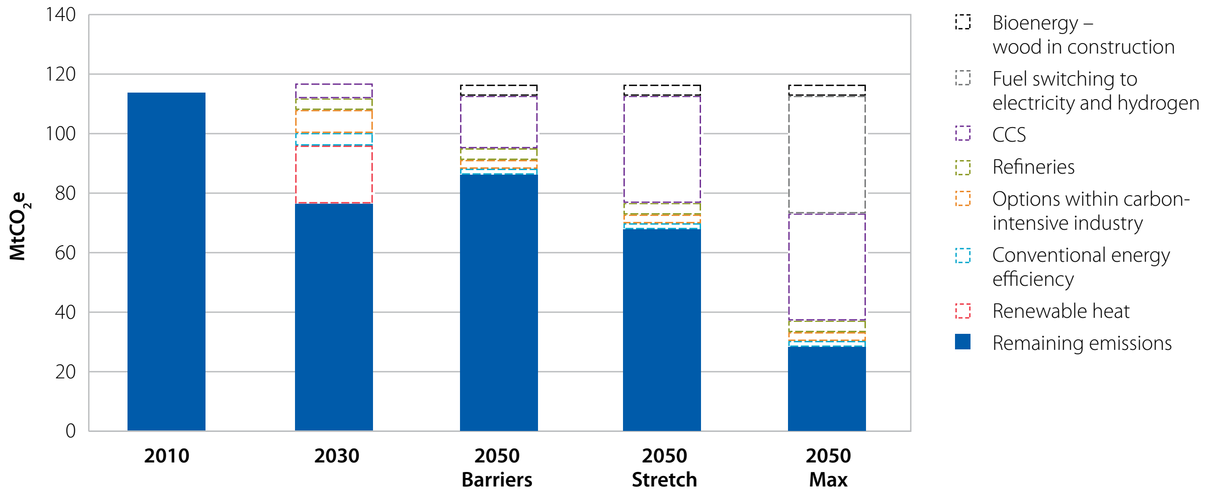
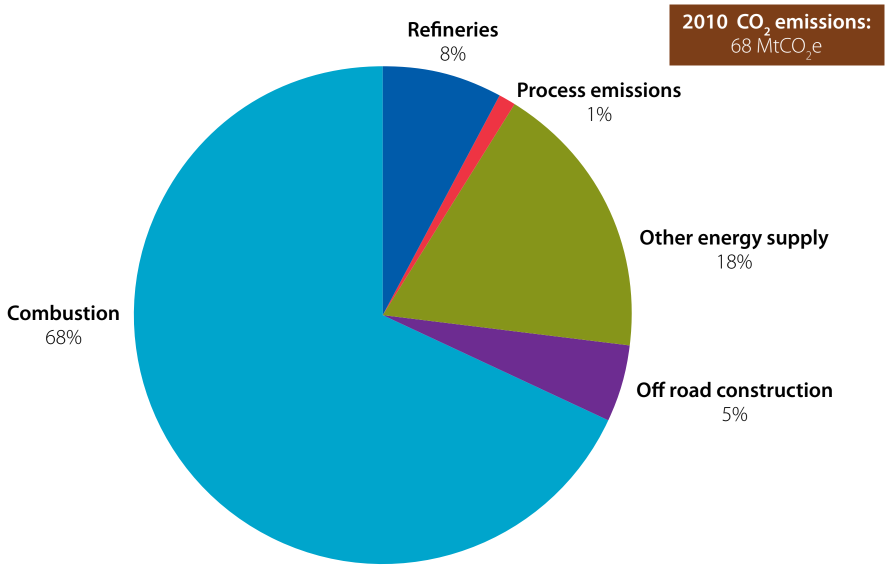
[6] This is slightly higher than the remaining emissions in 2030 in our fourth budget Extended Ambition scenario. This is a result of bioenergy that we had previously identified for use in industry being redirected to the power sector for use in combination with CCS to achieve negative emissions.

Figure 5.5: Direct emissions in industry (2010, 2030 and 2050)



Source: CCC modelling; NAEI (2012).
Note: CO_2 only. The DECC projection for industry emissions extends to 2030, beyond this industry emissions were assumed to be flat between 2030 and 2050.

Figure 5.6: Remaining direct emissions in 2050 by use (Stretch)



Source: CCC modelling.
Note: CO_2 only.

Costs of industry emissions reduction

The costs associated with reducing industry emissions increase as more stretching abatement options are deployed:

- **Energy efficiency measures and radical improvements in energy-intensive industry.** These are deployed prior to 2030 and have very low or negative abatement costs.
- **Bioenergy deployment.** There are typically small additional costs associated with use of bioenergy in place of fossil fuels, totalling £0.6 bn of annualised costs. The costs of using wood in construction have negative abatement costs. However, to the extent that these are imported, we note that if scarcity of bioenergy resources drives feedstock prices higher then this could feed through to higher costs for the UK.
- **CCS deployment.** The costs of CCS on industry depends on the sector in which it is deployed and the degree of concentration of the CO_2 stream. In the max deployment level the annualised costs are £2.4 bn in 2050.
- **Electrification and hydrogen.** The abatement costs are around £200/tCO_2, totalling £8.5 bn of annualised costs in 2050 at the max deployment level.

We therefore estimate a range for 2050 industry decarbonisation costs up to 0.3% of GDP.

4. Summary and implications for approaches to reducing industry emissions

In our economy-wide analysis (Chapter 1) we have a range of remaining emissions from industry in 2050 of 28-87 MtCO_2, with associated costs up to 0.3% of GDP.

Given that many of these sectors are globally traded, international approaches (such as the EU ETS) are appropriate ways of encouraging investment in low-carbon opportunities. As demonstrated above, the abatement options included in this study are predominantly below the Government`s projected carbon price.

However, abatement options in the industry sector face the particular delivery risks of long lead times and high capital costs, and there is therefore a risk that costs will increase if these barriers are not overcome:

- **Refurbishment cycles:** The abatement measures that we have identified typically have long lead times, requiring long-term planning and coordinated investments if these are to be successfully implemented.
- **Capital constraints:** Many of the cost-effective opportunities in energy-intensive industry have substantial upfront requirements for capital and for businesses making investment decisions in a capital constrained environment, low-carbon investment with longer paybacks may struggle to compete with investments in other parts of the supply chain.

In order to overcome these there is a role for Government support. For example, sector agreements could include a timetable and milestones that plan for long-term investments. To address capital constraints, these agreements could be complemented by new financial instruments.

For this abatement to remain feasible, there are a number of specific actions that will be required now to develop technologies and improve the evidence base:

- **Bioenergy.** There is a need to increase penetration of sustainable bioenergy in industry. The Renewable Heat Incentive (RHI) should provide a good basis for increased deployment. However, this should be closely monitored, and funding for the second phase of the RHI (from 2014/15) confirmed to reduce current uncertainties and therefore improve the investment climate.
- **CCS demonstration.** There is a need to move forward with CCS demonstration as a matter of urgency – reflecting both its importance as an abatement option and the implications of its availability for the decarbonisation strategy more generally. This will require a clear timetable for selecting and implementing the four power sector demonstration projects to which the UK is committed. Beyond this, an approach should be developed linking these and international demonstration projects with roll-out to energy-intensive industry in the UK.
- **Electrification and hydrogen.** Although the assessment for this report provided an indication of the costs and potential of these options, a more detailed assessment of these opportunities (e.g. including more detailed estimates of costs) is required.
- **Industry restructuring, product substitution and materials efficiency.** There is a need to better understand the implications of decarbonisation for the UK's industrial structure and to further explore scope for product substitution and materials efficiency. Each of these could be very useful in reducing industry emissions and freeing up scarce bioenergy for use in other sectors.

There is a particular opportunity for the Government to set out its thinking on these areas as part of its forthcoming industry strategy, due to be published in late 2012.

Chapter 6

Reducing emissions of non-CO_2 greenhouse gases

Introduction

Non-CO_2 greenhouse gas (GHG) emissions covered by the Climate Change Act and the Kyoto Protocol include methane (CH_4), nitrous oxide (N_2O) and certain fluorinated gases (F-gases; HFCs, PFCs, and SF_6).

Non-CO_2 emissions generally result from more complex processes than CO_2 (which result primarily from the burning of fossil fuels) and have a wide and varied range of sources, including agriculture, waste, industry, transport, refrigeration, and energy supply.

UK non-CO_2 emissions were around 90 $MtCO_2e$ in 2010, accounting for 14% of total UK GHG emissions.[1] They have fallen by 50% since 1990 mainly due to a decrease in methane emissions as waste has been diverted from landfills. Emissions have also fallen significantly in industrial processes due to the introduction of low-carbon technologies to abate N_2O emissions and in fugitive emissions from the gas distribution network and coal mines.

In our December 2010 advice on the fourth carbon budget we presented possible scenarios for non-CO_2 emissions reduction through the 2020s. Our assessment was that non-CO_2 could be reduced to around 70 $MtCO_2e$ in 2030. In this chapter we consider opportunities to go beyond this scenario.

Our key messages are:

- Non-CO_2 emissions could be reduced 70-75% relative to 1990 levels to around 50 $MtCO_2e$ with minimal changes in consumer behaviour and assuming strong take-up of well-characterised abatement measures. This would require:
  - Greater uptake of on-farm mitigation measures identified for the next two decades.
  - A reduction in waste sent to landfill in line with EU Landfill Directive targets.
  - A decrease in fugitive emissions from natural gas as gas pipes are replaced and in line with the reduction in fossil fuel use assumed in our core scenarios for the energy sectors.
- In a more stretching scenario, including some behaviour change and less well-characterised abatement options, non-CO_2 emissions could decrease by over 80% relative to 1990 levels to around 35 $MtCO_2e$ in 2050. This would require changes in consumption of agricultural products (e.g. food waste reduction and/or a rebalancing of diets away from livestock products), the diversion of all biodegradable wastes from landfill post-2020 (e.g. to anaerobic digestion), and reducing F-gases close to zero by replacing HFCs with alternative coolants.

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[1] DECC (February 2012), *2010 final UK greenhouse gas emissions*; this figure reflects total non-CO_2 emissions plus the small amount of CO_2 emissions arising from predominantly non-CO_2 emitting sectors (agriculture, LULUCF and waste).

- Further research into non-CO_2 emissions and their sources should be undertaken, as is currently underway for agriculture – in terms of both the actual current level of emissions and potential abatement options. This is important given that scientific uncertainties mean that there is a significant risk that emissions could turn out to be higher than assumed in our scenarios (e.g. agriculture N_2O emissions could be up to 90% lower or up to 250% higher[2] than currently recorded in the emissions inventory).

We consider emissions reduction in agriculture, waste and other sources of non-CO_2 separately and then combine these to create overall deployment levels to reduce non-CO_2 in 2050, in the following sections:

1. Agriculture and land use emissions
2. Waste emissions
3. Other non-CO_2 emissions
4. Remaining non-CO_2 emissions in 2050

1. Agriculture and land use emissions

Current agriculture emissions

Agriculture emissions in the UK were 51 $MtCO_2e$ in 2010, accounting for 8% of economy-wide greenhouse gas emissions. Emissions have fallen 20% since 1990 as livestock numbers and fertiliser use have fallen (Figure 6.1).

Agriculture emissions comprise around 29 $MtCO_2e$ (56%) nitrous oxide emissions from application of fertiliser to soils and 18 $MtCO_2e$ (36%) methane emissions from livestock, with the remainder (4 $MtCO_2e$, 8%) due to CO_2 emissions from heating buildings and use of farm machinery.

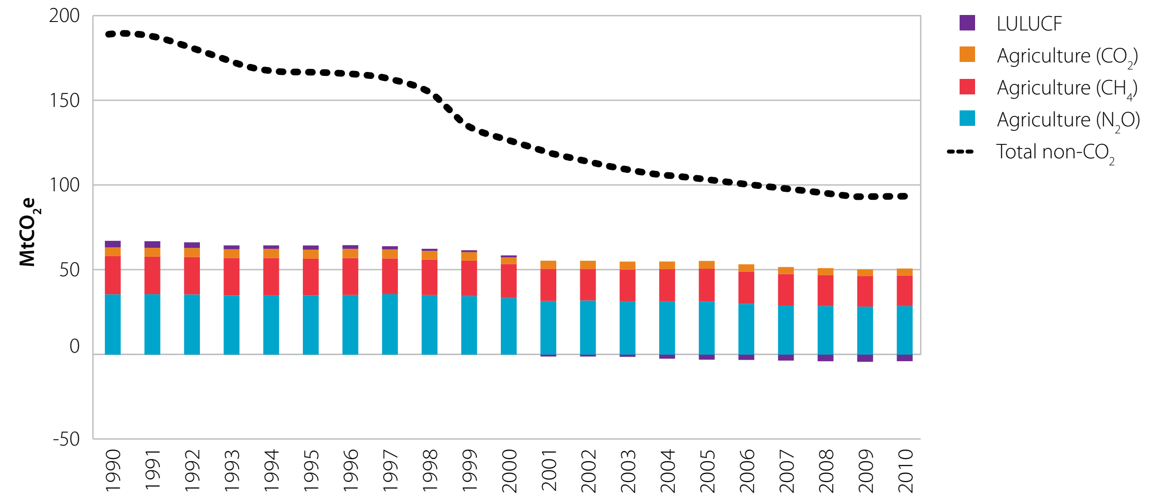
Although the trend reduction in emissions is well established, the absolute level of emissions is particularly uncertain for agriculture non-CO_2. This reflects, for example, that global or regional emissions factors are used but are unlikely to reflect soil or climatic conditions in the UK, and that current farming practice is not precisely measured. Given these factors, we reported in our 2011 Parliament report that agricultural non-CO_2 emissions could be 60% lower, or up to 150% higher than currently recorded in the emissions inventory. Defra has several research projects underway to improve the robustness of these estimates.

Reducing agriculture emissions to 2030

In our advice on the fourth carbon budget, we showed how non-CO_2 emissions could be reduced by up to 19 $MtCO_2e$ by 2030 based on analysis of technical potential we commissioned from the Scottish Agricultural College (Figure 6.2). This reflects potential for changed farming practice which could reduce 2010 emissions from soils by 4-14 $MtCO_2e$ (14-48%) and emissions from livestock by 4-5 $MtCO_2e$ (22-28%). The range covered pessimistic and optimistic views of technical abatement potential and includes the 4.5 $MtCO_2e$ reduction that is targeted in the 2010s in the Low Carbon Transition Plan (LTCP), scaled to the UK (since the LCTP relates only to England).

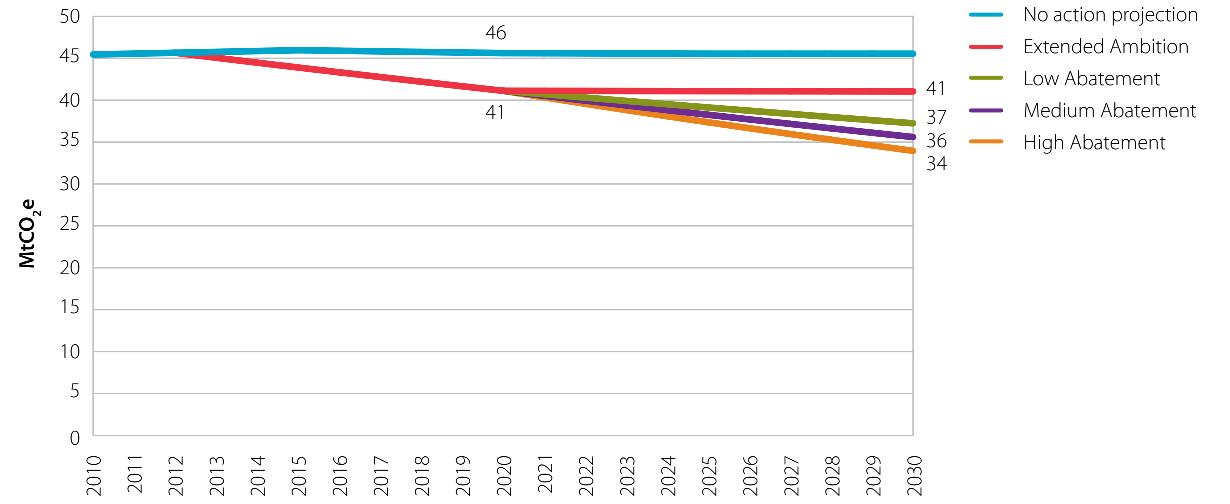
Our 2030 scenario for the fourth carbon budget built in 10 $MtCO_2e$ of this identified abatement (i.e. 4.5 $MtCO_2e$ in the 2010s and 5.5 $MtCO_2e$ in the 2020s). This was based on the mid-point of the estimated range for technical potential, excluding abatement from drainage, nitrification inhibitors and improved nitrogen use plants, for which there was a lower degree of confidence.

Figure 6.1: Agriculture and LULUCF emissions (1990-2010)



Source: DECC (2010), Defra (2011).

Figure 6.2: Projected non-CO_2 emissions under agriculture scenarios (2010-2030)



Source: DECC (2010); AEA Technology (2010); LTCP; CCC modelling.
Note: Extended Ambition includes Government ambition for England (3 $MtCO_2e$ reduction by 2020 scaled to the UK and includes an interpolated trajectory from 2010 to 2020, after which it is assumed agriculture continues to contribute 4.5 $MtCO_2e$ in emissions reductions to 2030.

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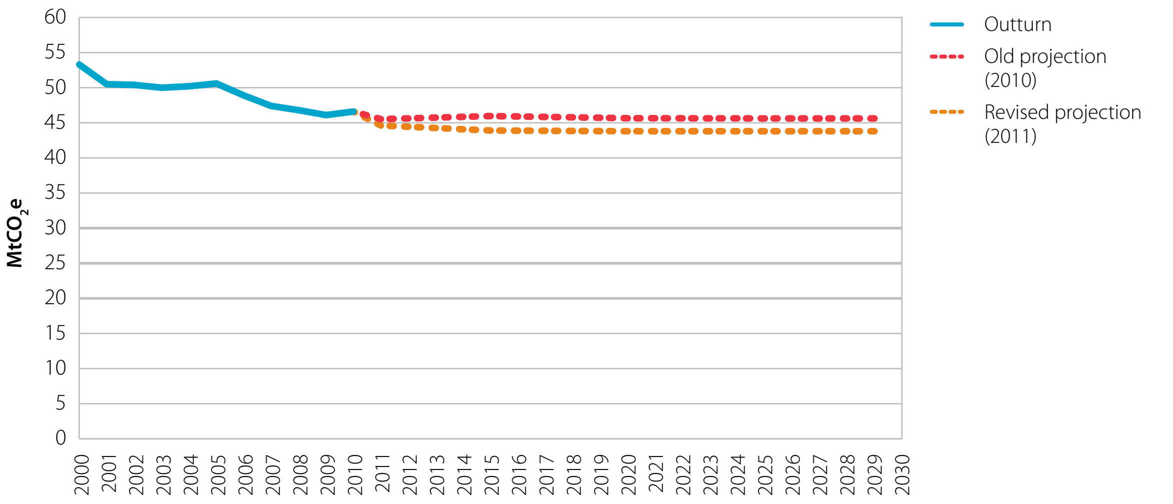
[2] AEA (2010), *Projections of non-CO_2 greenhouse gases*. A report on the non-CO2 projections to accompany the June 2010 energy projection update..

Figure 6.3: Revised agriculture non-CO_2 emissions projections to 2030



Source: DECC (2010), Defra (2011).
Notes: Projections assume no further action to reduce emissions.

We projected remaining non-CO_2 emissions from agriculture in this scenario as 36 $MtCO_2e$ in 2030, based on netting this potential off the Government's reference projections. The Government's projections have now been updated to better reflect the historic trend of declining emissions (Figure 6.3). Using the latest projection suggests agriculture non-CO_2 emissions in 2030 would be a further 2 $MtCO_2$ lower than assumed in our scenarios for the fourth carbon budget advice (i.e. 34 $MtCO_2e$).

We did not include any reductions in CO_2 emissions, but noted that various abatement possibilities exist in principle (e.g. use of efficient engine technology and alternative vehicle fuels). Recent work by AEA for Defra has identified potential for a 0.5 $MtCO_2$ reduction in agriculture, but more work is still required in this area. It is likely that potential savings by 2050 could be considerably higher (e.g. AEA only looked to 2030 and considered that electrification of farm machinery could not be delivered).

Our advice on the fourth carbon budget also set out new analysis of opportunities on the demand side (e.g. through reduced waste and less carbon-intensive consumption choices), but we did not include these in our emissions scenarios.

Reducing agriculture emissions further beyond 2030

Going beyond 2030, there may be scope for further non-CO_2 emissions reductions through changed farming practice and consumer behaviour change, and for reductions in CO_2 from farming activity:

- **Changed farming practice**. Although significant uncertainties exist we would expect that more abatement could be achieved through changed farming practices from 2030 to 2050:
  - The specific measures excluded from our 2030 scenario due to low confidence included drainage and nitrification inhibitors (NIs), which have a technical abatement potential of up to 4 $MtCO_2e$ and 2 $MtCO_2e$ respectively. However, while these measures remain uncertain, there are at least three reasons to suggest increased confidence over their applicability by 2050:
    - **Current understanding.** Existing drainage systems are old (e.g. a large proportion was installed in the late 19th century) implying that they may be working at a sub-optimal level with regards to mitigating the risk of denitrification and associated nitrous oxide losses.[3] NIs are applied successfully elsewhere in the world, and the largest uncertainties relate to costs rather than technical potential.[4]
    - **Development time.** The period to 2050 will provide time for better understanding of the status of the existing drainage system and how to optimise it to reduce nitrous oxide emissions.
    - **Higher carbon prices** to 2050 could support measures even if they turn out to be significantly more expensive (e.g. costs of applying NIs).
  - The Scottish Agricultural College also identified a broader set of options that could offer additional potential from use of alternative agricultural systems (e.g. organic and mixed use farming) and new technologies (e.g. mainstream food crops with nitrogen-fixing capabilities).
  - Given both these considerations (i.e. increased opportunity to make NIs cheaper and drainage work, along with potential to develop excluded options) we include 3 $MtCO_2e$ of further potential by 2050 (i.e. the mid-point of the range for NIs and drainage).
- **Changed consumer behaviour.** There are significant opportunities for emissions reduction through changed consumer behaviour, both as regards reduction of food waste and possible diet change.
  - **Food waste reduction.** Simple measures to reduce household (or other) food waste could reduce UK agriculture emissions by 2 $MtCO_2e$:
    - Food currently wasted by UK households (a fifth of all food brought into homes) was 7.2 million tonnes in 2010. Of this, 4.4 million tonnes could be avoided, with half of that preventable through simple measures including information provision and engagement of retailers, brands, local authorities and householders.[5]
    - Given such a reduction in waste, agriculture emissions could be 2 $MtCO_2e$ lower, allowing for the reduced emissions intensity implied by our assumptions for on-farm measures, and if reduced waste flows through to reduced emissions from UK agriculture production.

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[3] Defra are currently undertaking further detailed research on drainage under WQ0214: *Assessing the status of drainage in the UK*, due to report later this year.
[4] ADAS & North Wyke Research (2011), *Mitigation methods – user guide.*
[5] WRAP (2011), *New estimates for household food and drink waste in the UK.*

- Reducing waste can also offer emissions reduction downstream (i.e. from avoided landfill) and further upstream (e.g. in food processing and packaging). Further potential to reduce waste could be available from the supply chain, and in other streams including schools, hospitality and agriculture, although more evidence is required in order that this can be quantified.

- **Diet change.** There is scope for emissions reduction of 3-13 $MtCO_2e$ through reducing consumption of the most carbon-intensive foodstuffs – red meat and livestock products more generally.
  - Based on analysis that we commissioned from Cranfield University[6] for our advice on the fourth carbon budget, a rebalancing of red to white meat consumption could reduce emissions by 6 $MtCO_2e$, while a 50% reduction in consumption of livestock products would result in a 13 $MtCO_2e$ reduction. A 50% reduction in white meat consumption would reduce emissions by 3 $MtCO_2e$.
  - A high-level analysis of consumer responses to changing prices suggests that a £200/tCO_2e carbon price in 2050 would reduce emissions by around 3 $MtCO_2e$ if reflected in food prices (Box 6.1).
  - DECC's scenarios for the 2050 Calculator include a 20% reduction in livestock numbers by 2050, which based on the Cranfield analysis would suggest an emissions saving of around 5 $MtCO_2e$.
  - A reduction in consumption of livestock products would also free up agricultural land, potentially creating further opportunities for emissions reduction. For example, moving to a more extensive system on grasslands would result in emissions savings through reduced fertiliser use, or conversion to forestry could increase CO_2 sequestration and bioenergy supply.
  - Given these possibilities, we include potential emissions saving of up to 3 $MtCO_2e$ in our scenarios (i.e. equivalent to the reduction that could be achieved through diet choices that reflect the carbon cost associated with different foods).

Box 6.1: The GHG impact of reflecting a carbon price in food prices

Given the need for deep cuts in agricultural emissions to 2050, we identified a range of potential options that could be employed to encourage diet change in the fourth budget report. This included awareness raising, choice editing and providing financial incentives. Reflecting the relative carbon content of different food products in prices would provide a strong signal about full costs (resource and carbon) for consumer decisions. This would offer significant potential for emissions reductions, while maintaining nutritional balance, improving health and freeing up land.

Using life cycle assessment data on the emissions intensities of food products from Cranfield University and demand price elasticity data from Defra for key food products, applying a carbon price of £200/tCO_2e in 2050 on key food commodities would reduce direct emissions from 22 $MtCO_2e$ to 19 $MtCO_2e$. Over half of the 3 $MtCO_2e$ of savings would come from reduced consumption of beef, which has one of the highest carbon intensities of all food products of 15 kg CO_2e/kg product.

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[6] Cranfield University (2010), *The effect of changes in UK food consumption patterns on land requirements and greenhouse gas emissions.*

- **Measures to reduce on-farm CO_2.** On-farm CO_2 relates to buildings and mobile machinery. Insofar as our economy-wide scenarios imply that buildings and transport emissions would fall to close to zero in 2050, it is likely that similar reductions would be appropriate from buildings and vehicles on farms (e.g. through electrification, use of hydrogen, waste heat or local bioenergy resources). This implies a reduction in emissions of 4 $MtCO_2$, with further work still needed in this area to improve confidence.

Therefore in our agriculture scenarios we include further opportunities for emissions reduction through on-farm measures and through behaviour measures to reduce waste and/or consumption of livestock products.

Costs of reducing agriculture emissions

Costs associated with these measures for non-CO_2 are negative for much of the changed farming practice and behaviour change, whilst 1 $MtCO_2e$ of the potential from the application of nitrification inhibitors would cost around £60/tCO_2e.

The cost of reducing CO_2 emissions is uncertain, so we assign a cost in line with the long-term carbon price expectation (i.e. £200/tonne for the 4 $MtCO_2$ of abatement), which is similar, for example to the cost of electrification options in industry.

The potential total cost in 2050 is therefore up to around £1 billion, less than 0.05% of expected GDP in 2050.

2050 scenarios for agriculture emissions

Our scenarios for agriculture emissions in 2050 reflect scope for emissions reduction through changed farming practice and behaviour change (Figure 6.4):

- **Scenario 1** reflects our fourth budget scenario that includes changes in farming practice by 2030, adding in abatement from nitrification inhibitors and drainage, and CO_2 reductions in line with our core scenarios for transport and buildings emissions (i.e. these emissions are eliminated). No changes are assumed at the consumer level. Remaining agriculture emissions are 31 $MtCO_2e$ in 2050 (all of which is non-CO_2).
- **Scenario 2** adds emissions reductions due to avoidable waste, resulting in remaining emissions from agriculture in 2050 of 29 $MtCO_2e$.
- **Scenario 3** adds in scope for emissions reduction through reduction in livestock consumption, consistent with a £200/tCO_2e carbon price in 2050. It results in remaining agriculture emissions in 2050 of around 26 $MtCO_2e$.

We consider in Chapter 1 circumstances under which these different scenarios would have to be delivered to meet the 2050 target.

Land use, land use change and forestry

Related to agriculture emissions are emissions from land use, land use change and forestry (LULUCF). Currently LULUCF leads to a net removal of emissions of 3.8 $MtCO_2e$ (in 2010).

Looking forward, emissions are projected to reach 1 $MtCO_2e$ by 2030 and remain at similar levels to 2050. Such projections are highly uncertain given uncertainties over how the changing climate will impact on the sequestration potential of existing woodlands (e.g. on growth rates and the incidence of pests and diseases).

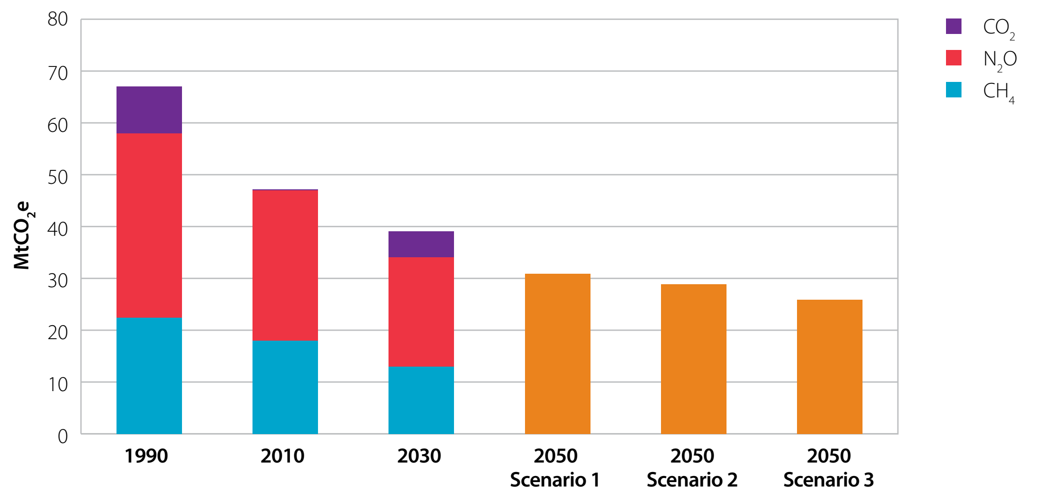
In our fourth budget advice we identified an opportunity to reduce emissions through afforestation of an additional 10,000 hectares a year over a 15-year period. We assumed in a central scenario that this could deliver savings of at least 1 $MtCO_2e$ by 2030.

Continuing this planting rate to 2050 could increase removals by a further 1 $MtCO_2e$. Such a scenario would require that land is freed up from alternative uses (e.g. a 1.5% reduction in livestock numbers could release over 200,000 hectares of land[7]) and that incentives are in place for conversion to forest. In which case, this scenario would provide emissions reductions that are additional to those from bioenergy.

There may also be an opportunity to avoid emissions associated with peat extraction. In 2010 this accounted for 0.4 $MtCO_2e$ of emissions in the UK. The Government has committed to a phase out of peat use in horticultural applications in England by 2030. If replicated throughout the UK this could reduce emissions by 0.4 $MtCO_2e$ given that horticulture accounts for almost all of the total peat extraction. There may also be scope to increase removals through restoration of degraded peat lands, but available potential is poorly understood given emissions from upland peat lands are currently unknown and therefore not included in the inventory. However, on-going work by Defra will look to address this.

We therefore include removals from LULUCF of 1 $MtCO_2$ in our economy-wide scenarios in Chapter 1, reflecting increasing emissions in a business-as-usual trajectory and scope for abatement from increased afforestation and avoidance of peat extraction.

Figure 6.4: Agriculture and LULUCF abatement scenarios to 2050



Source: DECC (2010), Defra (2011), CCC analysis.
Notes: By 2050 we assume that there are no remaining CO_2 emissions. Quantifying the precise mix of remaining of CH_4 and N_2O emissions is more uncertain given that reductions in food waste and changes in diet will impact on both gases through changes in agricultural production. For example, the Cranfield Study assumed that a 50% reduction in livestock consumption would release 50% of UK land which could see a corresponding decrease in N_2O emissions depending on change in land use (e.g. conversion to forestry).

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[7] The Cranfield Study assumed that a 50% reduction in livestock consumption would free up 7.3 million hectares of UK land, Scaling this down to obtain 10,000 hectares a year for 20 years (200,000 hectares) from 2030 for afforestation would require a 1.5% decrease in livestock consumption,

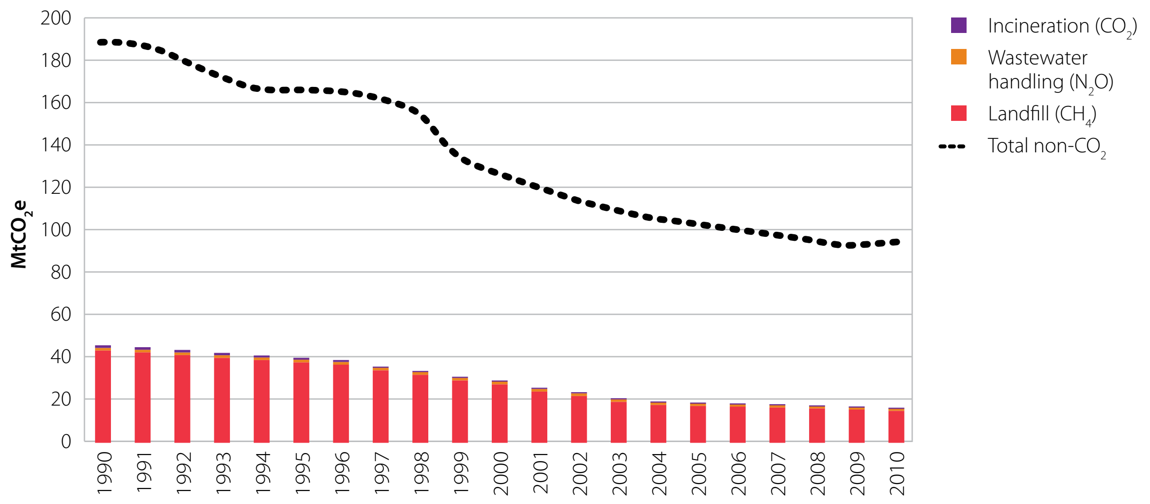
2. Waste emissions

Current emissions from waste disposal

Waste emissions were 17 $MtCO_2e$ in 2010, accounting for 3% of total UK greenhouse gas emissions. Emissions have fallen 65% since 1990 as waste has been diverted away from landfill.

Waste emissions are predominantly methane (91%) which arises as food, paper and other rotting rubbish biodegrade in landfills in the absence of oxygen. Methane emissions today reflect the slow decomposition of waste landfilled over the past few decades as well as waste landfilled more recently. Other emissions are nitrous oxide (N_2O) arising from wastewater handling (7%) and carbon dioxide (CO_2) arising from the incineration of wastes (2%) (Figure 6.5).

Figure 6.5: Waste emissions (1990-2010)



Source: DECC (2011).

Options for reducing waste emissions

There are three established approaches to reducing emissions from waste, which focus on reducing methane emissions arising from landfill sites:

- Reducing overall levels of waste, particularly biodegradable wastes, through waste minimisation campaigns (e.g. the Waste Reduction Action Programme's 'Love Food Hate Waste' initiative and responsibility deals with key sectors).
- Diverting more biodegradable waste away from landfills and towards recycling (e.g. of paper and card), composting and anaerobic digestion (e.g. of food waste), and incineration with or without energy recovery. The key mechanism for diverting waste from landfills is the landfill tax which was introduced in 1996 to meet EU Landfill Directive targets.

- Increasing the capture rate of methane emissions from landfill sites through adopting best practices and new technologies (e.g. the average methane capture rate in the UK is assumed to be 75% but in practice is site specific and can vary depending on the technology implemented, the point at which the technology becomes active, and its day-to-day operation).[8]

Moreover, the reduction, reuse and recycling of waste (rather than disposal) is associated with further emissions savings upstream (e.g. those arising from agricultural, energy, and industrial production), although the precise level of savings is often difficult to quantify.

There are also further opportunities to use waste as a bioenergy feedstock, both in power generation and for production of biogas (e.g. for use in vehicles). In our 2011 Bioenergy Review we noted that although UK waste policy follows a 'waste hierarchy' which prioritises re-use, recycling, other types of recovery, and last of all disposal, there is still a potentially significant UK waste resource that could be diverted for bioenergy use (approximately 47 TWh of primary energy supply in 2030 declining to 44 TWh in 2050).[9]

Reducing waste emissions to 2030

In our advice on the fourth carbon budget we assumed waste emissions would decrease to 17 $MtCO_2e$ in 2030 as waste is diverted from landfill.

Since we published that advice, the Government has updated historic and projected emissions for waste based on a review of data and key assumptions. The results suggest that waste emissions were lower in 1990 compared to previous modelling (46 $MtCO_2e$ rather than 53 $MtCO_2e$) and have since fallen more quickly to 17 $MtCO_2e$ in 2010 (rather than the previous estimate of 23 $MtCO_2e$).[10]

The new modelling further suggests that waste emissions will continue to decrease faster than previously expected after 2020, falling to 10.5 $MtCO_2e$ by 2030:

- Methane emissions, the key driver of waste emissions, are projected to fall to 8.5 $MtCO_2e$ by 2030. This reflects an assumption that the amount of biodegradable wastes sent to landfill continues to fall in line with targets in the EU Landfill Directive (i.e. by 20% for food waste and 30% for paper/card, by 2020 relative to current levels).[11] The amount of methane captured at landfill sites is assumed to remain at 75% in the future.
- Nitrous oxide emissions (currently around 1 $MtCO_2e$) are projected to increase slightly to 1.6 $MtCO_2e$ by 2030 reflecting increases in population and protein consumption.
- CO_2 emissions arising from the incineration of wastes are projected to remain around current levels (0.4 $MtCO_2e$) to 2030.

Therefore, the latest evidence suggests that emissions in 2030 will be around 7 $MtCO_2e$ lower in 2030 than assumed in our fourth carbon budget analysis, even without further measures beyond those required by the EU Landfill Directive.

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[8] Eunomia (2011), *Inventory Improvement Project – UK landfill methane emissions model.*

[9] Includes bioenergy supply from waste wood, the renewable fraction of solid waste, landfill gas, and food waste.

[10] DECC (2011), *Updated emissions projections*, Autumn update.

[11] Based on data in the latest version of Defra's MELMod model (2011), used to calculate UK landfill methane emissions. Tonnage sent to landfill remains constant post 2020.

Opportunities for further waste emissions reductions to 2050

Potential to reduce methane emissions to 2050

The new emissions projections suggest methane emissions from landfill will continue to fall after 2030, reaching 6 $MtCO_2e$ by 2050. This reflects the reductions described above in biodegradable waste sent to landfill over the next decade (i.e. to 2022) in line with the Landfill Directive, but no further reductions thereafter. Emissions continue to fall due to the lag caused by the long life of rotting materials in landfill (e.g. paper takes 12 to 17 years to fully degrade).

If additional measures encourage further diversion of wastes away from landfill in the UK beyond 2020, particularly for food and paper/card waste, there is potential for further emissions reduction. For example:

- If zero food and paper/card waste is landfilled post-2020, methane emissions could fall by a further 3.6 $MtCO_2e$ to 2.4 $MtCO_2e$ by 2050.
- If zero biodegradable waste is sent to landfill post-2020, emissions could drop by 5 $MtCO_2e$ to 1.3 $MtCO_2e$ by 2050.
- If zero food and paper/card waste is landfilled post-2030 instead of 2020, emissions would fall to 5.2 $MtCO_2e$ by 2050.

The European Commission has recently proposed that landfilling be 'virtually eliminated' by 2020.[12] A 2010 WRAP study further concludes that landfill bans, particularly for biodegradable wastes, could yield strong climate change benefits and resource efficiency gains, particularly coupled with policies to support waste sorting.[13]

In our 2008 report we presented analysis that we commissioned from Eunomia[14], which identified a range of treatment options available for residual wastestreams diverted from landfill. These alternative disposal routes for biodegradable wastes include:

- **Anaerobic digestion,** which produces a biogas that can be used to generate energy or as a vehicle fuel.
- **Composting,** which can be applied to land and thus displace fertiliser application levels.
- **Mechanical Biological Treatment,** which involves breaking down waste by shredding, removing recyclable materials, and the option for either composting or digesting the remaining waste to produce a biogas.
- **Incineration with energy recovery,** where waste is fed directly into a furnace or boiler without prior separation or sorting.

Many of the above treatment options are available at negative cost and most at a cost less than the expected price of carbon in 2050 (£200/tCO_2e), suggesting full diversion is economically desirable.

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[12] European Commission Communication (September 2011), *Roadmap to a Resource Efficient Europe.*

[13] WRAP (2010), *Landfill Bans: Feasibility Research.*

[14] Eunomia (2008) *Development of Marginal Abatement Cost Curves for the Waste Sector.*

Addressing emissions of nitrous oxide from wastewater to 2050

The slight upward trend in N_2O emissions arising from wastewater treatment (projected at 1.6 $MtCO_2e$ in 2030) is likely to continue as population increases, although there are no specific projections for the potential size of the increase and thus emissions are held constant to 2050.[15] Options to reduce these emissions are currently less clear.

Potential to reduce emissions of carbon dioxide from waste incineration to 2050

As more waste is diverted from landfill, there is a risk that CO_2 emissions arising from the incineration of residual waste streams could increase, particularly from the incineration of plastics, which have a high fossil carbon content.

Options for avoiding CO_2 emissions arising from waste incineration include:

- Increased recycling of plastics.
- Use of biodegradable plastics derived from renewable biomass source (e.g. vegetable fats, oils and starches) which could then be treated in the same way as other biodegradable wastestreams (e.g. via anaerobic digestion). It would be important to divert biodegradable plastics from landfill, where they would generate methane emissions.
- Use of carbon capture and storage (CCS) technologies in incineration plants to capture CO_2 emissions.
- Use of novel treatments that do not lead to combustion of fossil carbon (e.g. approaches to chemical synthesis or feedstock recycling).[16]

Given the likelihood of increased competition for biomass as bioenergy as well as uncertainties around the development of CCS technology and novel treatments, the increased recycling of plastics currently appears to be the best management option going forward to reduce CO_2 emissions arising from waste. Landfilling plastics would also perform better relative to incineration in carbon emissions terms, but could involve tradeoffs with other environmental objectives (e.g. local disamenity associated with landfill sites).

Remaining waste emissions in 2050

Our scenarios for waste emissions in 2050 reflect Government projections as well as scope for further reduction of methane and CO_2 emissions arising from landfill and incineration of plastics (Figure 6.6).

- **Scenario 1:** This reflects Government projections for waste emissions, with remaining emissions of 8.0 $MtCO_2e$ (6 $MtCO_2e$ in methane emissions, with nitrous oxide arising from wastewater treatment assumed to increase with population and CO_2 emissions from incineration held constant at 2030 levels).

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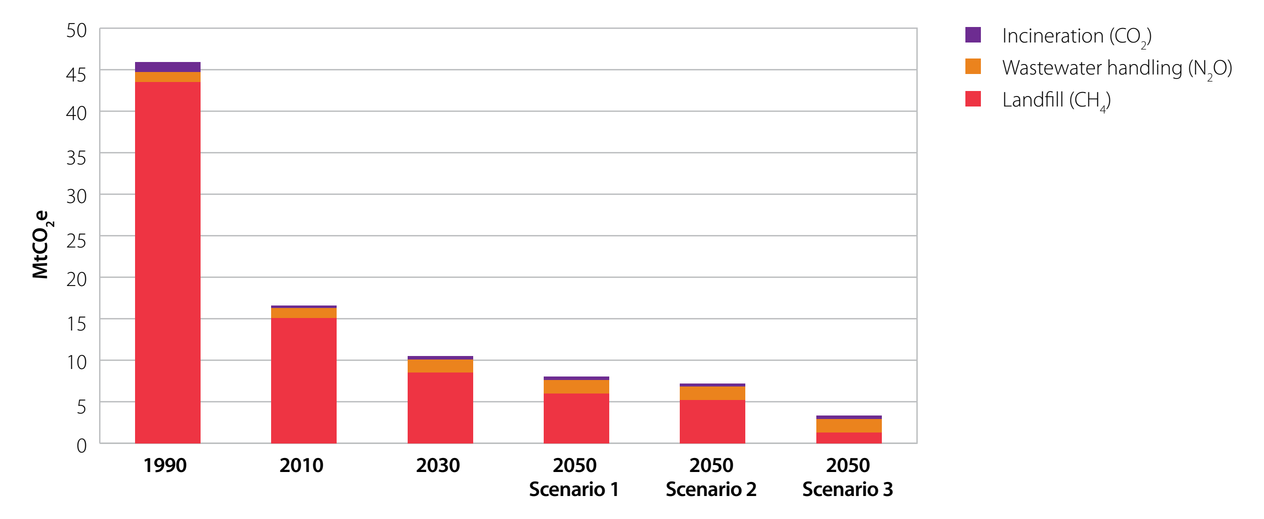
[15] DECC (2011), Projections of non-CO_2 greenhouse gas emissions, A report on the non-CO_2 projections to accompany the Autumn 2011 update; projections of N_2O emissions from waste water treatment are based on a constant emission factor per head of population. The historic inventory is based on protein consumption and population data. The projections assume that protein consumption will remain unchanged going forward.

[16] Eunomia (2008), *Development of Marginal Abatement Cost Curves for the Waste Sector.*

Figure 6.6: Waste abatement scenarios to 2050



Source: Defra (2011); DECC (2011); CCC analysis.

- **Scenario 2:** This scenario assumes all food and paper/card waste is diverted from landfill from 2030 (i.e. later than the EC proposals and for only part of the biodegradable waste stream). Remaining emissions are 7.2 $MtCO_2e$ for waste management in 2050 (5.2 $MtCO_2e$ of methane emissions plus nitrous oxide and CO_2 emissions as in scenario 1).
- **Scenario 3:** This scenario assumes all biodegradable waste is diverted from landfill from 2020, as currently proposed by the European Commission. Remaining emissions are 3.4 $MtCO_2e$ for waste management in 2050 (1.3 $MtCO_2e$ of methane emissions plus nitrous oxide and CO_2 emissions as in scenario 1).

We also note the risk of increased incineration of wastes with a high fossil fuel content (e.g. plastics). If this is not mitigated then CO_2 emissions could increase from projected levels of 0.4 $MtCO_2e$ to much higher levels (e.g. identified by Eunomia to range from 2.5 to 14.7 $MtCO_2e$ in a worst-case 2050 scenario if all fossil based materials are incinerated).[17]

3. Other non-CO_2 emissions

Current emissions from other sources of non-CO_2

Other non-CO_2 emissions (i.e. outside of the agriculture and waste sectors) were 29 $MtCO_2e$ in 2010, comprising 15 $MtCO_2e$ of F-gases, 3 $MtCO_2e$ in industry, 9 $MtCO_2e$ in energy supply and 1 $MtCO_2e$ from transport.

- **F-gases.** Emissions of F-gases come primarily from buildings and mobile air conditioning. They are used in applications such as refrigerators, inhalers, fire extinguishers and air conditioning.

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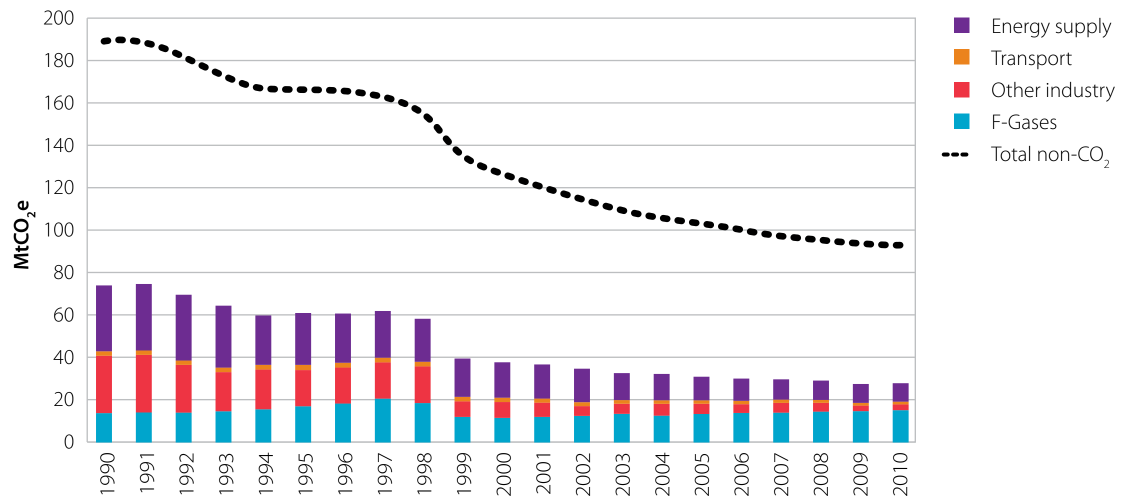
[17] Eunomia (2008), *Development of Marginal Abatement Cost Curves for the Waste Sector.*

- **Industry.** The majority of non-CO_2 emissions from industry are from nitrous oxide (N_2O) emitted during the production of nitric acid.
- **Energy Supply.** Methane is emitted in the energy supply sector as fugitive emissions from coal mines and gas pipes; there are also small amounts of methane and nitrous oxide resulting directly from fuel combustion.
- **Transport.** A small amount of nitrous oxide is emitted in the transport sector as a result of catalytic convertors.

Emissions have fallen by 62% since 1990 largely due to installation of abatement equipment at nitric and adipic acid plants, the decline of UK coal mining and gas pipe replacement (Figure 6.7).

Figure 6.7: Other non-CO_2 emissions by sector (1990-2010)



Source: NAEI (2012).

Reducing other non-CO_2 emissions to 2030

In our advice for the fourth carbon budget we assumed other non-CO_2 emissions would reduce to 14 $MtCO_2e$ by 2030 based upon a reduction in F-gases driven by EU legislation, as well as reduced fugitive emissions from coal and gas.

The Government's latest non-CO_2 projections suggest the same level of emissions in 2030.[18] Remaining emissions would be primarily from F-gases (5 $MtCO_2e$) and fugitive emissions from gas pipes (5 $MtCO_2e$).

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[18] DECC (2011) *Updated emissions projections.*

Opportunities for further non-CO_2 emissions reductions to 2050

Beyond 2030, there are two main potential sources of further abatement:

- **Decreasing fugitive emissions.** Remaining non-CO_2 emissions in 2030 from the energy supply sector mainly come from fugitive methane emissions from gas pipes. Continued replacement of gas pipes and other improvements to the network should lead to a decline in these emissions. This will be helped to some extent by the expected decline in fossil fuel usage to 2050. Achieving emissions reductions also relies on an assumption that there are no new sources of fugitive emissions (e.g. from new coal mines or unconventional gas extraction).
- **Phasing out of F-gases.** There are likely to be further opportunities to reduce F-gas emissions between 2030 and 2050, specifically HFC (hydrofluorocarbon) emissions, which are the majority of those projected to remain in 2030 (5 $MtCO_2e$ of the 6 $MtCO_2e$ total):
  - Various alternatives to HFCs exist with far lower global warming effects. For example, in commercial refrigeration there are already options to switch to using CO_2 as an alternative with much lower global warming impact. Across nearly all applications there are potentials for replacement with ammonia, less damaging HFCs and HFOs.
  - In work for Defra, AEA identified that alternative options could be implemented at reasonable cost (e.g. less than £40/tCO_2e) across the range of applications.[19]
  - A full ban of HFCs has been proposed at the EU level.[20]
  - If HFCs were fully phased out and replaced with low-carbon alternatives, then non-CO_2 emissions would decrease by 5 $MtCO_2e$.

Costs of decarbonising the energy sector are attributed to the CO_2 reductions in those sectors, no extra costs are assumed for expected gas pipe replacement, and costs of reducing F-gas emissions are likely to be small given the small quantity of emissions and the relatively low costs per tonne identified.

Remaining other non-CO_2 emissions in 2050

Our scenarios for emissions in 2050 reflect scope for emissions reduction through changes to F-gas regulations and through reductions due to CO_2 mitigation measures (Figure 6.8).

- **Scenario 1** reflects our 2030 emissions scenario and emissions reductions through mitigation of CO_2 in transport and energy supply (as discussed in chapters 2-5), as well as partial phase-out of HFCs. It results in remaining emissions in 2050 of 12 $MtCO_2e$.
- **Scenario 2** adds in further scope for emissions reduction through banning HFCs. It results in remaining emissions in 2050 of around 7 $MtCO_2e$.

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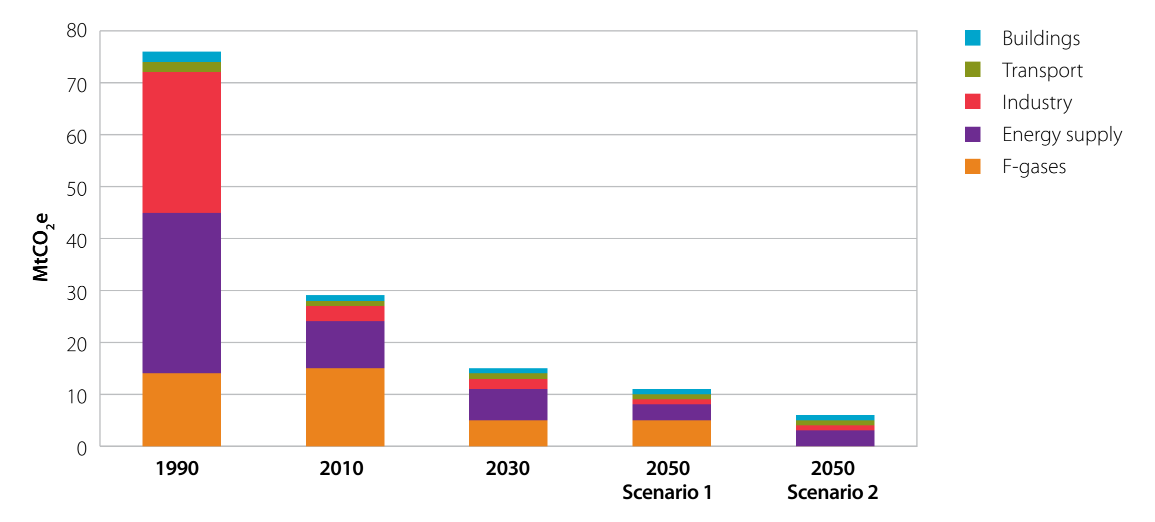
[19] AEA (2010), *HFC consumption and emissions forecasting.*

[20] A joint NGO submission on behalf of the Environmental Investigation Agency, European Environmental Bureau, Greenpeace European Unit, and World Wide Fund for Nature suggested in 2011 that the Commission should revise the F-Gas Regulation to prohibit the placement on the market of HFC technologies and products as soon as possible and at the latest by 2020.

Figure 6.8: Other non-CO_2 abatement scenarios to 2050



Source: DECC (2011) Updated emissions projections and CCC calculations.

4. Remaining non-CO_2 emissions in 2050

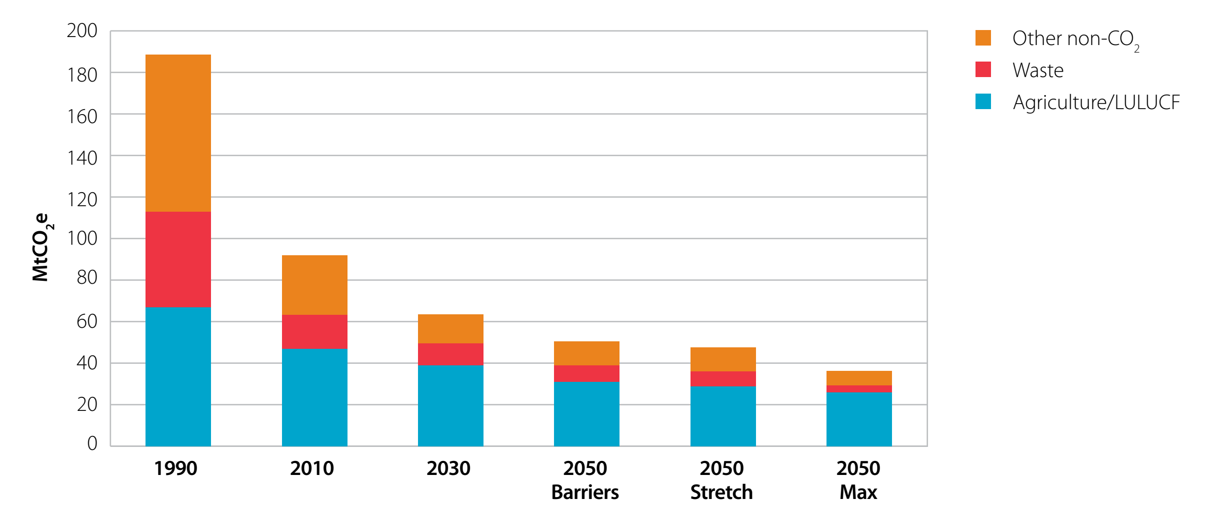
Taken together our identified measures for reducing non-CO_2 emissions to 2050 reconfirm our fourth budget assumption that these sectors could reduce by 70% by 2050 relative to 1990 levels. They also demonstrate that there are plausible routes to go further in these sectors, such that emissions could reduce in total by around 80%, in line with the economy as a whole.

Furthermore, if these emissions reductions can be unlocked they are likely to be at lower cost than some of the more stretching CO_2 reductions discussed earlier in this report, particularly if key options like carbon capture and storage are not available. In some cases they may also offer opportunities for broader benefits, such as improved air quality, increased biodiversity and healthier lifestyles.

As for other sectors, we define three levels for deployment of measures to reduce non-CO_2 emissions (Figure 6.9):

- **Max.** This includes the lowest emission scenarios for each of agriculture, waste and other non-CO_2. Total non-CO_2 emissions are reduced to 36 $MtCO_2e$, through full deployment of identified on-farm measures, reduced food waste and consumption of livestock products, full diversion of biodegradable waste away from landfill from 2020 and complete phasing out of HFCs.
- **Stretch.** This includes full deployment of on-farm measures and success in meeting the EU Landfill Directive targets. Further abatement is achieved through food waste reduction and further (but not full) diversion of waste from landfill (i.e. further diversion of paper/card waste above EU targets after 2030). Alternatively further abatement could come from a partial phase-out of HFCs, greater diversion of waste from landfill or diet change away from livestock products. As a result non-CO_2 emissions in 2050 are 48 $MtCO_2e$.

Figure 6.9: Non-CO_2 deployment levels to 2050



Source: DECC (2011); CCC analysis.

- **Barriers.** On-farm measures are fully delivered, and EU Landfill Directive targets are met (but not exceeded) in waste. Energy emissions fall as gas pipes are upgraded, and as fossil fuel use declines due to CO_2 measures. However, no progress is made in reducing food waste, or shifting diets away from livestock products. Non-CO_2 emissions are reduced to 50 $MtCO_2e$.

Given the uncertainties in these sectors, particularly over the opportunities for emissions reduction driven from the demand side, we do not rule out the possibility that non-CO_2 emissions as a whole could extend beyond this range. For example, reductions could be over 80% on 1990 levels by 2050 if more radical diet changes occur, or under 70% if measures prove less effective or more difficult to deploy.

There is also a very large degree of uncertainty over the current level of emissions, which could make successful deployment of measures to reduce them even more important.

It therefore remains a priority to improve understanding in these sectors – both of the level of current emissions, and of options to reduce them.

Glossary and abbreviations

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

Annual load factor (ALF)
Equivalent proportion of the year for which a generator is operating at its maximum rated output. For example, if output from a 1 GW nuclear plant over a year (8,760 hours) is 7,000 GWh, its ALF is 7,000/8,760 = 80%.

Availability
For an electricity generating station, this is the proportion of the time that the generator is physically able to supply electricity.

Baseload demand
Part of total demand that is present throughout most the year (e.g. 90% of the hours of the year), and therefore can be met by capacity running continuously.

Baseload-equivalent
Intermittent technologies (i.e. offshore wind, onshore wind, marine, solar) are adjusted in this figure by the difference between their average capacity factor and the availability of non-intermittent plants (e.g. nuclear, CCS) in order to put plants on an equivalent GW basis. For example, assuming non-intermittent plants are available to generate for 90% of the year, and offshore wind is able to generate at its maximum rated capacity for 42% of the year (i.e. capacity factor), 1 GW of offshore wind is equivalent to (42%/90%) * 1 GW = 0.47 GW of baseload-equivalent capacity.

Battery Electric Vehicle (BEV)
A vehicle that receives all motive power from a battery.

Biofuel
A fuel derived from biomass and used to power vehicles (can be liquid or gas). Biofuels are commonly derived from cereal crops but can also be derived from other plant material, trees and even algae.

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

Bunker fuels
Fuels consumed for international marine and air transportation.

Capacity factor
Energy produced by an electricity generator as a percentage of that which would be achieved if the generator were to operate at maximum output 100% of the time. For example, the capacity factor of a 1 GW offshore wind farm may be 40%, which means over a year (8,760 hours) it would generate 40% * 1 GW * 8,760 = 3,504 GWh.

Carbon Capture and Storage (CCS)
Technology which involves capturing the carbon dioxide emitted from burning fossil fuels, transporting it and storing it in secure spaces such as geological formations, including old oil and gas fields and aquifers under the seabed.

Carbon credits
Carbon credits purchased in international carbon markets, generally corresponding to 1 tCO_2e per credit. Also referred to as 'carbon units' in the Climate Change Act. Currently credits include allowances purchased in schemes such as the EU ETS, or offset credits from project-based schemes (e.g. such as those generated under the Kyoto treaty's project-based flexibility mechanisms, Joint Implementation and Clean Development Mechanism).

Carbon dioxide equivalent (CO_2e) emission
The amount of carbon dioxide emission that would give rise to the same level of radiative forcing, integrated over a 100-year time period, as a given amount of well-mixed greenhouse gas emission. For an individual greenhouse gas species, carbon dioxide equivalent emission is calculated by multiplying the mass emitted by the 100 year Global Warming Potential for that species.

Carbon leakage
Carbon leakage refers to an increase in emissions in one country/region as a result of emissions reduction by a second country/region with a strict climate policy.

Carbon price
The price at which 1 tCO_2e can be purchased. We use projections for the carbon price as a comparator for judging cost-effectiveness of potential emissions reduction measures.

Carbon price floor/underpin
Policy to ensure that carbon emitters pay a set minimum amount for every unit of carbon they emit. Government has implemented a floor for the power sector only, reaching £70/tCO_2 in 2030.

Carbon sink
An absorber of carbon (usually in the form of carbon dioxide). Natural carbon sinks include forests and oceans.

Combined Cycle Gas Turbine (CCGT)
A gas turbine generator that generates electricity. Waste heat is used to make steam to generate additional electricity via a steam turbine, thereby increasing the efficiency of the plant.

Combined Heat and Power (CHP)
The simultaneous generation of heat and power, putting to use heat that would normally be wasted. This results in a more efficient way to use both fossil and renewable fuels. Technologies range from small units similar to domestic gas boilers to large scale CCGT or biomass plants which supply heat for major industrial processes.

Contrail
A line of cloud caused by aircraft flying through supersaturated air. Contrails have a significant warming effect on surface temperatures but this only lasts up to a few hours.

Demand-side response
Changes in the timing of demand that help match the profile of demand with supply, and reduce the requirement for capacity at peak periods. For example, charging electric vehicles overnight when demand is low, or when output from intermittent renewables (e.g. wind) is high. This could, for example, be in response to real-time price signals, or to other incentive mechanisms provided by demand-side aggregators, or through more active centralised controls using smart infrastructure.

Departing/arriving flights
Departing flights are those that take off from a UK airport. Arriving flights are those that arrive at a UK airport.

Discount rate
The rate at which the valuation of future costs and benefits decline. The Social Discount Rate (3.5%) represents that society prefers consumption now over the future – so £1.035 next year is equivalent to £1 today. It reflects (a) pure time preference for consumption now over having to wait; (b) the value of the extra £1 is less as incomes in the future are higher; (c) a small risk of catastrophe means that future benefits are never enjoyed. Discount rates in the private sector generally reflect the real cost of raising capital, or the real interest rate at which consumers can borrow.

Eco-driving
Eco-driving involves driving in a more efficient way in order to improve fuel economy. Examples of eco-driving techniques include driving at an appropriate speed, not over-revving, ensuring tyres are correctly inflated, removing roof racks and reducing unnecessary weight.

Electric vehicle
Vehicle capable of full electric operation fuelled by battery power driven by an electric motor. These include battery electric (BEV), plug-in hybrid electric (PHEV) and hydrogen fuel-cell vehicles.

Energy Efficiency Design Index (EEDI)
IMO regulation, agreed in 2011, setting minimum energy efficiency standards for new ships.

European Commission (EC)
Executive arm of the European Union.

European Union Emissions Trading Scheme (EU ETS)
Cap and trade system covering the power sector and energy intensive industry in the EU.

Feed-in-tariffs (FITs)
A type of support scheme for electricity generators, whereby generators obtain a long-term guaranteed price for the output they deliver to the grid.

Fluorinated Gases (F-gases)
Family of greenhouse gases containing fluorine. Hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulphur hexafluoride (SF_6) are used in industrial processes, refrigeration and air conditioning. They have a high global warming potential.

Fuel cell
A device that converts a fuel into electrical energy through a chemical reaction. For example, a hydrogen fuel cell produces electrical energy from hydrogen, which can be used to power an electric vehicle.

Fugitive emissions
Greenhouse gases released, either intentionally or unintentionally, through anthropogenic activities excluding fuel combustion (e.g. methane released through leaks in gas pipes).

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.

Gross Domestic Product (GDP)
A measure of the total economic activity occurring in the UK.

Heat pumps
Can be an air source or ground source heat pump to provide heating for buildings. Working like a 'fridge in reverse', heat pumps use compression and expansion of gases or liquid to draw heat from the natural energy stored in the ground or air.

Heavy Goods Vehicle (HGV)
A truck over 3.5 tonnes (articulated or rigid).

Hybrid Vehicle
A vehicle powered by an internal combustion engine and electric motor that can provide drive train power individually or together.

Hydrocarbon
A chemical compound comprised of hydrogen and carbon atoms, often of fossil fuel origin. Examples include methane, crude oil and oil products (e.g. petroleum, diesel and kerosene). Hydrocarbons release CO_2 upon combustion.

Hydrogen fuel cell vehicle
Vehicle powered by an electric motor, with energy supplied by a hydrogen fuel cell.

Induced cirrus cloud (IC)
A high-altitude cloud of ice crystals caused from the spreading of aircraft contrails, or triggered by aerosol emissions from aircraft exhaust. Like contrails they have a significant warming effect on surface temperatures but this only lasts up to a few hours.

Intermittent/Intermittency
If an source of energy is intermittent, it is not available continuously or potentially 'on demand' (i.e. despatchable). Many forms of renewable energy are deemed intermittent as they are driven by availability of natural resources, which may be predictable (e.g. tidal) but outside direct control (e.g. the ebb and flow of tides). Output from some intermittent renewables may be difficult to predict (e.g. wind, which is subject to forecasting error).

International Air Transport Association (IATA)
The international industry trade group for airlines.

International aviation and shipping (IA&S)
Journeys by air or sea where one of the departure/destination points is within the UK and the other is outside.

International Civil Aviation Organisation (ICAO)
A specialised agency of the United Nations, responsible for regulating international civil aviation.

International Maritime Organisation (IMO)
A specialised agency of the United Nations, responsible for regulating the maritime industry.

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 gas
A greenhouse gas covered by the Kyoto Protocol , as adopted in 1997 under the United Nations Framework Convention on Climate Change (UNFCCC). Gases covered are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), sulphur hexafluoride (SF_6), hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs).

Levelised cost
Lifetime costs and output of electricity generation technologies are discounted back to their present values to produce estimates of cost per unit of output (e.g. p/kWh).

Life-cycle assessment
Methodology used to quantitatively assess the environmental performance (e.g. emissions) of a product or service from its cradle to grave (i.e. including emissions during production and disposal).

Load factor
A measure of the output of an electricity generator relative to the maximum output it could produce if operating at full capacity in every hour of the year.

Marginal Abatement Cost Curve (MACC)
Graph showing costs and potential for emissions reduction from different measures or technologies, ranking these from the cheapest to most expensive to represent the costs of achieving incremental levels of emissions reduction.

Methane (CH_4)
Greenhouse gas with a Global Warming Potential of 21 (i.e. 1 tonne of methane corresponds to 21 tonnes CO_2e). Arises in the agriculture sector as a result of enteric fermentation in the digestive systems of ruminant animals (e.g. cattle and sheep) as well as in manures. Arises in the waste sector as biodegradable waste decomposes in landfill sites in the absence of oxygen.

Mid-merit demand
Part of electricity demand that is higher than baseload demand and present in at least 20% of the hours of the year. For example, during the day (diurnal mid-merit) and throughout winter (seasonal mid-merit).

Minimum stable generation (MSG)
The lowest level of output that can be sustained by a plant at a particular point in time (given its technical operating limits). Usually expressed as a proportion of its rated (nameplate) capacity.

$MtCO_2$
Million tonnes of Carbon Dioxide (CO_2).

National Atmospheric Emissions Inventory (NAEI)
Data source compiling estimates of the UK's emissions to the atmosphere of various (particularly greenhouse) gases.

Negative emissions
Sustainable biomass absorbs carbon in the growth stage and releases it during conversion or combustion of the final fuel. Avoiding this release through sequestering of carbon potentially offers emissions reduction over the lifecycle of the biomass, often referred to as 'negative emissions'.

Nitrification inhibitors
Chemical additives that slow the rate of conversion of fertiliser ammonium to nitrate and reduce the chances for nitrogen loss.

Nitrous oxide (N_2O)
Greenhouse gas with a Global Warming Potential of 310 (1 tonne of nitrous oxide corresponds to 310 tonnes of CO_2e). Arises naturally in agricultural soils through biological processes and is influenced by a variety of soil and nutrient management practices and activities (e.g. synthetic fertiliser application).

NO_x
Oxides of nitrogen, defined as the sum of the amounts of nitric oxide (NO) and nitrogen dioxide (NO_2). While not greenhouse gases themselves, NO_x emissions result in a short-lived warming effect by enhancing ozone, and a longer-lived cooling effect by reducing methane.

Offset credits
See carbon credits.

Peak demand
High levels of electricity demand that occur relatively infrequently (e.g. less than 20% of the hours of the year).

Plug-in hybrid Electric Vehicle (PHEV)
A vehicle that receives motive power from both a battery and a secondary source (e.g. an internal combustion engine). The battery will generally be charged in the same way as that in a BEV, but all electric range will be more limited (e.g. 40 rather than 100 miles).

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

Renewables
Energy resources, where energy is derived from natural processes that are replenished constantly. They include geothermal, solar, wind, tide, wave, hydropower, biomass and biofuels.

Renewables 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.

Resistive electric heating
Resistive electric heaters produce heat by passing an electric current through a resistance (e.g. a coil or wire) that impedes the current. Examples of resistive electric heaters are storage heaters and electric boilers.

Resource costs
Payments for goods or services, based on the economic cost of the elements or inputs used – for example, the cost of materials, salaries. Resource costs do not include taxes or subsidies, which are transfers within the economy, or welfare costs (e.g. the potential reduction in comfort levels as a result of turning down the thermostat to save heating fuel).

Sequestration
The process of removing CO_2 from the atmosphere and capturing it, particularly in biomass and soils.

Smarter Choices
Measures that influence people's travel behaviour towards less carbon-intensive alternatives to the car such as public transport, cycling and walking by providing targeted information and opportunities to consider alternative modes.

Technical potential
The theoretical maximum amount of emissions reduction that is possible from a particular technology (e.g. What would be achieved if every cavity wall were filled). This measure ignores constraints on delivery and barriers to firms and consumers that may prevent up take.

Tidal stream
A form of renewable electricity generation which harnesses the energy contained in fast-flowing tidal currents.

United Nations Environment Programme (UNEP)
International organisation that coordinates United Nations environmental activities.

United Nations Framework Convention on Climate Change (UNFCCC)
International environmental treaty, signed in 1992, with the objective of stabilising greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system.

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